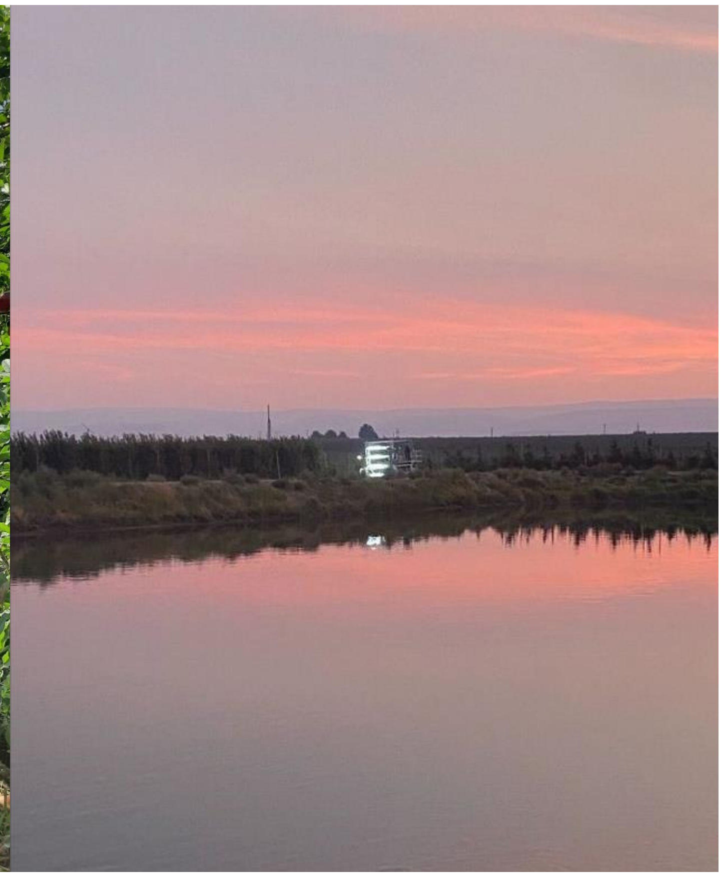
# 2023 Technology Research Review

Ines Hanrahan and scientists from Poznan University of Life Sciences (Poland) discuss the Fresh Fruit Robotics harvest robot with Avi Kahani.

Photo source: Paige Beuhler, WTFRC



Robotic picking prototype getting ready for a night of work near Quincy, WA in September 2022

Photo source: Peter Ferguson, Advanced Farm

## December 1, 2022

## Hybrid Format
## Wenatchee, WA

**Project Title: The Next Fruit 4.0**


| | | |
|---|---|---|
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**Cooperators:** Manoj Karkee and Lav Khot (Washington State University), Joseph Davidson (Oregon University)


**Project size**
**Amount:** 3,156k€ for 4 years
**Agency Name:** Dutch ministry of Ministry of Agriculture, Nature and Food Quality
**Notes:** Total project size is 3,156k€ for 4 years, the other half (1,578k€) is financed by Dutch growers and companies (in cash/in kind) and the Washington Tree Fruit Research Commission. The part that is financed by WTFRC is stated below.

| **Item** | **2021** | **2022** | **2023** |
|---|---|---|---|
| **Salaries** | $54,000 | $54,000 | $54,000 |
| **Benefits** | | | |
| **Wages** | | | |
| **Benefits** | | | |
| **Equipment** | $5,000 | $5,000 | $5,000 |
| **Supplies** | | | |
| **Travel** | | | |
| **Miscellaneous** | | | |
| **Plot Fees** | | | |
| **Total** | $59,000 | $59,000 | $59,000 |

**Objectives overall project**
Making fruit cultivation more efficient, intelligent, sustainable, and future-proof requires us to be able to monitor, manage, and make decisions at the level of individual trees. **Smart Technology** will enable getting the most out of an orchard through the targeted, efficient use of crop protection agents, plant hormones and fertilizers, while saving on labour and minimizing food waste. This all contributes to the creation of a sustainable fruit cultivation system.

The project has therefore three key objectives in relation to technology development:

1. Improving the sustainability of cultivation and the supply chain by:
   a) developing ways of applying crop protection agents, plant hormones or fertilisers to individual trees (or parts of trees) based on new ways of detecting stress, pests, and diseases (using sensors and new algorithms) and
   b) by combining data to develop new decision support models using AI. This will, for example, give decision support in storage duration and conditions to prevent loss and waste of the fruit, or help to determine the optimal dose of crop protection agents, growth regulators and fertilisers.
2. Maximising yields by optimising cultivation and storage through the optimisation of individual tree growth.

3. Minimising costs by developing multifunctional robots to replace human labour and ensure the efficient use of inputs.

The need to achieve these objectives has led to the project being organised in four cases. A brief description of the four case studies is provided below, including an explanation of how they mutually reinforce each other.

*Case study 1: Further development of precision sprayer*
The former project Fruit 4.0 demonstrated that precision spraying at the level of individual trees is possible. In The Next Fruit 4.0 we want to further develop and broaden the application of precision spraying by controlling it down to individual nozzles and by using sensors to detect pests and diseases and apply sprays in response. Being able to control sprays at the level of individual nozzles also optimises the use of regulators for growth and fruit setting, resulting in a more uniform orchard. Hot spots of insect infestation can also be controlled without spraying the whole orchard.

*Case study 2: Advanced crop management and yield registration*
This case study is based on the use of sensors to collect data and translate it into decision support models visualised as clear dashboards. This will involve making the sensor platform from the Fruit 4.0 project applicable to more than just apples. The wide range of data and information gathered will also be distilled into clear insights around cultivation management. With help from experts and the use of modern AI algorithms, decision models will be created that can contribute to optimising and improving the sustainability of fruit cultivation.

*Case study 3: Cool data*
Apples and pears are often stored for a long time, even up to the following harvest. Storing the fruit for any length of time often leads to substantial losses due to a lack of clear, objective information on how long a particular batch can be stored. This case study will focus on maximising the use of data derived from the cultivation phase (climate, crop, and soil) and the focused application of new technology (sensors), leading to decision models that deliver better risk assessments and storage strategies. This will help reduce loss and waste during storage.

*Case study 4: Multifunctional robot*
Finally, The Next Fruit 4.0 will also work on expanding the functionality of existing robots which are already in development (e.g. by adding a gripper for picking pears, or for pruning and removing suckers) and which could perform more efficiently through technological improvements and better orchard design. All of this will help solve the problem of increasingly limited availability of seasonal labour.

The results presented are from the last 12 months. Results are presented per case.

**Case study: Precision sprayer**

*Objectives*
A validated prototype precision sprayer for several fruit crops, which is directed at nozzle level on the basis of smart algorithms and decision models and combined with stress, disease and pest detection.

*Significant Findings*

- Laser scanner data can be translated into spray actions
- 2 prototype sprayers were build

*Methods*
The second year of the project will concentrate on:

- Building an improved sensor platform for a sprayer with lidar and GPS and (later in the project with RGB sensors).
- Processing data into usable data for spray decisions at nozzle level
- Build 2 sprayers with laser scanner that can spray at nozzle level and that can adapt dose on tree volume

*Results and Discussion*

With a Lidar (LIght Detection And Ranging) system of Pepperl + Fuchs three dimensional information is collected by driving through the orchard. The tree volume can be measured at different heights. Based on the tree volume at a specific location the amount of spray liquid is adjusted. For this setup Pulse Width Modulation (PWM) nozzles were used. In the past months WUR and spray machine manufacturers KWH and Munckhof worked on the integrations of the different components which resulted in 2 prototypes. Because of shortage of chips and labour it took much longer to get the prototypes ready. Therefor the planned deposition tests in the field have to be moved to next year.

Within this work package, there is regular contact with our colleagues in the US of the  Washington State University about the precision sprayer.

**Case study: Advanced crop management and yield registration**

*Objectives*

- Validated sensors and algorithms to collect physiological and phytopathological characteristics of apple and pear.
- Validated decision models developed on the basis of collected data and expert knowledge; targeted on production optimization.

*Significant Findings*

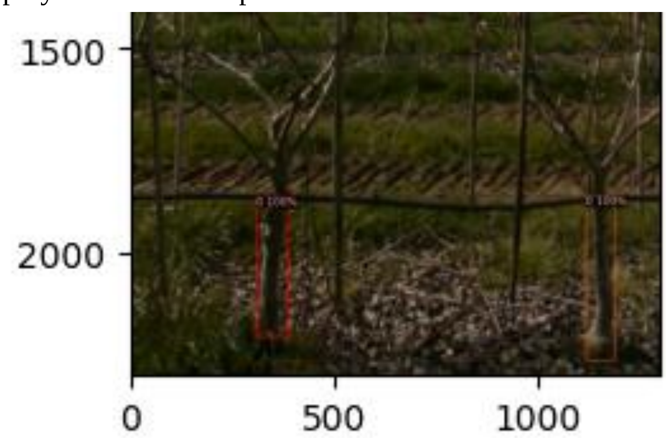
- Blossom detection method did not work sufficient enough, a higher resolution camera is needed in combination with flash lights.
- Detection method to detect fruit tree canker and apple blossom weevil
- Trunk detection to get the GPS locations for individual trees.
- Field trial on blossom and fruit thinning showed for second year in row that the orchard can be more uniform with precision spraying.
- Experiments were done to develop a thinning decision support system for Conference pear.
- Proof of principle was demonstrated for automated detection of apples in top layer of storage bins.

*Methods*
The second year of the project will concentrate on:

- Improving a sensor platform that can be used by non-professionals and is easy to transport. Sensor used are: RGB camera, laser scanner, chlorophyl sensor and GPS
- Data collection in the orchard and ground truth measurements on tree vigour, number of blossoms and fruits.
- Processing data into usable data for tree vigour, pear blossom and fruit detection
- Building data and decision support models and dash boards for growers for presentation and management at tree level
- Setting up trails on thinning based on sensor input

*Results and Discussion*

For apple a detection algorithm was designed in past but not for pear. This was designed in 2022 but the results were not sufficient to use in practice. Flower in the background from adjacent rows were also detected which caused false positives. Another way to find more flower clusters, camera's with higher resolutions need to be used next year. The last improvement is to use flash lights to overcome back light issues that were faced as well.
Algorithms for detection of fruit tree canker and apple blossom weevil were successfully developed. In the case of the apple blossom weevil we can use this information for a precision spray to control hot spots with the weevil.




The final algorithm that was worked on for in the field, was the detection of trunks to determine the GPS position of that tree. For growers this is very important since most of the orchards were not planted with GPS. In order to use precision spraying, it is important to know the exact position otherwise the wrong tree is sprayed or the collected data is also not accurate. From the first set of trees that was tested it was found that the right GPS position could be found with an average error of ~10 cm.

Related to that, field trials were done to see if the use of precision spraying would result in an higher yield or quality. The return bloom from the trial of last year showed that the return bloom of the treatment on a tree level was better than when the whole orchard was sprayed the same. Only the trees that were low in flowers last year showed too much flowers in the beginning of this year. Also the number of fruits were closer to the optimum amount of fruits in the plots where the trees were sprayed at tree level compared with the treatment on orchard level.

At harvest growers and sales organisation really like to know what the fruit quality is in the storage bins. For apple the size can easily be determined by making a picture from the top of a bin. For pear it is in development now. To make it as simple as possible to collect data of the bins a structure was developed were a picking train with several bins can drive through while making pictures when a bin is passing through. This was successful implemented. Next year the system will be tested with the apple and pear algorithm to determine size. A later development will also be to check the colour of the apples and pears but there standardized light conditions are essential.


**Case study: Cool data**

*Objectives*

The focus for this year was to select and evaluate tools for non-destructive quality assessment of fruit both preharvest and postharvest. Observed differences between batches of fruit should be related to relevant quality characteristics of the fruit. Not only aiming at quality assessment of freshly harvested fruits but also related to storage behavior of the respective batches.
In order to perform proper evaluation of the selected tools, a selection of batches that supposedly differ in (storage) quality is needed. This season was used to arrange different batches of Conference pear that can be used to evaluate the tools.

*Results and Discussion*

First the tools to evaluate the fruit have been selected. Non-destructive measurements using new tools are being related to common (destructive) quality assessment methods.

<u>Common quality assessment</u>

- Firmness, Brix, Weight
- Photographic analysis (color, shape, percentage russeting)

Nondestructive assessment

- Near Infrared – both a hand held sensor from the project partner Kubota and hyperspectral imaging from our in-house facility
- Microwave based –a hand held sensor from the project partner Vertigo



The microwave based sensor showed good relations for firmness for Conference pear. The possibility to test this also for apple is in consideration in collaboration with the WTFRC.

**Case Multifunctional robot**

*Objectives*
The main objective of the multifunctional robot case is to expand the functionality of existing orchard robots and of orchard robots currently under development in parallel research projects. The focus of the work is on two topics, namely the development of a sensing system and a gripper for picking pears and on a sensing system, robot control and end-effector(s) for robotic pruning of fruit trees and red currant bushes. On the longer term additional tasks such as automatic thinning, removing weeds and precision spraying will be targeted.

*Significant Findings*

- For robotic harvesting pear the detection system needs not only to be able detect the position but also the orientation and some key points of the fruit.
- The required motion to detach a pear from a tree is significantly different from that to detach an apple.
- Robotic pruning of fruit trees is exceptionally challenging due to the complex and dense structure and also due to the different pruning rules applied at different growers.
- Extensive knowledge and expertise on automatic pruning and fruit harvesting is present at Washington State University and Oregon State University. Close cooperation and knowledge exchange between Dutch and US researchers will be of mutual benefit.
- For the pruning of red currant bushes clearly defined rules are available. In consequence the project will target this crop first.

*Methods*
The second year of the project will concentrate on:

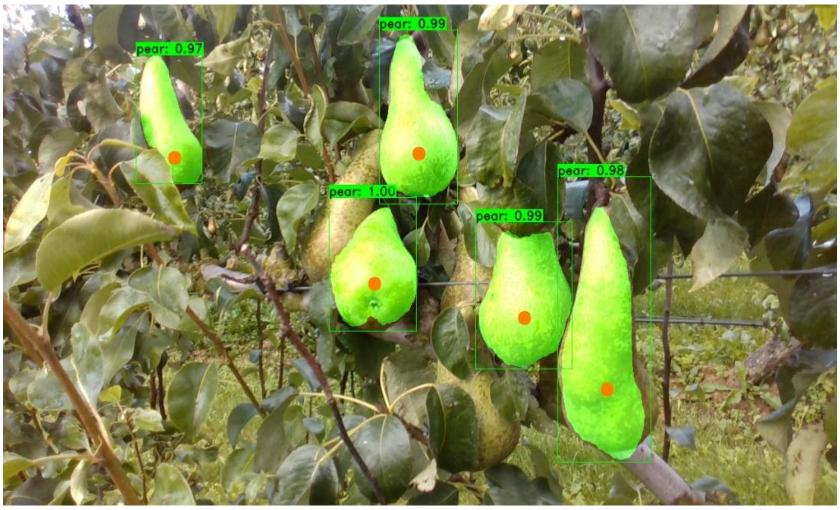
- Designing first prototypes for pruning and picking end effectors.

- Designing an algorithm to detect pears and pose estimation.
- Testing different camera’s for making 3D models of dormant red currant plants.

*Results and Discussion*

This year a first picking end effector was designed for picking pear. The end effector works by suction. With a special movement the pear is detached. The end effector was tested on a number of pears. At the moment the second prototype is designed.

In order to know where the suction cap should grab the pear, a detection algorithm was designed combined with pose estimation. Based on that the ideal position to grab the pear could be calculated.




For pruning we focussed on red currant since it has a more simple structure compared with apple and pear. A camera system was test to map the 3D branch structure of the plants. This was successful. Even the difference of 1 and 2 year old branches could be found. Another step was to design an end effector for pruning that also could hold the camera. Next winter all the components will be integrated on a robot platform and the first cuts will be made.

**Project Title:** Automated Apple Harvester

**Report Type:** Continuing Project Report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**Cooperators**: Yamaha, Kubota, Catapult VC

**Project Duration:** 3- year (already completed first year)

**Total Project Request for Year 1 Funding:** $ 180,000 (2022 - in progress)
**Total Project Request for Year 2 Funding:** $ 140,000 (2023)
**Total Project Request for Year 3 Funding:** $ 140,000 (2024)

**Other related/associated funding sources:** None

**WTFRC Collaborative Costs: None**

**Budget 1:**

**Primary PI:** Marc Grossman

**Organization Name:** Advanced Farm Technologies

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| 2022 | 2023 | 2024 |
|---|---|---|
| Half of Salary for additional mechanical engineer that will work on initial harvester development - **$50,000** | Compensation for two assembly technicians for building additional machines - **$70,000** | Half of salary for additional mechanical engineer that will work on automated stem-cutter - **$60,000** |
| Cost to have 1 full-time employee in WA during harvest season - **$30,000** | Engineering material costs - **$55,000** | Cost to have 3 full-time employees in WA during harvest - **$80,000** |
| Half of Salary for additional emulator developer - **$50,000** | Travel between WA and CA - **$15,000** | |
| Harvester Materials – Cost of 4 robots for prototype - **$50,000** | | |
| Total: $**180,000** | Total: **$140,000** | Total: **$140,000** |

**Footnotes: 2022 budget is already being funded. 2023 and 2024 total amounts match the amount originally proposed in the new proposal last year.**

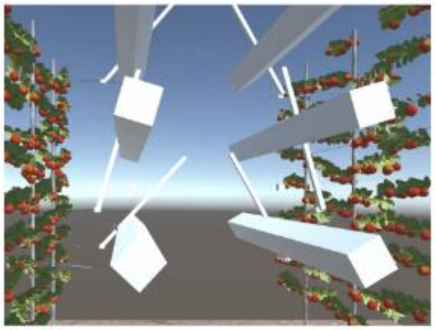
## Report

As stated in the 2021 proposal for advanced.farm, our initial objective was "to develop an automated apple harvester in order to give apple growers a sustainable solution to deal with labor shortages and rising labor costs. While we are very aware of the painful failures that have occurred in past attempts to develop an automated apple harvesting system, we believe that we have unique competitive advantages to help us meet this objective." This objective remains unchanged, and we have worked tirelessly for the past year to carry out this vision.

Our 2022 development goals submitted to the commission last year are summarized below in the italicized enumerated list. Text in the sub bullets lists our results.

1. *Build at least one robotic apple harvester that will pick in Washington apple orchards for the duration of the 2022 harvest.*
    a. advanced.farm deployed two harvesters to Washington that actively picked apples from August 1st through the beginning of November. At the time of this writing, the machines are still operating in Washington. Click here to see a video of the machine in action.
2. *Build an apple orchard emulator. The emulator is a virtual orchard and robot that can be used to test, improve, and debug the software that will control the harvester.*
    a. We built an apple emulator in the first half of the year and our testing in it proved vital to our development. As a result of our testing, we made major hardware changes to our machine design. For example, it greatly informed positioning of the robots. Since the apple harvest is only three months long, it was important to debug and verify many elements of the hardware and software before the season began. Our emulator engineering manager recently told me, "It's hard to see how our first year of apple

picking could have been so successful without the massive head-start that the emulator gave us."



3. *Leverage standard advanced.farm harvester software that is currently used on our robotic strawberry harvester.*

    a. We were able to successfully leverage our software from strawberries to pick apples, auto-drive the machine, and use machine vision to detect fruit.

4. *Build a gripper that can pick apples while minimizing drops and fruit damage.*

    a. Our suction cup gripper (pictured below) was able to pick most apple sizes. Through isolation testing, we were also able to determine that it damaged less than 5% of apples. Once grasped, we almost never dropped apples. Further in the report, I will discuss other common problems that resulted in damaged and dropped apples.

5. *advanced.farm has developed a unique robot kinematic, optimized for range of motion, cost, and cooperation between adjacent robots. It was originally intended to stack horizontally to cover multiple strawberry beds. Based upon our initial testing and designs, we intend to reconfigure these robots to be adjacent vertically, with three or possibly four robots able to cover the full height of a single vertical trellis. By utilizing a proven design and kinematic, we hope to quickly*

*achieve full coverage of the trellis across a number of several cooperating robotic arms. To limit scope, it is possible that in year one, we will only have robots on one side of the harvester, but we view picking on both sides as the needed solution.*

   a. We were able to successfully reuse the same robots that we use on our strawberry harvester as described above. We increased our scope from the original plan and put three robots on each side, six total, to pick on both sides of the row. Later in the paper, I will discuss how reusing our technology significantly accelerated our progress.

6. *Build a harvester with a drive system that can semi-autonomously navigate rows. We have carefully evaluated the space constraints to ensure our harvester can function in 10-foot rows. The harvester will be Two-Wheel Drive, unable to operate on severely steep blocks.*

   a. For most of the season, we operated the harvester with manual controls, but during the final weeks, we added a lidar sensor that has allowed us to navigate the rows autonomously. This greatly reduced our error count because we were able to stay centered in the rows. With manual controls, we often veered to one side and would then have to reset.

**Commented [d1]:** I don't know if it was greatly, or if we really have the data to prove this, it is just a gut feeling at this point. The difference in the tree structure can also impact this a lot so its hard to tell if when we were using it, the trees were just really well pruned, or it being more centered was helping. Still need to do further testing. Just a little more context

7. *For 2022, we will focus on vertical trellis and fruiting-wall architectures.*

   a. We have remained committed to limiting our scope to vertical growing systems. To pick on both sides of the row at once, it is necessary to constrain the machine to one type of architecture. Without picking on both sides of the row, it would be nearly impossible to pick fast enough to justify the cost of the machine. In the future, it will be possible to reconfigure our solution for different architectures.

8. *Integrate harvester with a bin filler and a bin system that allows bins to pass through the harvester. We will develop a method for the apples to travel to the bin, possibly involving tubes and/or a conveyor.*

   a. We purchased Van Doren bin fillers and built conveyors and belts for the apples to travel to the bin.

9. *Build a vision system to detect apples and color-pick different varieties. It will also recognize apples that are within an appropriate size profile. We will reuse the custom stereo camera that is currently deployed for strawberries, but we will need labeled data sets of the various varieties with fruit that is ripe, unripe, bruised, etc. For year one, the harvester will operate at night to mitigate the image processing challenges posed by natural lighting.*

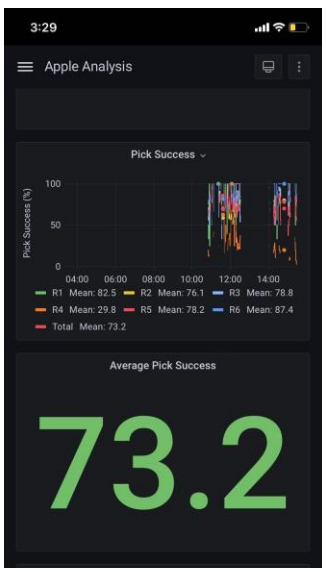
   a. The vision system has now been trained for five varieties of apples. While we spent the first half of the season picking strictly at night, we transitioned to more daytime picking as the season progressed. Our camera can also recognize size, but we did not utilize this functionality.

10. *In addition to frequent trips to Washington by members of the engineering team (especially during harvest), at least one AFT employee will live in Washington full time during the harvest season.*

   a. We sent one of our strawberry operations specialists to live in Washington continuously during the season. This was very important for farm communication and consistency. The engineering team traveled back and forth to Washington during the season. Generally, there were always at least four people from our company in Washington.

**Significant Findings**

- **Gripper:** During the pre-season development, we went through six major iterations of the gripper, eventually settling on a version that had a very low failure rate. While in the field, we paid close attention to the pick modality that should be used for each variety. For example, we found that Honeycrisp apples required a faster pull than on some of the other varieties, like Gala. At the beginning of the season, we utilized a rotation to pick Gala apples, but later found that to be unnecessary. To pick the correct modality, we paid attention to how often the stem was pulled out or if the apple was picked with the spurs attached. We were fortunately able to keep both instances low.
- **Color picking:** Throughout the season, we received high marks for our color quality. We were able to build a system that works like a control knob, where the color percentage we are targeting can be easily increased or decreased. We had a similar knob for occlusion. This means that if an apple was x% occluded, we wouldn't even try to pick it. We adjusted this number many times throughout the season as we tracked what percentage of occlusion optimized our speed and kept our number of failed picks low.




*Our data and monitoring tools allow us to track many metrics. For example, this image shows our pick success percentage which is the number of apples that we successfully pick divided by the apples we try to pick. Optimizing this number increases our overall pick-rate.*

- **Fruit damage:** As previously mentioned, our gripper caused very little damage to the fruit. We were able to test all subsystems in an isolated manner to determine where the damage was coming from. Most of the damage occurred on our conveyor belts and drop ramps, as well as the Van Doren bin filler. Throughout the season, we made four iterations of the conveyor belting. We started with purchasing them from a supplier and later fabricated them completely in-house. We created our own impact apple sensor to measure g-forces in different parts of the machine during acceleration and deceleration. The bin filler was noted as a serious issue. One of the lead engineers of Van Doren came to the field and directed us to slow down the rotation of the flaps.

- **Cables and Routing:** As seen in the picture above of the gripper, we have various cables attached to the camera and end-effector. At the beginning of the season, these cables snagged on branches when reaching into the tree. We developed a shield to prevent this.
- **Operations:** Our company has 16 robotic strawberry harvesters that are commercially leased by farmers. These machines are operated by the local farmworkers. Since this was our first year in apple harvest, our team operated the machines. While this was necessary for year one, we know that going forward we will want to pass off the operation of the machine to local operators. This will allow us to maximize run time of the machine, while our engineers focus on R&D rather than operating the equipment.
- **Orchard architecture:** Our machine picked on many different orchards. Our best consistent performances came at a Honeycrisp block that was formally trained to be a 2D wall, and a Juici orchard that was on a spindle system, but that had been meticulously pruned to be close to 2-Dimensional. We were able to achieve similar pick rates (apples per hour) on bushier orchards, but we picked a much lower percentage of the fruit and lacked consistency.

**Methods**

We went through three major iterations of the architecture of the harvester during design period. Changes included width and length of the harvester and robot placement. In total, we built three harvesters, although only two were in Washington during the season. The first harvester was finished earlier in the year. We brought it to Washington in May to test its ability to pick up bins and navigate the orchard rows. We immediately identified some needed changes while on the trip. For example, the bins used for testing at our headquarters in California were a different size than the bins at Starr Ranch. Our next version of the harvester could pick up all bin sizes. This required us to raise the harvester chassis to give more room to the bin conveyor system.

Our field visit in May also helped us realize that we would need to make the harvester slightly narrower in order to fit in the rows. To make the harvester six inches narrower, we brought the frame of the chassis and the tires closer together and made the harvester six inches longer. We initially estimated our machine's width allowances for a 10-foot row, however we later learned that we would need to allow for more clearance due to branches that stick into the row.

The original harvester that we built was not deployed to Washington for the harvest season, but it continued to be used for development purposes. We built a mock-trellis in our facility next to the harvester so we could start debugging issues with the robots while they were picking (plastic) apples.

The second harvester we built was deployed to Washington on August 1st and picked its first apple that same day. The third harvester was sent to Washington a week later. Throughout the season, we referred to one of the machines as the "production harvester" and the other as the "R&D harvester." Functionally this meant that we operationally planned for one harvester to have as high of an uptime as possible, while the other was being utilized to test iterations to both software and hardware. During these tests, we would take the time to bring the harvester into the rows, verify these changes, then push the improvements over to the production harvester

**Commented [d2]:** Change to say, "being utilized to test iterations to both software and hardware. During these tests, we'd take the time to bring the harvester into the rows, verify these changes were improvements, then push the improvements over to the production harvester."

We worked with four different farms during the season. We started the season picking for NWFM in Mattawa, where we picked Wildfire Galas and Premier Honeycrisps. We purposely chose this partnership because we had been told that they would start harvest as early as August 1st. It was important to us to be able to spend as much time in Washington as possible during the harvest season. After several weeks at their ranch, we moved to another Mattawa ranch run by Starr Ranch. We continued to work with Starr Ranch for the rest of the season, mostly in Quincy. We also had short trials with Columbia Reach in Cowiche and IFC/Agrimacs in Quincy. When targeting potential partners, we focused on orchard architecture and excitement for the project. At the core of our company is a belief that our success will be intrinsically tied to how closely we work with our farming partners. While we may be good at building technology, we need partners that are experts in farming if we are to build something truly valuable.

**Results and Discussion**

Throughout the season, our machines picked 600 apples per hour, on average. We had peaks higher than 1500 apples per hour. To put this in perspective, in strawberry harvesting, it took us over three years to pick at a rate of 1000 berries per hour. Our fast progress in apples is directly attributable to reusing our technology that had already been purpose-built for robotically picking fruit on farms.

Our damage rate continued to be too high throughout the season. Starr Ranch provided us with quality checks near the end of the season which showed we were at around a 35% damage rate. While this was improvement from the beginning of the season, it was still too high. Due to the short harvest season, our company made the decision to prioritize picking improvements that needed to be developed while there were apples on the trees. We knew that the conveyor belts could be improved during the off-season.

Being our first season picking apples, we were unsure how to direct people to prepare their orchards for us. As a result, most of the blocks we picked on were not optimized for robotics, so therefore we picked a relatively small percent of the total fruit available. We spent some time on orchards that were more meticulously trained, and on these we did acquire a large percentage of the fruit. The below photos show a before and after snapshot of fruit picked on a robot-optimized orchard. A lot of the fruit left over would have been picked when we went down the next row. In the future, we believe it will be important to pick

a minimum of 30-50% of the fruit with robots. This way, if an orchard typically has two manual harvest passes, it can transition to needing only one.

**2023 & 2024 Development Goals**

advanced.farm's 2023 and 2024 objectives as set forth in our 2021 proposal are listed below in italics.

*2023 Development Goals*

1. *Modify current harvester(s) based on learnings during the 2022 harvest season and build more harvesters for a total fleet size of at least four harvesters. By having more harvesters, we can prove our model of one person running a fleet of multiple harvesters at once. We can also gain more learning than we would with just one.*
2. *Improve and specialize gripper based on variety specific learnings. In our current testing, we have learned that we will want to tailor our gripper based on varietal differences. The information gathered in 2022 will inform further gripper iterations that are optimized for varieties. As an example, we have found that with Envy apples we are much more likely to pull off fruiting wood than we are with Pink Lady apples.*
3. *Demonstrate positive unit economics - not on a spreadsheet, but in the orchard. We don't intend to show this through the whole season in 2023, but on a micro-scale we want to show that our pick-rate (how many apples we pick in one time unit) can be cost-effective - both for AFT's cost of building the machines and for growers' cost to lease the machine.*
4. *Add robots to both sides of the machine so that we can pick on both sides of the row.*
5. *Pick apples while the harvester is moving.*

*2024 Development Goals*

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 to further reduce labor cost. (Prior to 2024, stems will need to be cut manually.)*

From a high-level, many of these goals were already met in 2022. For example, we already pick apples on both sides of the row, and we have already implemented auto-drive. Additionally, our vision system has been improved to pick apples both day and night. Of course, we will want to further improve on these systems, but we are very pleased with our rapid progress. For example, our daytime picking is still less effective than night-time. This is something we will continue to work on. Below I list our updated plans for 2023 and 2024.

**2023**

1. Change the conveyor belts and bin filler to bring damage rate down to less than 15%.
2. Adjust harvester size to accommodate nine-foot rows. The majority of formally trained vertical orchards are grown in nine-foot rows. This year we couldn't accommodate anything narrower than nine feet six inches.
3. Build user friendly operating interface. To operate the harvester this year, you needed to use a laptop and understand basic software code. Our strawberry harvesters have joysticks and simple controls. For this upcoming season, we want to be able to train local operators to use the machines instead of using our engineering team.
4. Increase average apples per hour from 600 to over 1000.
5. Build three new machines. To maximize our run-time, we will build two production harvesters and one R&D machine.
6. Work with our growing partners to optimize their orchards for robots. This year we had little pruning done in preparation for the season. For next year, we will work with our partners in the winter to optimize an area for our trial.
7. Trial new systems such as an automated stem trimmer and drive system updates that allow us to handle steeper slopes.

**2024**

1. Increase average pick rate to 1800 apples per hour.
2. Decrease damage rate to be under 10%.
3. Automate bin conveyors to drop bins off the back automatically when they are full.
4. Optimize operations so that one human operator can operate three machines at once.
5. Grow fleet size from three machines to at least six machines.
6. Begin to generate meaningful revenue from contracts with growers.

**Economic model**

We have built the below economic model to show different performance scenarios that would lead to at least breakeven for the farmer if they were to use our equipment. All these scenarios would lead to us being able to commercialize our apple harvesting business.

| Robotic Harvest Monthly Charge | Operating Hrs / Month | Apples / Hr | Robotic Harvest Fee / Bin | Operator Cost / Bin | Maintenance & Repairs / Bin | Total Cost / Bin |
|---|---|---|---|---|---|---|
| $10,000 | 364 | 1800 | $31 | $7 | $4 | $42.38 |
| $11,000 | 364 | 2200 | $27 | $6 | $4 | $37.17 |
| $15,000 | 364 | 2700 | $31 | $3 | $3 | $36.45 |

The robotic harvest monthly charge is based on our current business model in strawberry harvest, in which our machines are leased for a monthly fee. It is possible that we could sell the machines in the future, but for the purposes of this model, the monthly fee represents the value we are adding in the month.

Operating hours/month are based on the machine running for 26 days and 14 hours a day. To do this, the machine will need to be very reliable. We started picking strawberries in 2018, and 2022 was the first year that we were able to reliably have two shifts per day. Thankfully, our shared technology has led to the apple harvester starting with a higher level of reliability.

The robotic harvest fee/bin is the monthly Service Fee ÷ total bins picked during month. Bins are assumed to be 2000 apples. The operator cost/bin assumes all-in hourly operator cost of $20/hr and a ratio of one operator to three robotic harvesters. The maintenance & repairs/bin includes the cost of gas, oil changes and consumables that grower would bear in the future.

We have good reason to believe that these numbers are achievable. This year, we already saw peak pick rates close to the 1800 apples per hour outlined in the first scenario.

**Funding Request**

| **Year** | **2023** |
|---|---|
| Compensation for two assembly technicians for building additional machines | $70,000 |
| Engineering material costs | $55,000 |
| Travel between WA and CA | $15,000 |
| **Total Funding Requested for 2023** | **$140,000** |

| Year | 2024 |
|---|---|
| Half of salary for additional mechanical engineer that will work on automated stem-cutter | $60,000 |
| Cost to have 3 full-time employees in WA during harvest | $80,000 |
| **Total Funding Requested for 2024** | **$140,000** |

**Conclusion**

We are passionate about working with the Washington farming community and truly desire to add value by building robots that can alleviate their labor issues. Our work with members of the WTFRC over the last year has proven invaluable. We have appreciated the funding and hope that this fruitful partnership can continue.

Project Title: End Effector and Apple Transport System

**Primary PI:** Dominic Milano

**Co-PI:** Gualberto Hernandez E.

**Co-PI 2**: Soummya Datta

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**City/State/Zip**: Merced, CA 95340

**Project Duration:** 2-Year

**Total Project Request for Year 1 Funding:** $ 146,000
**Total Project Request for Year 2 Funding:** $ 99,000

**Budget**

| Item | 2022 | 2023 | |
|---|---|---|---|
| **Salaries** | 67000 | 40000 | |
| **Benefits** | 23100 | 15000 | |
| **Wages** | | | |
| **Benefits** | | | |
| **Equipment** | 55900 | 26000 | |
| **Supplies** | | | |
| **Travel** | | 18000 | |
| **Miscellaneous** | | | |
| **Plot Fees** | | | |
| **Total** | Total year 1 $146,000 | Total year 2 $99,000 | Total year 3 |

**Objectives**

The primary objectives of this effort will be
1. Design and build a Robotic Apple Harvester System to include: an Apple Harvest End Effector, arm structure, and an Apple Harvest Transportation (to bin) Subsystem.
    A. Pick will preserve fruit, tree and bud integrity
    B. Transporter will prevent bruising and puncturing

C. Economically designed for low cost of manufacturing

2. Measure the performance of a single subs system to prove both design and economic viability
    a. End effector (each) will be capable of picking once every 3-4 seconds
    b. End effector (each) will be engineered to reliably perform 3 million plus actuations
    c. Full gripper and subsystem (Harvester Wall with 8 end effector configuration) will be engineered for sub-half second harvest while moving through an orchard on a platform.

This is a two-year proposal with a focus in the first year on proving performance of a single Apple Harvest End Effector and showing the full design and architecture of the Apple Harvest Transportation Subsystem. During the second year, the focus will be to prove the performance and economic viability of the full architecture by integrating and verifying the performance of up to 2 Apple Harvest End Effectors to the Apple Harvest Transportation Subsystem. Once complete MTG will invite collaborators from growers within The Washington Tree Fruit Research Commission to test and use the system.

## Significant Findings:

- Preliminary tests show picker to chassis apple transportation system operates and viable to use for further testing and likely commercial use.
- Initial design shows commercially viable costs and low complexity of design
- Physics model and simulations shows speed between apples to be below 4 seconds/arm
- Reliable picking of 1 apple with end effector design

## Method: System Design

1. Overview

The design effort in this study will be focused on the controller, hardware and the mechanisms required for physical robotic harvest. The system architecture will include the advanced control system, the wall and 8 harvest end effectors. An identified challenge seen as a primary factor of failure in similar systems in the past is the development of an advanced control system. MTG will ensure that the hardware and control system is tackled early on to address this challenge. The architecture will integrate into known platform configurations, and computer vision systems in the future to allow for autonomous harvest.

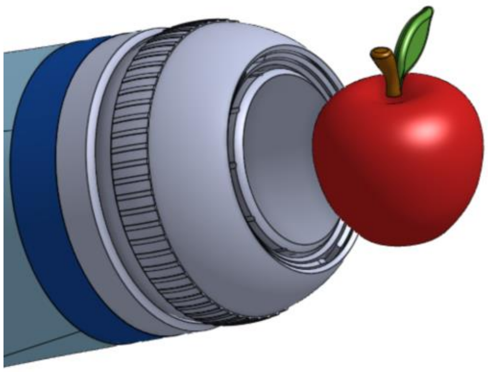

**Figure 4:** Apple Harvest End Effector. Note: material will be compliant and will not damage fruit.

Design considerations for the end effector and arm include material considerations for: handling of the fruit, manufacturability, cost and reliability. As discussed in the objectives, the end effector actuation is being designed such that total harvest time per apple per arm takes 3-4 seconds. The harvest end effector arm includes: a telescoping tube that is attached to a two axis gimbal mechanism at its base. Once the apple is selected, and the gimbal mechanism orients the arm, the telescoping tube will extend the end effector to the apple. At this point the end effector will grasp and twist to remove the apple. A full-time budget for the system is developed during our study. Initial calculations show the two processes, closing of the end effector and twisting, is estimated to take 300-500 ms per apple. The telescoping tube and gimbal mechanism concepts are shown in Figure 5.

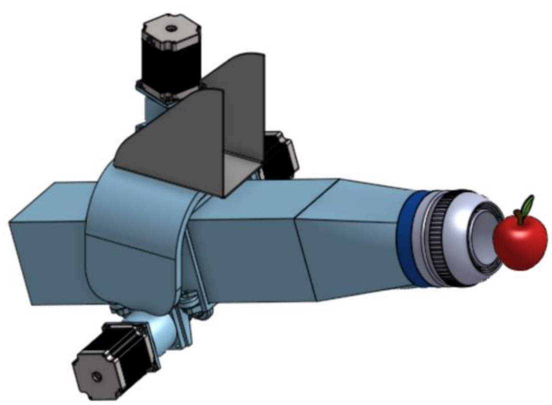

*Figure 5 – Very Early Prototype*

**Figure 5:** Robotic Arm:Telescoping Arm shown in yellow and black. Two axis gimbal (rotating joint) shown on the left.

Within the first year the robotic arm will be developed at a prototype level. Utilizing 3-D printining and onsite machining MTG will ensure rapid itterations get the Harvest End Effector to a reliable low cost design.

As for the control system. This will be developed in parallel such that within the first year of design the arm will be able to execute a harvest routine reliably.

**Method: System Evaluation**

The end effector will be evaluated against a requirements matrix for performance prior to integration to the Apple Transport Wall. By doing this, MTG will ensure that we verify everything that will be important to both growers and a potential manufacturer. The following items will be evaluated.

Functionality:

1. Grasping effectiveness of apple
2. Positioning to apple (3 varieties and fruiting wall configuration chosen in year 1)
   a. Telescoping tube functionality
   b. Gimbal mechanism functionality
3. End effector closure functionality
4. End effector twist functionality
5. Apple handling – measurement of bruising, puncture potential and other damage through full system.
6. Labor requirements for system use (anticipation of 1 user per harvest system)

Reliability:

1. Actuator life for all actuators
2. Material performance over life of material
   a. End effector closing material.
   b. Tube and transport material.

In additional to functionality and reliability, the full system will be evaluated for manufacturability, ruggedness, and cost.

During year 2, the system will be available for growers to utilize and provide feedback. Our anticipation of a successful development effort will be in-field trials starting with growers (3+ growers, 2 week trials each) with a fruiting wall (spindle) configuration that are open to equipping one of their existing platforms with an Apple Transport Wall with one (1) to two (2) Harvest End Effectors.

Challenges that will be verified during the start of test will include logistics of apple handling to bin, interaction of apples from various end effectors, and the ability to grasp apples in multiple trellis orientations and varieties.

## Results and Discussion

We focused on three major areas of research and Development:

End-of-arm Tool, Arm design, and economics behind the physics and cost of manufacturing.

### END-OF-ARM TOOL

The intent of End-of-arm Tool was to create a system that enables very quick, reliable grasping of a variable size apple from multiple approach vectors. Our work on the design resulted in the fundamental understanding of the fruit-mechanism interaction. The main area of testing focused on the device encompassing, actuating, and releasing the apple. The risks that remain are the potential damage imparted onto the buds/branches and other. We suspect there will be a great amount of tuning for the controls and approach to the apple and greater understanding of proper materials to prevent fruit damage that needs to take place during field testing occurring in 2023.

### ARM DESIGN

The largest technical challenge for the arm design is the balance between cost, speed, and reliability. We designed our testing to take place in two distinct portions; the end of arm tool and in parallel, the arm itself. Our focus for 2022 has been the experimentation of multiple motion control techniques, material selection, and actuation methods.  The challenges encountered during testing has been to control the deceleration of the apple through the robotic arm. With multiple materials and mechanisms selected for the internal transport system of the arm we are continuing testing to find one that prevent puncture and bruising. We believe we have a reasonable combination of tubing and a food grade soft material to handle. Field testing will need to take place to understand the final effects.

### COST AND PHYSICS

Understanding the time allotment to pick each apple and total picks per hour are crucial to design success. If the goal is to keep or lower total cost of harvest this needs to be balanced with a proper cost of performing these tasks. To address this pick time we have been developing our simulation and control model sin parallel with mechanical design. With data (in picture and video form) that we collected in multiple varieties we calculated the median distance away from each other an apple in each of our arm “sectors” are. From here we created our models of moving between each of those apples including actuation for grasping. Our models have confirmed each arm can indeed perform 1 pick in under 4 seconds with commercially available components. However the number of arms per side must be increased by 4 for a total of 12 arms. This increase will likely not increase the cost in a substantial way due to decreased components cost compared to the 8 arm configuration.

**Project/Proposal Title:** Modeling orchard effects on meteorological measurements

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**Cooperators**: METER Group, Pullman, WA

**Report Type:** Continuing Project Report

**Project Duration:** 3 Year

**Total Project Request for Year 1 Funding:** $60,025
**Total Project Request for Year 2 Funding:** $62,916
**Total Project Request for Year 3 Funding:** $65,113

**Other related/associated funding sources:**

**WTFRC Collaborative Costs:**
**Budget 1**
**PIs:** Lee Kalcsits, Lav Khot
**Organization Name: Washington State University**
**Contract Administrator: Anastasia Mondy**
**Telephone: 916-897-1960**
**Contract administrator email address: Anastasia.mondy@wsu.edu**

| Item | 2020 | 2021 | 2022 |
|---|---|---|---|
| **Salaries** | $13,245.75 | $40,693 | $42,321 |
| **Benefits** | $4,517.25 | $14,223 | $14,792 |
| **Equipment** | $36,150 | $0 | $0 |
| **Travel** | $6,000 | $8,000 | $8,000 |
| **Total** | $60,025 | $62,916 | $65,113 |

**[1] Salaries include 2 months of postdoc time at AgWeatherNet in year 1 and 4 months in years 2-3, 1.5 months of research associate time in the Kalcsits lab (years 1-3), 1 month of field meteorologist time at AgWeatherNet (years 1-3), and 1.75 months of systems analyst/programmer time (years 1-3).**
**[2] Benefit rates are budgeted for 35%.**

**[3] Equipment includes 8 weather sensors, 8 soil moisture sensors, and 2 instrument towers.**
**[4] Travel budgeted for travel to field sites, meetings with collaborators and presentation of results at industry winter meetings in Washington State.**

**Objectives.**

1. Measure the effects of irrigated orchard canopies on meteorological measurements relative to standard unobstructed, unirrigated meteorological sites.
2. Construct statistical models that estimate the magnitude of orchard effects on air temperature, relative humidity, and wind speed as a function of weather conditions and irrigation.
3. Develop and implement algorithms in AgWeatherNet to dynamically correct for orchard effects and support orchard-specific delivery of weather data, forecasts, and decision-support tools.

**Year 1 –**
*Goal:* Identify paired sites, acquire instruments, initiate field measurements for both paired Atmos 41 stations and met towers. Restructure database as needed to secure Tier 3 station data.
*Progress:* Deployed 8 sets of paired ATMOS-41 stations in early summer 2020 which continue to operate. Completed two weeks of met towers observations at Sunrise research orchard in early August 2020. Completed database restructuring to support Tier 3 station data.
**Year 2 –**
*Goal:* Complete full year of field data acquisition, initiate modeling, code framework required to implement transformation models.
*Updates:* We have now acquired 1+ year of field data. We are making some adjustments to field deployments based on lessons learned in year 1. Modelling has been initiated.
**Year 3 –**
*Goal:* Continue field data acquisition as needed, complete modeling, complete coding to automate model implementation in the AWN system.
*Updates:* No change to year 3 goals.

**Significant findings.**

1. Daily orchard effects: Results indicated lower solar radiation (28.8 W $m^{-2}$ to 93.2 W $m^{-2}$), air temperature (0.23 ℃ to 1.21 ℃) and wind speed (1.1 m $s^{-1}$ to 1.32 m $s^{-1}$) inside the orchard for all the training systems. The relative humidity inside the orchard was higher (0 to -10.60%) due to evapotranspiration from the orchard canopies. Among the solaxe, V-trellis and bi-axis modern orchard training systems, the solaxe training system has the largest magnitude of orchard effects.
2. Monthly orchard effects: Orchard effects vary from month to month depending on the phenological growth stages. The peak solar radiation offset ($SR_o$), air temperature offset ($AT_o$), relative humidity offset ($RH_o$) and wind speed offset ($WS_o$) were 230 W $m^{-2}$, 3.9 ℃, - 32%, and 1.9 m $s^{-1}$, respectively. These peak offsets were observed during May to July. The solaxe trellis trained apple trees have the highest magnitude of orchard effects compared to the other trellis systems.
3. Seasonal variability in orchard effects: The peak (offsets) in $SR_o$, $AT_o$, $RH_o$ and $WS_o$ were 687 W $m^{-2}$, 3 ℃, -27% and 2.3 m $s^{-1}$ during the summer season (June, July, and August) while the same for the winter season (December, January, and February) were 100 W $m^{-2}$, 1℃, -5% and 1.4 m $s^{-1}$, respectively. The air temperature offset was higher during the night-time (0.5 to 3 ℃) compared to daytime (-1.4 to 1.8 ℃).

4. <u>Effect of irrigation or heat stress management practices:</u>
Overall, overhead sprinklers had prominent effect on air temperature (+ve offset) and relative humidity (-ve offset) compared to other variables. The orchard effect was evident during 1 to 6 pm, which is the typical heat stress management period for the orchards. Drip irrigation had lesser, but non-negligible effects on in-orchard atmospheric conditions. *Micro-emitter or overhead sprinklers were detected by the rain gauge data and under-tree/ drip irrigation event were detected by soil metric potential increase trends.*

**Methods.**

**Objective 1 –** Paired stations in the experimental orchard have been collecting meteorological data since 2020 season. Collecting paired stations data is important for quantifying the orchard effects for different apple orchard sites and orchard training systems (Figs. 1 and 2). The collected data has been being used for quantifying the orchard effects. 15 mins recordings of meteorological variables namely solar radiation, air temperature, relative humidity, wind speed and precipitation were compared from the paired in-field and open-field stations at the three experimental sites namely SMART 1 (Pasco, WA, USA), SMART 2 (Grandview, WA, USA) and Quincy, WA, USA. To compare the orchard effects in trellis systems, the data related to days with overhead sprinkler operation were removed. In the later part of the study, effects of overhead sprinklers and irrigation were quantified during the crop growing season (May to September). Overhead and under-tree sprinkler/drip operating conditions were detected using rain gauge (threshold: 0.25 mm) and daily soil metric potential (threshold: 1.25 kPa) increase data, respectively. All the data has been analyzed in Python 3.8.

(a) (b) (c) (d)

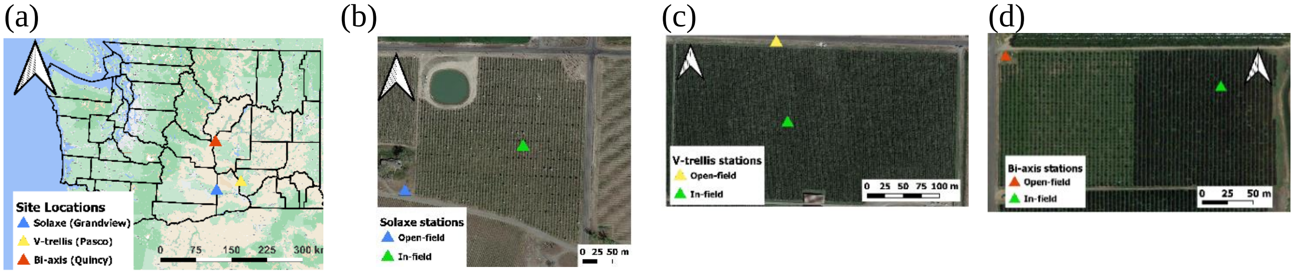


Fig. 1. Map of (a) the combined experimental site locations and individual sites with paired in-field and open-field weather stations for (b-d) three sites, respectively.

(a) (b)

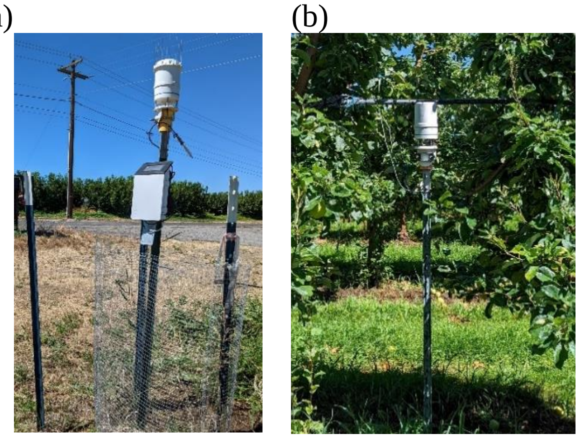

Fig. 2. (a) Open-field, and (b) in-field weather station installations at bi-axis orchard.

Objective 2 – This is an on-going effort. Four machine learning (ML) models have been trained and compared for highest accuracy in predicting the in-orchard meteorological variables. The models with the best accuracy and computation expense balance will be used with AgWeatherNet station observations and forecast to predict in-field conditions. Independent models are developed for solar radiation, wind speed, air temperature and relative humidity. Four models will be constructed for each meteorological variable for potential orchard effects including dry conditions, overhead sprinkler operation, under or drip irrigation operation and precipitation events. Use of this model array will allow for growers to understand the effect on in-orchard conditions under different management scenarios.

Objective 3 – This is an on-going effort. Open-field to In-field machine learning models will be tested for AWN current weather conditions and weather forecasts when model development and testing is complete. These models will then be implemented along with the AWN forecast to predict real time orchard-specific weather conditions and orchards effects corresponding to different management scenarios.

## RESULTS AND DISCUSSION

### Objective 1

**1.1. Daily orchard effects.** Table 1 reports the daily orchard effects on solar radiation ($SR_o$), air temperature ($AT_o$), relative humidity ($RH_o$), and wind speed ($WS_o$). In general, the solar radiation inside the orchards was lower than that of the open-field due to shading by the orchard canopies. However, the timing of shading varies with respect to the orchard training system. The wind speeds inside the orchards are lower than the open-field weather station data as the canopies cause friction which reduces wind speed and creates more turbulent motion. Among the solaxe, V-trellis and bi-axis modern orchard training systems, the solaxe training system has the largest magnitude of orchard effects.

Table 1. Daily orchard effects on solar radiation ($SR_o$), air temperature ($AT_o$), relative humidity ($RH_o$), and wind speed ($WS_o$) measurements.

| Variables* | Statistics | Orchard training system | | |
|---|---|---|---|---|
| | | Solaxe | V-trellis | Bi axis |
| $SR_o$($W/m^2$) | Mean | 93.20 | 32.17 | 28.80 |
| | SD | 83.47 | 30.20 | 26.59 |
| | CV (%) | 90 | 94 | 92 |
| $AT_o$ (°C) | Mean | 1.21 | 0.23 | 0.28 |
| | SD | 1.30 | 0.62 | 0.47 |
| | CV (%) | 107 | 270 | 168 |
| $RH_o$ (%) | Mean | -10.60 | 0.94 | -2.24 |
| | SD | 9.98 | 5.68 | 5.08 |
| | CV (%) | 106 | 604 | 227 |
| $WS_o$ (m/s) | Mean | 1.32 | 1.11 | 1.10 |
| | SD | 0.67 | 0.56 | 0.54 |
| | CV (%) | 51 | 51 | 49 |

**1.2. Monthly orchard effects.** Figure 3 shows mean monthly offsets between open- and in-field (left) air temperature ($AT_o$), (right) relative humidity ($RH_o$) for apple orchards with different training systems. Orchard effects vary from month to month depending on the phenological growth stages. The solaxe training system, which has strong and vigorous canopies have higher magnitude of orchard effects compared to the V-trellis and bi-axis training systems. The peak air temperature offset ($AT_o$), relative humidity offset ($RH_o$) was 3.9 ℃, and - 32%, respectively. These peak offsets were observed during May to July.

Overall, the air temperature and relative humidity effects increase from April and peaked in July, which is also the month where the mean air temperature was highest. During July, the $RH_o$ effects were -33%, -11% and -8% for solaxe, V-trellis and bi-axis, respectively. Cooler temperature and higher humidity inside the orchard are majorly due to evapotranspiration of the canopies. During the dormant season, the orchard effects were minimal.

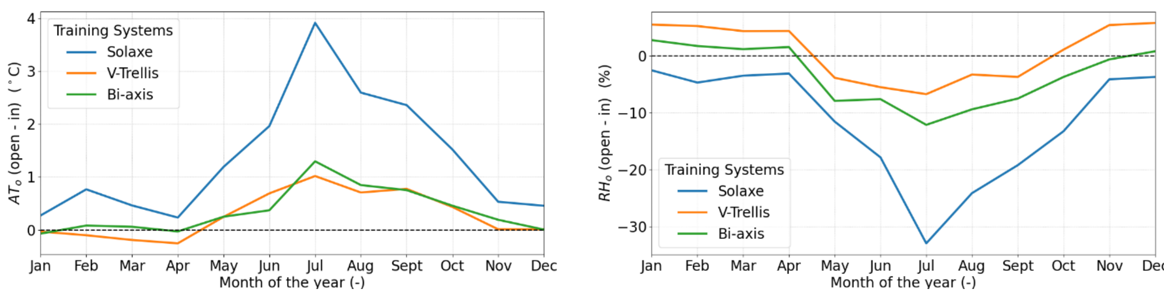


Figure 3. Mean monthly offsets between open- and in-field (left) air temperature ($AT_o$), (right) relative humidity ($RH_o$) for apple orchards with different training systems.

**1.3. Seasonal hourly orchard effects.** Figure 4 shows the mean hourly seasonal offsets in solar radiation, wind speed, air temperature and relative humidity. Orchard effects vary across the seasons and are highest during the summer and lowest during the winter. The effects also differ during the daytime and nighttime hours.

The solar radiation offset ($SR_o$) in solaxe trained apple orchard have a single peak that occurs at 12-13 hours while the V-trellis and bi-axis has two peaks occurring at early morning and either noon time (Bi-axis) or afternoon (V-trellis). This indicates different shading of the in-field sensor by the respective orchard training system.

The $AT_o$ show contrasting scenarios during daytime and nighttime. In general, the orchard is cooler than the open field during the nighttime, when the air temperature is usually low. However, during the daytime, the orchard canopies warm up gradually (indicated by decreasing positive $AT_o$) as $SR_o$ increases to the point that the inside temperature is higher than the outside temperature around noon (indicated by negative $AT_o$). As the orchard receives lower solar radiation (indicated by higher positive offset), it is likely that the warm air gets trapped by the canopies impeding the wind to mix this warm air, thereby resulting in higher temperatures inside the orchard (0.1–1.5 ℃ warmer) around noon.

The $RH_o$ is highest during the summer season when air temperatures and solar radiation effects were also higher. The RH effect during the nighttime varies from -1 to -10%, -5 to -24%, -1 to -17% and +4 to -6 % during spring, summer, fall and winter seasons, respectively. During daytime, the RH effects varies from +4 to -10% during spring, -5 to -27% for summer, +5 to -12% during fall, and +11 to -5% during winter. The saturation vapor pressure is lower for cold air meaning less water vapor can exist in the air before it condenses into liquid compared to warm air. Decreasing saturation vapor pressure due to decreasing air temperature at night causes the relative humidity effects to be higher.

Wind effects are higher during spring (0.9 to 2.3 m $s^{-1}$) and summer (0.8 to 2.3 m $s^{-1}$), when there are higher wind speeds, and comparatively low during fall (0.8 to 1.7 m $s^{-1}$) and winter season (0.8 to 1.4 m $s^{-1}$).

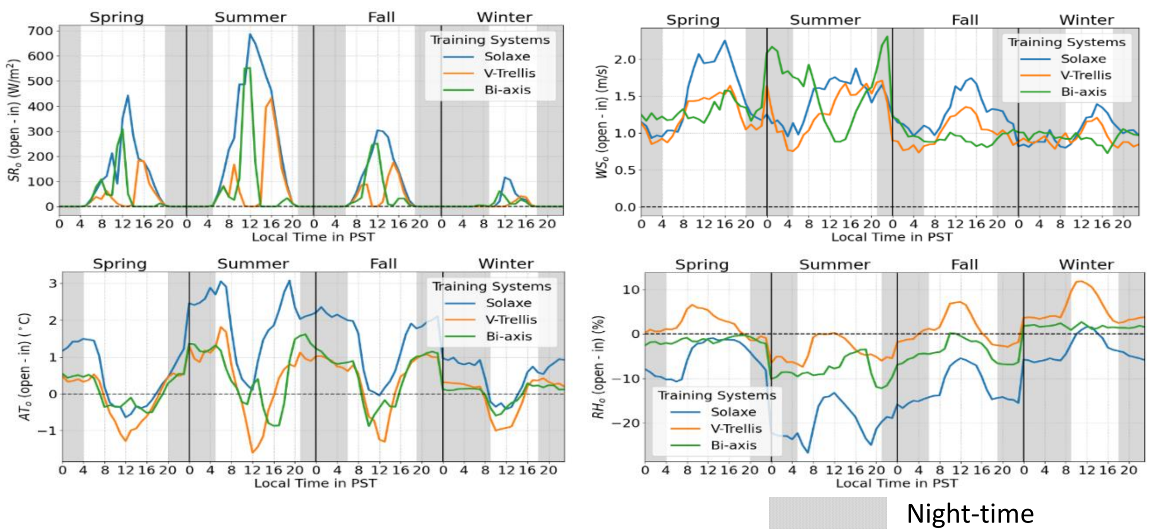


Figure 4. Mean hourly seasonal offsets between open- and in-field (top left) solar radiation ($SR_o$), (bottom left) air temperature ($AT_o$), (top right) relative humidity ($RH_o$), and (bottom right) wind speed ($WS_o$) for apple orchards with different training systems.

**1.4**. **Effect of irrigation/heat stress management.** Orchards effects are expected to vary depending on the management practices. For instance, when micro-emitters or sprinklers are operated for heat stress management in apples, moisture is added to the orchard microclimate, which results in cooler air temperature inside the orchards. These effects are less likely to be observed on a normal rainfall day. Therefore, it is important to treat the orchard effects differently for different conditions. In order to understand the effects of management practices, hourly orchard effects for four categories namely, wet days (open-field precipitation & in-field precipitation > 0.25 mm), overhead sprinkler days (open-field precipitation ≤ 0.25 mm & in-field precipitation > 0.25mm), under/drip irrigation days (daily soil metric potential increase > 1.25 kPa), and no irrigation days (daily soil metric potential increase ≤ 1.25 kPa) were quantified.

Figure 5 shows the box-whisker plots of hourly offsets in (a) air temperature, (b) relative humidity for wet days, overhead sprinkler days, under tree/drip irrigation days and no irrigation days during the growing season (May to September). Overall, overhead sprinklers had prominent effect on air temperature and relative humidity compared to other variables. The effects were large during 1 to 6 pm, typical heat stress management period for the orchards. The effects also lingered during the early evening/night hours.

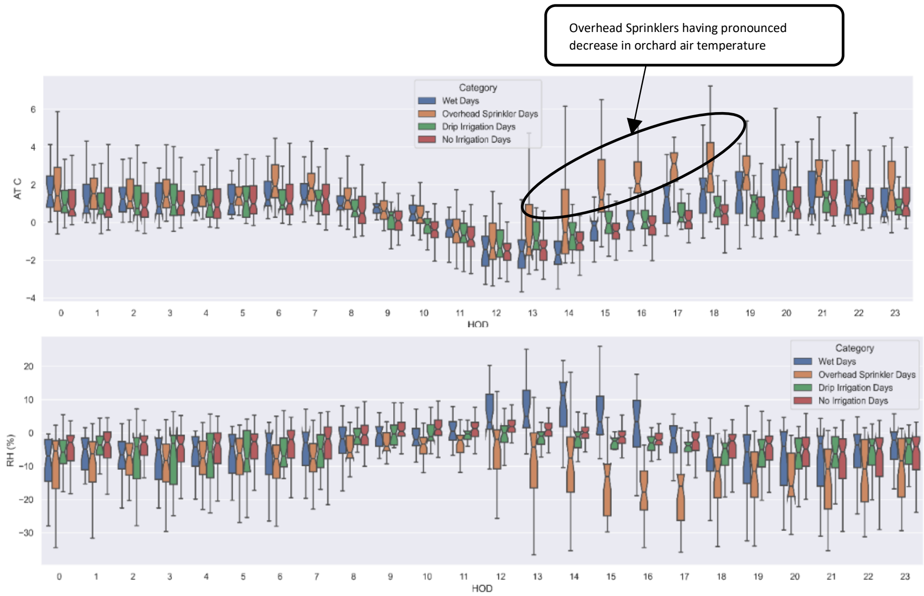

Figure 5. Box plots of hourly offsets in (a) air temperature, (b) relative humidity for wet days, dry days, overhead sprinkler days and under or irrigation days during the growing season.

**Project Title:** Decision Support Tool for Precision Orchard Management

**Report Type:** Continuing Project Report

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**Cooperators**: Dave Allan (Allan Brothers Fruit Co)

**Project Duration:** 3 Year

**Total Project Request for Year 1 Funding:** $73,569
**Total Project Request for Year 2 Funding:** $77,335
**Total Project Request for Year 3 Funding:** $71,596

**Other related/associated funding sources:** None

**WTFRC Collaborative Costs:** None

**Budget 1**
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| **Item** | **2020** | **2021** | **2022** |
|---|---|---|---|
| Salaries | $31,331.00 | $32,271.00 | $26,622.00 |
| Benefits | $8,311.00 | $9,206.00 | $8,162.00 |
| Wages | | | |
| Benefits | | | |
| RCA Room Rental | | | |
| Shipping | | | |
| Supplies | $2,986.00 | $4,000.00 | $4,000.00 |
| Travel | $3,000.00 | $3,000.00 | $3,000.00 |
| Plot Fees | | | |
| Miscellaneous | | | |
| | | | |
| | | | |
| | | | |
| Total | $45,628.00 | $48,477.00 | $41,784.00 |

**[1]Salaries includes a Graduate Research Assistant on a 12-month, 0.49 FTE appointment in years 1 and 2, and a 9-month, 0.49 FTE appointment in year 3. Salaries also include 0.25 months per year for Joe Davidson and Cindy Grimm.**
**[2]Leaf samples are included in the supply budget.**
**[3]Travel budget is requested to support mileage and lodging for data collection and field experiments.**

**Budget 2**
**Co PI 2:** Manoj Karkee
**Organization Name:** Washington State University
**Contract Administrator:** Katy Roberts
**Telephone:** 509-335-4564
**Contract administrator email address:** katy.roberts@wsu.edu

| **Item** | **2020** | **2021** | **2022** |
|---|---|---|---|
| Salaries | $17,840.00 | $18,554.00 | $19,296.00 |
| Benefits | $5,101.00 | $5,304.00 | $5,516.00 |
| Wages | | | |
| Benefits | | | |
| RCA Room Rental | | | |
| Shipping | | | |
| Supplies | $4,000.00 | $4,000.00 | $4,000.00 |
| Travel | $1,000.00 | $1,000.00 | $1,000.00 |
| Plot Fees | | | |
| Miscellaneous | | | |
| | | | |
| | | | |
| | | | |
| Total | $27,941.00 | $28,858.00 | $29,812.00 |

[1]**Travel budget is requested to cover the mileage for field experiments.**

The standard practice of broad-acre management does not result in targeted actions that are optimal for individual trees – this reduces the impact of management decisions and wastes resources while falling short on achieving the yield and quality potential of individual blocks. **Our team's overall goal is to improve fruit quality and yields by managing individual trees through a combination of automated sensing, learning algorithms, decision support tools, and precision application with variable rate technology**. While for this project we focus on matching nitrogen fertilizer to nitrogen demand, our long-term vision is to extend this framework for farming at the tree level to other orchard management decisions (e.g. plant growth regulators, root pruning, tree pruning, chemical thinning). The conceptual framework that we have developed for precision nitrogen application is shown in Fig. 1 and includes the following sequence of activities:

1. Build a site map of individual trees (performed once at the beginning of the project)
2. Use non-contact sensing to estimate tree nutrition (performed annually)
3. Recommend tree-specific fertilization plans using decision support tools incorporating machine learning
4. Apply variable rate nitrogen using real-time vehicle localization and precision technology
5. Use historical data to improve the performance of the decision support tool

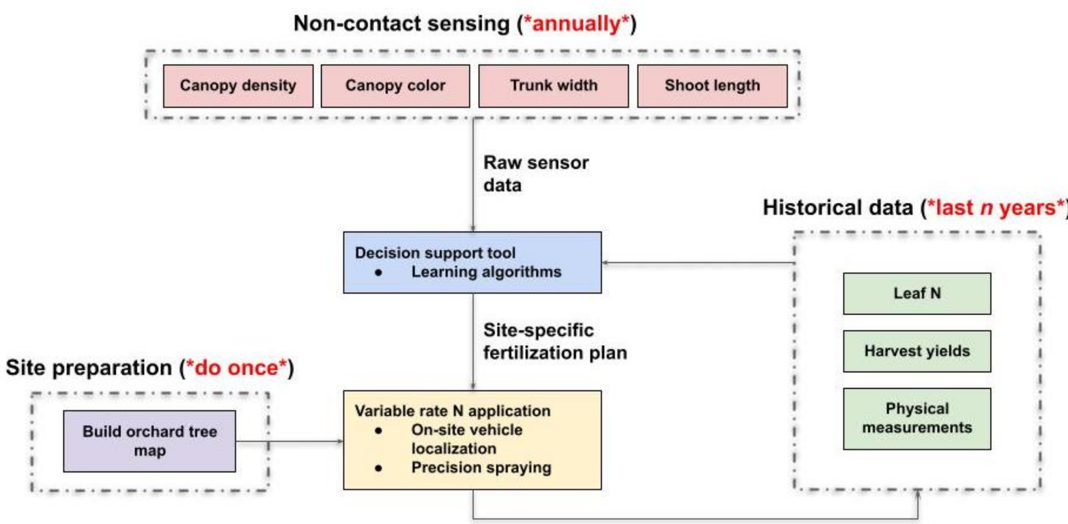


**Figure 1. Project framework. A detailed tree map is developed for the site at the beginning of the project. Raw sensor data on various orchard parameters is used as input to a learning algorithm that provides precision fertilization plans. Onsite vehicle localization is used to execute precision application of nitrogen. Historical data on destructive leaf N measurements, horticultural measurements, harvest yields, etc. is used to tune the learning algorithm.**

To implement the framework shown in Fig. 1, we have created the following three specific research objectives:

1. Develop a ground vehicle-mounted sensor system that *i*) maps the geographic location of individual trees within an orchard block; and *ii*) measures plant parameters (e.g. shoot vigor, trunk cross-sectional area, and fall leaf color) to estimate the nitrogen status of individual trees
2. Develop a decision support tool that recommends nitrogen application levels per tree and tracks the tree's long-term response

3. Develop and demonstrate a proof-of-concept precision spray system that localizes the vehicle with the orchard map, identifies the neighboring trees, and then selectively applies the desired level of nitrogen within the root zone

This continuing report summarizes research progress for the performance period of November 2021 – October 2022. The most significant findings from this performance period include the following:

- Consumer grade RGB-D sensors and state-of-the-art deep learning models can be used for automatic measurement of trunk cross sectional area
- Trees in the test plot are more likely to have excess nitrogen than be nitrogen-deficient
- While additional analysis is required, preliminary results show that canopy density measurements are positively correlated with shoot vigor assessments provide by a subject matter expert
- Temporal changes in leaf yellowness/color is a potential indicator of tree nutrition; preliminary results indicate that nitrogen-deficient trees turn yellow sooner

**Objective 1: Orchard mapping & nitrogen sensing**

**Task 1 - Tree trunk detection (OSU lead, WSU participant)**

We previously reported results on the detection of tree trunks using computer vision. This year we improved the deep learning model to include an estimate of trunk cross sectional area (TCSA), which is an important metric for measuring tree productivity in terms of wood mass and is typically correlated with fruit yield. From the data we have collected over the past several years, TCSA has also been shown to have a slight positive correlation with nitrogen status and is therefore one of the parameters being collected in order to design a decision support tool. Additionally, trunk width provides a useful data point for in-row localization, which will be explained in more detail in Obj. 3/Task 1.

**Methods**: We have developed an automated method of trunk width estimation using a consumer-grade RGB-D sensor and a state-of-the-art deep learning approach. The RGB-D camera (Intel RealSense D435i) was directed towards the base of the trees so that it captured the graft union and about the first meter of the trunk. The sensor produces an RGB image with a depth value for each pixel, which can then be used to generate a 3D point cloud of the scene. Some typical trunk images can be seen in Figure 2. The images were collected on three separate occasions to capture variability in tree growth and environmental conditions (e.g. lighting). This variability in training data helps develop models that are more robust in the real world.

**Figure 2. Sample RGB images of the trunk during peak vegetation (*left*) and dormancy (*right*). The test block at Yakima Valley Orchards (Prosser, WA) uses a tall spindle system (Jazz) with a vertical trellis.**

The first step in estimating the trunk width is to segment the trunk in the image. For this step we use the Masked-attention Mask Transformer (Masked2Former) model, a deep learning algorithm that was trained on the labeled data described in the previous paragraph. The output of the model is a mask, or the area of the image with the trunk. Next, we calculate the medial axis of the mask and then take a slice of pixels at the desired height (see Figure 3). We then use the point cloud to find the depth of the pixels that constitute the width, i.e., the distance between the camera and the tree. This depth, along with the camera's field of view and the resolution of the image, is used to calculate the distance per pixel at the tree's location relative to the camera. Finally, we multiply this per pixel distance by the total width of the slice in pixels to estimate the width of the trunk.

**Figure 3. An illustration of the medial axis (yellow) and trunk slice (green).**

**Results & Discussion**: The automated width estimation technique was tested on three diverse datasets using human measurements as ground truth (measurements taken 20-30 cm above the graft union with calipers). The mean absolute errors against the manual data were 0.305 cm, 0.294 cm, and 0.295 cm for the three datasets, relative to an average tree width of 6.71 cm (~5% error). The average image inference time was within 0.67 seconds per estimate. Figure 4 shows the predicted width plotted against the actual width for representative rows from each of the three data sets.

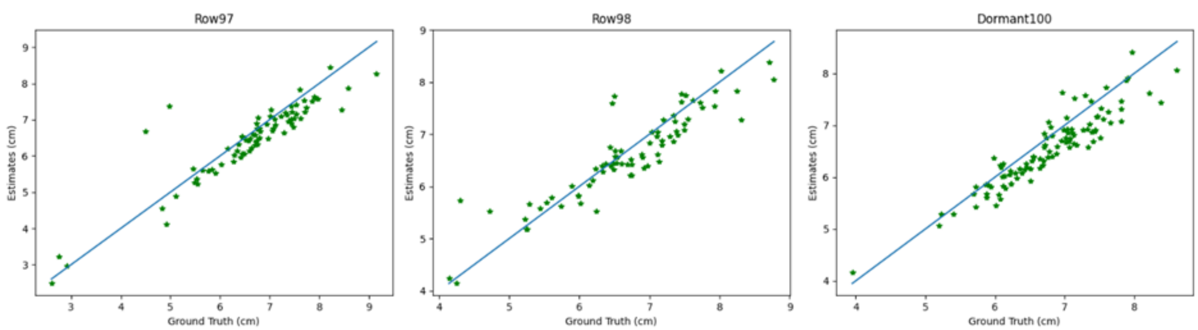


**Figure 4. Width estimation vs. the ground truth manual measurements for each of the data sets.**

**<u>Task 3 - Nitrogen measurements and non-contact sensing (WSU lead, OSU participant)</u>**

This task includes annual leaf mineral analysis as well as the development of non-contact sensing methods for estimating the features that we hypothesize are key indicators of tree nutrition. Figure 5 shows spatial plots of leaf nitrogen for each of the 200 treatment trees for the past three years. In general, it is more likely that trees will have excess nitrogen than be nitrogen-deficient. In the following subsections we present results from our non-contact sensing work. Based on conversations with our grower collaborator, we have prioritized canopy density and temporal changes in canopy color.

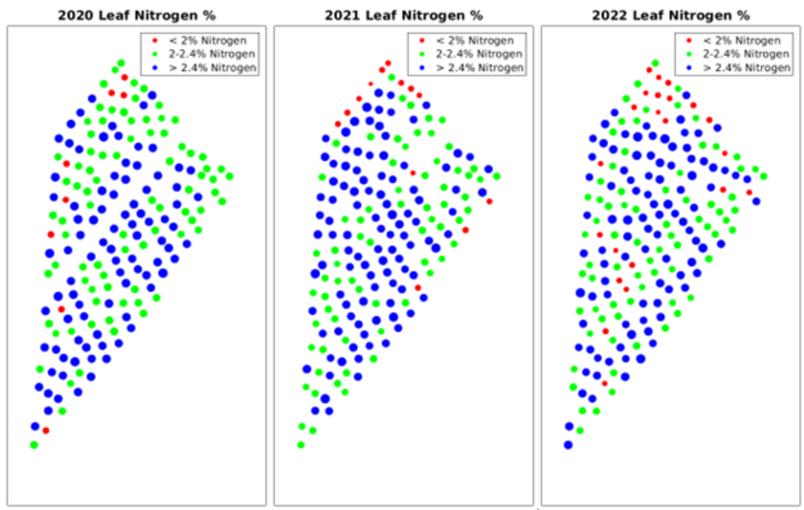


**Figure 5. Spatial distribution of nitrogen within the orchard for 2020-2022. The location of the dot for each treatment tree corresponds to its actual position in the orchard and the size and color correspond to the leaf nitrogen content.**

## Canopy density estimation

**Methods:** We collected data in July 2021 at Yakima Valley Orchards (Prosser, WA) using a ground utility vehicle and a ZED2 camera (Figure 6) which provides a depth estimate from a stereo vision pair. Images were taken from the moving vehicle 1.5–2 m from the row of trunks (in natural lighting conditions) so that the entire canopy was visible in a single image. The frames containing the treatment trees were manually annotated and extracted during post-processing. We used the ZED python API to extract the depth and RGB images of each frame with a treatment tree.


**Figure 6. Ground utility vehicle and imaging sensor used to capture canopy images.**

We then applied K-means clustering to the images to separate the visible sky from the vegetation as the sky had a clearly different color. After the separation of the background sky, we used a depth threshold at 85 percentile to remove the background trees (i.e. trees in rows behind the target row). A dynamic (percentile-based) depth threshold was used over a fixed threshold as this would adapt to the differences in depth of the trees from the imaging system and since the majority of the pixels were occupied by the foreground/target tree canopy. After the foreground tree canopy was segmented, we fit a fixed-size rectangle of 850 x 2058 pixels to each tree so that the area around the trunk of the tree was covered and not affected by branches from neighboring trees. We then calculated canopy density within the rectangle for each tree using equation 1. Figure 7 shows the sequence of operations.

$$Canopy\ Density\ =\ Pixels\ occupied\ by\ vegetation/\ Total\ number\ of\ pixels \qquad (1)$$

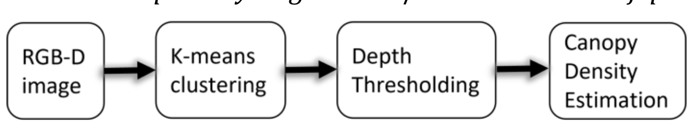


**Figure 7. Data collection and image processing flow for canopy density estimation.**

As an estimate of the canopy density, an expert grower with more than thirty years of experience was asked to participate during data collection and rate the trees on a scale of 1 to 5 – 1 being lowest vigor and 5 being the most vigorous. The grower completed this assessment twice so that any bias would be averaged. The canopy density of the tree can be related to the vigor of the tree or the amount of growth. The vigor ratings were based on visual assessment of the shoot growth throughout the tree. These ratings were used as a ground truth to compare the performance of the density estimation algorithm.

**Results & Discussion:** After the segmentation of the trees into foreground and background, the density of each sample tree (within the corresponding bounding box) was estimated using equation 1. The analysis for one of the treatment trees is shown in Figure 8. Figure 9 shows a comparison of canopy density with the expert's canopy vigor estimation. We calculate density on a continuous scale (0-1) and compare with the expert's assessment, which uses a discrete scale (1-5). A linear fit of the median canopy density from each of the discrete values of the expert's vigor assessment returned an $R^2$ value of 0.82. We did not find a strong correlation between the calculated canopy density and leaf nitrogen content.

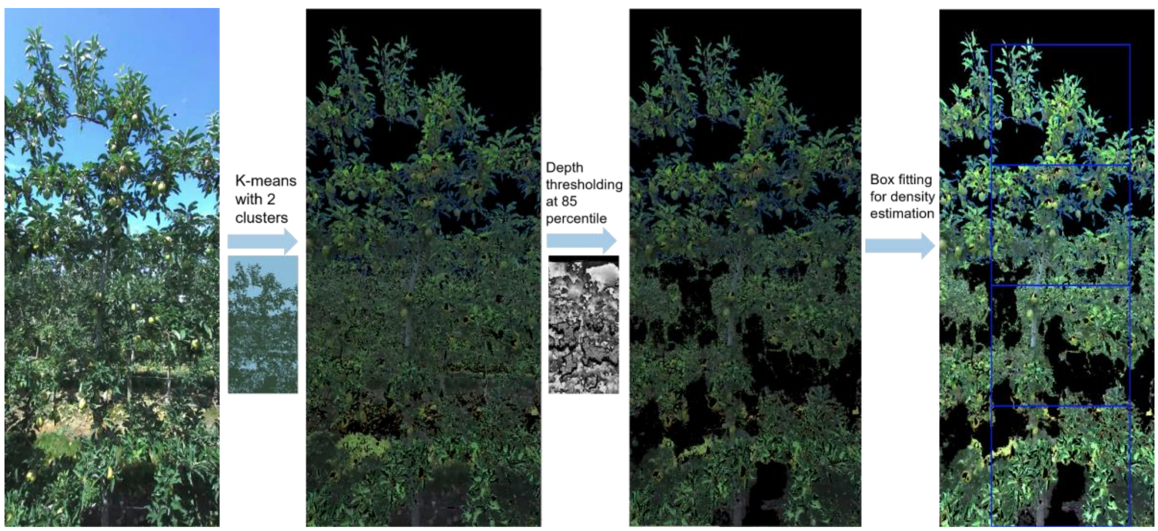


**Figure 8. A sample tree with results at different stages of segmentation during canopy density estimation.**

__Temporal leaf color assessment__

**Methods:** Another parameter of interest is the temporal change in leaf color during the fall. For this study we collected images of the leaves' color change from green to yellow over six weeks starting on October 8, 2021 (more data is being collected now for 2022 season). The data collection setup and the color during the different weeks of the study for one of the sample trees are shown in Figure 10. The point cloud obtained from the camera was thresholded using color and depth thresholds and downsampled uniformly at a 10:1 ratio (Figure 11). The downsampled point cloud was then clustered using a hierarchical clustering technique on the CIE-L*a*b color space. A hierarchical K-means clustering was used to first group the points into 20 clusters. A threshold in both a* and b* spaces for the group centers was applied to merge the classes into 3 final clusters: $Yellow$, $Green$, and $Trunk$. The $Yellow$ cluster included the foliage that had

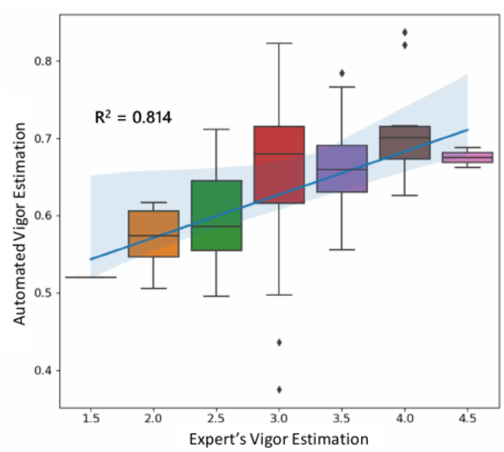


**Figure 9. Relationship between automated canopy density estimation and expert's estimation of canopy vigor.**

turned yellow, the *Green* cluster included foliage that was still green, and the *Trunk* cluster included the remaining points from the trunk, branches, some brown leaves, and soil from the background (and the leaves that had turned red on a few trees). The final output from the clustering algorithm included three clusters: Green cluster ($c_g$), Yellow cluster ($c_y$), and Trunk cluster ($c_t$). The result of the clustering technique for one of the sample trees is shown in Figure 12 where yellow, green, and trunk clusters belong to $c_y$, $c_g$, and $c_t$ respectively.

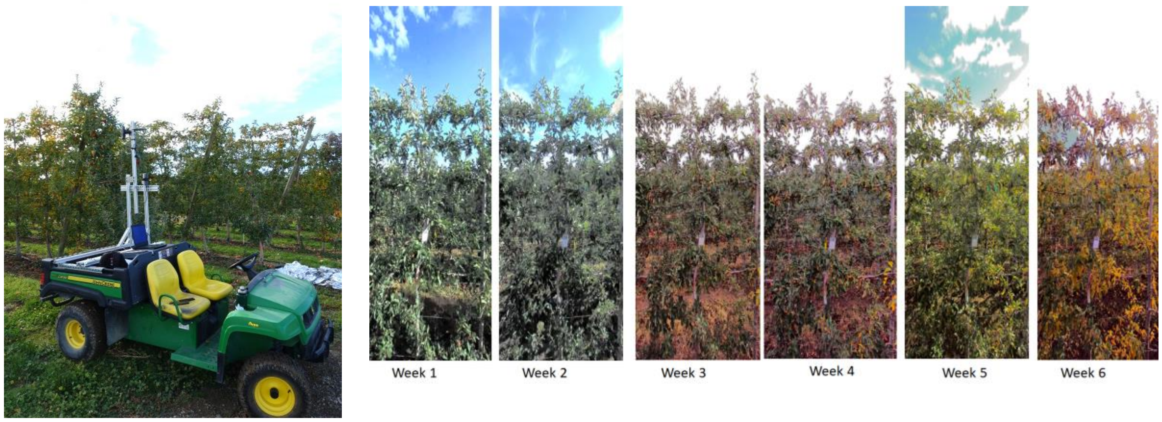


**Figure 10. Data collection setup and color change during the six weeks of the study.**

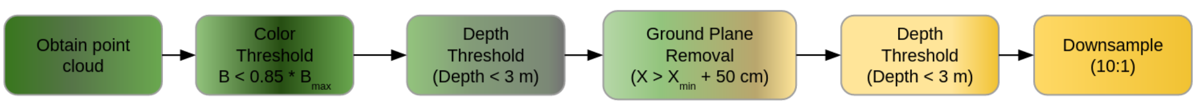


**Figure 11. Sequence of activities to segment a tree image during the temporal analysis of leaf color.**

After the grouping of points into three clusters/classes, the Yellow ($c_y$) and Green ($c_g$) classes were used to calculate the *yellowness* of each tree, a metric that we defined to indicate what fraction of the foliage is yellow as compared to green . The *yellowness* of each tree was calculated using equation 2.

$$yellowness = (y - g) \,/\, (y + g) \quad (2)$$

where,

$y$ = number of pixels/points in Yellow Cluster, $c_y$

$g$ = number of pixels/points in Green Cluster, $c_g$

**Results & Discussion:** The *yellowness* of each tree was calculated over the six weeks of the study. A plot of yellowness for all trees during the six weeks is shown in Figure 13. The results show a general trend of yellowness increasing with each week (i.e. trees turning more

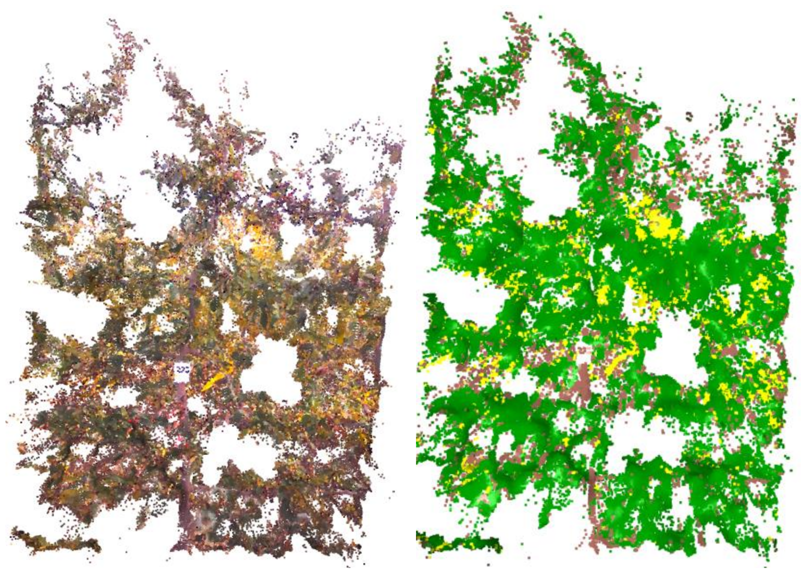

**Figure 12. Segmented point cloud and clustered point cloud (i.e. Green, Yellow, and Trunk cluster) of a sample tree.**

yellow), as expected. The boxplot shows that all trees start out at a $yellowness$ of ~-1 during the first week (i.e. all trees were completely green). However, at week 3 we start to see an increase in $yellowness$. At week 4, the change is more prominent where there is a significant increase in $yellowness$. By week 6, most of the trees have a high $yellowness$ value (i.e. they are almost through the complete color change and have turned yellow). However, there are still some trees with negative $yellowness$ (i.e. still on the greener side).

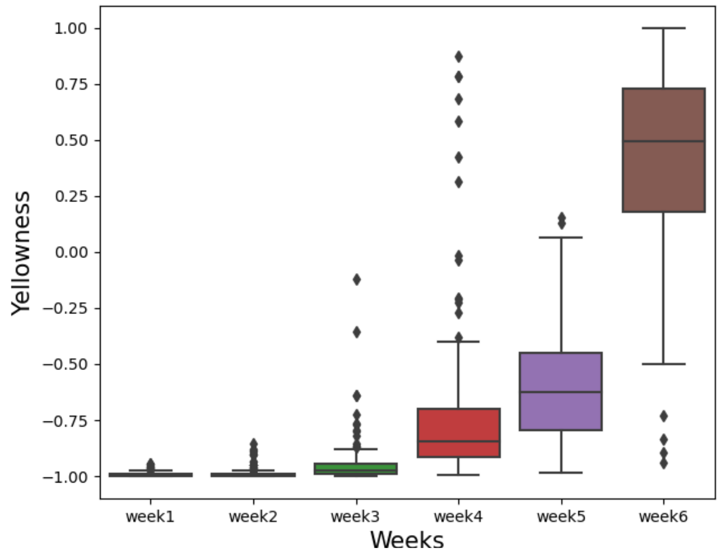


**Figure 13. Yellowness for all trees during different weeks of study.**

We have classified all trees into five classes of nitrogen status: Very low N ($N < 1.7$), Low N ($1.7 < N < 2$), Good N ($2 < N < 2.4$), High N ($2.4 < N < 2.6$), and Very high N ($N > 2.6$). Figure 14 shows the yellowness values by week with a color code assigned to trees from the different nitrogen classes. Trees with lower N start the transition earlier in the season. At week 4, this is more clear as the trees with lower N start the transition to yellow. However, most of the higher N trees are still towards the greener side. At week 6, most of the lower N trees are already at yellowness index of +1 (i.e. completely yellow), however, there are still quite a few higher N trees transitioning color. This transition is affected by a number of factors including environmental stress, nutritional stresses, and aging. The results as shown in Figure 14 show correlation between the $yellowness$ and the nitrogen content at different weeks ($R^2 = 0.14 - 0.18$). The results indicate that yellowness of a tree at different weeks and the pattern in which they are changing can be a potential indicator of the nitrogen status in the tree. Also, weeks 3-4 can be a good time to differentiate between high N and low N trees as the trees with low N start to change color.

**Shoot length estimation**

**Future work**: We are attempting to estimate shoot lengths from dormant season data. We captured images and point clouds during the winter of 2022 before pruning so that the overall growth of the shoot during the season can be determined. The point cloud data will be used to segment shoots, which usually have different orientations and cross-section thicknesses than trunks and branches. We plan to use eigenvalues of the local neighborhood of points to provide semantic labels to each point and then identify the points belonging to a shoot. After the identification of the shoot points, the point cloud can be skeletonized to obtain the trajectory and length of the individual shoot identified. An example of the current method of clustering using eigenvalues and eigenvectors is shown in Figure 15 where red points are points belonging to a shoot.

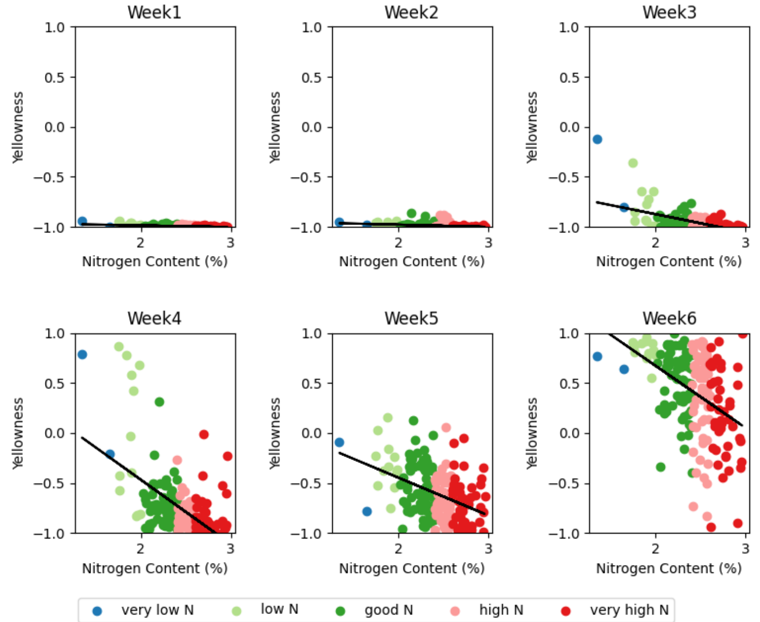


**Figure 14. Yellowness during different weeks of the study for trees with different nitrogen levels. Week 1 started on October 8, 2021.**

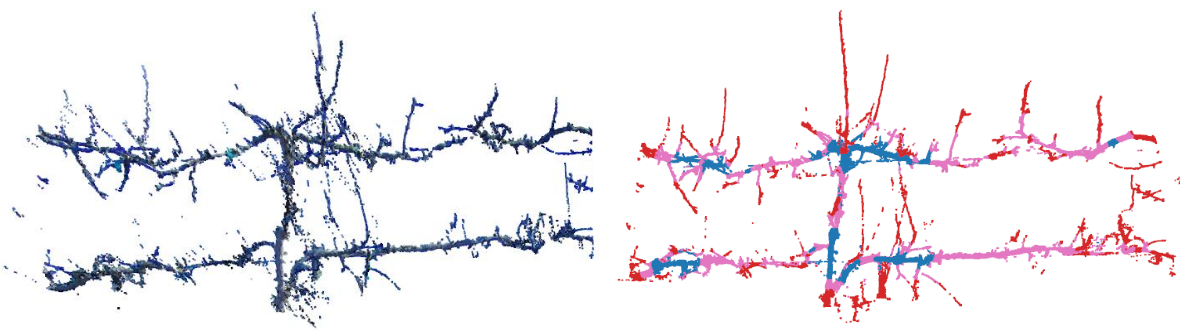

**Figure 15. Original point cloud (*left*) and clustering of point cloud (*right*) to detect the points belonging to shoots based on eigenvectors and eigenvalues.**

### Objective 2: Decision support tool (WSU/OSU joint lead)

**Future work:** We will be using all of the parameters described previously in a decision support tool for classifying the trees and recommending nitrogen application rates for each tree. Our approach will be to combine the features and their distributions to create a classifier and then train the classifier using the data collected over the previous years of the project. We will be using the grower's recommended N fertilization rate as feedback to adjust the model. We will focus on suggesting a rate of application to the grower and updating our model based on changes in leaf nitrogen next year. We will also investigate the potential of using fruit yield and quality to optimize the decision support tool.

**Objective 3: Variable rate N application**

**<u>Task 1 - Vehicle localization (OSU lead, WSU participant)</u>**

To autonomously track the metrics of individual trees over time, a vehicle must be able to localize itself within a row so that it can determine which tree it is looking at (and then later match the recorded data to that tree). To this end, we have continued refining a system for in-row localization that uses a particle filter and two sensors, an inertial measurement unit and a camera.

**Methods**: Thus far, we have created a simulation (Figure 16) to evaluate how the particle filter performs with various orchard configurations and sensor capabilities. Upon start-up, as can be seen in the figure, the particles are spread out around the starting position of the vehicle. As the vehicle moves, new information is obtained from the sensors which allows the system to determine the particles that are more or less likely, which is then used to eliminate some particles and propagate others. The first sensor, the inertial measurement unit, is used to determine how far the vehicle moves or rotates. The second sensor, the camera, is used to detect nearby trees and their position relative to the vehicle. This information, along with a map of the actual tree locations, can then be used to compare the trees the system would expect to see if it was at each of the particle locations with the trees it actually sees. Using statistics, the tracking algorithm can iteratively narrow down its location. Finally, as mentioned in the previous task, trunk width measurements from the camera have been added as another feature for improving the precision of the location estimation.

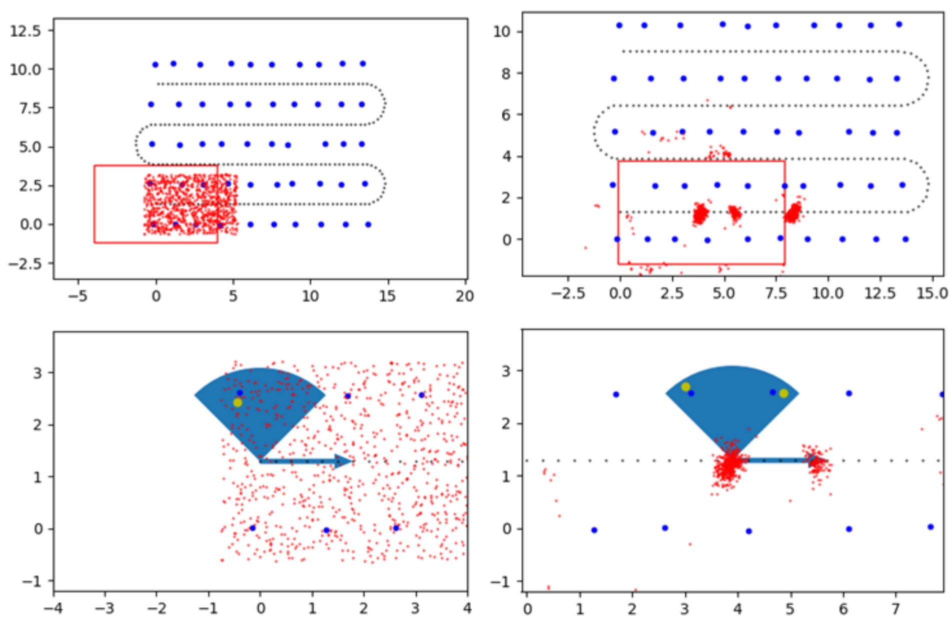

**Figure 16. Screenshots of the particle filter simulation that is being used to refine in-row localization. The top left plot shows the simulation upon startup and the top right shows it after the vehicle has moved. The red dots are particles, which represent possible poses of the vehicle, the blue dots are trees, the yellow dots are where the system thinks it sees a tree. The red squares in the top displays show the views of the bottom displays, and the black dots show the path the vehicle will take. Lastly, the arrow with the arc is the actual vehicle position, with the arrow showing the vehicle's orientation and the shaded arc showing what the camera can see. Note, this is only for illustration purposes, the system does not know its actual location, only the general area it will start in.**

**Results & Discussion**: The simulation has been a helpful tool for evaluating new particle filter algorithms as well as the effects of changing the orchard configuration and sensor capabilities. The results were generally as would be expected. For example, increasing the variability in the spacing between the trees helped the system localize as it was easier to distinguish between different areas along the row. Additionally, adding the tree width sensor also allowed the vehicle to localize quicker and more precisely. Alternatively, decreasing the range at which the camera could detect trees had a negative effect on the system's capabilities, especially if the threshold was lowered to the point that it could only ever see one tree at a time.

During the upcoming year we will build on the in-row localization work by developing a more advanced simulation in Gazebo, an open-source 3D robotics simulator that integrates a physics engine and support code for sensor simulation and actuator control. With Gazebo, we will be able to develop and evaluate software that could be deployed on an actual robot. The first step will be to create the simulated environment; our intent is to populate the orchard world with apple trees grown from an L-Py simulation (a computational technique for realistically modeling the growth of plants). Once we create a digital orchard that represents our test plot, we will then add an autonomous ground vehicle to the simulation and begin to integrate various sensors, algorithms, and control schemes.

**Schedule**

Table 1 shows the project's original objectives, subtasks, and current schedule (an **X** marker indicates an activity in progress). During the first 28 months of this project, we have focused on collecting extensive datasets (i.e. sensors, horticultural measurements, and yield/quality at harvest) and developing computational techniques for trunk detection, non-contact N estimation, and vehicle localization. During the upcoming year, we will dedicate additional resources to using the collected datasets to develop a Decision Support Tool for precision fertilization plants. We will also begin working on some of the hardware required for an initial prototype of a variable rate N application system.

| Objective | Research Activity | Year 1 | | Year 2 | | Year 3 | |
|---|---|---|---|---|---|---|---|
| 1 | Develop methods & algorithms for tree trunk detection | X | X | X | X | X | |
| | Discussions with experts and N data collection (e.g. leaf samples, physical measurements, N applied) | X | X | X | X | X | X |
| | Map the orchard block with RTK-GPS | | X | X | | | |
| | Develop methods & algorithms for vehicle localization | | X | X | X | X | X |
| | Develop methods & algorithms for N sensing: geometric, color, and spectral characteristics | X | X | X | X | X | X |
| 2 | Create a collaborative decision-making framework for recommending fertilizer plans | | | | | | X |
| 3 | Design and develop a variable rate, proof-of-concept sprayer | | | | | | X |
| | System integration with limited field trials demonstrating variable rate N application | | | | | | |

**Project/Proposal Title:** Validation of plant-based sensors for making irrigation decisions

**Primary PI:** **Lee Kalcsits**
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**Cooperators**: Lav Khot (WSU), Steve Mantle (Innov8ag), Bernardita Sallato (WSU), Karl Wirth (Dynamax),

**Report Type:** Final Project Report

**Project Duration:** 2-Year

**Total Project Request for Year 1 Funding:** $ 60,355
**Total Project Request for Year 2 Funding:** $ 45,050

**Other related/associated funding sources:** Awarded
**Funding Duration:** 2021 - 2027
**Amount: 20,000,000**
**Agency Name: NSF/USDA AI Institute**
**Notes: This sensor project allowed us to leverage this as a key contributor to the water ag thrust and getting a running start on data analysis and collaborations for this project.**

**Budget 1**
**Primary PI: Lee Kalcsits**
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**Contract administrator email address: darla.ewald@wsu.edu**

| Item | 2021 | 2022 |
|---|---|---|
| **Salaries** | 18,000[1] | 18,720[1] |
| **Benefits** | 8,437[2] | 8,774[2] |
| **Wages** | 7,800[3] | 8,112[3] |
| **Benefits** | 1,749[4] | 1,819[4] |
| **Equipment** | | |
| **Supplies** | 20,344[5] | 3,600[5] |
| **Travel** | 4,025 | 4,025 |
| **Miscellaneous** | | |
| **Plot Fees** | | |
| **Total** | 60,355 | 45,050 |

**Footnotes:**
**[1] Support of a research assistant at 50% for the duration of the project to collect and curate data, maintain experiments and prepare results for reporting and publication**
**[2] Benefits are at a rate of 46.87%**
**[3] Wages are to support a summer staff person to aid in collecting data, writing extension material, and for maintaining experiments**
**[4] Benefits for the summer staff position is 22.4%**
**[5] Supplies include the purchase of stem and fruit dendrometers, field consumables, and cellular data loggers. Both the sap flow system and microtensiometers were already purchased.**

## Objectives

1. Deploy and evaluate the accuracy and precision of dendrometers, sap flow sensors, and stem microtensiometers in measuring plant water status
2. Identify critical factors affecting the adoption of these technologies in Washington state tree fruit production
3. Develop Extension materials and train growers in using these technologies.

All sensors were installed in both 2021 and 2022 in the smart orchard and were also used for experiments conducted in pear at the WSU Sunrise Research Orchard. We have completed all three objectives and the report below will highlight our key findings and recommendations for the use of these different sensors in orchard decision making.

## Significant Findings

- Florapulse microtensiometers were highly accurate and precise in measuring stem water potential in real-time. These can be a viable replacement to making pressure chamber measurements manually.
- Florapulse sensors had a ~90% installation success. Minimum trunk diameter for installation is ~40 mm. Smaller trunks make installation difficult.
- Fruit growth sensors are difficult to maintain. They were knocked off the fruit easily and need to be checked daily. Furthermore, the orientation of the sensor on the fruit affects measurements and the spring tension affects fruit growth. These factors suggest that irrigation decisions cannot be made with fruit sensors alone. Fruit growth rates are heavily influenced by many factors that are difficult to account including crop load.
- Stem dendrometers and sap flow sensors have been more commonly used as research tools. Stem dendrometers are useful integrators of plant stress. However, their sensitivity decreases when stem water potential decreases under water limitations. These sensors are more useful when trying to optimize irrigation for maximizing fruit diameter.
- In order of ease of interpretation of data: Florapulse = Pressure Chamber > Stem Dendrometer > Sap flow > Fruit diameter
- In order of ease of installation: Fruit diameter> Stem dendrometer > Florapulse > Sap flow
- Costs for these sensors can vary and depend on variability and the number of irrigation zones in the orchard.

## Methods

### *Smart Orchard*

We deployed commercially available dendrometers (fruit, trunk, and stem), sap flow sensors, and stem microtensiometers into the WTFRC-funded sensor orchards (in collaboration with Bernardita Sallato, Lav Khot, Dave Brown, and Steve Mantle) (Figure 1). Two trees were selected from a high and low vigor site within the spatially variable block. These same sites were aligned with the deployment for other sensors and monitoring equipment from other collaborators.

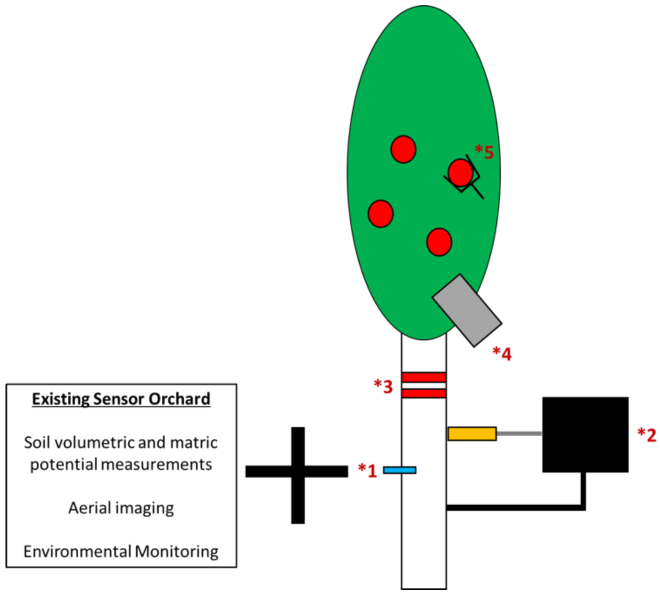


**Figure 1. Plant-based monitoring approaches that are proposed to be added to the sensor orchard in Grandview, WA that will include: 1. Microtensiometers, 2. Stem dendrometers, 3. Sap flow sensors, 4. Traditional stem water potential checks, and 5. Fruit dendrometer sensors.**

**Table 1. Sensor deployment in Smart Orchard in 2021 and 2022**

| Plant Sensors | Environmental Sensors | Soil Sensors |
|---|---|---|
| Stem dendrometer (Edaphic Scientific)<br>Fruit dendrometer (Edaphic Scientific)<br>Microtensiometer stem water potential (Florpulse)<br>Scholander chamber stem water potential<br>Sap flow (Dynamax and Tree2Scope) | Air temperature<br>Relative Humidity<br>Wind speed<br>Radiation | Soil volumetric water content |

***Pear study site and irrigation treatments***

The experiment was conducted in 2021 and 2022 at the experimental orchard of the Washington State University located in Rock Island (Washington State, USA, 47° 19′ N, 120° 04′ W) on a 2 acre pear block (*Pyrus communis* L.), planted in 2007 on a shallow sandy loam soil. ‘D'Anjou’' pear trees were grafted on OHxF.87 rootstock and trained on a central leader system at a tree density of 344 trees per acre. Horticultural practices (e.g. fertilization, pruning and weed control) were the same for all trees in the block and followed commercial regular practices. Full bloom was in April, and harvest was in late August. Trees were drip irrigated by a system consisted of a single drip line per tree row and five emitters per tree of 0.5 gallon h-1 discharge rate.

Two irrigation treatments were imposed, a control treatment (CTL) irrigated at 100% of crop evapotranspiration ($ET_c$) to ensure non limiting soil water conditions and a regulated deficit irrigation treatment (DI), irrigated at 100% of $ET_c$ from April 1st to June 27th, and 50 % of $ET_c$ from June 28th to October 15th. Crop water requirements ($ET_c$) were calculated using: $ETc = ET_o \times K_c \times K_r$, where $ET_o$ is the reference evapotranspiration, $K_c$ is the crop-specific coefficient reported for adult pear trees, and $K_r$ is a factor of localization. Treatments were distributed according to a completely randomized block design with three replicates per treatment. Within each replicate, two trees were selected to assess their tree water status during the season. All measurements were conducted in the same 12 trees selected for their uniformity (average ground cover of 41 % and mean trunk diameter of 10.5 ± 0.23 cm).

Environmental data and soil water content

Air temperature, relative humidity, wind speed, precipitation, solar radiation and reference evapotranspiration were continuous recorded by an AgweatherNet weather station located at the experimental orchard (http://www.weather.wsu.edu; "Sunrise sta-tion"). Moreover, two temperature and relative humidity sensors (ATMOS-14, METER Group Inc., Pullman, WA, USA) were installed in the pear block. Every 15 minutes, mean air vapour pressure deficit (VPD) was calculated using air temperature and relative humidity data (Allen 1998). Soil volumetric water content (SWC) was obtained with two capacitance/frequency domain sensors (TEROS 11, Meter Group, Pullman, WA, USA) per replicate at 10 and 20 inch depths located under the canopy projection at 10 inches from the drip emitter per replicate.

Stem water potential

$\Psi_{stem}$ was measured by two different methods with the Scholander pressure chamber (PC) and with the microtensiometers (MT). $\Psi_{stem}$ measured with the PC (Model 615D, PMS Instrument Company, Albany, OR, USA). Mature and healthy leaves close to the trunk were wrapped with black polyethylene bags and aluminum foil two hours prior to the measurement. Measures were performed on one leaf per tree, two trees per replicate. In the same six trees, six MT (FloraPulse, Davis, CA, USA) were embedded into the tree trunk away from the sunlight at 1.0 m height.

Trunk diameter fluctuations

Trunk diameter was monitored in 8 trees every 10 minutes using linear voltage differential pressure transducer dendrometers (LVDT, model DE-1T, Implexx Sense, Melbourne, Australia) installed on the northern side of the trunks, 30 cm above the point where the microtensiometers were installed. Sensors had a 0.001 mm resolution. Maximum daily shrinkage (MDS) was calculated as the daily difference in diameter between the maximum and the minimum values.

## Results and Discussion

### *Smart orchard data examples and data analysis plan (Apple)*

Connectivity was improved in 2022 compared to 2021 with signal boosters installed in the Florapulse sensors and stem water potential, sap flow, and dendrometer data. We have collected microtensiometer, dendrometer, sap flow, fruit growth, soil moisture, and environmental conditions from the orchard location. We did not have dendrometers in both high and low vigor locations, but we have all other data sets for high and low vigor locations within the orchard. Data was organized and provided to the AgAID project for model development to predict plant water status from these various parallel datasets. This will help provide feedback for users with soil-based or weather-based sensors for making irrigation decisions as well as to fine tune baseline values for making stem-water potential-based irrigation decisions.

Trees at the low vigor site consistently had lower stem water potential than the high vigor site which has implications for not just overall tree vigor but also fruit growth and size potential. Stem water potential acquired with a pressure chamber corresponded well to those measured with microtensiometers (Figure 2). Fruit growth rates were the highest when evapotranspiration demand was the lowest. However, inconsistency in fruit monitoring, movement of sensors, and low replication across an orchard block limit the application of this type of monitoring to make progress for irrigation management (Figure 4).

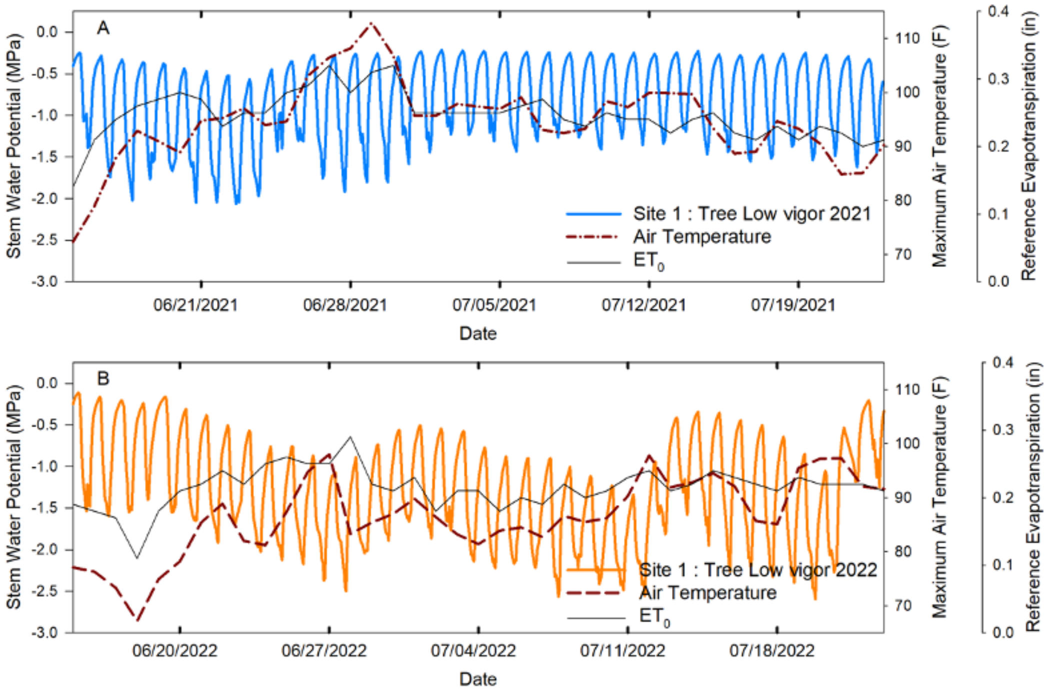


Figure 2. Evolution of the daily maximum air temperature, reference evapotranspiration and stem water potential recorded by the microtensiometers in the same tree (site 1 -low vigor) for the same period in 2021 (A) and 2022 (B)

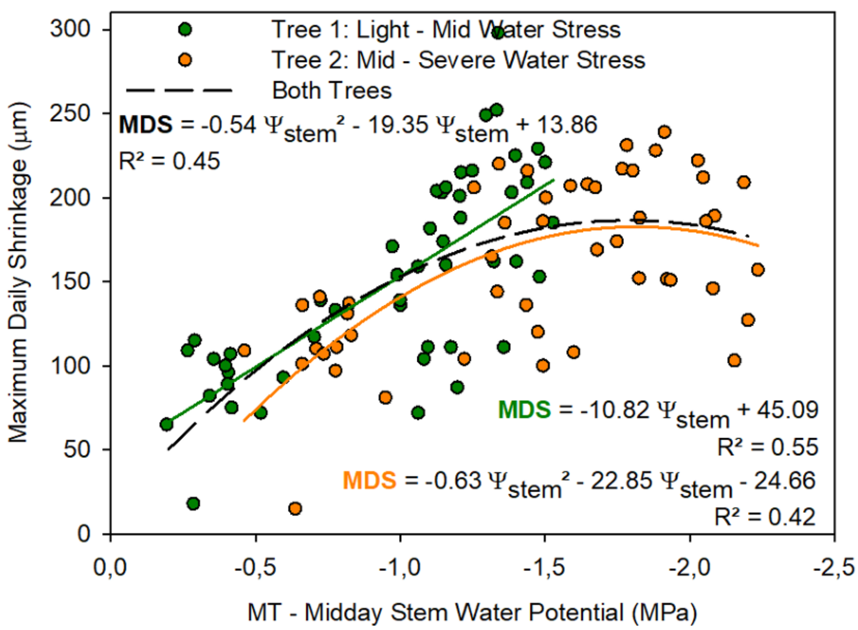


Figure 3. Relationship between the midday stem water potential and the maximum daily trunk shrinkage (MDS) of two trees in site 1 - low vigor (green – light mid water stress and orange – mid severe water stress). Data recorded from June to July, 2022.

MDS values never exceeded 300 µm in either location in the apple orchard and when stem water potential was exceptionally low (below -1.5 MPa), MDS did not continue to increase showing when these relationships break down (Figure 3). This demonstrates the limitation of using dendrometers. They are good for maximizing stem water potential and maintaining fruit growth but are not suitable for deficit irrigation practices in cultivars like Honeycrisp.

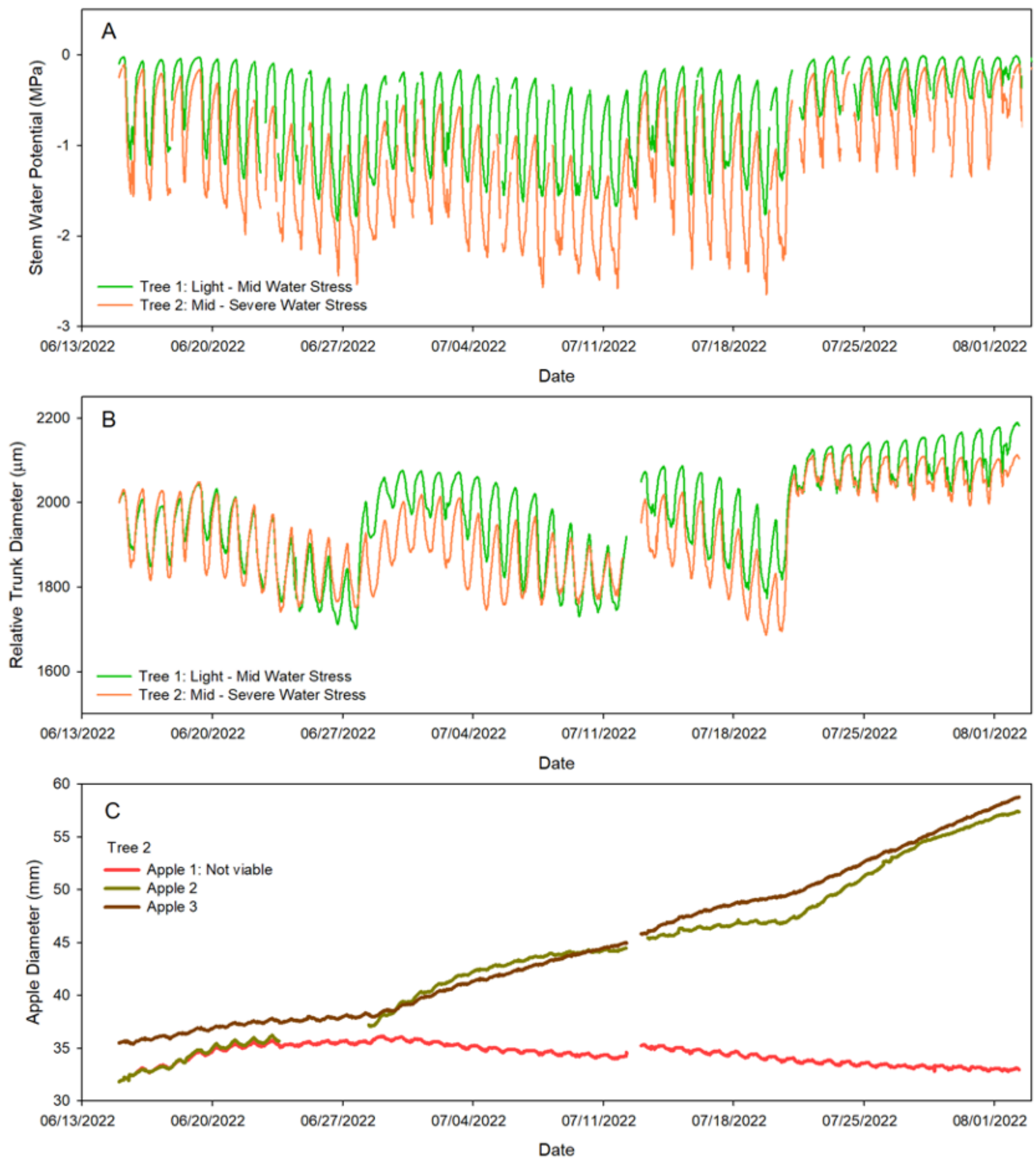


Figure 4. Evolution of the stem water potential recorded by the microtensiometers (A) and the variations of trunk (B) and fruit (C) recorded by the dendrometers in two trees in site 1 -low vigor (green – light mid water stress and orange – mid severe water stress) from June to July, 2022.

Stem dendrometers and microtensiometers were both sensitive to changes in water availability and corresponding changes in stem water potential measured with a pressure chamber. However, stem dendrometers and variable changes in trunk diameter decrease during the season, even under non-limiting conditions that affect how we interpret the sensors and associated irrigation decisions. Microtensiometers were effective but reliability and reuse of the sensors still need to be addressed. When installation is successful, microtensiometers are very accurate in determining irrigation needs by the tree and sensors are responsive to sudden changes in water supply or demand (e.g. evaporative cooling or precipitation event). Fruit dendrometers are useful but monitoring a small number of fruit has a high risk of not monitoring the average fruit in the block. Furthermore, small changes in positioning, fruit drop, or the tension affecting fruit growth are three things that need to be considered when using these sensors to make irrigation decisions.

***Inducing differences in plant water status to detect sensitivity of real-time stem water potential sensing (Pear)***

Through the application of deficit treatments in pears, we were able to test these different plant sensors across a range of soil moisture and environmental conditions (Figure 5). Direct measurements of plant stress have the potential for application of precision irrigation strategies. Other than $\Psi_{stem}$ and MDS, other direct measures of plant water relations with potential for irrigation automation include canopy temperature, leaf turgor pressure, and trunk water content. However, since canopy temperature can be related to stomata closure, this thermal index might not be able to detect water stress as early as those water status indicators which directly measure $\Psi_{stem}$. Sap flow can be useful to assess the water status but can have high variability and is not as sensitive to the changes in soil and the atmosphere water status in the early season as plant water potential. There are also trunk water content sensors that are able to monitor changes in the tree water status. These sensors are related to trunk diameter but, unlike microtensiometers, are delayed by three hours compared to diurnal variations in trunk diameter. $\Psi_{stem}$ recorded by microtensiometers responded quicker than variations in trunk diameter and do not require individual calibration like some sap flow and trunk water content sensors. Microtensiometers directly measure $\Psi_{stem}$ and do not need to be transformed into a different index like thermal indices or leaf turgor. However, across an entire season, microtensiometers consistently underestimated $\Psi_{stem}$ during the afternoon (Figure 6) and did not detect water deficit earlier than the pressure chamber in either season.

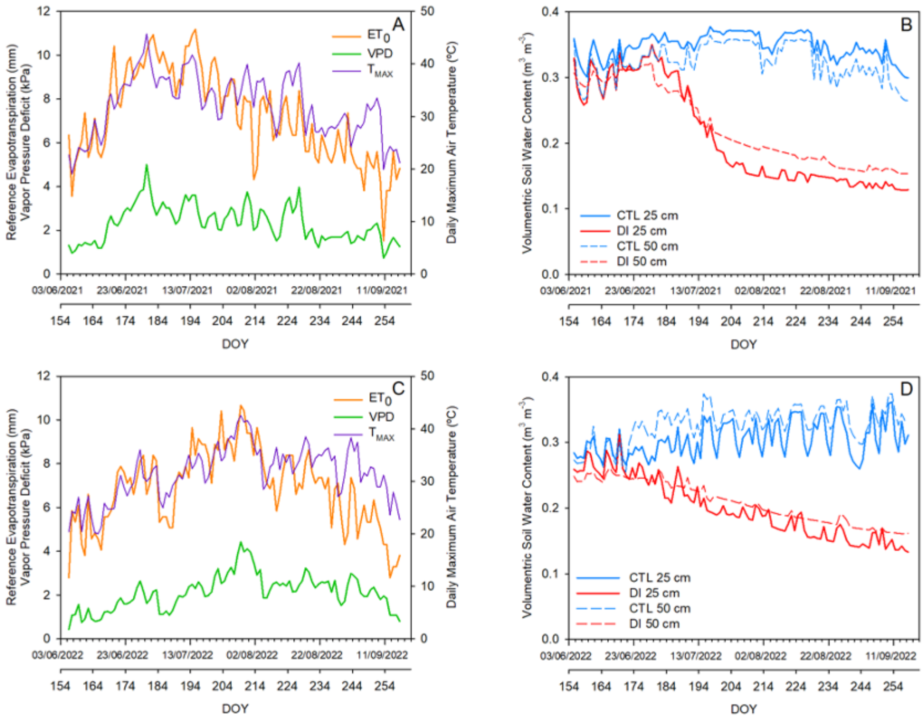


Figure 5. Evapotranspiration ($ET_0$), vapor pressure deficit (VPD), and maximum daily temperatures ($T_{max}$) (A and C) and volumetric soil water content ($m^3$ $m^{-3}$) at 25 and 50 cm depth (B and D) for 2021 and 2022.

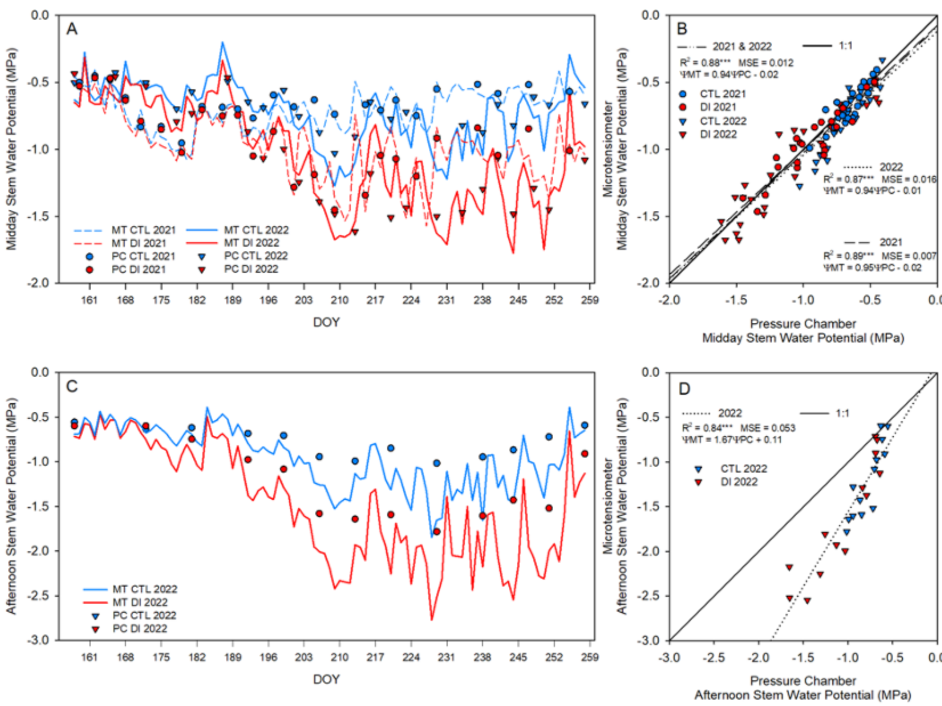


Figure 6. Top: Daily midday stem water potential measured with the microtensiometers (MT) and the pressure chamber (PC) for both years 2021 and 2022 (A) and the linear relationship between them for each season and both seasons together (B). Bottom: Daily stem water potential measured in the afternoon (15:30 - 16:30 h) with the MT and the PC during the 2022 season (C) and the linear relationship between them (D).

Stem water potential measured at noon were the same either using the microtensiometer or through using a pressure chamber. These patterns were repeated across years and under different water availability. However, microtensiometers were lower later in the afternoon than the pressure chamber (Figure 6). Further work is needed to resolve these differences and understand whether it is a problem with the microtensiometer or with the approaches used to indirectly measure stem water potential using a leaf with a pressure chamber. Regardless, these clear relationships and responsiveness of microtensiometers demonstrate their usefulness for monitoring plant water status during the season. Even when soil moisture levels are high, stressful conditions contribute to lower stem water potential for the control on days when temperatures and vapor pressure deficit are high.

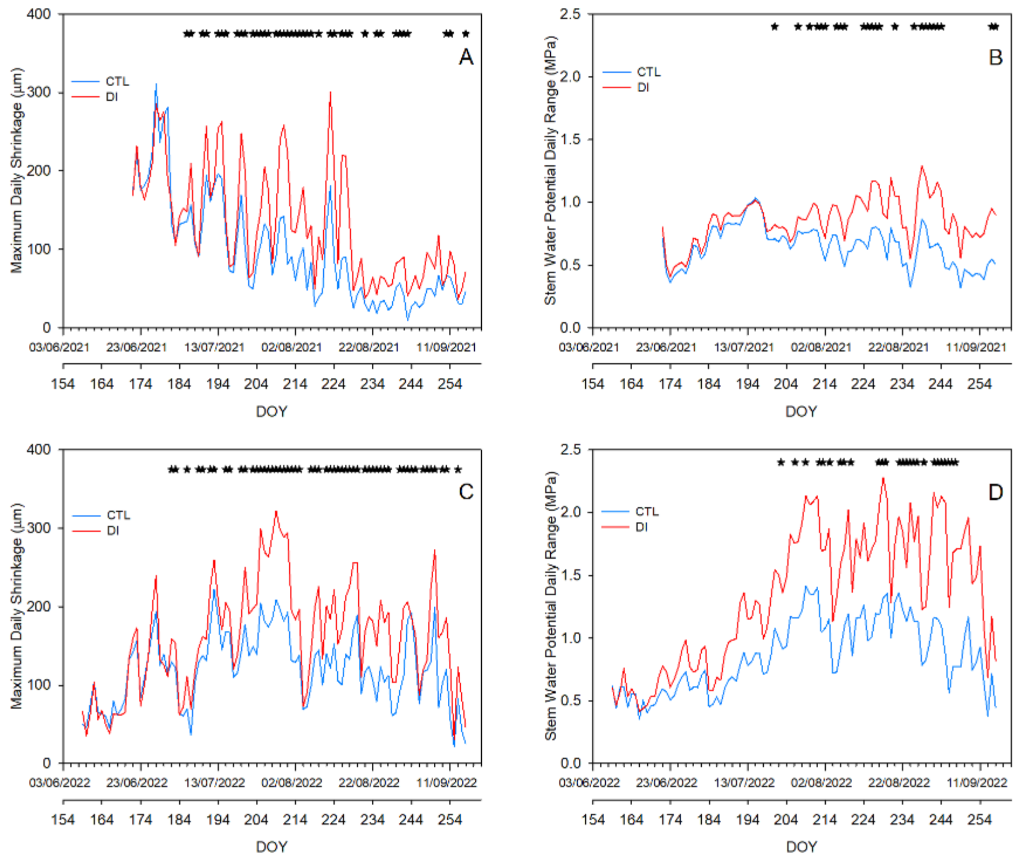


Figure 7. Mean maximum daily shrinkage of CTL and DI trees (N = 4) in 2021 (A) and 2022 (C) and daily stem water potential range (N = 6) for the same period in 2021 (B) and 2022 (D). Black asterisks denote significant differences between CTL and DI trees according to ANOVA (P < 0.05).

Maximum daily shrinkage was less variable when temperatures were lower. For example, in the second half of August in 2021, mean daily maximum temperatures were below 80 F and maximum daily shrinkage (MDS) rapidly decreased as a result. However, in 2022, when temperatures were warmer during the same time period (daily maximum temperatures of 95-100 F), MDS values were higher (Figure 7). When comparing the patterns of MDS with the daily range of stem water potential (Max-Min), there was little agreement, especially in 2021. Differences appeared between the deficit irrigated and control treatments earlier for MDS than the daily range in stem water potential. Moreover, when the relationship between the stem water potential and the trunk diameter changes was studied, we observed that fluctuations in trunk diameter followed changes in water potential (Figure 8).

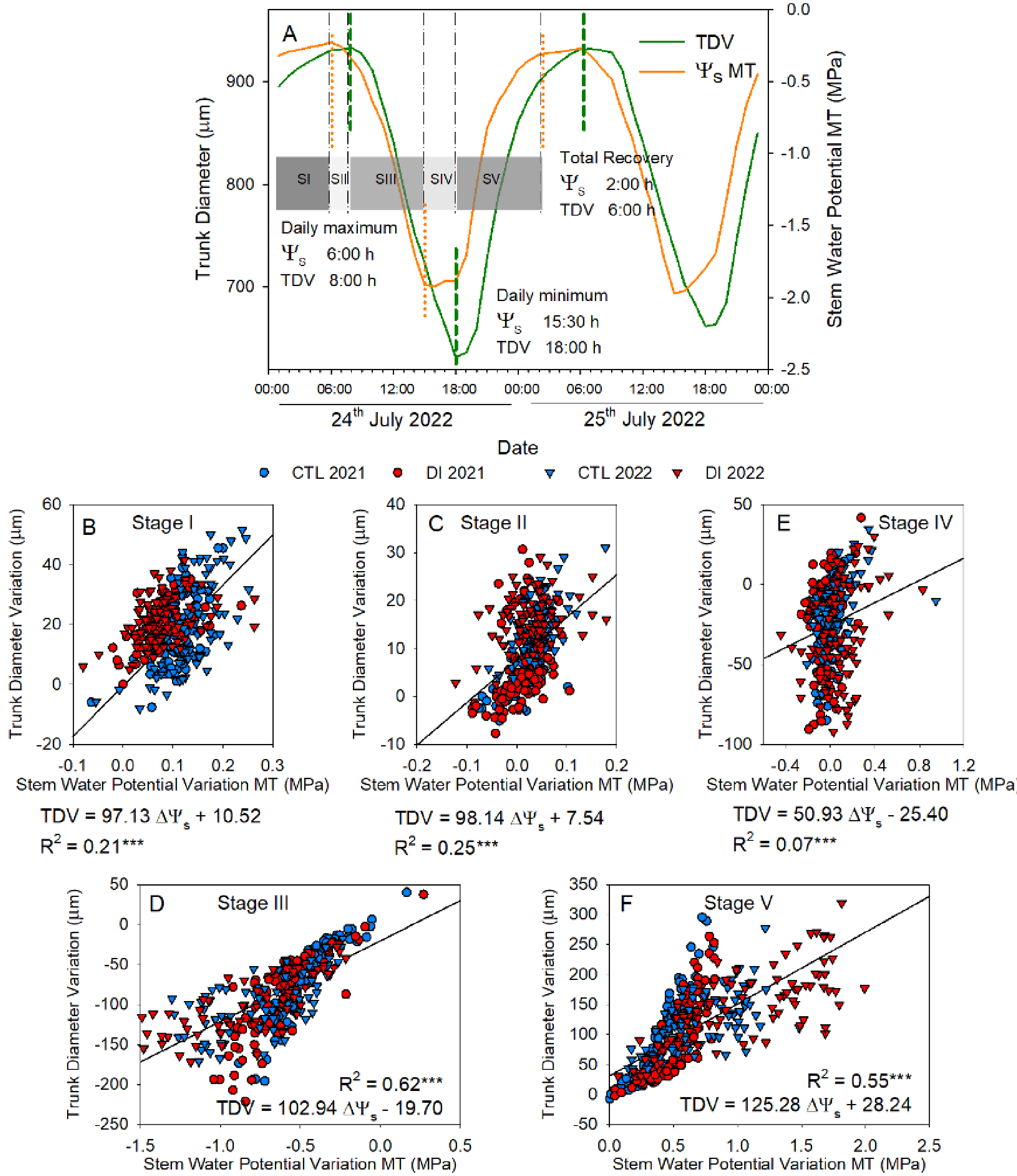


Figure 8. Daily evolution of trunk diameter and $\Psi_{stem}$ on July 24 and 25, 2022 (A). Daily maximum, minimum, and recovery of trunk diameter and stem water potential are indicated. Linear relationships between the variation of both indicators are indicated by five stages: Stage I (SI; B), Stage II (SII; C), Stage III (SIII; D), Stage IV (SIV; E) and Stage V (SV; F) for both treatments (CTL and DI) and both seasons (2021 and 2022).

## Extension programming

***Smart Orchard Field Day***. We organized and participated in field days in 2021 and 2022 to provide firsthand information of the plant sensors installed in the smart orchard and we were part of the Next Generation Growers Network. The target audience were growers, and farm-making decision individuals in the tree fruit industry. Ninety-four participants attended the event in 2021 and almost the same amount in 2022. Overall, from the participants that completed the evaluation of the field day, 95% valued the information presented as excellent (60%) or good (35%).

With the purpose to evaluate the effectiveness of the field day to transfer the information about sensors, we assessed the level of knowledge before and after this event (Figure 9). The participants gained knowledge about the use of plant sensors in the orchards, as most of them reported to have little knowledge prior to the event but higher after the field day.

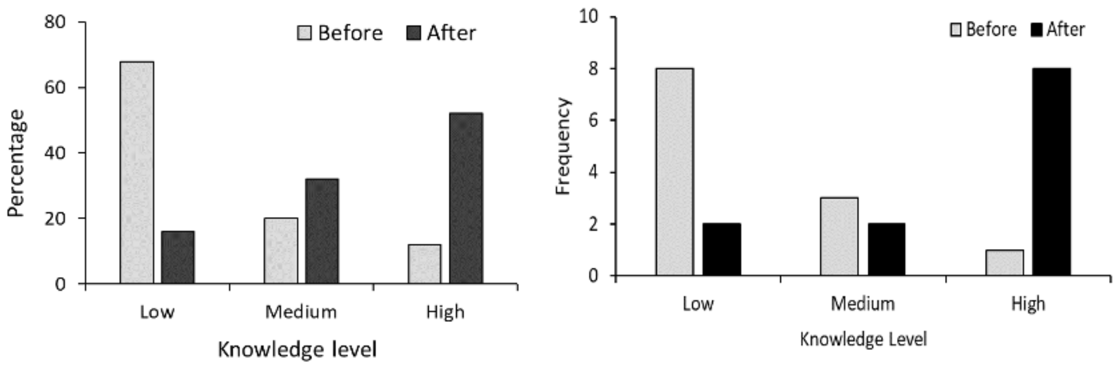


**Figure 9.** Percentage of participants and knowledge level before (gray bars) and after (solid bars) attending Field days. **Left:** Smart Orchard- Plant based sensors section. (n = 30). **Right:** Field Day at the Roza in Spanish. (n= 15).

***Field day in Spanish*.** During a field day in Spanish organized in the experimental orchard the Roza-WSU – IAREC, we presented basic information related to the use of dendrometers in the apple industry, and we also prepared and shared an infographic about this topic. The event was attended by 15 farmworkers from the south area of the state. Similar to the Smart Orchard event, the evaluation of the field day shows that the participants understood the information provided, and gained knowledge related to the dendrometers. (Figure 9).

**Multi-year sensor installation.** None of the microtensiometers that remained in either pear or apple during the winter worked correctly for the entire second year. Some sensors started the season working correctly but stopped working mid-season. There is potential to remove and reinstall the sensors each year following a specific protocol to protect the pressure transducer chip but that still needs to be tested.

**Table 2. Summary table. Evaluation of sensors response.**

| Plant Sensors | Ready for Industry Use | Pros | Cons |
|---|---|---|---|
| Scholander chamber stem water potential | Yes | Gold standard of measuring plant water status<br>Easy to interpret data | Not continuous<br>Labor intensive |
| Fruit dendrometer (Edaphic Scientific) | No | Direct measurement of fruit growth and how it is affected by irrigation.<br>Precise and accurate technology | High variability among fruit even in the same tree.<br>High maintenance, need to check that the dendrometer is attached to the fruit. |
| Microtensiometer stem water potential (Florpulse) | Yes | Continuous measurements of stem water potential<br>Highly accurate and precise | Cost of sensors<br>Reusability of sensors is questionable |
| Stem dendrometer (Edaphic Scientific) | Yes | Real-time, continuous and direct measurements of the tree water status.<br>Early water stress detection.<br>Rapid response to changes in the tree water status. | Need to calculate the MDS and TGR.<br>It is difficult to interpret absolute values, need to compare the trees with a reference tree in the orchard.<br>Highly dependent on other factors, not only water stress. |
| Sap flow (Dynamax and Tree2Scope) | No | Continuous | Inconsistent data that may not be associated with plant water status |

***Project outputs***

(Publication) Blanco V, Kalcsits L. 2022. Long-term validation of continuous measurements indicate different diurnal patterns of stem water potential and trunk diameter under water limitations in pear. In review.

(Publication) Blanco V, Kalcsits L. 2021. Microtensiometers Accurately Measure Stem Water Potential in Woody Perennials. *Plants*, *10*(12), 2780.

(Extension Publication) Blanco, V, Bolivar-Medina J, Casagrande-Biasuz E, Willsea N, Kalcsits L. 2022. Trunk and Fruit dendrometers: Detecting early signs of water stress in fruit trees before visual cues. Fruit Matters June 2022. http://treefruit.wsu.edu/trunk-and-fruit-dendrometers-detecting-early-signs-of-water-stress-in-fruit-trees-before-visual-cues/

(Extension Publication) Blanco, V, Bolivar-Medina J, Casagrande-Biasuz E, Willsea N, Kalcsits L. 2022. Microtensiometers: a new tool to monitor your apple trees for deciding when and how much to irrigate. Fruit Matters May 2022. [http://treefruit.wsu.edu/microtensiometers-a-new-tool-to-monitor-your-apple-trees-for-deciding-when-and-how-much-to-irrigate/](http://treefruit.wsu.edu/microtensiometers-a-new-tool-to-monitor-your-apple-trees-for-deciding-when-and-how-much-to-irrigate/)

(Field Day) July 30 (English) and August 2 (Spanish), 2021. Smart Orchard Field Day.

(Field Day) July 26 (English) and 27 (Spanish), 2022. Smart Orchard Field Day.

(Field Day) October 11, 2022. Next Generation Growers Network: Irrigation strategies and technology. Sunrise Research Orchard

(Presentation) Kalcsits L. 2021. Water management in pears. Southern Oregon Research Station. May 27, 2021.

(Presentation) Kalcsits L, Khot L, Sallato B, Mantle S, Blanco V. 2022. Smart Orchard 2.0. HortGro Annual Tree Fruit Meeting. Sumerset West, South Africa. June 4, 2022.

(Presentation) Blanco V, Willsea N. Plant-based sensors for irrigation. Columbia Club Growers Meeting. June 30, 2022.

(Presentation) Kalcsits L, Blanco V, Horning P. 2022. Plant-based sensors for managing irrigation. International Tree Fruit Association Summer Tour. July 18, 2022.

(Presentation) Blanco V, Kalcsits L. 2022. Irrigation Strategies and Technology. Next Generation Fruit Growers Meeting. Cashmere, WA. October 12, 2022.

(Presentation) Kalcsits L, Blanco V. 2022. Panelist: Why is regulated water stress not widely used in commercial horticulture? International Horticulture Congress. Angers, France. August 18, 2022.

(Presentation) Blanco V, Kalcsits L. 2022. Soil temperature and water stress affect the physiological response, nutrient uptake and distribution of young pear trees. International Horticulture Congress. Angers, France. August 16, 2022.

EXECUTIVE SUMMARY

Project title: Validation of plant-based sensors for making irrigation decisions

Key words: Stem water potential, dendrometers, fruit diameter, sap flow, microtensiometers, water relations

Abstract: Early detection of undesirable water deficit is important for avoiding any penalization in fruit size, yield and tree growth. Early visual cues indicating water stress in apple trees are not so perceptible once they appear, it is often too late to avoid negative effects of severe water stress causes on fruit quality, yield, and tree growth. Precision sensors such as dendrometers can be crucial and make that task much easier. Dendrometers are well-studied, plant-based sensors that continuously measure small fluctuations (shrinkage and swelling) in trunk or fruit diameter resulting from variation in sap flow. Trunk and fruit dendrometers can be used to detect and quantify water stress to improve irrigation scheduling in fruit trees. Microtensiometers are plant-based water status sensors than can continuously measure stem water potential, the reference indicator for assessing water status in trees. Midday stem water potential measured with microtensiometers and with a pressure chamber and maximum daily shrinkage, (MDS) were compared in both pear and apple. Stem water potential measured by the microtensiometers and the pressure chamber as well as the MDS were directly influenced by the water supply to the trees from the soil and atmospheric demand from environmental conditions. MDS was able to detect water stress in DI trees the earliest. However, it showed the highest variability and was not sensitive enough to detect significant differences between irrigation treatments late in the season. On the other hand, midday stem water potential measured by both methods had low variation and was able to distinguish both irrigation strategies during both seasons. Midday stem water potential measured by both methods had a strong linear relationship with no differences between the two methods. However, when stem water potential was measured in the middle of the afternoon, stem water potential measured by microtensiometers were much lower than stem water potential measured using a pressure chamber. This behaviour was observed on hot and cold days and these differences were more visible when trees were water limited. The daily relationship between the trunk diameter variations and midday stem water potential measured with the microtensiometers followed five different stages. Changes in trunk diameter were delayed relative to changes in xylem potential. The seasonal relationship between the MDS and stem water potential was strongly related at the start of water limitations in apple and pear, but when the complete season was considered, this relationship declined. MDS appeared to have a maximum season value of 300 µm despite water limitations that should have pushed those trunk contractions higher. Stem dendrometers are also useful but loss accuracy when water limitations are applied indicating a best fit for use in low stress situations when trying to maximize fruit weight. Fruit dendrometers suffer from reliability and stability of measurements. Sap flow sensors are not good integrators of factors that contribute to fruit growth and are difficult to interpret right now. Microtensiometers are highly accurate and ready for use as a continuous sensor in automatic irrigation systems as a reliable method to monitor tree water status and provide a continuous alternative to a pressure chamber.

**Project Title:** Low-cost, reliable soft arm for automated tree fruit operations

**Report Type:** Final Project Report


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**Cooperators**: Dave Allan, Allan Brothers Fruits; Tim Welsh, Columbia Orchard Management, Inc.; FFRobotics, Israel


**Project Duration:** 1-Year

**Total Project Request for Year 1 Funding:** $ 122,476

**Other related/associated funding sources:** Awarded,

**Funding Duration:** 2022
**Amount: $50,000 + 1 year research assistantship**
**Agency Name:** WSU Multi-disciplinary Grant
**Notes:** Title: Universal Robotic Solution for Future Tree Fruit Orchards.
This funding supports us to develop large grant (USDA SCRI/SCMP) which includes the soft grow manipulator.

**WTFRC Collaborative Costs: None**

**Budget 1**
**Primary PI: Ming Luo**
**Organization Name:**
**Contract Administrator: Ian Leibbrandt**
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**Contract administrator email address: ian.leibbrandt@wsu.edu**
**Station Manager/Supervisor:**
**Station manager/supervisor email address:**

| Item | 2022 |
|---|---|
| Salaries | $31,615.00 |
| Benefits | $5,618.00 |
| Wages | $13,800.00 |
| Benefits | $243.00 |
| RCA Room Rental | |
| Shipping | |
| Supplies | $5,000.00 |
| Travel | $3,000.00 |
| Plot Fees | |
| Miscellaneous | |
| | |
| | |
| | |
| Total | $59,276.00 |

**Footnotes:**

**If project duration is only 1 year, delete Year 2 and Year 3 columns.**

**(***Complete the following budget tables if funding is split between organizations,* ***otherwise delete*** *extra tables.)*

**Budget 2**
**Co PI 2: Manoj Karkee**
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**Contract Administrator: Samantha Bridger**
**Telephone:**
**Contract administrator email address: prosser.grants@wsu.edu**
**Station Manager/Supervisor:**
**Station manager/supervisor email address:**

| Item | 2022 |
|---|---:|
| Salaries | $21,393.00 |
| Benefits | $2,696.00 |
| Wages | $13,800.00 |
| Benefits | $243.00 |
| RCA Room Rental | |
| Shipping | |
| Supplies | |
| Travel | $5,000.00 |
| Plot Fees | |
| Miscellaneous | |
| | |
| | |
| | |
| Total | $43,132.00 |

**Footnotes:**

**If project duration is only 1 year, delete Year 2 and Year 3 columns.**

**Budget 3**
**Co-PI 3: Matthew Whiting**
**Organization Name:**
**Contract Administrator: Samantha Bridger**
**Telephone:**
**Contract administrator email address: prosser.grants@wsu.edu**
**Station Manager/Supervisor:**
**Station manager/supervisor email address:**
**Email Address:**

| Item | 2022 |
|---|---|
| Salaries | 16045 |
| Benefits | 2022 |
| Wages | |
| Benefits | |
| RCA Room Rental | |
| Shipping | |
| Supplies | 2000 |
| Travel | |
| Plot Fees | |
| Miscellaneous | |
| | |
| | |
| | |
| Total | $20,067.00 |

**Footnotes:**

**Recap original objectives and significant findings**

*Objective#1:* Design, fabricate, test, and optimize a growing arm/manipulator for orchard operations (Luo – Lead, Karkee – Co Lead;)

*Overview in the proposal:* To perform various field operations in tree fruit production, our soft growing manipulator will have the following mechanical features: 1) 7 ft radius workspace - the proposed manipulator length (7 ft) is expected to cover the entire tree height (~14ft) when installed on a ground platform that is approximately half of the tree height. 2) Free movement in 3D space with up to 3 lbs payload (which is sufficient to carry most of the end-effectors such as a fruit picker or an electric scissors for pruning) - Our proposed manipulator must overcome gravity to grow, retract, and steer to reach any target within its workspace. 3) Ability to maneuver freely inside most tree canopies under 14 ft height: The diameter of our proposed manipulator and updated design of end-effector adaptor/mount allows the manipulator to pass through narrow spaces between branches.

*Our current achievement:*

Soft growing manipulator:

- *<u>Length:</u>* can extend 4 ft (We found 4 ft is enough length to achieve apple harvesting according to the current modern orchard's tree architecture and commercial robotic platforms.
- *<u>Speed:</u>* Growing speed, manipulator displays 0.7 ft/s growing speed at 7 psi. We have observed that higher internal pressure results in dramatically faster extension speed. Based on our analytical calculations, we can achieve an extension/growing speed of 1.7 ft/s. There are two ways to increase the speed. One is to increase the pressure, however, due to safety issues in the lab, higher pressure cannot be reliably tested. The second one is to increase the air flow rate. We are working on the latter approach to increase the size of the outlet of the container, and we will update the results during our presentation.
- *Payload:* 2 lbs payload around 9 psi pressure input. The current payload of the end-effector including the tip mount and the soft robotic gripper is around 1 lbs, so there is sufficient payload to carry an apple under 1 lbs. The payload can be increased by the increase of the pressure input.
- *<u>Workspace:</u>* One ZED2 camera is able to detect around 6ft * 6ft range within 3 ft depth. Our robot's workspace has a spherical sector shape with a radius of 4 ft and 60 degrees of actuation in the 2D plane.
- Reliability: The maximum input pressure of our fabric material's sealing is around 18 psi, and 9 psi is our operation pressure since it has enough payload. In addition, we install the pressure relief valve to reduce the risk of pressure overloading. For future work, we are collaborating with Dr. Liu, a polymeric fabric expert at WSU, to improve the sealing technique used to create the fabric arms.
- R&D cost: The current prototyping cost of a single robot manipulator is eight times less than a single commercially available rigid manipulator. The estimated cost is approximately $4230, which is broken down into $920 for materials, $520 for manufacturing, and $2790 for electronics. The most expensive part is central cable motor, which costs $1000. Due to the current shortage of the supply chain and urgent timeline, we purchase the expensive motor to verify our system first. We believe we can find alternative item under $100 when system verification is done, and the overall cost will be under $1000 at the commercial manufacturing stage.

*Objective#2:* Manipulator integration with a low-cost machine vision system and selected end-effector tools (e.g. for picking, year 1) (Karkee – Lead, Luo – Co Lead).

*Overview in the proposal:* To prototype a robotic system for field testing with various operations, we will develop a perception system and integrate it with the soft, growing manipulator. In addition, a commercially available cable driven soft gripper will be integrated (one at a time) with the end-effector mount (Obj # 1) to support apple harvesting use case.

*Our current achievement:*

Perception: The global ZED2 depth camera and image processing system developed can provide target apples' 3D location and the relative position of the manipulator's end-effector to build the close loop system.

Soft gripper: 0.66 lbs and can grasp an apple without the force feedback control

*Objective#3:* Design and implement a low-level controller to achieve automated operation (Luo – Lead).

*Overview in the proposal:* Once the perception/vision system, end-effector tool (Obj#2) and soft manipulator (Obj#1) have been tested separately for their functionality, they will be integrated together for overall system evaluation in the simulated, laboratory environment as well as in the field environment using automated motion/control techniques discussed below.

*Our current achievement:*

Our research team is working on the system integration including the robotic platform, perception, and soft robotic gripper. Currently, the robotic arm's motion can be teleoperated, and we will implement the low-level controller after the system integration. Figure. 1 summaries the goals and our current progress.

*Overall progress*

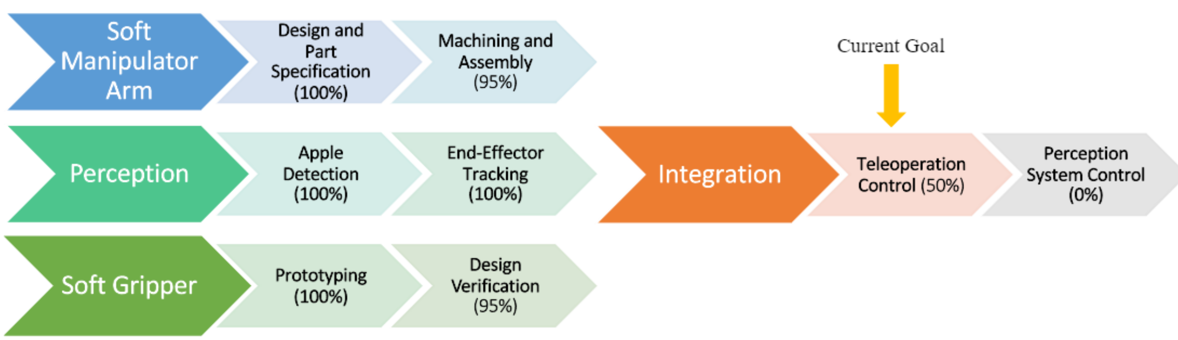


Figure. 1 Goals vs Current progress

**Results and Discussion**

So far, our research team have reached 90% of the overall goal with 1-year funding provided to the team in 2022. One design change we implemented was to reduce the soft-manipulator length from proposed 7-ft to 4-ft as it was found to be optimal for modern orchard architectures. Our research team is in the process of system integration, which will be completed (including the low-level control) by the end of funding period (02/2023).

## Executive Summary

*Project title:* Low-cost, reliable soft arm for automated tree fruit operations

*Keywords:* Manipulator, Fruit, Harvesting

*Abstract:* During this one-year project, we have completed and verified all sub-components of our soft growing manipulator to achieve robotic apple harvesting with a soft manipulator: robot design and prototyping, local perception system development, and the end-effector tools. In the rest of this project period (by Feb, 2023), we will conduct the system integration and implement the low-level position control to our system.

### 1. Overview

Our report introduces three components: robot, perception system and the end-effector for apple harvesting. Each component includes the requirement of its functionality and our approach and experimental verification. Lastly, we will include one sub-section to discuss the cost of the technology being developed.

### 2. Soft Growing Manipulator

#### *2.1 Requirement*

In this project, several key design decisions were made to meet the desired specifications. In particular, these decisions revolved around the pressurized enclosure, motors, steering system, pressure control system, and fabric selection. These choices balanced the functional requirements with the cost in order to minimize cost of manufacturing while maximizing performance.

For the pressurized enclosure, the primary requirement was the maximum internal pressure for the system. The original goal for this project was a maximum internal pressure of 20 psi. Thus, the enclosure had to hold this high pressure with a factor of safety of at least 2. So, to meet this requirement, the enclosure was chosen to be made out of machined aluminum. This choice allows the enclosure to hold significantly high pressures while being easily machinable. The enclosure was also designed to use readily available stock tubes and aluminum plates. This choice decreased the overall cost and machining time.

The motors were chosen based on the torque required to get the desired motion for steering, extension and retraction. The steering motors were chosen based on a buckling test conducted on the arm whilst it was pressurized. This test involved using a force scale to pull on one of the heat-welded tabs on the tube arm to approximately 30 degrees in one direction. From preliminary testing, the force to buckle the tube at 3 psi and 10 psi was estimated to be around 15 lbs and 30 lbs respectively. With these results, the torque required to buckle the tube is only dependent on the radius of the steering pulleys. The steering pulleys have a radius of 0.5 in. Thus, the torque required to kink the tube at 3 and 10 psi is 7.5 lb*in and 15 lb*in respectively. The chosen gear motors have a torque rating of approximately 42.5 lb*in, which exceeds the minimum torque requirement. This decision was made to ensure that the steering motors could buckle the arm under any condition. The central motor was chosen based on the retraction pressure. At 3 psi, the end of the arm is under approximately 24 lbs, and based on the diameter of the central pulley, the torque required to hold the arm position is around 42.2 lb*in. Despite this being lower than the torque output of the steering motors, the steering gearmotors could not be used for this application. This is due to the slow free spin speed of the steering gearmotors. For the arm to extend at a reasonable speed without damaging the central motor, a high torque and high free spin speed gearmotor is needed.

For the rest of the steering system, various design choices were made to ensure reliability, reduce manufacturing time, and prolong fabric arm integrity. Firstly, a steering guide plate was attached to the front of the manipulator arm base in between the steering motors and the steering collar. The guide plate directs the steering cables in the appropriate direction and orientation. This component provides a level of consistency in the assembly and control of the device. Secondly, a steering collar was designed to mount onto the fabric arm at the heat-welded tabs. This collar provides a consistent location for the steering cables to attach to the fabric arm. The collar also reduces the complexity of the fabric arm design and distributes the steering torque load on the arm. This makes manufacturing the fabric arms easier and prolongs the life of the heat-welded tabs.

For the pressure control system, a high flow rate low pressure tolerable digital pressure regulator was chosen. This was based on the intricate requirements of the system. For this system, the minimum pressure is 3 psi and the maximum pressure is 10 psi. These pressures are relatively low for pneumatic systems since typical pneumatic valves only function at around 15 psi. So, a low-pressure tolerable device is needed for this system. The system also has to be able to switch between these pressures at a fast speed. Thus, a high flow rate is required to get the system to switch as fast as possible. Based on these requirements, a digital pressure regulator that can handle vacuum pressures and has the highest possible flow rate was chosen.

The fabric was chosen based on a series of tests and the pressure requirements of the system. Various heat-weldable materials were tested at different pressures. These tests aimed to evaluate the maximum pressure the heat-welded fabric could reliably hold. From this process, a heat-weldable TPU-coated fabric was chosen based on its reliable maximum pressure around 10 psi.

### *2.2 Design and Fabrication*

For this project, an initial prototype was designed to meet the expected outcomes outlined in the project proposal, shown in Figure 2. This design uses a pressurized enclosure, manipulator arm, and electronics subsystems. All of which have their own subcomponents and interface with each other. Specifically, the pressurized enclosure has an aluminum enclosure, central pulley assembly, central motor, and pressure regulation system. The manipulator arm has the fabric arm, steering motors, steering pulleys, steering collar, steering guide plate, and the central pulley cord. The electronics system consists of the logic and motor driver circuit board, the wire connections, and the power supplies needed for all electrical components. The manipulator arm is mounted onto the front of the pressurized enclosure and the electrics subsystem is connected to all of the various electrical hardware.

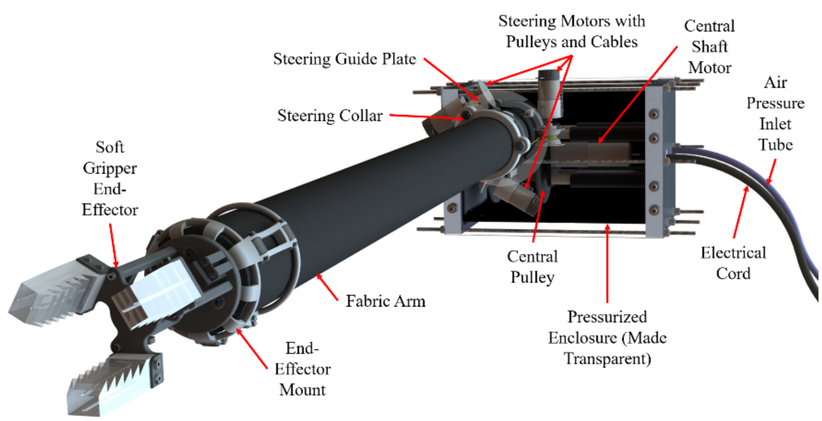


Figure. 2 Soft Growing Robotic Manipulator System

Pressurized Enclosure: The pressurized enclosure consists of an aluminum airtight enclosure that houses the central pulley assembly and central motor. The enclosure is designed to withstand high pressures while using readily available materials to reduce the overall cost. Specifically, the enclosure utilizes stock aluminum plates, a square aluminum tube, and a round aluminum tube which are easily CNCed or water-jet cut. In this design, two square aluminum plates are clamped onto the open ends of the square tube, and the round tube is threaded into a hole made in the square tube. The center of this hole is aligned to be tangent to the central pulley. There are rubber gaskets located at the interface of the two side plates and the square tube as well as the interface of the square and round tubes. The design uses 8 threaded rods to clamp the side plates onto the ends of the square tube. Two rectangular plates mount on the front and back sides of the enclosure. The front plate provides a mounting location for the steering motors, and the back plate provides a mounting hole pattern for the entire enclosure. There are two holes in the right-side plate for the air pressure inlet and the motor power cable. The air pressure inlet uses a threaded pneumatic tube insert and the power cable is fed through a brewer's stopper to keep the system airtight. The enclosure was designed to hold up to 20 psi with a factor of safety above 2. However, the enclosure has not been tested above 20 psi due to the fabric arms rupturing at pressures below 20 psi. The maximum pressure the enclosure has been tested at so far has been 18 psi.

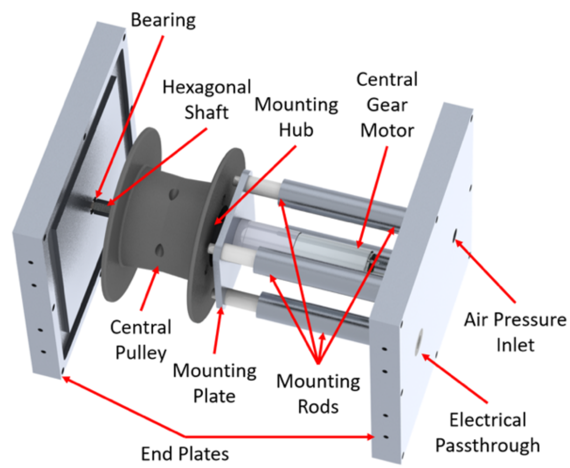

Figure. 3 Internal Components of the Pressurized Enclosure

Central Pulley and Motor: The central motor is a 24 VDC gearmotor with a digital encoder and 1:12 gear reduction. The central motor is connected to the central pulley assembly using a modified 10mm mounting hub, and the pulley assembly is connected to the main pulley cord of the manipulator arm. The motor is mounted to the right-side plate using an aluminum mounting plate and aluminum mounting rods. The pulley assembly has a 0.5 in hexagonal shaft running through it which is supported by a 6 mm shaft that fits into a bearing mounted in the left-side plate. This configuration allows the motor to control the extension and retraction of the manipulator arm by pulling on or releasing the main pulley cord. These components are shown in Figure 3. From preliminary calculations, the free-spin speed of the central motor will allow the manipulator arm to extend at a speed of 4.8125 ft/s. However, the actual extension speed will be dependent on the extension pressure setting of the enclosure. Since the internal pressure of the arm is the driving force in the extension process. Higher internal pressure will result in a higher extension speed and vice versa. The retraction speed will be dependent on the load and the pressure setting. However, based on the rated speed of the motor, the arm will have a retraction speed of 2.292 ft/s. A large payload or higher internal pressure will reduce the retraction speed. These preliminary calculation speeds display that the design is capable of fast movement speeds. Thus, the design allows for the execution of quick movement in fruit tree operations.

Central Pulley Assembly: The central pulley assembly is made up of two 3D-printed PLA pulley halves, a hexagonal aluminum shaft, and a modified mounting hub. The two pulley halves are bolted together using three partially threaded bolts. There is an off-center hole at the interface of the two halves for the main pulley cord to go through and be tied off. The mounting hub is bolted to the end of the pulley using heat-inserts, and the hexagonal aluminum rod is inserted into the other end of the pulley assembly. The central pulley assembly is mounted into the pressurized enclosure by connecting one end of the aluminum rod to the central motor shaft and the other end to the bearing in the left-side plate.

Fabric Arm: The fabric arm is made from a Heat-Sealable TPU-Coated Fabric that is heat-welded together. The fabric is cut and welded into a tube-like shape with one end of the tube sealed shut. The tube has an outer diameter of 3.2 in and a length of 4.9 ft. The diameter is slightly greater than 3 in to provide enough tolerance for the inner layer of rubber used to create an airtight seal between the fabric arm and the aluminum tube. The arm length is significantly longer than 4 ft to ensure that there is enough material to seal the end and attach the arm to the enclosure. The sealed end is pulled into the body of the fabric tube and is connected to the main pulley cord. The end of the pulley cord is tied around the sealed end of the arm. The base of the arm goes over the round aluminum tube with a sheet of rubber in between the fabric and the metal. Another sheet of rubber wraps around the fabric at the base, where two hose clamps hold the arm to the pressurized enclosure. Three TPU-coated fabric tabs are heat welded to the fabric arm at three specific points. These tabs are made out of a strip of heat-weldable fabric that was heat-welded into a ‘T’ shape. Then a hole is punched through the bottom part of the ‘T’ strip to allow the bolts in the steering collar to pass through.

Steering System: The steering system is composed of three steering motors, pulleys, cables, the steering guide plate, and the steering collar. The steering system is shown in Figure 4. This system controls the buckling or actuation angle of the fabric arm.

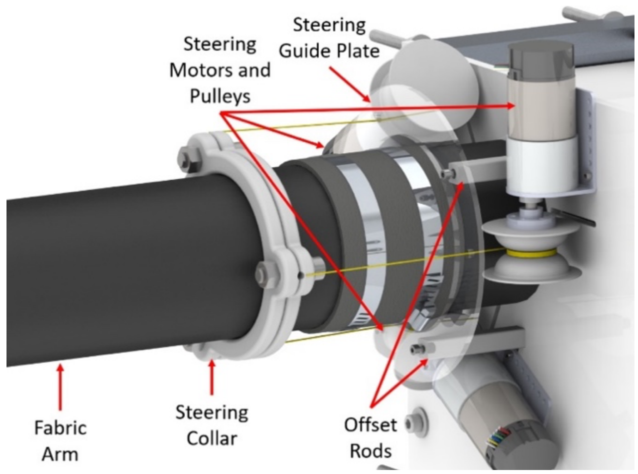

Figure. 4 Steering System Component Diagram

Steering Motors: Located at the base of the manipulator arm are three 12V DC gearmotors with digital encoders. The motors have a 150:1 gear ratio to ensure a relatively high amount of torque. The motors are fastened to mounting brackets, and these brackets are fastened to the front plate of the pressurized enclosure. The motors are connected to small pulleys, which are connected to the steering cables. The steering cables are attached to the steering collar which is mounted at the base of the fabric arm. The steering motors use the pulleys to pull at the base of the arm at specific points to buckle the base of the arm. A pressure test was conducted to determine the torque required to buckle the arm.

Steering Cables and Pulleys: The steering cables act like tendons in an arm. Specifically, they pull at the steering collar at the base of the arm at specific points and with a specified torque to kink the arm to a certain angle. The pulleys are made from 3D-printed PLA plastic and have threaded heat-inserts to fasten the pulleys to the mounting hubs on the steering motors. The pulley cords are made of a heavy-duty Kevlar braided string. This decision makes the steering pulleys and cords easily manufacturable and relatively inexpensive. The cords are tied around the bolts that clamp the steering collar together, and the cords are fed through the string openings in the steering collar.

Steering Cable Guide Plate: An acrylic plate mounted on the front of the pressurized enclosure at the base of the manipulator arm that guides the steering cables to specific angles and points on the fabric arm. The plate is made out of a 1/8-inch laser-cut acrylic sheet to decrease cost and manufacturing time. The steering cable guide plate helps provide a level of consistency in the set-up of the steering system. This consistency greatly improves the modeling and control of the system. The steering guide plate is mounted to the front mounting plate using 3D-printed PLA offset rods.

Steering Collar: The steering collar is made out of two 3D-printed PLA plastic circular plates that are clamped together using three threaded bolts with washers and nuts. The collar plate is a circular loop with an inner hole of the same diameter as the fabric arm and three tabs for the clamping bolts. The steering collar goes over the fabric arm and is mounted to the arm at a specified point by clamping the collar onto heat-welded fabric tabs on the arm. By clamping the collar onto these tabs, the collar’s position on the arm is fixed. The steering cables are tied to the bolts in-between the two plates and are pulled through specially designed gaps in-between the plates. This configuration makes it so that the steering cables pull on the bolts rather than the 3D-printed plastic. The steering collar allows for distributed steering loads and easily adjustable steering mount locations. It also makes the production of fabric arms far less time-consuming and expensive. The steering collar also dramatically reduces the impact of fatigue on any heat-welded joints.

Pressure Regulation System: The pressure regulation system consists of a single digital closed-loop pressure regulator, pneumatic tubing, a hand-adjustable pressure regulator, and a building's air supply, shown in Figure. 5. The hand-adjustable pressure regulator restricts the building air supply pressure to safe operating pressures. The digital pressure regulator controls the operating pressure of the system and is connected to the hand-adjustable pressure regulator. This process also reduces the pressure gradient required for the digital pressure regulator to control. The connections between all components are 0.5 in OD vinyl pneumatic tubing.


Figure. 5 Hand Adjustable Pressure Regulator (Left) Digital Pressure Regulator (Right)

Electronics Subsystem: The electronics are composed of a single soldered breadboard circuit board that controls the logic, motor drivers, and pressure regulator. The three steering motors all use the same model of 12V DC motor driver, while the central motor has its own 24V DC model. One 12V DC power supply and one 24 V DC power supply are used to power the entire system. The entire system is shown in Figure 6.

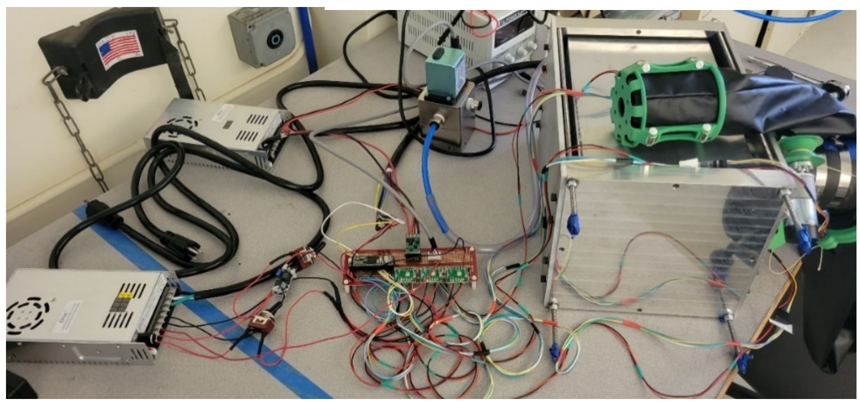

Figure. 6 Entire Electronics Subsystem of the Manipulator Arm

End-effector Mount: Located at the end of the manipulator arm is the end-effector mount, which has an internal and an external component. Shown in Figure 7. The internal component travels inside of the fabric arm while the external component travels outside of the arm. Both components are made from 3D-printed PLA plastic and are easily manufacturable. These components stay together using rolling magnets that are strong enough to hold the 3 lbs payload without disconnecting. Specifically, the end-effector mount can hold up to 6 lbs vertically before the magnets begin to slip. The external component has six mounting holes located on the front plate to allow any desired end-effector to be mounted.

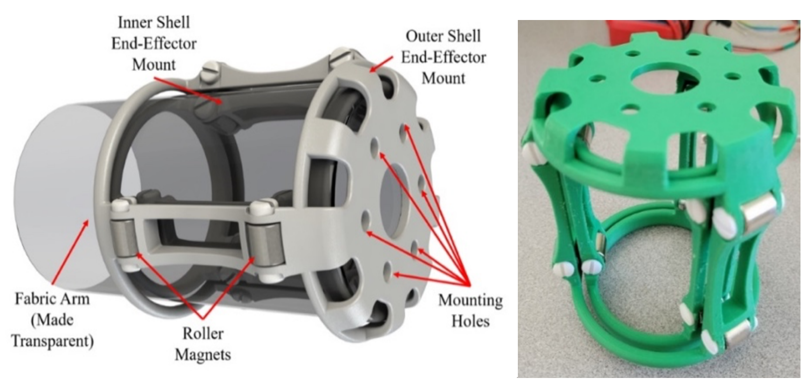


Figure. 7 Labeled Component End-Effector Mount Diagram (Left) Physical 3D Printed End-Effector Mount (Right)

### *2.3 Experimental Verification*

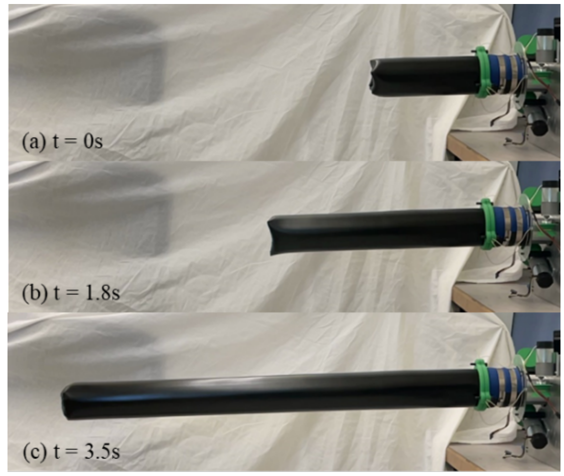

Figure. 8 Arm Extension Process (a) Initial Position at t=0s (b) Half-way position at t=1.8s (c) Full Extension at t=3.5s

<u>Growing Speed Testing:</u> The growing speed of the manipulator arm was determined by analyzing a slow-motion video of the arm extension process. This process involved pressurizing the arm to a predetermined pressure, then allowing the arm to extend, and then using a video analysis program to determine the speed of the extension. For this test, the arm was pressurized to 7 psi, due to lab safety concerns, higher pressures were not tested. Once the system was pressurized, the central motor was set to freely spin, allowing the arm to extend. This process is shown in Figure 8. Next, the video of this process was loaded on a computer with the software Tracker. The software tracked the position of the end of the arm over a time interval. Through this process, the extension speed of the arm was found to be 0.7 ft/s at 7 psi. However, based on calculations, the manipulator arm is capable of reaching an extension speed of 1.7 ft/s. The discrepancy between these two speed values can be attributed to the low internal pressure setting, low inlet airflow rate, and friction between sections of the arm fabric. We are working on increasing the extension speed by increasing the maximum internal pressure and airflow rate of the system.

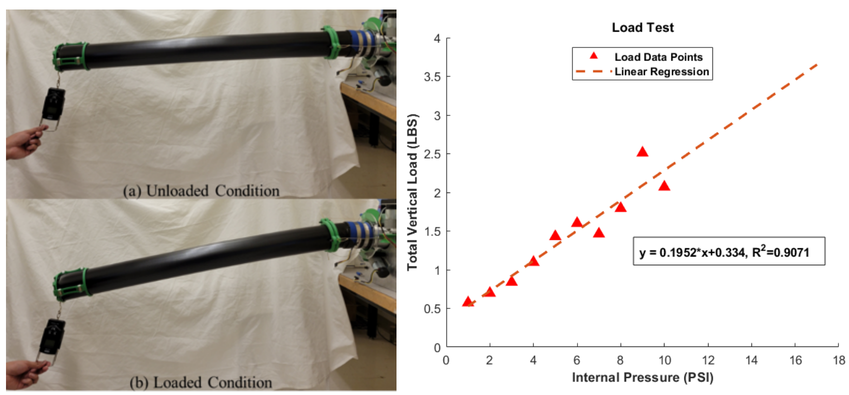

Figure. 9 Payload Testing Process (a) No Applied load (b) Applied Load Induces Buckling at the Base of the Arm (Left) Plot of the Total Vertically Applied Load, in lbs, over the Internal Pressure, in psi (Right)

<u>Manipulator Arm Payload Testing:</u> The maximum payload of the manipulator arm was determined by conducting a simple load test. This process involved pressurizing the system to a set pressure and then pulling the end of the arm down with a digital force scale until the base of the arm buckled and the robot loses control. This process is shown in Figure 9. The force measurement reading from the scale was then recorded. This process was repeated three times for a given pressure reading and then the entire measurement process was repeated for pressures ranging from 1 to 10 psi in 1 psi increments. The average of the three data points for each pressure was taken to account for irregularities. This data was then loaded into Microsoft Excel, where a linear regression was performed to estimate the maximum load of the manipulator arm at higher pressures. Based on fabric arm pressure tests, we set the safe operating pressure range to pressures below 15 psi. Thus, due to lab safety concerns, we only tested the arm once at 9 and 10 psi. We are working with a polymeric fabric expert to increase the maximum safe operating pressure of the fabric arms. The results of this process are shown in Figure 8. This plot shows that the manipulator arm is capable of supporting a 2 lbs payload at approximately 9 psi. This payload is more than sufficient to hold the end-effector and carry a large apple.

Workspace and Steering Testing: To determine and verify the workspace of the manipulator arm, the physical limitations of the system were used. These physical limitations include the maximum actuation angle of the arm in a 2D plane and the maximum length of the arm. From preliminary testing, the maximum actuation angle of the arm was found to be 30 degrees from the neutral position. This actuation angle is shown in Figure 10. Since this result was from a single motor actuating in a single direction, the total maximum actuation angle for the manipulator arm is 60 degrees in the 2D plane. The maximum length of the arm, of 4 ft, was predetermined during the manufacturing of the arm. With this information, the workspace of the manipulator arm was determined to be a spherical sector with a radius equal to the maximum arm length and 60 degrees of actuation in the 2D plane. This workspace is shown in Figure 11. This workspace was verified by a simple movement test, in which the arm length and actuation angle of the arm were adjusted. Next, the workspace of the manipulator arm was compared to the camera view, shown in Figure 11. From this process, the 6*6-ft and 3 ft depth camera view was found to match the workspace of the manipulator arm very well.

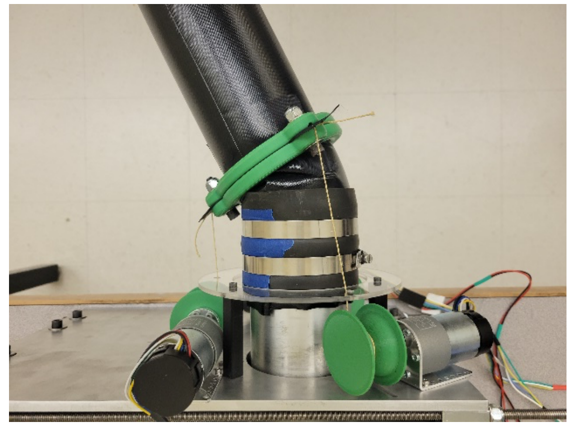
Figure. 10 Manipulator Arm Steering Test

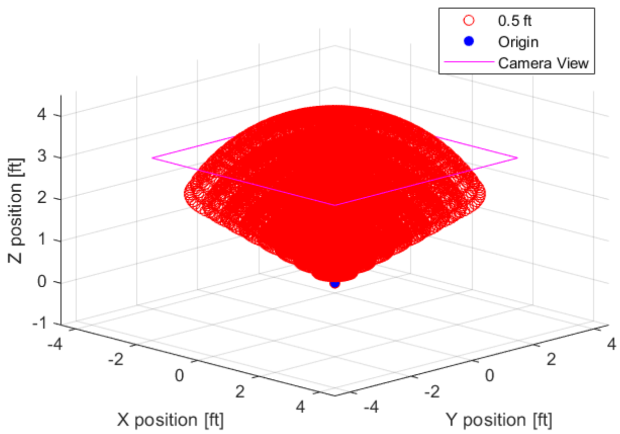

Figure. 11 Plot of the Manipulator Arm Workspace and the Camera View

## 3. Perception

### *3.1 Requirement*

The perception system includes two subsystems: i) apple detection system; and ii) end-effector tracking systems with one single ZED 2 depth camera. The apple detection system is based on the modified You-Only-Look-Once (YOLO) v5 model to detect the mature apples on the apple canopy in the field environment. Since there is no attitude sensing for the soft manipulator, it is necessary to provide a vision system solution that tracks the pose of the end-effector to achieve a close-loop control system to achieve precise apple harvesting.

### *3.2 Components*

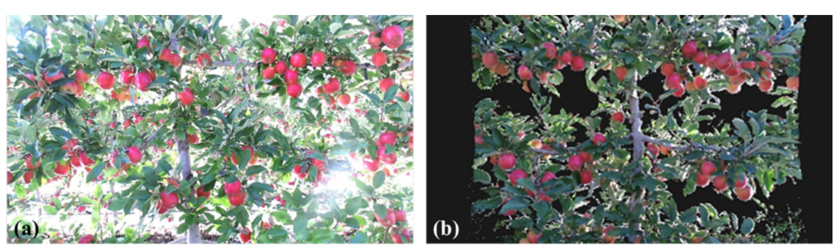

Figure. 12 Apple detection training images for YOLv5s

Apple detection system: The apple detection system was specialized for the vertical fruiting-wall tree architecture, as a common SNAP (simple, narrow, accessible, and productive) system planted in WA (experimental orchard was located in Prosser, WA). A database including 1,600

RGB images collected by Co-PI Karkee's team from the 2017 and 2018 harvesting seasons was used as a training dataset in this research (Figure 11). There were around 10~20% of the apples from the background, which were not suitable harvesting targets. A total of 800 images in the dataset were applied with a depth filter to remove the background, including unwanted apples from the adjacent rows. All images were annotated manually with rectangular annotations of the 'apple' class and corresponding annotation files were saved. The dataset was used as an input for training a modified YOLOv5s [1].

End effector detection system: To track the 3D location and orientation (attitude) of the end-effector in the global camera's frame, we adopted the "ArUco Marker tracking" method [2]. ArUco markers are binary square markers that can be used for camera pose estimation (shown in Figure 13). We attached a 2*2*2-in lightweight cube with six different ArUco codes (one in each face of of the cube) to the end effector (Figure 13). These codes were detected to estimate 6 DoFs (location and orientation in 3D) of the end-effector in real-time. The mechanism of this algorithm is that the 6 DoFs information can be calculated if two different ArUco markers of the cube can be detected by a single camera. The benefit of this algorithm is that this approach is robust, fast and simple (binary detection without dealing color information).

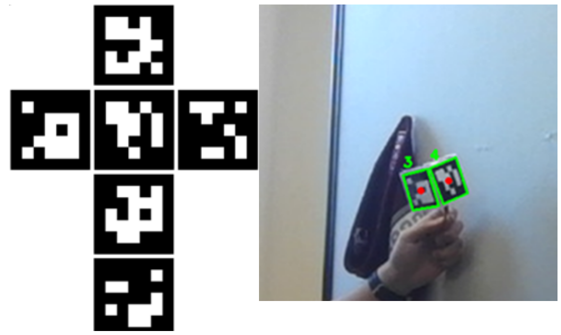

Figure. 13 ArUco Codes Print-Out (Left) and ArUco Cube track the end effector (Right)

### *3.3 Experimental results.*

Apple detection system: The apple detection system was built on a modified YOLOv5s with backbone (GhostNet) and neck (Bi-FPN). The mean average precision of the proposed model in this project was 95.4% based on a testing dataset including 100 images. The average processing speed was 43.5 frames per second (22 ms per image) with an image resolution of 648*648 pixels. The detection results indicated that the vision system achieved good performance in open-field environments while keeping a real-time detection speed. The effective range of apple detection was between 1.3 and 7.5 ft. An example output of the apple detection system is shown in Figure 14. The image processing system faced some challenges with occlusion of apples from the canopy objects.

Figure. 14 Apple detection in orchard environment

End effector detection system: As discussed above, the ArUco code cube was attached to the top of the end-effector, which could show at least one surface to the camera during the movement of the manipulator. The processing speed on ArUco cube detection and pose estimation was 32.5 frames per second, which is sufficient for the low-level position control developed in this work.

Integrated Vision/Perception System: Figure 15 shows the overall perception process. A ZED 2 camera, located on the top of the robotic arm's container, provided one stationary 2D image with depth information. Image processing technique estimated 3D location of target apples and end-effector, which will be sent to the planner to generate the optimal sequence that the single robotic manipulator should follow (will develop the optimal planning algorithm with the next year's funding). In the future orchard evaluation, we may adapt two ZED 2 cameras to deal with more unpredictable environments with the same algorithms to detect target apples and the end-effector.

Figure. 15 One ZED 2 camera provided 3D position of target apples and 6 DoF (position and orientation) of the end- effector in global camera frame.

## 4. Soft Robotic Gripper

### *4.1 Requirement*

For the soft gripper end-effector, a lightweight, highly supportive, and low-impact end-effector was needed. Specifically, the gripper could not weigh more than 0.66 lbs, the gripper had to hold large apples weighing up to 0.66 lbs without slipping, and the gripper could not damage the fruit during picking. To accomplish these objectives several key design decisions were made. Firstly, the frame and palm of the gripper were made out of 3D-printed PLA plastic. This allowed for lightweight rapid prototyping and design testing. Secondly, a servo-actuated pulley system was used to contract the gripper fingers around the target apple. This system used a cable actuation method whereby one side of the finger is contracted while the other is released. A pulley system is simple, lightweight, and can induce the torque needed to contract the fingers of the gripper. This system also allows the gripper fingers to wrap around the target apple, restricting its movements while giving sufficient support. The servo is also relatively inexpensive and has moderate weight for its size. Thirdly, the gripper fingers were chosen to be made out of DragonSkin30 silicon rubber. This silicon rubber has a high stiffness but is still soft to the touch. Thus, it easily supports the weight of the apple without causing any damage to the fruit. This silicon rubber is also relatively lightweight and has moderate friction with apple skin. Fourthly, the palm of the gripper was made out of 3D-printed PLA and was made with a 1.15 in radius. This kept the design lightweight, increased the potential amount of surface area the fingers could grab onto the apple, and reduced the likelihood of an apple slipping between the fingers. Lastly, a limit switch was used as the activation method for the gripper. The simplicity of this method reduced the weight and complexity of the overall design.

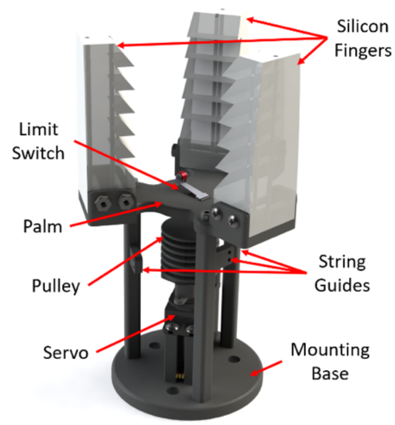


Figure. 16 Components of the Soft Gripper End-Effector

### *4.2 Design and Fabrication*

Soft Gripper Frame and Palm: All structural components of the soft gripper end-effector are made out of 3D-printed PLA plastic. This allowed for rapid prototyping and testing while minimizing overall weight. The structural components include the mounting base, string guide support rods, the palm, servo mounting rods, and the pulley. The mounting base can be connected to the end-effector mount at the end of the manipulator arm. The support rods and the servo mounting rods are bolted directly to the mounting base. The support rods have guide holes for the strings on the pulley at certain levels to ensure the strings are guided properly. The pulley is attached to a servo motor, and the palm is bolted to the support rods. The limit switch is fitted into a hole in the palm and the silicon fingers are bolted to the mounting locations in the palm. This design is shown and labeled in Figure 16.

Silicon Fingers: The fingers of the soft gripper end-effector are made out of DragonSkin30, a high-stiffness silicon rubber. From preliminary testing, the fingers require a high multidirectional stiffness in order to properly support the weight of the apple and resist the opposing forces during apple picking. The fingers were made using a 3D-printed PLA plastic mold and rod inserts to create the mounting holes and thread holes. Due to the wear caused by the internal threads, M2 nuts were embedded into the silicon rubber during the molding process. These nuts act as bearings inside the silicon, limiting the damage caused by wear, and thereby prolonging the life of the fingers.

Pulley System: The pulley system is composed of the servo motor, the 3D-printed pulley, and the strings threaded through the silicon fingers. The servo and the pulley were mounted vertically to reduce weight and the complexity of the design. The strings on the pulley alternate in winding so that when the pulley rotates one set of strings release off the pulley while the other set is pulled onto the pulley. This allows for the pulley system to contract one side of the fingers while releasing the other side of the fingers. The strings are threaded through the string guides on the supporting rods and then threaded through the silicon fingers. At the top of each finger, the threads are crimped together using aluminum metal crimps and then hot-glued to ensure that the tension in the threads does not loosen.

### *4.3 Experimental Verification*

Apple Picking Test: To verify the design and functionality of the soft gripper end-effector, two prototypes were tested at two different apple orchards. One was tested in Prosser on Dave Allen's commercial apple orchards, and the other in Pullman on the Spillman Farm's traditional apple orchards. We realize that apples vary widely between different varieties and farming styles. Prosser utilizes modern trees which are easier to pick while Pullman utilizes traditional trees which are more challenging to pick. However, successfully picking an apple, in either case, verifies the functionality of the design. The first prototype was tested in the Prosser orchard but could not reliably pick apples. This was due to multiple key design flaws that were remedied in the second prototype. This new prototype was tested in the Pullam orchard during inclement weather. During this, the gripper was able to successfully pick multiple apples. The process of a successful apple pick is shown in Figure 17. While this design was successful under poor weather conditions, we are still working on improving this design. For example, we are working on making the design more adaptable for various apple sizes. This involves allowing for adjustable palm size, controllable finger gaps, and adjustable string tensioning. We are also looking into increasing the friction between the fingers and the apple surface so that the gripper will more reliably hold onto an apple even in inclement weather.

Figure. 17 Successful Apple Picking Process (a) Gripper Approaches Apple (b) Finger Contract around Apple (c) Gripper Pulls Away with Apple in its Grasp

### 5. Overall R&D cost of a single robotic arm

In total, the materials including 3D printing, store bought components, and stock metal for this project cost approximately $920, the manufacturing cost (CNCing, water-jet cutting, and milling cost) was $520, and the electronics cost was $2790. Specifically, the stock metal cost was $405, the ZED 2 Stereo Camera cost was $449, the gearmotors cost was $1046. Thus, the R&D cost for the entire manipulator is approximately $4230, which is about 8 times cheaper than a typical 6 degree of freedom robotic arm. Since this is rapid prototyping that needs to verify our proposed solution and the current pandemic causes the shortage supply chain issue, some components' functionalities much beyond our system's specification. For example, we purchase an approximately $1000 Maxon motor to control the robotic length, and this can be replaced by much cheaper brushless DC motor. Before the commercialization, customized circuit board including controllers and drivers and the supply chain for those motors needs to be worked more, which beyond this R&D project. PI Luo has much experiences on the technology transfer (Dr. Luo helped two technology patents be commercialized before). The cost of an entire manipulator should be around $1000 without camera system when at the manufacturing stage.

**Reference:**


1. Prokscha, R., M. Schneider, and A. Höß, Efficient Edge Deployment Demonstrated on YOLOv5 and Coral Edge TPU.
2. Sani, M.F. and G. Karimian. Automatic navigation and landing of an indoor AR. drone quadrotor using ArUco marker and inertial sensors. in 2017 international conference on computer and drone applications (IConDA). 2017. IEEE.

# FINAL PROJECT REPORT

**Project Title:** Smart Orchard Year 3 + Connectivity
Smart Orchard Year 2 + Connectivity

**PI**: Steve Mantle

Report is forthcoming.

**CONTINUING PROJECT REPORT** **YEAR**: 4

**WTFRC Project Number:**

**Project Title**: Multi-purpose Robotic System for Orchards


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**Cooperators**: Columbia Fruit Packers, Auvil Fruits Inc.

**Total Project Request:** **Year 1:** 248,058 **Year 2: 250,780** **Year 3:** 255,692

**Percentage time per crop:** Apple: 100% Pear: Cherry: Stone Fruit:
(Whole % only)

**Other funding sources**

**(***If no other funding sources are anticipated, type in "None" and delete agency name, amt. request and notes)*

**Agency Name:**
**Amt. requested/awarded:** **(retain either requested or awarded and delete the other)**
**Notes:**

**Budget 1**
**Organization Name: FFRobotics** **Contract Administrator: Avi Kahani**
**Telephone: +972 545615020** **Email address: avikahani@ffrobotics.com**

| **Item** | **2018** | **2019** | **2020** | **2021 NCE** |
|---|---|---|---|---|
| **Salaries** | $59,400 | $63,000 | $66,150 | |
| **Benefits** | $5,940 | $6,300 | $6,615 | |
| **Wages** | $30,450 | $31,500 | $33,075 | |
| **Benefits** | $3,045 | $3,150 | $3,308 | |
| **Equipment** | $25,000 | | | |
| **Shipping (**)** | | $10,000 | $10,000 | |
| **Supplies** | $12,000 | $8,000 | $6,000 | |
| **Travel (*)** | $20,000 | $21,000 | $22,000 | |
| **Plot Fees** | | | | |
| **Miscellaneous (***)** | $10,000 | $25,000 | $25,000 | |
| **Total** | $167,950 | **$167,950** | $172,148 | |

**Footnotes: Footnotes: (*) Travel budget is requested to cover the travel and accommodation (Travel from Israel)**
**(**) Shipping product to field experiments (***) Equipment**

**Budget 2**
**Organization Name:** Washington State University **Contract Administrator:** Katy Roberts
**Telephone:** (509) 335-4564 **Email address:** katy.roberts@wsu.edu

| Item | 2018 | 2019 | 2020 | 2021 NCE |
|---|---|---|---|---|
| **Salaries** | $53,522 | $55,662 | $57,889 | |
| **Benefits** | $5,101 | $5,304 | $5,516 | |
| **Wages** | $6,000 | $6,240 | $6,490 | |
| **Benefits** | $600 | $624 | $649 | |
| **Equipment** | | | | |
| **Supplies** | $12,000 | $10,000 | $8,000 | |
| **Travel *** | $5,000 | $5,000 | $5,000 | |
| **Plot Fees** | | | | |
| **Miscellaneous** | | | | |
| **Total** | $82,223 | **$82,830** | $83,544 | |

**Footnotes: *Travel budget is requested to cover the mileage for field experiments and to visit collaborators/co-PIs**

## 1. OBJECTIVES

The following are the project objectives that remained same as the ones proposed in the original proposal.

*1) Optimize camera configuration for multi-arm operation of our robotic harvesting machine*
*2) Integrate and demonstrate multi-arm harvesting robot to cover entire tree height*
*3) Evaluate the performance of the harvesting robot while in motion*
*4) Demonstrate integration of the harvesting robot with fruit conveying and bin filling system*
*5) Investigate machine vision and robotic end-effectors for blossom and green fruit thinning*

### 1.1 Timeline of the Project Activities

| **Obj. #** | **Research Activities** | **Time** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Year 1 | | Year 2 | | Year 3 | | Year 4 |
| 1 | Develop a robotic system with multiple cameras | | | | | | | |
| | Optimize camera locations and create fruit map for harvesting based on accessibility | | | | (1) | | | |
| 2 | Develop and evaluate a robotic harvesting system with multiple arms for entire tree | | | | | | | |
| 3 | Develop a control system for automated forward motion control | | | | | | | |
| | Evaluate the machine for automated operation during motion | | | | | | | |
| 4 | Integrate multi-arm robot with a harvest aid platform | | | | | | | |
| | Evaluate the performance of the machine for harvesting, conveying and bin filling | | | | | | (2) | (3) |
| 5 | Develop machine vision system for flower and green fruit detection | | | | | | | |
| | Preliminary evaluation of a robotic system for flower and green fruit thinning | | | | | | | |

## 2. SIGNIFICANT FINDINGS

The most important accomplishment of this project is that we were able to build a full-scale integrated system and evaluate it in Washington, which shows that the robotic apple picking is technically and economically viable. The trials in Washington also exposed us to new apple varieties including Ambrosia, Honeycrisp, and Kanzi, which added a substantial and significant amount of data in our continuing efforts to improve the FFRobot.

- The fruit detection algorithm developed based on a deep learning technique worked properly. The technique and technology used also showed promise for detecting obstacles such as branches and trellis wire.
- The multi-arm system was working correctly with minimum interferences between the different arms.
- The current robotic system is now able to work in 10-14 foot rows.
- The analysis of robot limitation and the description of suggested setting of the fruit is underway; we will work with the tech committee to distribute the document.

- Results with the blossom and green fruit detection algorithm showed great promise for accurate detection of blossom clusters and estimation of blossom density in orchard environment. A number of end-effectors technologies assessed for effective, robotic blossom and green fruit thinning. A robotic blossom thinning system tested in the field.

## 3. METHODS

**Harvesting Objectives 1 to 4:**

*3.1 Obj.# 1: Optimize camera configuration for multi-arm operation of robotic harvesting machine*

*Introduction:* Our team has been developing and evaluating a robotic apple harvesting machine over the past several years (www.ffrobotics.com). Until 2017, field tests have been conducted with one robotic arm (simple, linear actuation) with a single picking hand in conjunction with a single camera attached to the platform.

Our teams from FFRobotics and WSU found that, in a modern fruiting wall orchard, more than 95% of apples can be detected (e.g. Silwal, 2016). Adding additional robotic arms (12 arms by now – tested in Washington) made it necessary to evaluate whether the location of the camera on the platform will yield the same results, and investigate the alternative of attaching camera to the base of the robotic arm to achieve best data acquisition results. WSU team lead this objective in collaboration with FFRobotics team.

*Materials:* The current vision system has been modified to facilitate placement of the required hardware on the base of the robotic arm which is attached to the platform frame. Field data was collected to determine the percentage of apples detected by the vision system from different locations. The system was evaluated in different kinds of orchards including -

(A) An orchard with fruit thinning to singles and pruning tree growth to approximately 10 inches beyond the trellis wires.
(B) An orchard with mechanical pruning
(C) Different canopy architectures including V-shape and Tall Spindle system.

*Procedure:* The entire image acquisition process began by scanning the canopy directly in front of the initial multi-arms robot position. Some apples were blocked by other apples, leaves, branches, trunks and trellis wire, which were difficult to be accessed and picked using a robotic hand. A deep learning-based image processing technique was used to identify different parts of the canopy and other objects as potential obstruction to apples for robotic picking. The image processing technique was able to detect apples that are not obstructed by other fruit, branches, trellis wire and trunk. These fruits are identified as completely visible and accessible fruit, which were picked by robotic hands. After the initial picking cycle was completed, the same section was re-scanned to see if more fruit are exposed with desired level of visibility and accessibility. The process was repeated until no accessible fruit are available in the canopy. The picking system then moved down the row and the process was repeated (as discussed in the following sub-sections). Missed apples were hand counted and compared to the number of detected apples. For vertical trees, this process was repeated from other side of the canopies to maximize the fruit harvesting percentage. The technique has been also extended to process videos collected by moving machine, which allows understanding the potential improvement in fruit detection through different viewing angles.

*3.2 Obj.# 2: Integrate and demonstrate multi-arm harvesting robot to cover entire tree height*

*Introduction:* As discussed in Obj. #1, our prior prototypes were based on one arm which limited the ability of the robot to pick the entire tree. It was proposed to investigate and introduce hardware and software changes to enable the dynamic structure of several robotic arms to gain the full range of 3 feet width, 3 feet depth, and 12 feet height canopies. We built such a system and evaluated (preliminary) in Israel during 2018 harvest season and an improved machine was evaluated in Washington in 2019, 2021, and 2022 seasons (2020 season was missed due to pandemic). FFRobotics led this research activity in collaboration with WSU team.

*Fig. 1: Multiple robotic arms supported by one frame*

*Materials:* Hardware and software was modified to support the multi robot arms (6 robotic arms on each side) in the same frame allowing dynamic movements along the height axis of the tree (Fig. 1). The new software algorithms controlled the entire system to allow best performance with dynamic coordination between arms in term of their work-space.

*Procedure:* The image acquisition and processing system (described in Obj.#1) provided coordinates of linearly accessible fruit in the entire work space of the machine (which is roughly 3ftx3ftx12ft). Optimization techniques were employed to provide sequence of fruit to be picked by each arm of the multi-arm robotic system. To optimize the system, more experiments were carried out by sending, but not picking apples, the robotic arms to the desired fruit. This experiment allowed evaluating several techniques of sequencing fruit picking pattern in the same location.

*3.3 Obj.# 3: Evaluate the performance of the harvesting robot while in motion*

*Introduction:* We have introduced both hardware and software changes to our current picking system to automatically move down the row in optimal steps as per the progress in fruit picking estimated by the camera system. FFRobotics team ledi this research activity in collaboration with WSU team.

*Procedure:* The entire system began by scanning the canopy to detect the fruits, which then started the picking process and automatically moved to the next stop. During the field evaluation, machine capacity, percentages of picked and bruises apples, time between the consecutive locations and the time to stabilize the robotic frame to be ready for the next picking session has been collected. The picking system was then move down the row by certain distance (e.g. 1 meter) and the process was repeated.

*3.4 Obj.# 4: Demonstrate integration of harvesting robot with fruit conveying and bin filling system*
*Introduction:* Picking system and the Harvesting Aid system were integrated and evaluated to demonstrate bruise-free end-to-end, fully functional harvesting solution.

*Materials/Procedure:* There are 6 robotic arms in the same frame allowing dynamic movements along the height of the tree as an add-on for an existing Harvesting Aid System (Automated Ag. Platform). The integration of Harvesting Aid machine and multi-robot conveyer system presented end-to-end solution from fruit harvesting from the trees through to conveyance all the way to the bin. FFRobotics team lead this research activity in collaboration with WSU.

**Blossom and Green Fruit Thinning Objectives 5:**
*3.5 Obj. #5: Investigate machine vision and robotic end-effectors for blossom and green fruit thinning*

*Introduction:* Once harvesting is automated, blossom and green fruit thinning will be another crucial step requiring automation or robotic solution. In this project, while fully developing and evaluating an integrated robotic harvesting system, some efforts was placed on robotic blossom and green fruit thinning. Our hypothesis was that, in the long term, all the manual operations in the field need to be automated and the machines need to be multi-functional with plug and play capability. WSU team lead this objective in collaboration with FFRobotics team.

*Materials:* A multi-camera system was developed and used in Obj.#1 of this proposal for detecting accessible fruit for harvesting. We used the same cameras and sensors to collect images from apple orchards during bloom and green fruit stages. The images were analyzed to detect and localize flowers and green fruit and a robotic system was used to approach targeted flower clusteres for destroying or removing desired amount of flower (no efficacy analysis was performed in this work).

*Procedure:* In this work, the deep learning algorithm developed in Obj. #1 has been revised and improved to detect flowers during the bloom stage and has been adopted to detect green fruit as well. Flower and green fruit locations was estimated using a stereo-vision system, which consisted of two cameras (as a part of sensor like RealSense camera). The locations of flower in the given work space was provided to a robotic machine for reaching and removing unnecessary flowers. Various end-effector technologies has been evaluated for precision and effectiveness in removing desired amount of flower -from target canopy regions, which include pressure hose, waterjet, electrically actuated brush system.

## 4. RESULTS & DISCUSSION

### *4.1 Obj.# 1: Optimize camera configuration for multi-arm operation*

Images and videos have been collected and were processed for improved detection and localization of apples for fruit harvesting. Data were collected using an Intel RealSense 435 camera (Intel, USA) mounted on top of a robotic arm moving across its workspace.

In addition, the machine vision system, developed using a Mask RCNN (one of the latest deep learning techniques), was expanded to detect additional parts of tree canopies, including branches and leaves along with fruits, so that important orchard characteristics such as branch obstruction, occlusion and pseudo-pendulum effects can be detected, Fig. 2.

The proposed method detected fruit parts with a mean average precision (mAP) value of 87% on a test dataset**Error! Reference source not found.**The binary mask obtained for each class from Mask-RCNN output was further analyzed to provide safe (avoiding apples that are occluded or not safe to pick for the given view) and reliable (providing right picking orientation by considering the fruits immediate surrounding) harvesting decision to the robot. With this proposed approach, the system was able to identify apples that were safe to harvest with 92% accuracy and was able to predict the fruits challenging to harvest with 91% accuracy compared to ground truth data. Though the current robotic system for picking may not utilize the variable approach direction, new capability of the vision system provides an opportunity to improve the overall harvesting system in the future.

***Fig. 2: The row data for harvesting based on MaskCRNN***

In addition to branches and other fruit, trellis wires also presented significant obstacles to robotic picking and thinning. Trellis wires were only partially visible (in segments) in images due to their thin size, and occlusion due to branches and leaves. A trellis wire detection technique was developed utilizing binary line descriptors and Haar-like features were combined at the decision level. Segments of the trellis wires detected by the vision system were combined using Hough Transform so that wire location could be estimated in the occluded regions as well. Preliminary analysis showed the trellis wire detection F1-score of 83% (Fig. 3). This technique can be integrated with the current robotic harvesting system to avoid robot collision with trellis wires.

***Fig. 3: Trellis wire and trunk detection to avoid end-effector and trellis wire collision. Even though only parts of the trellis wire are visible, the algorithm can reliably estimate the occluded part of the trellis wire assuming a linear geometry.***

The additional information gained with the improved algorithms, and the improved mechanism (additional degree of freedom – controlling the twist of the gripper), allowed us to catch the fruit based on the stem orientation and to twist each fruit based on its specific/particular orientation. Based on the tests and improvements over 3 years of this project, we reached a good result of picking fruits. Some challenges we faced in picking included picking with spurs or small brunches (7%-15%), and bruising rate of 6%. "Blocked Apple" - an apple which we identified as one we cannot pick, are left behind in the sections we picked (Fig 4)

***Fig. 4: Sample of before and after harvesting by the machine***

We took more than 20,000 images to train the system with a better understanding of the 3D location of trellis wire and the fruits, which were used in the algorithm discussed earlier for trellis wire detection.

*Objective 2,3 and 4: Full-scale, integrated robotic system development and evaluation*

As discussed before, we designed and improved a full-scale robotic harvesting systems (Fig. 5) and manufactured two versions of those (the latest improvement was completed in Sep 2021). The commercial-ready mechanical prototype was used in the field trials in Washington and Israel. The robotic picking mechanism was integrated with a dedicated platfrom from Automated Ag Systems and a dedicated convey system and Bin Filler from Maf Roda Industries, for evaluating the completed (end-to-end) harvesting process. Based on the feedback from the growers, we added a sorting/clipping station ("table") before the bin filler to enable the growers to implement the sorting /clipping manually before we automate this task in the future.

Due to the delays, the performance of the entire system was not tested in 2021. A quick video demonstrating the latest machine and its operation in a commercial orchard in WA can be found at https://youtu.be/NjPgO4VnmN8.


*Fig. 5: End-to-end system developed for robotic fruit harvesting, conveying and bin filling.*

*In 2021, we also completed an initial evaluation of the full-scale harvesting robot in a V-traillis canopy architecture to assess the practical usefulness of the same Robot frame for varying canopy architectures. We will need further studies to come up with a improved system for such applications (Fig 6).*

***Fig 6. V shape harvesting using the lower two self total 4 robotic arms***

<u>*Obj. #5: Investigate machine vision and robotic end-effectors for blossom and green fruit thinning*</u>

*Blossom Thinning:* Flowers are densely located in clusters making individual flower segmentation highly challenging. Furthermore, for the robotic system to operate efficiently, it would be sensible to estimate the number of flowers in each cluster and other orchard parameters such as trunk diameter, branch diameter, and cluster spacing to thin a portion of excess flowers en masse instead of localizing and removing individual flowers. The proposed approach involves segmenting the flower clusters, counting the number of flowers per cluster, and removing a proportion

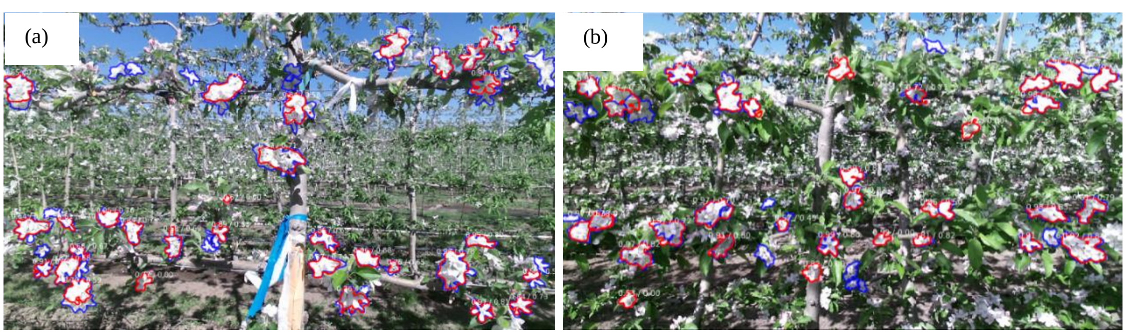


***Fig. 7: Detection result achieved by Mask R-CNN algorithm compared with ground truth dataset. Objects inside blue, and red polygons indicate ground truth and detection results respectively; (a) Scifresh apple blossoms; (b) Envi apple blossoms. Mask R-CNN was robust enough to detect true blossoms that are even missed by humans during manual labelling procedure.***

of flowers. The effectiveness of automated/robotic thinning heavily depends on blossom detection and estimation of spatial distribution of blossoms under varying background and lighting condition.

To detect flower clusters, a deep learning (Mask R-CNN) based unified semantic segmentation architecture was used. The algorithm takes single image as an input and returns all the instance of flowers/blossoms at pixel level for precise localization of blossoms. Additional images were collected from commercial apple orchard in WA during hand blossom thinning in daylight condition without background manipulation. The image dataset constituted more than 200 images with ~10,000 blossom instances. Mask R-CNN based deep learning algorithm was powerful in learning features of blossoms and was capable of correctly performing pixel level detection of blossoms in images that were never seen by the deep learning model before. Fig. 7 shows the comparison between the human labelled ground truth (blue polygons) and detection results (red polygons) achieved by Mask R-CNN algorithm. Furthermore, with the additional dataset, it was observed that blossom detection in deep learning algorithm was minimally affected by background sky which happens to have similar appearance as blossom. The system achieved a mean average precision (mAP) of 0.86 in detecting blossoms in apple trees.

In addition to flower cluster segmentation, efforts were made to estimate the flower distribution in canopies. We developed and implemented an end-to-end attention-guided regression-based deep learning network to estimate flowers' spatial distribution and count leveraging a point annotation. The proposed approach works on simple point annotation and bypasses the individual object detection, and segmentation, making the spatial distribution and count estimation problem simpler and computationally lighter. The algorithm generated a heatmap identifying the highly probable flower regions. Fig. 8 shows the result of the proposed algorithm where the density map (heat map) is overlayed on the top of the canopy image. Each image is divided into grids to compute flower distribution and count in a localized region. The proposed deep learning-based network showed a promising result with an accuracy of 87.2% to count flowers in images with an average of 89 flowers. The achieved density map can also be easily combined with the cluster segmentation results discussed earlier to compute number of flowers/clusters, which can then be used to develop thinning rules for automated flower thinning.

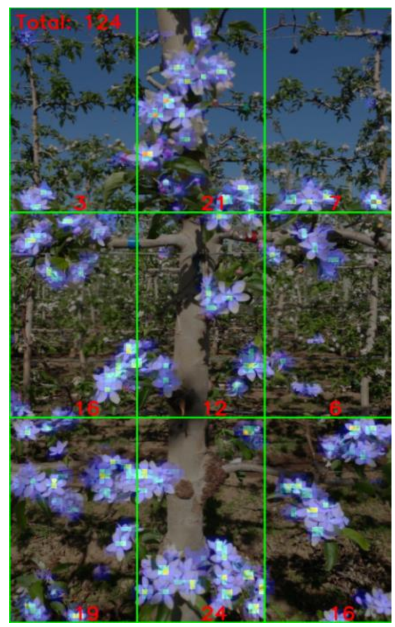

***Fig. 8: Flower spatial distribution and count estimation using deep learning based algorithm using point annotation. Heatmaps show the highly probable flower regions which can be used to estimate number of flowers in each cluster.***

Furthermore, in 2020 we investigated and evaluated the performance/efficiency of multiple off-the-shelf end effectors for blossom removal. We tested the operation of pneumatic hose (pressurized air), Waterjet (high-velocity pressurized water), electrically actuated brush system, and commercially available bloom thinner (Bloom bandit/Buster; Fig. 9). The pneumatic hose and Waterjet were ineffective, often dragging the remaining blossoms in the water/airflow direction and badly affecting surrounding flowers that need to be saved. While effective on some occasions, the electric brush system did not easily engage with the blossoms, often rotating and weakening the stem during operation. The commercially available handheld bloom thinner was able to perform targeted thinning. Since the accompanying end-effector (spindle-string configuration) was of fixed size, different end-effector configurations such as varying spindle length, string length, string spacing were developed and tested. The end-effector with shorter strings achieved better control over thinning.


*Fig.9: (a) Pneumatic hose end-effector; (b) Waterjet end-effector; (c) Electric wire brush; (d) Commercially available bloom thinner.*

Learning from the experiments in 2020, in 2021, a miniature spindle-string end-effector was developed and tested in a commercial apple orchard. The system consisted of custom-designed end-effector connected with a variable speed electrically actuated motor. Experiments were conducted varying the rotational speed, spindle string length, and approach direction to the flower cluster. The custom-designed effector was effective in mechanically removing a proportion of flowers.

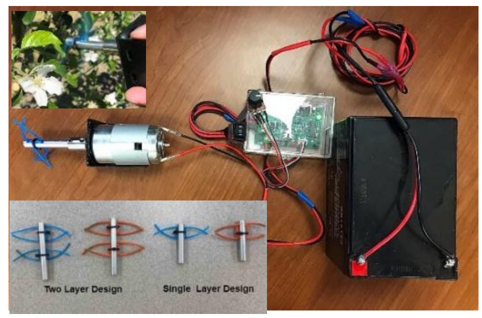


*Fig.10: Setup for actuation mechanism for costom-designed end-effector system*

In 2022, robotic blossom thinning system was developed and tested for thinning efficiency in commercial apple orchard in Prosser, WA (see Fig. 11). The system included UR5e robotic manipulator, end effecor and the camera system accompanied by machine vision and control system for situational awareness and thinning decision. Two thinning approaches were implemented: i) Boundary thinning; and ii) Center thinning. In boundary thinning the end effector was actuated around the flower cluster boundary while cluster center was targeted and thinned in center thinning approach. Out of ~900 apple flowers in each experimental category, ~69 % of flowers were thinned using the center thinning approach while ~62% of flowes were thinned using the boundary thinning approach. Field evaluation in commercial orcahard can be found in following links; i) Boundary thinning https://drive.google.com/file/d/18_oO-VW_xW7BJrhVz5sB4ptcjfqZfQXB/view?usp=sharing ii) Center thinning; https://drive.google.com/file/d/1kDsm5-dAYSiHMPrdqTdQD7665jIQcD5J/view?usp=sharing

*Fig.11: Robotic blossom thinning system during experimental evaluation in commercial apple orchard in Prosser, WA in April 2022*

*Green Fruit Thinning:* In 2022, we also put efforts and resources towards development of robotic green fruit thinning system. Particularly we focused on development of machine vision system to delineate green fruits and developing a decision support system to identify candidate fruit for thinning. RGB images were collected from commercial apple orchard and processed for precise detection and localization of apple green fruits. Similar to what we achieved in apple flower thinning, leveraging the green fruit detection information, the thinning end effector can be navigated to the desired location to remove excess green fruitlets. Fig. 12 shows the segmentaion masks of green fruits in highly challenging commercial orchard images where color properties of fruit and leaves are similar.


***Fig.12: Green fruit detection and segmentation results from commercial orchard images***

## Executive Summary

The *long-term* goal of this project is to develop an affordable, effective and *sustainable production system* for *apples* through adoption of integrated horticultural and engineering solutions. The multipurpose platforms equipped with efficient and fast robotic mechanisms at a reasonable cost will be needed to streamline labor-intensive orchard operations (Pruning, Thinning, and harvesting). Furthermore, robotic systems must be developed in a cohort with horticultural that optimizes the interaction between human, plant and robot.

FFRobotics, is developing full-scale fruit-picking robots that consists of 12 arms supported by a low-cost machine vision system and has been tested in apple orchards in WA and Israel. While a single use in operation, harvesting is the first implementation, we believe that in order to have a sustainable solution we must develop a multi-purpose robot for the orchard.

While providing a harvesting solution is essential, for the first time the robot can show the apple distribution throughout a tree, row and block. Ultimately, data such as these will help decrease the growing costs for tree fruit by enabling precision farming to better target efforts and costs only where they provide benefit.

During the project, we developed and demonstrated an end-to-end solution for harvesting based on the current operations in the orchards. Bin pass through the system, we integrated our solution with WA local manufacturer Automated Ag Systems and use one the leaders in the packing house equipment to ensure the best quality fruits in the bin.

During the project, we improved the solution to support the WA common practice of 10-14 foot row, developed a few methods for picking the different varieties of apples, and demonstrated a working system is working day and night.

Throughout the field tests, the robot operated almost flawlessly, including operation in temperatures well above 100°F, or rain, with no failures caused by heat or continuous operation for the computers and cameras.

Although during 2022, the Robot throughput increased, the system still requires an optimization algorithm and further development to increase the throughput of another 4-6 times to achieve the economic justification.

The next phase of development will move the Multi-Purpose Robot toward production.

The join efforts with Co-PI , Manoj Karkee and Qin Zhang from Cetr for Precision & Automated Ag Systems, Washington State University, is one of the key factors to our success. The develop next feature of the multi-purpose robot - the thining, will be based on their research and sharing information. WSU and the company can start to transfer the knowledge to our commercial robot structure.

The company shared with WSU two of our robotic arms to continue our joint effort to develop the multi-purpose robot.

The Muti-Purpose robot and the data collected during the work is the next level orchard management system to ensure orchard value and sustainability. It is important to continue the efforts keeping in mind, the robotic systems must be in cohort with horticultural that optimizes the interaction between human, plant and robot.

**Project Title:** Multi-Purpose robotic system for orchards

**Report Type:** Final Project Report

**PI**: Avi Kahani **B.Sc.**
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**Cooperators**: Stemilt, Columbia Fruit Packers,

**Project Duration:** 1 Year

**Total Project Request for Year 1 Funding:** $ 175,000
**Total Project Request for Year 2 Funding:** $
**Total Project Request for Year 3 Funding:** $

**Other related/associated funding sources:** Awarded
**Funding Duration:** 2022
**Amount:** $100,000
**Agency Name:** Western Growers Service Corp
**Notes:**

**WTFRC Collaborative Costs:**

| Item | 2022 | (Type year start date of year 2 here if relevant) | (Type year start date of year 3 here if relevant) |
|---|---|---|---|
| Salaries | | | |
| Benefits | | | |
| Wages | | | |
| Benefits | | | |
| RCA Room Rental | | | |
| Shipping | | | |
| Supplies | | | |
| Travel | | | |
| Plot Fees | | | |
| Miscellaneous | | | |
| | | | |
| | | | |
| | | | |
| Total | $0.00 | $0.00 | $0.00 |

**Footnotes:**

**Budget 1**
**Primary PI:**
**Organization Name:** FFRobotics
**Contract Administrator:** Avi Kahani
**Telephone:** +972 545615020
**Contract administrator email address:** avikahani@ffrobotics.com
**Station Manager/Supervisor:**
**Station manager/supervisor email address:**

| Item | (Type year of project start date here) | (Type year start date of year 2 here if relevant) | (Type year start date of year 3 here if relevant) |
|---|---|---|---|
| Salaries | $38,936.00 | | |
| Benefits | $11,681.00 | | |
| Wages | $33,075.00 | | |
| Benefits | $3,308.00 | | |
| RCA Room Rental | $25,000.00 | | |
| Shipping | $16,000.00 | | |
| Supplies | | | |
| Travel | $22,000.00 | | |
| Plot Fees | | | |
| Miscellaneous | $25,000.00 | | |
| | | | |
| | | | |
| | | | |
| Total | $175,000.00 | $0.00 | $0.00 |

## 1. OBJECTIVES

The following are the project objectives.

*1) Integrate and demonstrate multi-arm harvesting robot to cover entire tree height*
*2) Evaluate the performance of the harvesting robot while in motion*
*3) Improving robot throughput*
*4) Demonstrate integration of the harvesting robot with fruit conveying and bin filling system*

| Obj. # | Research Activities | Time | | | |
|---|---|---|---|---|---|
| | | H1 | | H2 | |
| 1 | Updated graphics | | | | |
| | Updated Platform (Automated Ag integration) | | | | |
| 2 | Improve picking Mechanism (Grippers and Software) | | | | |
| 3 | Lab Testing - WSU Sunrise Research Orchard | | | | |
| | Field Testing Commercial orchard | | | | |

## 2. SIGNIFICANT FINDINGS

The most important accomplishment of this project is that we were able to build a full-scale integrated system and evaluate it in Washington, which shows that robotic apple picking is a working system.
The trials in Washington also exposed us to new apple varieties, including Gala, Honeycrisp, CosmiCrisp and Kanzi, which added substantial data to our continuing efforts to improve the FFRobot.

- The fruit detection algorithm developed based on a deep learning technique worked properly. The technique and technology used also detect obstacles such as branches and trellis wires.
- There is a need for different harvesting movements based on the specific variety.
- The multi-arm system was working with minimum interferences between the different arms.
- The robotic system can now work in 10-14 foot rows. Work is to be done to improve the throughput of the entire system.
- The analysis of robot limitation and the description of the suggested setting of the fruit is underway.
- The flexible joint in the gripper improves the quality of harvesting, limits bruising

## 3. Harvesting Objectives 1 to 4:

*3.1) Integrate and demonstrate multi-arm harvesting robot to cover entire tree height*

*Following the challenges we faced during the 2021 season, we will work on the integration during the winter and test the integration solution in Automated Ag facilities before the season (running the integrated solution ahead of August 2022 (minimum two-shift in a roll)*
Automated Ag team lead this objective in collaboration with FFRobotics team.

*Materials:* The current Engine/Generator solution failure prevents working for more than a few hours. We need to upgrade the HW system to facilitate the required 24/7 working methods.

*Procedure:* Installing the new integrated solution of Motor/Generator and testing it in the Automated Ag shop for a few shifts in a roll to make sure it is working correctly.

***Done- we did not face major issues with the Engine/Generator solution.***

*3.2) Evaluate the performance of the harvesting robot while in motion*

*Following the challenges we faced during the 2021 season,* the current integrated solution was not tested. W*e will try and improve the integrated solution before the season and at Automated Ag facilities before the season.* FFRobotics team will lead this objective in collaboration with the Automated Ag team.

*Materials:*
Testing bins handling. Bin Loading / Unloading
The unload bin system we implement in the robot is working in two stages: the fork going down and only in the last stage the tilt appears

*Procedure:*
Loading and unloading bins before the season.
Make sure we can do it with the supervisor of the robot. Testing the unload bin system that is now working in two stages: the fork going down and only in the last stage the tilt appears

***Done -the system is working correctly and bins are successfully unloaded. There is a need to automate the process to shorten the cycle time***

*3.3) Improving robot throughput*
Improve the number of bins per hour (including the bin loading and replacement)

*Materials:*
Upgrade the system's computing power and improve the harvesting algorithms and bin handling.

*Procedure:*
There are 4 layers to improve *robot throughput of the system:*
1) Upgrade the PC and the GPU card,
2) Software improvements (software processing time that are not related to the HW)
3) Procedure improvements during harvesting - load bins/unload bins, movements between stages
4) Improving the end effector

We are now working on the 4 layers:
1) New HW
2) SW improvements in the main controller and low-level controller
3) Based on objective 3.2 to implement the best harvesting procedure

4) Improve the end effector, flexible grippers to avoid toque issues, and avoiding unnecessary movements of the arms

***Done, but further work is needed to improve the robot throughput of the system.***

1) ***New HW – installed new PC with a new GPU – Processing time is 8 times faster.***
2) ***Robot throughput of the system – We have made ongoing upgrades during the season and are still working to improve the SW. Work is being done to evaluate the improvement of changing the arm design.***
3) **implement the best harvesting procedure – done**
4) **Improve the end effector: flexible grippers – done (two cycles)**

*3.4) Demonstrate integration of the harvesting robot with fruit conveying and bin filling system*
Demonstrate a complete solution in a commercial orchard.

*Materials:*
The upgraded FFRobot in the Commercial orchard

*Procedure:*
Harvest starting at WSU Sunrise Research Orchard with the FFRobotics team – Target date Aug 1st 2022.
Testing the system's improvement to make sure no degradation following the changes, using the same harvesting method and capacity.
Increasing the capacity while ensuring the harvesting quality remains at the right level.
Following reaching the maximum capacity moving to the commercial orchard (Columbia Fruit) Target Date – no later than Aug 20th

***Done:***
***We signed a commercial agreement with one of the Cooperators. Based on the customer request and the season's development, we arrived at the commercial orchard by Aug 15, and worked till the end of October. The quantities we picked were not as expected and we did not reach the commercial quantities.***

## Collaborators (to be secured by WFTRC, in-kind contribution):

- Advisory team (frequent input throughout the entire season): interested technology/apple horticulture committee members, growers in Ephrata area
- WTFRC and WSU postharvest ITT will independently evaluate fruit quality (bruising, stems etc.)

## 4. RESULTS & DISCUSSION

*4.1 Obj.# 1 Integrate and demonstrate multi-arm harvesting robot to cover entire tree height*

*Following the challenges we faced during the 2021 season, we integrated a new coupling between the Generator and the Motor. We tested the solution at Automated Ag facilities before the season (running the integrated solution ahead of August 2022).*

*We did not face any major mechanical failure during the season, and we feel comfortable with the current integration,*

*4.2 Objective # 2,3 Evaluate the performance of the harvesting robot while in motion & Improving robot throughput*

*FFRobot designed as a full-scale robotic harvesting systems. The commercial-ready mechanical prototype was used in the field trials in Washington and Israel. The robotic picking mechanism was integrated with a dedicated platform from Automated Ag Systems and a dedicated convey system and Bin Filler from Maf Roda Industries, for evaluating the completed (end-to-end) harvesting process. Based on the feedback from the growers, we added a sorting/clipping station ("table") before the bin filler to enable the growers to implement the sorting /clipping manually before we automate this task in the future.*

*Images and videos have been collected and were processed for improved detection and localization of apples for fruit harvesting. Data were collected using an Intel RealSense 435 camera (Intel, USA) mounted on top of a robotic arm moving across its workspace.*
*In addition, the machine vision system, developed using a Mask RCNN (one of the latest deep learning techniques), was expanded to detect additional parts of tree canopies, including branches and leaves along with fruits, so that important orchard characteristics such as branch obstruction, occlusion and pseudo-pendulum effects can be detected, Fig. 2.*
*The proposed method detected fruit parts with a mean average precision (mAP) value of 87% on a test dataset**Error! Reference source not found.**The binary mask obtained for each class from Mask-RCNN output was further analyzed to provide safe (avoiding apples that are occluded or not safe to pick for the given view) and reliable (providing right picking orientation by considering the fruits immediate surrounding) harvesting decision to the robot. With this proposed approach, the system was able to identify apples that were safe to harvest with 92% accuracy and was able to predict the fruits challenging to harvest with 91% accuracy compared to ground truth data. Though the current robotic system for picking may not utilize the variable approach direction, new capability of the vision system provides an improvement on the overall harvesting system.*

***Fig. 2: The row data for harvesting based on MaskCRNN***

*In addition to branches and other fruit, trellis wires also presented significant obstacles to robotic picking and thinning. Trellis wires were only partially visible (in segments) in images due to their thin size, and occlusion due to branches and leaves. A trellis wire detection technique was developed utilizing binary line descriptors and Haar-like features were combined at the decision level. Segments of the trellis wires detected by the vision system were combined using Hough Transform so that wire location could be estimated in the occluded regions as well. Preliminary analysis showed the trellis wire detection F1-score of 83% (Fig. 3). This technique integrated with the current robotic harvesting system to avoid robot collision with trellis wires.*

**Fig. 3: Trellis wire and trunk detection to avoid end-effector and trellis wire collision. Even though only parts of the trellis wire are visible, the algorithm can reliably estimate the occluded part of the trellis wire assuming a linear geometry.**

*The additional information gained with the improved algorithms, and the improved mechanism (additional degree of freedom – controlling the twist of the gripper), allowed us to catch the fruit based on the stem orientation and to twist each fruit based on its specific/particular orientation. Based on the tests and improvements over 3 years of this project, we reached a good result of picking fruits. Some challenges we faced in picking included picking with spurs or small brunches (7%-15%), and bruising rate of 6%.*

*"Blocked Apple" - an apple which we identified as one we cannot pick, are left behind in the sections we picked (Fig 4)*

**Fig. 4: Sample of before and after harvesting by the machine**

*In vertical orchards & summer pruning (Non Fruiting Wall structure), we picked around 50% of the fruits, We need to discuss further the percentage we aim for the robotic harvesting. We demonstrated successful identification and harvesting of fruit doubles. We demonstrated night harvesting.*

*During the season we picked few varieties each one with its challenge to name a few:*

1) *Gala- clusters of fruits*
2) *Honey Crisp- very sensitive, in some cases put fruit after fruit in the bin, while we are using the bn filler*
3) *Cosmic Crisp – we faced a lot of damage fruits (not related to the robot) the robot pick the entire fruits and we need to do the sorting on the sorting conveyors, size of the fruits*
4) *Fuji- fruits size - not homogeneous*
5) *Kanzi - picking with spurs or small brunches*

*Based on our experience we build a different harvesting method based on the variety, pull, twist and pull, slow movement towards the fruits etc.*

*A general concern we can identify the number of fruits that fall during the picking process. We see it as a major issue, as if we pick 50-60% of the fruits we must make sure we are not causing loss by dropping fruits to the ground,*

*The solution is working hand in hand with the growers by pruning and thinning from one hand and deciding what fruits the robot pick to reduce the number of fruits we lose during the robotic harvesting.*

**Fig. 5: Sample of Fruits on the ground Left- robot Right- hand picking**

*Note that the implementation of the multi-purpose robot will expedite this process.*

*Performance:*
*The company invested a lot of efforts to improve the performance of the system, and a lot of work a head of us. The 4 main activities in this regard:*

1) *New HW – installed new PC with a new GPU – 8 times faster*
2) *robot throughput of the system  we have made on going upgrades during the season, still working to improve the SW.*
3) *implement the best harvesting procedure – done*
4) *Improve the end effector, flexible grippers – done (two cycles)*

*We demonstrate a manual bin replacement process – but the process is currently manual, and we need to automate the process to reduce the cycle time.*

*It is an ongoing process to improve the system's throughput, from theoretical calculation to actual practice. It is related to the number of fruits per session, the accessible fruits, the success rate of picking and more.*

*Following the season, we are running in-depth study to determine the next steps to achieve our goal.*

*4.3 Objective # 4* The upgraded FFRobot in the Commercial orchard
*We signed a commercial agreement with one of the Cooperators. Based on the customer request and the season's development, we arrived at the commercial orchard Aug 15, and worked till the end of October. The quantities we picked were not as expected and we did not reach the commercial quantities.*
*Following the activities this year and the support of the WTFRC we have now a new 3 commitment letters for commercial harvesting next year.*

Night harvesting

Day Harvesting

Harvesting during rain

## Executive Summary

EXECUTIVE SUMMARY The Multi-Purpose Robot for apple trees. The *long-term* goal of this project is to develop an affordable, effective and *sustainable* *production* *system* for *apples* through adoption of integrated horticultural and engineering solutions. The Lessons from earlier efforts of Co-PI Kahani (FFRobotics), PD Karkee and other investigators, suggest that multipurpose platforms equipped with efficient and fast robotic mechanisms at a reasonable cost will be needed to streamline labor-intensive orchard operations (Pruning, Thinning and harvesting) . Furthermore, robotic systems must be developed in cohort with horticultural that optimizes the interaction between human, plant and robot. FFRobotics, is developing full-scale fruit-picking robots that consists of 12 arms supported by a low-cost machine vision system and has been tested in apple orchards in WA and Israel. While a single use in operation, harvesting is the first implementation, we believe that in order to have a sustainable solution we must develop a multi-purpose robot for the orchard.

While providing a harvesting solution is essential, for the first time the robot can show the apple distribution throughout a tree, row and block. Ultimately, data such as these will help decrease the growing costs for tree fruit by enabling precision farming to better target efforts and costs only where they provide benefit.

During the project, we developed and demonstrated an end-to-end solution for harvesting based on the current operations in the orchards. Bin pass through the system, we integrated our solution with WA local manufacturer Automated Ag Systems and use one the leaders in the packing house equipment to ensure the best quality fruits in the bin.

During the project, we improved the solution to support the WA common practice of 10-14 foot row, developed a few methods for picking the different varieties of apples, and demonstrated a working system is working day and night.

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The next phase of development will move the Multi-Purpose Robot toward production.

# FINAL PROJECT REPORT

**Project Title:** Novel Automatic Crop Health Observer

**PI**: Curtis Garner

Report is forthcoming.

# FINAL PROJECT REPORT

**Project Title:** On-the-fly Variable-rate Airflow Spray-distribution Sprayer

**PI**: Curtis Garner

Report is forthcoming.