2026 Technology Research Review

Wireless sensing network (WSN) based heat stress system to monitor apple fruit surface temperature taken at the Smart Orchard at Mattawa.

Photo Source: Melissa Garcia

December 4, 2025

Hybrid Format
Prosser, WA

Proposal Title:	Robotic renewal pruning of fruit tree orchards
Report Type:	Interim Report

Primary PI:	Wei Guo
Organization:	The University of Tokyo
Telephone:	+81-80-3520-1527
Email:	guowei@g.ecc.u-tokyo.ac.jp
Address:	1-1-1 Midoricho
City/State/Zip:	Nishi-Tokyo city, Tokyo, Japan

Co-PI 2:	Joseph Davidson
Organization:	Oregon State University
Telephone:	541-737-9193
Email:	joseph.davidson@oregonstate.edu
Address:	204 Rogers Hall
Address 2:	200 SW Monroe Avenue
City/State/Zip:	Corvallis, OR 97331

Co-PI 3:	James Burridge
Organization:	The University of Tokyo
Telephone:	+81-70-6442-9514
Email:	burridge-j@g.ecc.u-tokyo.ac.jp
Address:	1-1-1 Midoricho
City/State/Zip:	Nishi-Tokyo city, Tokyo, Japan

Cooperators:	Dave Allan, Allan Bros. Fruit Co.; Olsen Brothers Ranches, Inc.; Dr. Matt Whiting, Washington State University

Project Duration:	3 years

Total Project Request for Year 1 Funding: $100,000

Total Project Request for Year 2 Funding: $100,000

Total Project Request for Year 3 Funding: $100,000

Other related/associated funding sources: None

WTFRC Collaborative Costs: None

Budget 1

Primary PI: Wei Guo

Organization Name: The University of Tokyo

Contract Administrator: Ryuzo ARITA

Telephone: 0081-03-5841-5032

Contract administrator email address: arita.ryuzo@mail.u-tokyo.ac.jp

Item	2024	2025	2026
Salaries	$43,900	$43,900	$43,900
Benefits			
Wages			
RCA Room Rental			
Shipping			
Supplies	$9,700	$16,100	$6,500
Travel	$6,400	$3,200	$9,600
Plot Fees			

Miscellaneous			
Total	$60,000	$60,000	$60,000

Footnotes:

[1]UTokyo salary costs are based on 30% of the current salary standard for two senior researchers and 50% for two junior researchers.

[2]The travel budget supports flight and lodging for data collection and field experiments. The calculation of travel costs is based on UTokyo standards. The budget covers two person trips in 2024, one trip in 2025 and three person trips in 2026 from the UTokyo team. If necessary, the UTokyo team will leverage funds to support two additional trips per year.

[3]Supplies include consumables such as fittings for hardware, electronics, stock materials and off-the-shelf sensors.

[4]In the Japanese academic system assistant professors, such as James Burridge and Pieter Blok, are subordinates of the Associate professor, Wei Guo, and do not have independent budgets.

Budget 2

Co-PI 2: Joseph Davidson

Organization Name: Oregon State University/Agricultural Research Foundation

Contract Administrator: Charlene Wilkinson

Telephone: (541) 737-3228

Contract administrator email address: charlene.wilkinson@oregonstate.edu

Item	2024	2025	2026
Salaries	$17,715	$25,567	$26,334
Benefits	$5,968	$9,297	$10,103
Wages			
RCA Room Rental			

Shipping			
Supplies	$14,393	$3,154	$1,522
Travel	$1,925	$1,983	$2,042
Plot Fees			
Miscellaneous			
Total	$40,000	$40,000	$40,000

Footnotes:

[1]Salaries include a Graduate Research Assistant on a 6-month, 0.40 FTE appointment in year 1 and a 9-month, 0.40 FTE appointment in years 2-3 (no tuition). Salaries also include 0.25 months per year for Dr. Joe Davidson.

[2]Supplies includes an $11,500 allotment in year 1 to cover 50% of the purchase price of a Farm-NG ground robot (the remaining 50% will be provided by other sources). The remaining supplies budget includes actuators and consumables such as fittings, raw stock, and off-the-shelf sensors.

[3]Travel budget is requested to support mileage and lodging for data collection and field experiments in Prosser, Washington (for 2 travelers each year of the project).

Objectives

Pruning is a laborious operation required to maintain fruit yield and quality and to keep the orchard healthy. In addition to being labor intensive, pruning requires a certain amount of expertise and training, further complicating matters for labor-limited orchard managers. Currently, there are no commercially available robotic pruners. Our goal is to develop a prototype robotic pruner that will accomplish simpler tasks in dormant season renewal pruning in UFO cherry and bi-axe Cosmic Crisp. Dormant season renewal pruning is a sensible first step for automation since it targets relatively simple cuts and thicker wood. We also aim to contribute a segmentation and annotation tool that will catalyze robotic training capabilities at the community level.

In the first year of research we evaluated several LiDAR scanning products in Washington and Japanese orchards. Last winter we focused on 1) robot navigation and 2) collecting LiDAR data using two platforms in multiple orchards before and after pruning. Since collecting data last winter we have focused on resolving artificial object segmentation, designing and building the pruning robot.

To reiterate, our overall objective remains to develop and test an autonomous robot that can perform dormant season renewal pruning. We have divided this into 3 sub-objectives.

1. Collect data from fruit tree orchards in Washington State and optimize data processing pipeline
2. Develop algorithms to determine renewal cut locations for the robotic pruner

3. Develop, deploy and evaluate a first robotic pruner prototype in Washington apple and cherry orchards

Significant Findings

1. Collected real orchard data using handheld LiDAR platforms.
2. Developed semi-automatic annotation tool to segment support posts, trellis wires and individual trees.
3. Developed a tool to optimize the robotic manipulator arm using real work conditions and identified the ideal number of joints and types of articulations.
4. Developed an integrated, mobile robot (i.e. software and hardware) with an arm and sensors.

Methods

1. *Orchard scanning*
2. *LiDAR and RGB data extraction,* post-processing, segmentation
3. *Machine learning of pruning points* using pre and post pruning scans
4. *Robotic arm path planning* and training in virtual environment

Results and discussion

OSU

Integrated system design: The OSU team completed software and hardware integration of our mobile orchard robot. Note, this effort also leverages funding support from some of Co-PI Davidson's other grants, including the AI Institute for Transforming Workforce & Decision Support (AgAID). Shown below in Figure 1, the mobile robot includes a FarmNg Amiga ground robot, industrial six degree of freedom robotic arm, an actuated linear slider, on-board battery power, and several sensors (e.g. GNSS and RGB-Depth cameras). This platform will be used for future dormant pruning experiments.

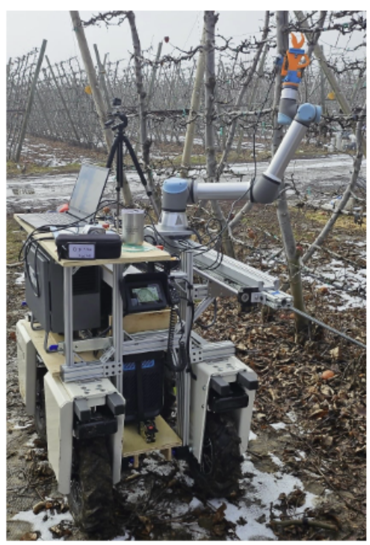


Figure 1. OSU's mobile orchard manipulation robot.

Robot pruning arm optimization: Robotic manipulators/arms are essential for advancing orchard robotics for tasks such as pruning, which demand precise, dexterous motion in cluttered and unstructured environments. Off-the-shelf industrial arms like the one shown in Figure 1, while readily available, often lack the reach and dexterity required for these settings. Over the past year we developed a simulation-driven, multi-objective optimization framework (see Figure 2) for task-specific manipulator kinematics, leveraging the NSGA-II evolutionary algorithm and physics-based evaluation. Candidate designs are encoded with high-level parameters specifically selected for their importance to dormant pruning – joint type, axis orientation, link length, and joint count – then automatically generated as URDF models and evaluated in simulation for reachability, manipulability, torque demand, and motion planning cost. Trade-offs were revealed on a Pareto front, enabling exploration across diverse designs. The framework was demonstrated on a real-world dormant orchard tree pruning task collected over the prior year, using collected 3D scans of expert-pruned UFO sweet cherry trees and an automated prune point identification pipeline (shown in Figure 3) to generate target points to guide the optimization. Results show that the proposed approach produces task-specific manipulator designs with improved workspace accessibility and reduced operational constraints compared to a commercial industrial arm, offering a viable pathway toward deployable agricultural manipulation systems that improve performance in orchards for tasks such as pruning.

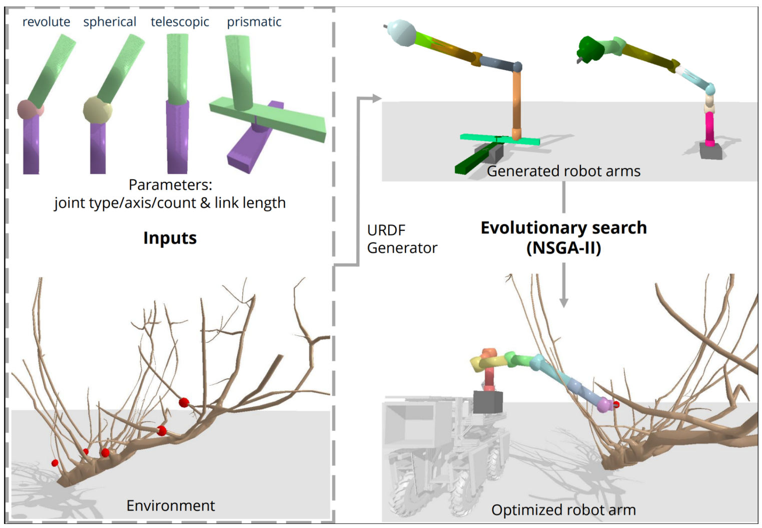


Figure 2. The system takes as input the joint types, joint axes, link lengths, and number of joints/links, along with the environment model and target reachable points (e.g., a tree mesh with designated prune points). The NSGA-II–based generative design process iteratively searches for the optimal kinematic structure for operating within the target task space.

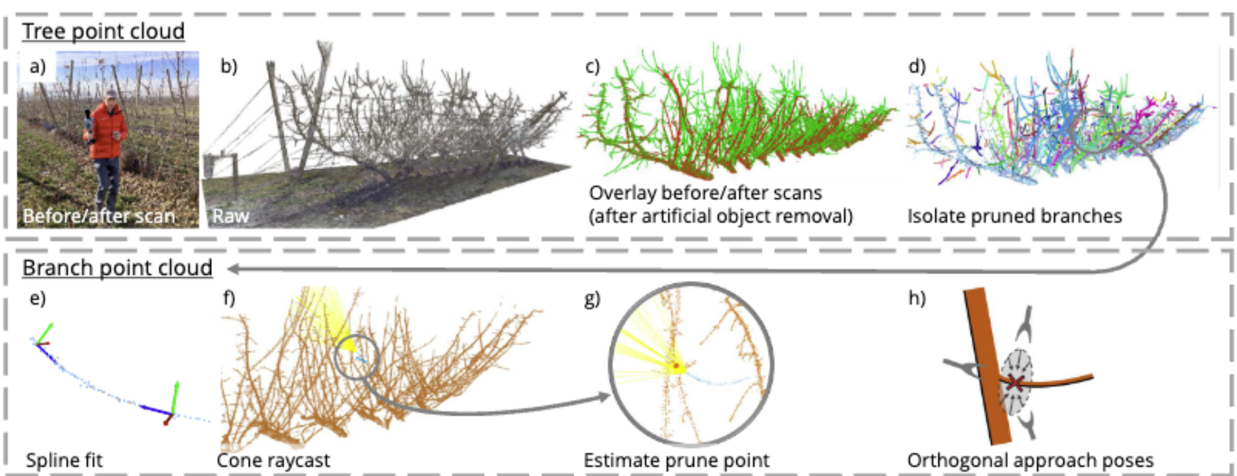


Figure 3. Prune point identification pipeline. Entire canopy: (a-b) Collect before/after scans of pruned trees, (c) Clean point clouds by removing artificial objects and outlier points, followed by overlaying the before/after scans, (d) Cluster individual pruned branches. Individual branches: (e) Skeletonize, fit spline, and align end-point coordinate frames, (f) Cone-based raycast projecting from the base of the branch, (g) Estimate prune point by selecting the ray with shorted length, (h) Generate approach poses orthogonal to the pruned branch.

UTokyo

Our experience over the first year demonstrated that efficiently labeling artificial objects, such as support posts and trellising wires will be a fundamental challenge. Artificial objects must be correctly identified prior to any pruning point determination but they cannot be simply removed because they must be avoided by the pruning robot and they may constitute important reference points. Our focus has therefore been on developing a tool for semi-automatic labelling of artificial objects in point clouds.

Our semi-automatic method involves fusion of 3D Gaussian Splats (3DGS) from RGB and intensity from LiDAR, what we call *multi-modal feature fusion* (described in detail below). The objective is to generate useful labelled datasets that can be used for robot training. Generating this method has been largely accomplished but work still needs to be done to streamline the process and facilitate data labelling by others. Optimizing the method should be accomplished in 3 months. We then plan to publish the semi-automatic method and invite others to collaborate with us by using our method to annotate more datasets. This is a time and cost effective approach to increase the volume of data available and accelerate development of autonomous pruning at the community level.

Following the streamlining of the semi-automatic artificial object annotation tools we will concentrate on 1) improving the methodology to automatically identify prune points by using before and after pruning scans 2) developing a similar semi-automatic data annotation technique in Omniverse, a state of the art simulation platform with exceeding strong potential for machine learning. We have already demonstrated the tool to Japanese fruit growers who saw the visualization of before and after pruning scans as a useful teaching tool for training human pruners.

An updated version of our preferred LiDAR scanner will be used winter 2025-2026 for orchard scans; FJD Trion P2 LiDAR scanner. It has already been acquired by the UTokyo team and is being tested.

Multi-modal feature fusion

Point cloud data and 3DGS data are different and contain different types of information. 3DGS derives from the RGB data and is needed to make high quality reconstructions. It contains what is called opacity information, which is a color related metric. The original point cloud data contains intensity information, which refers to the characteristic reflectance signature of a light beam that reflects off a surface. In our case it is relevant that wood and metal have different intensity signatures. Both opacity and intensity derived features are needed to segment poles and wires from trees. Therefore, we take the intensity information from the original point cloud data and the opacity information from the 3DGS data. Reflection intensity for original point cloud data helps to differentiate wires because metal and wood have different reflection signatures. However, since the original point cloud data also has a larger amount of noise, the 3DGS data is preferred for segmentation.

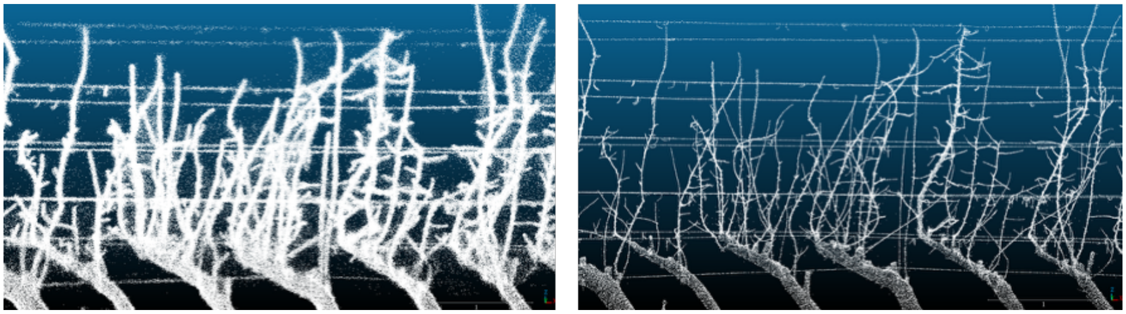


Figure 4. Left, original raw point cloud data. Right, 3D Gaussian Splat (3DGS) data.

An outline of the workflow for artificial object segmentation, tree segmentation and pruning point determination being developed is presented below. The basic steps include; 1) ground segmentation, 2) support pole and trellis wire segmentation, 3) individual tree segmentation and 4) pruning point determination. At this stage the pipeline is semi-automatic in the interest of ensuring highest quality. For example, at the step of support pole and trellis wire segmentation, two key points need to be manually annotated per object (i.e. 2 per per wire and 2 per pole).

Once the segmentation tool is finished it will be published as an open source tool and a call for collaboration will be issued. The objective is to build a larger scale real world training dataset of orchard pruning robots. Posting the tool and a call for collaboration is the most effective way to rapidly increase the training dataset size and improve the chances of a robot to learn to operate in many types of orchards. NVIDIA Omniverse will be proposed as the robot simulation platform and it will be one of the activities at the “International Consortium on Ag Robotics” led by Prof. Manoj Karkee at Cornell University.

Artificial object segmentation, tree segmentation and pruning point determination workflow

1. **Ground segmentation**, cloth simulation filter. A virtual cloth is draped over the inverted point cloud. It adapts smoothly to the underlying surface.

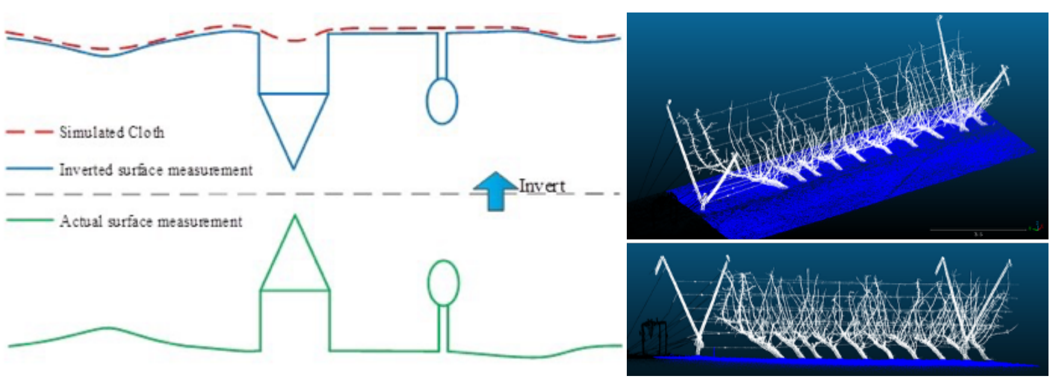
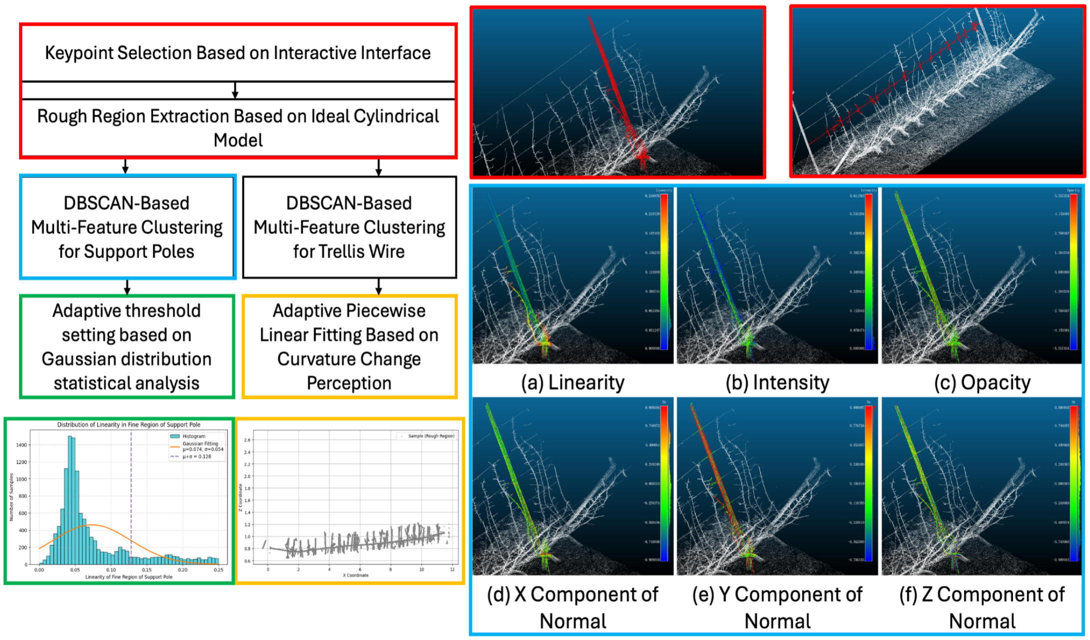
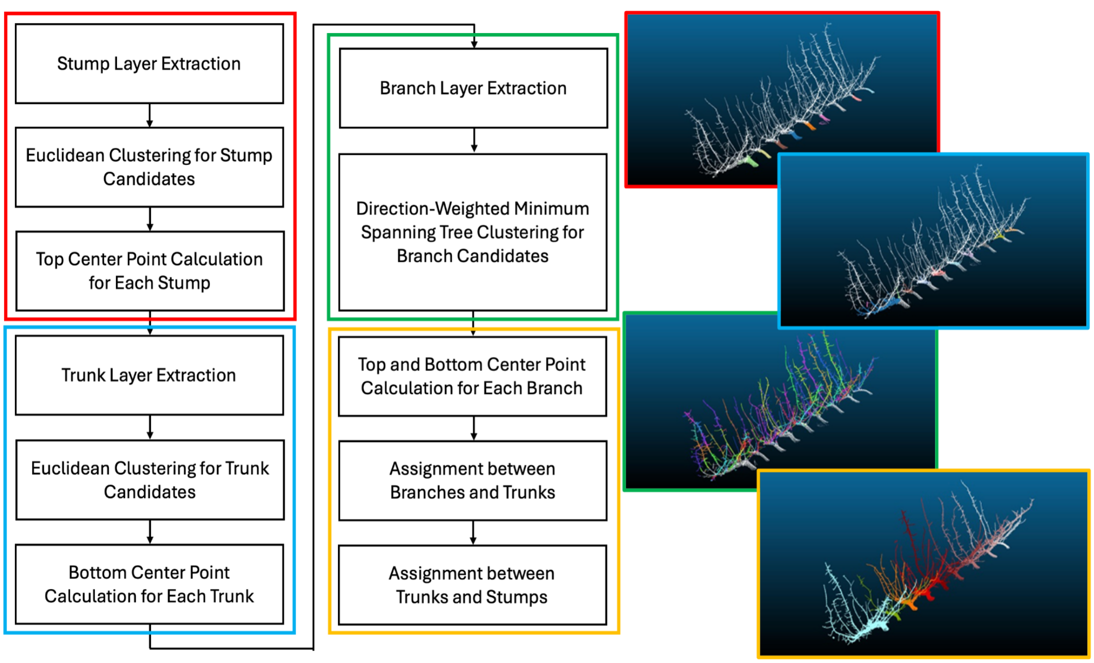


Figure 5. Left, cartoon example of inverted virtual cloth techniques. Right, ground segmentation result.

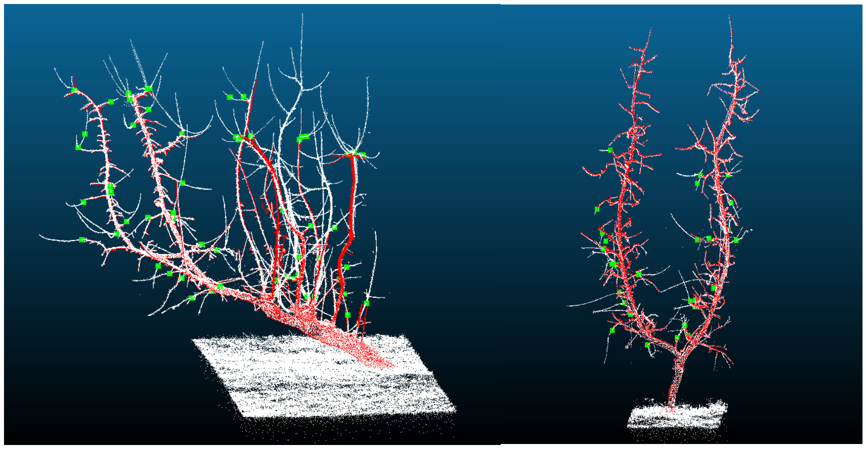
2. Support pole and trellis wire segmentation



3. Individual tree segmentation



4. Preliminary pruning point determination workflow



1. **Point Cloud Registration;** Use Generalized Iterative Closest Point (GICP) for robust alignment of before-pruning and after-pruning point clouds. Check alignment quality using Root Mean Square Error (RMSE) and visual overlay.

2. **Pruned Change Detection;** For each point in the before-pruning cloud, compute the distance to its nearest neighbor in the after-pruning cloud. Define the threshold as the sum of pruning cut thickness and scanner noise margin. Points exceeding this threshold are marked as candidate pruned points.

3. **Pruned Branch Extraction;** Apply DBSCAN clustering method to group candidate pruned points into coherent clusters. Each coherent cluster is considered as a pruned branch.

4. **Pruned Point Calculation;** Compute principal component analysis (PCA) to find the main axis of each pruned branch. Project points onto this axis to identify the two extreme endpoints. Compute the center coordinates of these two endpoints. The one closer to the trunk axis is considered the pruned point of the corresponding branch.

Proposal Title: Smart Apple Orchard: Technology Testbed and Demonstration Site
Report Type: Continuing Project Report

Primary PI: **Lav Khot**
Organization: Washington State University
Telephone: 509-786-9302
Email: lav.khot@wsu.edu
Address: 24106 N Bunn Rd.,
City/State/Zip: Prosser, WA 99350

Co-PI 2: Bernardita Sallato
Organization: Washington State University
Telephone: 509-789-9205
Email: b.sallato@wsu.edu
Address: 24106 N Bunn Rd.,
City/State/Zip: Prosser, WA 99350

CO-PI 3: Steve Mantle
Organization: Innov8Ag
Telephone: 509-795-1395
Email: steve@innovate.ag
Address:
City/State/Zip: Walla Walla, WA 99362

Co-PI 4: R. Troy Peters
Organization: Washington State University
Telephone: 509-786-9247
Email: troy_peters@wsu.edu
Address: 24106 N Bunn Rd.,
City/State/Zip: Prosser, WA 99350

Co-PI 5: Anantharaman Kalyanaraman
Organization: Washington State University
Telephone: 509-335-6760
Email: ananth@wsu.edu
Address: School of Electrical Engineering and Computer Science
City/State/Zip: Pullman, WA 99163

Cooperators: G*rower*: Sean Sahli (Columbia Farm Services, Mattawa, WA), Keith Veselka (NWFM, LLC, Zillah, WA); ***Private Industry:*** *See image below (Figure 1)*; *WSU*: G.-A. Hoheisel, Rui Lee.

Graduate students/Research Associates: Srikanth Gorthi, Dattatray Bhalekar, Juan Carlos Munguia Delacruz; Prassana Medarametla; Members of Khot Precision Ag Lab and Sallato Lab

Project Duration: 3-Year
Total Project Request for Year 1 Funding: $75,901
Total Project Request for Year 2 Funding: $77,281
Total Project Request for Year 3 Funding: $77,206

Other related/associated funding sources: AI Institute for Transforming Workforce and Decision Support (Awarded)
Funding Duration: 2021 - 2025
Amount: $20 M
Agency Name: USDA NIFA
Notes: External funding for smart orchard project sustainability. In 2024 & 2025, the commercial Smart Apple Orchard testbed will be supported in parts by WSU AgAID Institute (PIs: Kalyanaraman, Khot, Sallato, Peters, Mantle). The support comes as 'WSU Smart Farm Engineer' helping team with initial installation and monitoring of the established sensing network, in collaboration with the grower cooperator and help our team to jointly organize field days, and outreach events and content creation on technology know-how. In 2024-2025, will identify key USDA NIFA and NSF grant programs and submit large project proposals on the themes of "Farms-of-the-Future", "Cybersecure Farms", etc. to have long-term funds to sustain the on-going efforts.

Budget 1
Primary PI: Lav Khot (PIs sub-awards have been done internally at WSU)
Organization Name: Washington State University
Contract Administrator: Hollie Tuttle
Contract administrator email address: mailto:Prosser.grants@wsu.edu **hollie.tuttle@wsu.edu; prosser.grants@wsu.edu**

Category/Object	Year 1	Year 2	Year 3
Salaries and Wages - 00 & 01	31,249	31,992	32,765
Purchased Services - 02	-	-	-
Goods/Services - 03	25,040	25,040	22,540
Travel - 04	9,696	9,696	5,993
Equipment - 06	-	-	-
Benefits - 07	7,088	7,725	7,967
Tuition (QTR) - 07QT	2,828	2,828	2,941
Scholarships and Fellowships - 08	-	-	-
Award Restrictions - 14	-	-	-
Total Direct Costs	75,901	77,281	72,206
F&A - 13	-	-	-
Total Costs	75,901	77,281	72,206

Footnotes: Year 3. Salaries ($18,979) with benefits ($2,469) are requested for part of spring & summer support of a PhD level graduate student to continue maintaining LoRAWAN at the testbed. Additional salaries ($13,786) with benefits ($4,743) are requested for a classified staff and summer intern to collect ground truth data throughout the season. Supplies of $22,540 include upkeep of LoRAWAN hardware nodes, with Gateway, soil moisture and flow sensors, stem-water quantification sensors, all-in-one weather station, and AWS Cloud storage costs. PI Mantle's services through Innov8Ag are estimated to be at $5,000. Travel costs include Khot, and Sallato team member travel from WSU IAREC to Mattawa/Zillah site ($0.70/mile).

Objectives.

1. Establish "Smart Apple Orchard: Technology Testbed and Demonstration Site" in a commercial setting with focus on *Integrated Automation of Irrigation and Plant stress Mitigation Management (Year 1 and 2).*
2. Provide a testbed for evaluation and validation of mapping technology.
   Years 1 and 2 will also continue focusing on mapping technology (example; bloom, crop count, soil) and contrasting sensors/techniques (example; nutrient tests, sap, flow meters).
3. Provide outreach and extension education through field days, workshops, know-how videos, fact sheets, etc.

Progress Update Year 2 & plan for Year 3

- We have two operational Smart Apple Orchard testbeds; *Testbed 1*: Mattawa, WA (2024 & 2025 season, changed management from NWFM LLC to Columbia Farm Services in 2025; Cultivar: Cosmic Crisp®); *Testbed 2*: Zillah, WA (added in 2025 season; managed by NWFM LLC; Cultivar: Envy).
- Irrigation and heat stress automation efforts continued at Mattawa, WA Testbed, whereas Crop load monitoring and management technology evaluation has moved to Testbed 2 (Zillah, WA).
- Over 30 private industry partners have deployed and /or demonstrated their technology at these testbeds and the WSU team continues validation efforts.

- *Irrigation and Heat Stress Automation*: We continued evaluating automated irrigation and heat stress mitigation scenarios at Testbed 1 (Mattawa, WA) that run on either schedule or modeling driven automated actuation. The WSU team also added research to practice precision & automated irrigation (based on soil moisture and stem water potential) and heat stress (thermistor insert based fruit temperature) management scenario that is operationalized using AWN Smart Farm platform. Year 2 data is being analyzed and contrasted against yield and fruit quality. We will continue to evaluate these scenarios in year 3.
- *Crop Load Monitoring and Management*: At Testbed 2 (Zillah, WA), various ground (Innov8.Ag with Green Atlas, Vivid Machines, Orchard Robotics, Aurea Imaging, Aerobotics) and aerial (Tyton Aviation with Outfield technologies, and Precision Agri Tech.) imaging-based mapping technology providers collected data in Year 2. Each technology provider mapped the orchard block for estimating various crop parameters, including apple blossom count, fruit size, and fruit count and WSU team validated the findings. Vivid Machines and Green Atlas mapping results are in this report. Other providers are yet to transfer us complete 2025 season datasets for analysis. We will continue the mapping and ground-truthing efforts in year 3.
- *Autonomy/Precision Spraying/Weed Management*: Collaborating PIs Sallato, Mantle and Hoheisel are leading projects on precision nutrient management, precision blossom thinning and evaluating autonomous/precision crop protection sprayers and pertinent results can be found in those continuing reports.
- *2025 WSU Smart Apple Orchard Field Days:* Two field days (Precision and Automated Irrigation Systems [July 25] and Precision Crop Load Management & Automation Technologies [Aug 3]) were a success with over 200 folks in attendance. We also have international groups (Polish, South Africa and Chile Growers/Tech transfer) visiting the testbeds. We will continue these efforts in year 3.

Methods and Results Summary (Year 2)

Objective 1. Establish the WSU Smart Apple Orchard: Technology Testbed and Demonstration Sites 1 and 2.

Testbed 1. The "WSU Smart Apple Orchard: Technology Testbed and Demonstration Site 1" was established at Mattawa, WA in 2024 (46.712803, -119.852839) as shown in Figure 1. This is a 'WA 38' orchard on M9 Nic29 and inter-plantings of Bud 9 rootstock, managed by Columbia Farm Services (Cooperator: Mr. Sean Sahli). The block is trained as tall spindle, at 12 ft by 3 ft spacing and by 1.5 ft spacing. The first commercial harvest was in 2024 season. The block is irrigated via drip, sprinklers and has an overhead fognet (fogging + netting) installed for heat stress mitigation.

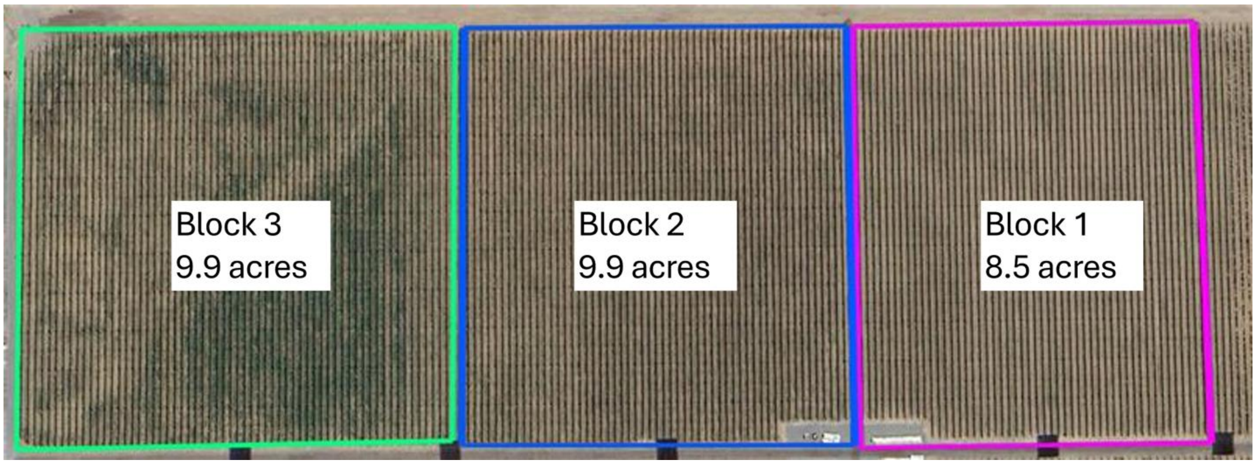


Figure 1. Smart apple orchard testbed block with tall spindle training at 12 x 3 ft spacing.

Testbed 2. The "WSU Smart Apple Orchard: Technology Testbed and Demonstration Site 2" has been established at Zillah, WA (46°25'18.5", -120°12'12.0") in 2025 as shown in Figure 2. The block was planted in 2021 with G41 rootstock over 8.89 acres and is managed by grower cooperator (Keith Veselka, NWFM LLC). The plants are trained as tall spindle at 10 ft by 4 ft spacing. The block is irrigated via drip, sprinklers and has an overhead fognet (fogging + netting) installed for heat stress mitigation.

Figure 2. Smart apple orchard testbed block with tall spindle training at 10 x 4 ft spacing.

Irrigation and Heat Stress Automation. We continued to evaluate soil-plant-atmosphere continuum sensing, climatic modeling driven decision support, and automated irrigation control in year 2 at Testbed 1. As illustrated in Figure 2, we demonstrated three scenarios conducted in block 1, 2 and 3. In year 2, WSU team added an additional scenario in block 3 for precision and automation of irrigation and heat stress management.

Scenario 1: In block 1, irrigation system has been completely automated using a centralized controller (RF-X1, Drop Control, Wiseconn Engineering). Soil moisture probe (Drill & Drop 36'', Sentek Inc.) data from up to 3 ft (90 cm) is being logged using a field station node (RF-X1, Drop Control, Wiseconn Engineering) at 15-min interval. SWAN Systems (Water, Nutrient, & Precision irrigation Software, SWAN Systems Inc.) uses this data along with AgWeatherNet station data, crop coefficient (varied across the season), and site-specific weather forecasts (Source: MeteoBlue, Basel, Switzerland) to run the climatic model to realize a weekly irrigation schedule. SWAN Systems has a web interface to run the irrigation scheduling and push it to the controller (e.g., Drop Control, Wiseconn Engineering). This model-based irrigation scheduling was implemented during the growing season until harvest. Similarly for heat stress management in block 1, commercial partners have integrated hardware to realize automated fogging during summer (July to September) months. Overhead fogging system has been installed underneath the netting (12% shade net). An IR temperature sensor (SapIP-IRT, Dynamax Inc.) continually monitors the canopy temperature in upper top sections at 15-min interval. At set threshold of canopy temperature (e.g., 38.6 °C [101 °F]) drop controller triggers actuation of solenoid valve to operate foggers (Jain by Rivulis, USA) with a differential temperature (3.4 °C [at 95 °F]) to turn off the cooling system.

Scenario 2: Similarly, in continuation from year 1, in block 2, the irrigation (and heat stress) has been managed by Columbia Farm Services using a solenoid valve controller (TWIG-V, Nelson Irrigation Corp.) tied to soil moisture probes data (Semios Inc., CA). These probes are installed at 8, 16, 24, 36-in. and send data to Semios web interface. In contrast to year 1, the new grower management decided to use under-tree sprinklers aggressively for row cover crop management, which added significant moisture in addition to drip irrigation scheduling. Moreover, soil and plant water stress indicators were collected using sap flow sensors (SGEX-25, Dynamax Inc.). Similarly, the cooling system (overhead foggers) was automated using the solenoid valve controller with continuous water application until 18:00 starting at fruit surface temperatures higher than 38.6 °C [101 °F].

Scenario 3: In block 3, WSU team has deployed sensors to monitor soil-plant-atmosphere continuum. To account for spatial variability, we deployed the set of sensors at four different locations inside the block having consistent root stock and soil properties. Each set of location have air temperature and humidity probes (ATMOS 14, Meter Group Inc.), thermistors (ST-200, Apogee Instruments), IR temperature sensor (SI-141, Apogee Instruments), stem water potential sensor (SWP, Florapulse Inc.), soil moisture and matric potential sensors (TEROS 11; TEROS 21, Meter Group Inc.) at 8 and 24 in. monitoring the microclimate and soil/plant water stress for precision and automated irrigation and heat stress management. The data was collected at 5-min intervals for all the sensors except for thermistors, which was configured at 1-min for noise filtering and decision making. All these sensors are integrated with LoRaWAN sensing nodes, where the decision support for irrigation and heat stress management was performed on AWN Smart Farm platform (beta version). For precision irrigation, the platform performs sensor fusion between soil moisture and stem water potential (SWP) with thresholds of 12 bars for SWP and 75% of plant available water. For precision heat stress management, data from multiple sensing nodes is aggregated and the cooling system is triggered at set threshold of fruit temperature (e.g., 38.6 °C [101 °F]) and operate foggers (Jain by Rivulis, USA) with a differential temperature (3.4 °C [at 95 °F]) to turn off the cooling system.

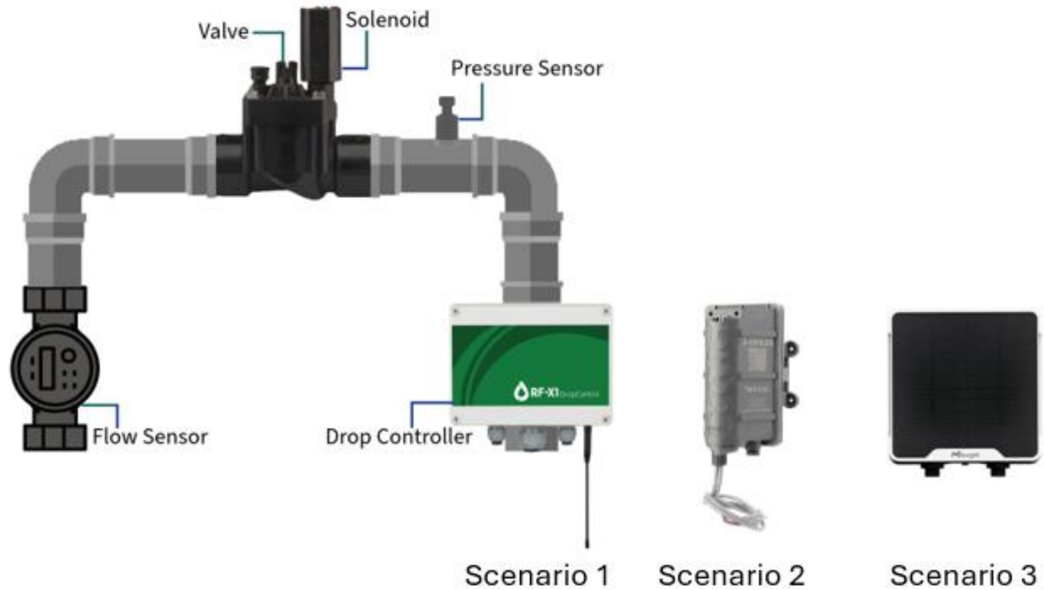


Figure 3. Smart apple orchard testbed scenarios for precision and automated irrigation and heat stress management.

Ground-truthing: In all blocks, WSU Precision Ag group has installed water flow meters (SW-3L, Dragino Inc.) to monitor and quantify water used for heat stress mitigation. This block also has micro-tensiometer probes (MT FloraPulse, Davis) inserted into the trunks for real-time plant water status monitoring along with soil moisture probes (TEROS 12, Meter Group Inc.) at 8 and 24 in. for soil moisture tracking. An all-in-one weather station (ATMOS 41, Meter Group Inc.) has been deployed inside and outside the orchard to quantify the orchard effects on weather variables. For evapotranspiration (ET) estimation and its comparison with weather data derived estimates, an eddy covariance based actual ET sensor (LI-710, LI-COR Environmental) has been deployed at 2-m (6 ft) above the canopy. All the data gets collected through LoRaWAN (Long range wide area network) based wireless sensing network (WSN) developed by our team. Similarly in block 2, micro-tensiometer and soil moisture probes have been installed to monitor plant and soil water status. In addition, Sallato lab has been doing ground truthing of canopy water stress, nutrient status, fruit size, and quality.

To evaluate the fogging systems, periodic (30 minutes) manual measurements were taken using a contact temperature probe (Thermapen Blue, ThermoWorks Inc.) and non-contact thermal-infrared imager (One Edge pro, FLIR Systems, Inc.) (Figure below). Contact temperature probe quantifies fruit surface temperature (FST), and non-contact thermal-infrared imager quantifies FST and canopy temperature. These measurements were taken in all the treatments on selective heat events (five days) throughout 2025 summer season. Moreover, to assess the effect of cooling treatments on yield (fruit count and weight per tree) and fruit quality parameters, five randomly selected trees per treatment were harvested at starch content index 2. The fruit quality was quantified by visually assessing the incidence of various disorders, including necrosis, photooxidative sunburn, browning, early sunburn, and green spot.

Results: We had encouraging results in 2024 season with 52.4% and 46.4% water savings with precision/automated irrigation and heat stress management, respectively. 2025 season data is being analyzed and contrasted against yield and fruit quality.

Objective 2. Provide a testbed for evaluation and validation of mapping technology.

Crop Load Mapping Technologies. In 2025, the crop parameters mapping technologies explored at smart orchard testbed 2 are as follows (figure 4): Innov8.Ag (Innov8.Ag Pvt Co.) uses Green Atlas Cartographer (Green Atlas Pty Ltd.), a commercial sensing platform equipped with multiple sensors, including a 2D-LiDAR, high resolution RGB cameras with strobe lights, and GPS receiver. These hardware and machine learning algorithms are integrated and mounted on an all-terrain vehicle which can be driven at 5.6 m/s to collect ground-based imagery data. Pertinent data is post-processed using propriety algorithms to generate the variability maps of estimated crop parameters. Innov8.Ag can provide these estimates in the top and bottom canopy sections at tree level resolution. The data can be used to estimate bud count, canopy vigor, and fruit color.

The Vivid XV3 Vision System (Vivid Machines Inc.) comprises a multispectral sensor capturing multiple bands in visible and near-infrared (VISNIR) spectral range, a GPS receiver, and an integrated propriety data processing algorithm. This ground-based imagery system can be universally mounted on any farm vehicle with 2.2-4.5 m/s travel speed. The vision system can scan up to 20,000 trees/hour, processing and providing real-time insights. The system generates a variability map of estimated crop parameters at a tree-level resolution. The variability maps, data, and scanning reports can be accessed remotely using a smartphone or tablet installed with the Vivid Control app and cloud-based dashboards.

The Tyton Aviation (Tyton Aviation Pvt Co.) and Outfield Technologies (Outfield Technologies Ltd., London, England) collaboration uses an unmanned aerial vehicle (Mavic 3 Enterprise Multispectral, DJI Technologies) equipped with an integrated, gimbaled RGB (CMOS Hasselblad 20MP, DJI Technologies; resolution: 5280×3956 pixels) and multispectral (bands: Green, Red, Red-Edge, and Near-Infrared) sensors. During the flight campaigns at the smart orchard, the UAV was flown at an altitude of 7.6 m AGL and 5 m/s forward speed with 45° sensor orientation, providing a complete side-view of the tree from trunk to top. These flight parameters allow users to collect aerial imagery data at 16.2 ha/h which is post-processed using proprietary machine vision and deep learning algorithms to create variability maps.

Figure 4. Crop monitoring technologies being validated at the smart orchard testbed.

In addition, Aurea imaging, Orchard Robotics, and Precision AgriTech also join the efforts in Testbed 2. Aurea imaging efforts are reported in another project led by PI Mantle. Aurea imaging efforts are reported in another project led by PI Mantle. Orchard Robotics did not scan the rows WSU team was ground truthing, hence we cannot provide any quantitative assessment. Precision AgriTech scans started late in the season and data is being proceeded by the vendor prior to the transfer to WSU team.

Ground-truthing: Similar to 2024, crop load mapping campaigns were conducted at key growth stages throughout the season. Eight ground truth locations with five trees per location were selected. These locations were geotagged using a precise RTK device; however, these details were not shared with partners to perform blind ground truthing. Blossom count, fruit count, and fruit size per tree parameters were measured manually on these locations. This data was compared with estimates from mapping solutions.

Results: Below is the summary of results for Vivid Machines and GreenAltas (by Innov8.ag). Other vendors are still processing the data for WSU team's consumption.

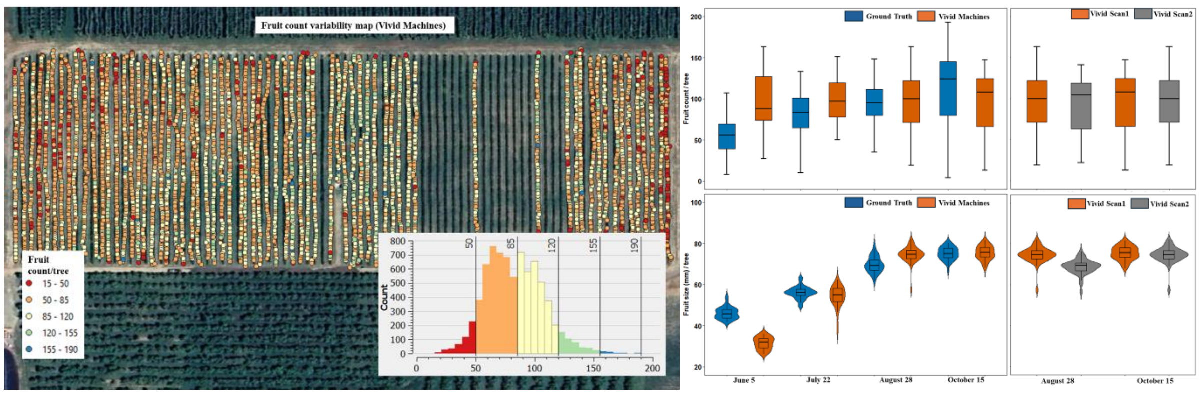


Figure 5. Comparison between the average estimated fruit size, and count /tree data by Vivid Machines and the ground truth data (season 2025).

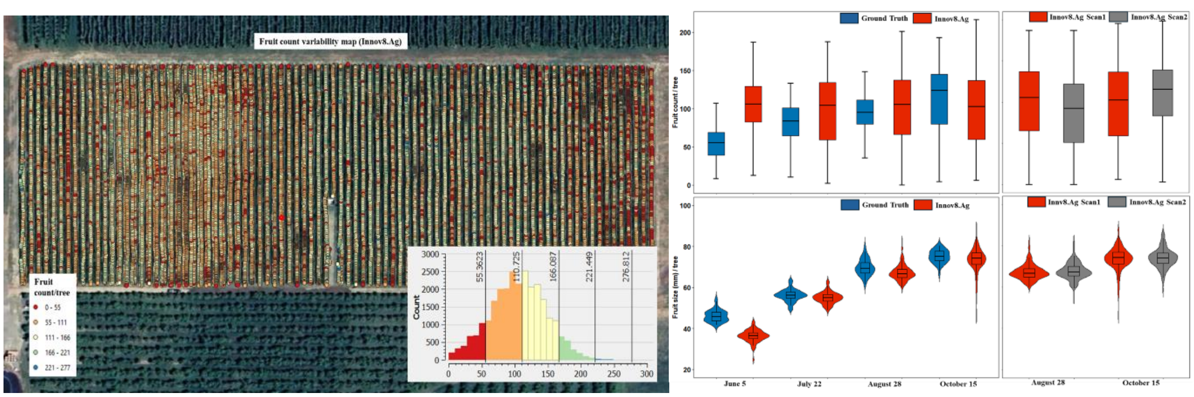


Figure 6. Comparison between the average estimated fruit size, and count /tree data by Innov8.Ag and the ground truth data (season 2025).

Objective 3. Outreach and extension education. In 2024, WSU Smart Apple Orchard Field Day was organized on August 2, 2024, with over 200 participants, highlighted in Good Fruit Growers and PNW Ag Network (https://pnwag.net/smart-orchard-nwfm-interview). We also have created a technology know-how video (https://youtu.be/KMmTDGGYu3U) on irrigation and heat stress automation. We created a website https://smartorchard.wsu.edu/, that is being kept up to date with pertinent information. We also have hosted several visits at the Mattawa smart orchard, including California Research Board (Sebastian Saa) and a technology transfer group from Chile.

In 2025, we conducted two Field days: Precision and Automated Irrigation Systems [July 25] and Precision Crop Load Management & Automation Technologies [Aug 1]) and observed over 200 in attendance. We have also created a technology know-how video (https://youtu.be/KMmTDGGYu3U) on irrigation and heat stress automation. The field days and related technologies were highlighted in media reports Report 1 and Report 2. We also continue to maintain the WSU smart orchard website, updating current information on evaluated technologies and results. We also have hosted several visits at the Mattawa smart orchard from Polish fruit industry, South Africa, Chile, and Dutch groups.

Project Title: Dutch & American Tech in Action: Sensor-Driven Precision Spray

Report Type: Continuing Project Report

Primary PI: **Steve Mantle**
Organization: innov8.ag
Telephone: 509-795-1395
Email: steve@innovate.ag
Address: 103 E Main St Ste 301
Address 2:
City/State/Zip: Walla Walla WA 99362

Co-PI 2: Joost Hazelhoff
Organization: Aurea Imaging
Telephone: +31-626-640-659
Email: joost@aureaimaging.com
Address: Nijverheidsweg 16A,
Address 2:
City/State/Zip: 3534 AM Utrecht Netherlands

CO-PI 3: Gwen Hoheisel
Organization: WSU
Telephone: 509-788-5459
Email: ghoheisel@wsu.edu
Address: 620 Market St.
Address 2:
City/State/Zip: Prosser, WA 99350

Co-PI 4: Lav Khot
Organization: WSU
Telephone: 509-786-9302
Email: lav.khot@wsu.edu
Address: 24106 N Bunn Road
Address 2:
City/State/Zip: Prosser, WA 99350

Cooperators:
- Agromanager (software)
- Kragworks (software)
- Burrows Tractor (equipment loan)
- Raven/CNH (equipment loan)
- Slimline/Turbomist (equipment loan)
- Grower Candidates (we'll finalize on 2) – Allan Bros, Columbia Fruit, McDougall & Sons, Price, Superfresh

Project Duration: 2-Year

Total Project Request for Year 1 Funding: $ 74565
Total Project Request for Year 2 Funding: $ 75284
Total Project Request for Year 3 Funding: $ N/A

Other related/associated funding sources:
Awarded: The project is already running for 3 years. Below is the information of the total project.
Amount: 2.481 million euro for 4 years
Agency Name: Dutch ministry of Ministry of Agriculture, Nature and Food Quality
Notes: Total project size is 4,962k€ for 4 years, the other half (2,481k€) is financed by Dutch growers and companies (in cash/in kind) and the Washington Tree Fruit Research Commission (for the past 3 years).
Requested: Innowide grant (EU) requested by Aurea to assist with project.

WTFRC Collaborative Costs: none

Footnotes:

Budget 1
Primary PI: Steve Mantle
Organization Name: innov8.ag
Contract Administrator: Susan Colter
Telephone: 509-473-0252
Contract administrator email address: susan@innovate.ag

Item	2025	2026
Salaries		
Benefits		
Wages	$8,250.00	$8,662.50
Benefits	$1,650.00	$1,732.50
RCA Room Rental		
Shipping		
Supplies	$11,000.00	$2,500.00
Travel	$1,305.60	$1,370.88
Plot Fees		
Miscellaneous		
Total	$22,205.60	$14,265.88

Footnotes: Wages calculated at blended $50/hr, and benefits at 20%, estimating ~ 160 hours of labor each year to support equipment integration and coordination across co-PIs and collaborators to meet objectives. Travel to/from sites and collaborators estimated at .67/mi in 2025 & 5% increase in 2026. Supplies are to support equipment install/integration.

Budget 2
Co PI 2: Joost Hazelhoff
Organization Name: Aurea Imaging
Contract Administrator: Stefan Kueken

Telephone: +31 611 279 512
Contract administrator email address: stefan@aureaimaging.com

Item	2025	2026
Salaries	$24,000.00	$24,000.00
Benefits		
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies		
Travel	$10,000.00	$10,000.00
Plot Fees		
Miscellaneous	$9,500.00	$9,500.00
Total	$43,500.00	$43,500.00

Footnotes: Misc = data processing & cloud compute / software services. Travel includes multiple flights & accommodations to/from Netherlands to Washington to support equipment install & operation. Grower participation is expected to include allocating a budget for data collection equipment rental.

Budget 3

Co-PI 3: Gwen-Alyn Hoheisel
Organization Name: Washington State University
Contract Administrator: Lesa Neumann
Telephone: 509-335-8467
Contract administrator email address: lneumann@wsu.edu
Station Manager/Supervisor: Naidu Rayapati/Karen Lewis

Item	2025	2026
Salaries	$2,203.00	$2,291.00
Benefits	$566.00	$589.00
Wages		$3,197.00
Benefits		$591.00
RCA Room Rental		
Shipping		
Supplies		$4,500.00
Travel	$453.00	$453.00
Plot Fees		
Miscellaneous		
Total	$3,222.00	$11,621.00

Footnotes:

Budget 4
Co-PI 4: Lav Khot
Organization Name: Washington State University
Contract Administrator: Lesa Neumann
Telephone: 509-335-8467
Contract administrator email address: lneumann@wsu.edu
Station Manager/Supervisor: Naidu Rayapati/Manuel Garcia-Perez

Item	2025	2026
Salaries	$4,100.00	$4,305.00
Benefits	$1,086.50	$1,140.83
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies		
Travel	$452.00	$452.00
Plot Fees		
Miscellaneous		
Total	$5,638.50	$5,897.83

Summary / Abstract

Year 1 validated an end-to-end precision-spray workflow under commercial orchard conditions. Using *Aurea Imaging's* TreeScout, the team demonstrated tree-level canopy sensing linked to two spray-control configurations: an OEM-integrated *New Holland RCM* system and a low-cost *Red Ant Agri* retrofit system.

The OEM configuration confirmed full data-to-application functionality but proved costly and firmware-dependent. Insights from that effort informed a pivot to a modular retrofit stack achieving equivalent left/right variable-rate control at a fraction of the cost. These findings outline a practical adoption path for Washington growers—large and small—using existing tractors and sprayers.

Year 2 will extend demonstrations to blossom-thinning and foliar-fertility applications, emphasizing workflow reliability, operator training, and scalable retrofit deployment.

Objectives

1. Validate precision-spray workflows linking TreeScout sensing with variable-rate sprayers.
2. Compare OEM-integrated versus retrofit configurations for cost, reliability, and scalability.
3. Demonstrate complete data flow—from canopy mapping through spray execution and as-applied tracking.
4. Engage growers, equipment dealers, and research partners in real-world validation and education.

Significant Findings

- **TreeScout–New Holland RCM Integration:** Achieved end-to-end data flow from TreeScout prescription maps to independent left/right spray control using Raven RS1 RTK, Viper display, and RCM controller on a T4.100 tractor with Turbomist Tower sprayer.
- **Red Ant Retrofit Validation:** Demonstrated a low-cost retrofit (< $3 K per sprayer) using a T4.80V open-station tractor, Emlid RS3 RTK, Turbomist non-tower sprayer, and **Red Ant controller tethered via Wi-Fi to a ruggedized Android phone running the Red Ant app**.
- **Geospatial Alignment:** Drone imagery (Mar 11 2025) and corner-post datums established tree positions for aligning TreeScout scans and spray maps.
- **TreeScout Data Collection:** Vigor (Mar 21 & Jul 30), blossom (Apr 15–17), and fruit-density (Sep 29–30) maps generated prescription files used in both control systems.

- **Cross-Platform Interoperability:** Both systems successfully ingested TreeScout maps and external prescription maps from **Green Atlas (Australia)** and **Outfield / Tyton (UK)** without modification.
- **Collaborative Support:** Burrows Tractor (equipment & technical support), NWFM (field site & equipment), AgAID Institute (intern funding), and WSU Extension (project oversight) enabled project success.

Methods

Two orchard configurations were tested under commercial conditions.

- **Scenario 1 – OEM Integrated System**

  New Holland T4.100 (closed cab) with Raven RS1 RTK (Burrows / New Holland NTRIP), Viper display, and New Holland RCM controller operating a Turbomist Tower sprayer (left/right control).

- **Scenario 2 – Retrofit System**

  New Holland T4.80V (open station with ROPS) with Emlid RS3 RTK (TreeScout scans) and Turbomist non-tower sprayer controlled by a **Red Ant controller tethered via Wi-Fi to a ruggedized Android phone running the Red Ant app**, actuating two US Solid ¾″ 12 V DC brass solenoid valves (left/right).

TreeScout scans were collected on Mar 21, Apr 15–17, Jul 30, and Sep 29–30 (2025). *Aurea Imaging* processed data into prescription maps (.shp / .iso.xml) for upload into each system. All spray runs used water for validation; as-applied data were logged and uploaded to Agromanager.

Results and Discussion

Scenario 1 – OEM Integration Proof

The New Holland RCM system verified that TreeScout-generated maps could be interpreted and executed by a modern OEM controller. Firmware updates provided by New Holland corporate one week before the Smart Orchard Field Day enabled successful left/right spray control. Although sulfur blossom-thinning applications were delayed past bloom, water-only runs confirmed full data transfer and control. This scenario proved technical feasibility but highlighted cost and dependency limitations for grower adoption.

Scenario 2 – Retrofit Practicality

The retrofit configuration achieved the same left/right precision at < $3 K per sprayer without OEM integration. The Red Ant controller's Wi-Fi link to an Android phone provided an intuitive interface for loading jobs, starting sprays, and viewing as-applied maps. Multiple passes at NWFM showed reliable actuation and data logging. TreeScout was mounted on open-cab tractors at NWFM and Daniel Rowley's John Deere orchard, demonstrating tractor-agnostic compatibility. These results prove a viable retrofit path for small and medium-scale growers.

In the 2025 configuration, GPS data were supplied separately to the TreeScout and spray-control systems. An **Emlid RS3 RTK receiver (~ $3 K)** provided positional data to TreeScout, while the **Red Ant controller (~ $3 K, including two solenoids)** used its own integrated GPS to drive variable-rate spraying. The next stage of development for 2026 aims to streamline this setup by having the Red Ant controller provide GPS to both the TreeScout and the sprayer, reducing duplication and simplifying connectivity. This consolidation would bring the total retrofit cost for Scenario 2 to approximately **$3 K plus TreeScout**, while maintaining full RTK-level accuracy and portability across tractors and sprayers.

Technology Partner Adoption Status

- **Aurea Imaging** (aureaimaging.com) operates TreeScout systems across Europe and South Africa with **45 active deployments**, and has received **pre-orders from U.S. East Coast growers for 2026**.
- **Red Ant Agri** (redantagri.co.za) has deployed **120 + Smart Node implements** worldwide—including granular, auger, lime, and spray applications—and is expanding into U.S. tree-fruit production.

These established partners ensure that the systems tested are commercially grounded and supported beyond research settings.

Cross-Platform Interoperability

Both control systems successfully ingested and executed prescription task maps generated from multiple sensor platforms. Primary data sources were **Aurea Imaging TreeScout** vigor, blossom, and fruit-density maps. In addition, both systems were tested with externally produced prescription maps from **Green Atlas (Australia)** and **Outfield Technologies / Tyton Aviation (UK)**. All map types imported directly into the *Viper display* (Scenario 1) and *Red Ant Android app* (Scenario 2) without modification and executed correctly in the field. This demonstrates that the workflow supports both TreeScout and non-TreeScout map sources, ensuring long-term flexibility and preventing vendor lock-in.

Regional Context and Adoption Dynamics

European farms are small, owner-operated, and use closed-cab ISOBUS tractors. In Washington, orchards are larger and depend on dedicated spray operators who **often speak only Spanish** and work with open-station tractors. A $100 K closed-cab tractor common in Europe is rare here. The Red Ant retrofit kit's simplicity and Spanish-friendly interface align with U.S. labor and economic realities.

Operational Scale, Modularity, and Connectivity

Growers range from < 10 tractors (*Rowley*) to > 70 (*large enterprises*). Given industry financial stress, the OEM new tractor model is not viable for broad adoption. The 2026 goal is to advance Scenario 2 into **modular retrofit kits for existing sprayers** that install or remove in minutes, making any tractor precision-ready on demand. Future work will add **removable, secure controller mounts**, support **foliar-fertility applications**, and expand data connectivity through cellular and cloud sync.

TreeScout can also be mounted on tractors performing routine operations (mowing, fertilizing), collecting canopy data passively throughout the season. A class of "TreeScout-ready" tractors with standardized mount points is being defined, and UTV deployment for irrigator routes is under exploration.

Comparative Insights

Parameter	Scenario 1 (OEM RCM)	Scenario 2 (Retrofit Red Ant)
Underlying Tractor Requirement	New Holland T4.100 (closed cab, ≈ $85 K +)	Existing tractor (open-cab compatible; tested on T4.80V and John Deere)
GPS / Display Source	Raven RS1 RTK receiver + Viper display (feeds GPS to RCM-U and TreeScout)	2025: Emlid RS3 RTK for TreeScout + Red Ant controller GPS for sprayer (~ $3 K each); 2026 target: single Red Ant GPS feeding both systems

Parameter	Scenario 1 (OEM RCM)	Scenario 2 (Retrofit Red Ant)
Sprayer Retrofit Cost	≈ $20K + for RCM + RS1 GPS + Viper integration	≈ $3 K for Red Ant controller + 2 solenoids (2026 target includes shared GPS source)
TreeScout Sensing Platform	TBD flat price / unlimited acreage 3-year license (same for both)	TBD flat price / unlimited acreage 3-year license (same for both)
Complexity (2025 trials)	High (OEM firmware support required; dependent on New Holland corporate updates)	Low (open interface; retrofits onto existing sprayers via Android app)
Grower Modifiability	Limited	High
Spray Control Capability	Independent left/right control	Independent left/right control
Tractor Compatibility	Closed-cab only	Agnostic (open or closed cab; tested on New Holland and John Deere)
Field Readiness	0 RCM units in tree fruit (early validation)	Active deployments in tree fruit (South Africa) and 120 + Smart Node implements globally; U.S. expansion underway
Product Reference Links & Field Activity	New Holland RCM – Raven Industries	Red Ant Agri – Spray Controller / Aurea Imaging – TreeScout (**[INSERT AUREA 2025 DEPLOYMENT COUNT] global deployments; U.S. East Coast pre-orders for 2026**) / Interoperability validated with TreeScout, Green Atlas, and Outfield / Tyton maps

---

Next Steps (2026)

- Conduct spray applications using chemicals to validate full workflow reliability (not efficacy trials).
- **Integrate GPS:** demonstrate Red Ant's GPS feeding both TreeScout and sprayer systems to reduce hardware cost and complexity.
- Scale modular retrofit kits for commercial availability through Burrows Tractor and WSU Extension demonstrations.
- Develop bilingual operator training modules (English / Spanish) [may require separate grant application to scale]
- Integrate TreeScout vigor maps with soil-health layers for variable-rate foliar-fertility applications.
- Continue testing interoperability with TreeScout, Green Atlas, and Outfield / Tyton maps.

- Advance removable controller security and cloud-sync connectivity.

Project Title: Integrated sensing and real-time control for intelligent fruit picking

Report Type: Continuing Project Report

Primary PI: Joseph Davidson
Organization: Oregon State University
Telephone: 541-737-9193
Email: joseph.davidson@oregonstate.edu
Address: 224 Rogers Hall
Address 2: 2000 SW Monroe Ave
City/State/Zip: Corvallis, OR 97331

Co-PI 2: Cindy Grimm
Organization: Oregon State University
Telephone: 541-737-2600
Email: cindy.grimm@oregonstate.edu
Address: 224 Rogers Hall
Address 2: 2000 SW Monroe Ave
City/State/Zip: Corvallis, OR 97331

CO-PI 3: Jochen Hemming
Organization: Stichting Wageningen Research
Telephone: +31 317 486710
Email: jochen.hemming@wur.nl
Address: Droevendaalsesteeg 1
Address 2:
City/State/Zip: 6708 PB Wageningen, the Netherlands

Cooperators: Munckhof Fruit Tech Innovators, Allan Bros., Inc., Thompson Hill Orchards

Project Duration: 3-Year

Total Project Request for Year 1 Funding: $83,701
Total Project Request for Year 2 Funding: $81,836
Total Project Request for Year 3 Funding: $84,463

Other related/associated funding sources: None

WTFRC Collaborative Costs: None

Budget 1
Primary PI: Joseph Davidson
Organization Name: Oregon State University/Agricultural Research Foundation
Contract Administrator: Charlene Wilkinson
Telephone: (541) 737-3228
Contract administrator email address: charlene.wilkinson@oregonstate.edu

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	$28,177.00	$29,022.00	$29,893.00
Benefits	$8,674.00	$9,360.00	$10,080.00
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies	$3,000.00	$1,524.00	$1,500.00
Travel	$800.00	$3,500.00	$800.00
Plot Fees			
Miscellaneous			
Total	$40,651.00	$43,406.00	$42,273.00

Footnotes:
[1]Salaries includes a Graduate Assistant on a 9-month, 0.40 FTE appointment in years 1-3 (no tuition). Salaries also include 0.25 months per year for Joe Davidson and Cindy Grimm.
[2]Supplies include consumables such as fittings, raw stock, and off-the-shelf sensors.
[3]Travel budget is requested to support mileage and lodging for data collection and field experiments.

Budget 2
Co PI 2: Jochen Hemming
Organization Name: Stichting Wageningen Research
Contract Administrator: Tom Molthof (Finance & Control)
Telephone: +31634510679
Contract administrator email address: tom.molthof@wur.nl

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	$35,550.00	$35,430.00	$36,690.00
Benefits			
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies	$3,000.00	$1,500.00	$1,000.00
Travel	$3,500.00	$500.00	$3,500.00
Plot Fees	$1,000.00	$1,000.00	$1,000.00
Miscellaneous			
Total	$43,050.00	$38,430.00	$42,190.00

Footnotes:
Salary costs WUR are based on the so-called topsector tariff (lower rate than market b2b tariff). Topsector tariff is for example also applied in The Next Fruit 4.0 project. It is a well-balanced calculation of a team consisting of research assistants, junior researchers and senior researchers. Per year the researchers on this project will be able to work about 270 hours (=34 days).

Introduction

Harvesting is the most labor-intensive activity in fresh-market tree fruit production. The H2A program is becoming increasingly important for filling temporary, seasonal agricultural jobs, despite the costs and logistical complexities incurred by growers using the program. While the industry is highly motivated to automate its labor-intensive operations, there are still no commercial harvesters available for the fresh tree fruit market despite nearly four decades of research. Much of the prior work has focused exclusively on vision as the primary sensing modality, disregarding what happens after initial contact and ignoring the sense of touch that humans use to manipulate fruit during a pick. This has resulted in machines that can effectively see fruit on the tree, but not robustly pick and store them at the rates required for commercial adoption.

Our team's primary goal is to increase fruit detachment rates, reduce fruit spur separations, and minimize fruit damage via a novel, sensorized end-effector embodied with a human-like sense of touch. To accomplish our goal, we have defined the following three research objectives:

1. Develop a prototype picking end-effector with integrated vision, force, and tactile sensors
2. Design i) algorithms for fusing multiple sensor streams during the pick; and ii) novel, closed-loop tactile picking controllers that incorporate this multi-sensory feedback
3. Evaluate the end-effector in preliminary lab/field trials in both Washington and the Netherlands to study the effects of cultivar, orchard system, and management practices on technology performance

This Continuing Report summarizes research results from the performance period of December 2024 - November 2025. During the third year of the project we made substantial progress across all research objectives, including new developments in sensor fusion, intelligent control, and hardware integration. A highlight from this performance period was joint, collaborative field experiments in Prosser, WA.

Significant findings

- Inspired by the findings from this project, Dutch companies developing robotic harvesting technology are incorporating new, 'near-contact' sensors in their suction cup gripper
- In lab-based studies, the stiffness-seeking controller performed better than other picking motions
- During field trials, the rigid fingers performed better than the softer, 'finray'-style fingers
- The whisker sensors require additional modifications for long-term use in the orchard

Objective 1: Develop prototype end-effector (OSU lead, WUR participant): Our first objective is fabricating a prototype apple harvesting end-effector with multi-modal in-hand sensing. For this effort we are comparing three different prototypes, each of which uses suction cups. Our goal is to identify the respective advantages and disadvantages of each design. For example, a potential advantage of "suction only" is less interference from collisions between fingers and vegetation. A potential advantage of "suction + soft fingers" is a more secure grip that enables high acceleration pick motions; also, the fingers provide a surface to capture additional sensor streams about contact conditions, grasp quality, etc.

'Single-mode' gripper: This year the OSU team developed a modified version of Wageningen University's single suction cup gripper, shown in Figure 1. The system features one large suction cup fitted with four flexible "whiskers" (bend sensors), a Time-of-Flight (TOF) sensor for depth measurement, and in-line pressure sensors integrated into the vacuum line to monitor suction level. Our updated hardware includes a redesigned WUR-inspired layout with the TOF sensor positioned further back to prevent fruit damage during picking, and a new vacuum enclosure and pump.

'Dual-mode' gripper / rigid fingers: This year we enhanced the gripper's robustness by improving its mechanics, electronics and firmware (see Figure 2). From the **mechanical** perspective, we reduced the number of components and simplified the assembly process: (i) simplified track supports from 3d printed l-shaped to screws; (ii) modified the body of the gripper to channel all wires through the gripper's interior, reducing chances of disconnections in the field. From the **electronic** perspective, we: (i) added hall-effect limit sensors at the beginning and end of the nut path, as feedback for the stepper-motor; (ii) modified all connectors from push-pin to socket-socket type; (iii) relocated the air-pressure sensors to a position more ergonomic for assembly; (iv) changed the previous stepper driver to a smaller and more powerful one; and (v) added a 12-24V voltage booster in order to reduce the number of power cables. From the **firmware** perspective, we: (i) replaced the Arduino-zero board with an ESP32 with wifi and microROS capabilities; (ii) switched from pySerial to microROS; and (iii) switched microROS transports to wifi and reduced the number of cables going into the gripper.

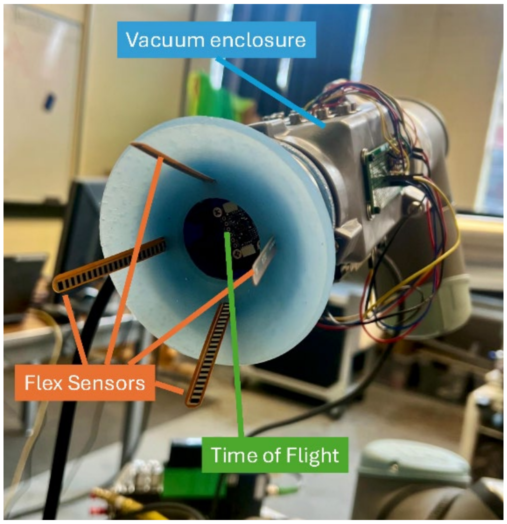


Figure 1. Sensorized, single suction cup gripper.

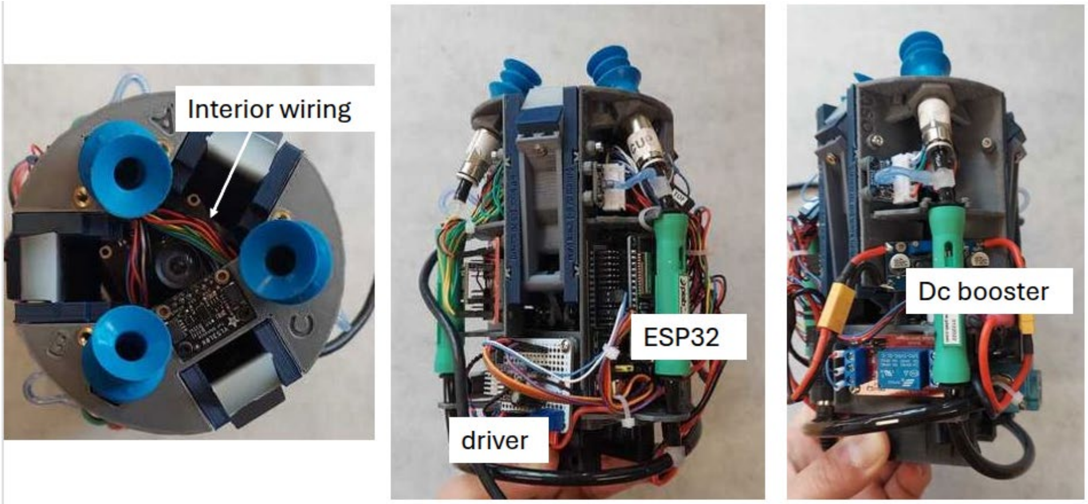


Figure 2. Updated multi-suction cup gripper prototype with modified components designed to improve robustness.

Additionally, we overhauled our apple proxy (see Figure 3) for in-lab trials. From the **frame** perspective, we: (i) increased the width and height of the proxy gantry; (ii) added a retractable net for catching released / picked apples; and (iii) improved the fixtures with the table. From the **apple pick mechanics** perspective, we: (i) moved the spring-based mechanism that mimics branch stiffness to the edges of the branch; (ii) added spur links made from flexible, 3D-printed TPU; and (iii) improved and simplified the stem-apple joint by replacing the 3D-printed spherical joint with a steel, cable-based stem.

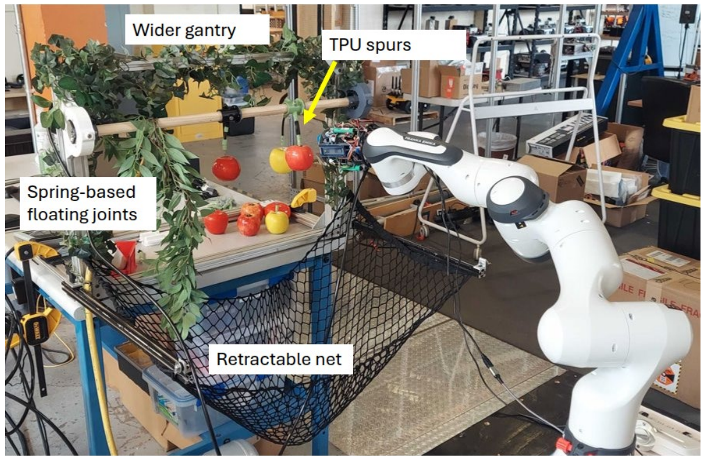


Figure 3: Artificial apple proxy designed for in-lab experiments.

'Dual-mode' gripper / fin ray fingers: This year we developed a new dual-mode, flexible finger gripper to help enhance the grip. The gripper uses three fin-ray style fingers actuated in the same manner as the dual-mode rigid finger gripper (see Figure 4). This design of the fingers allows them to conform to the apple's shape, creating a better grip. The motor has been upgraded to a brushless direct current (BLDC) motor to provide the increased required higher torque to conform the fin-ray fingers to the apple. An Odrive micro BLDC motor controller is used to control the new motor with an ESP32 with WIFI and microROS acting as the overall controller. Power is supplied at 24V with a 24-12V set down converter supplying power to the ESP32. The gripper's frame has been redesigned to accommodate the larger fin-ray fingers along with new tracks to allow the fingers to conform.

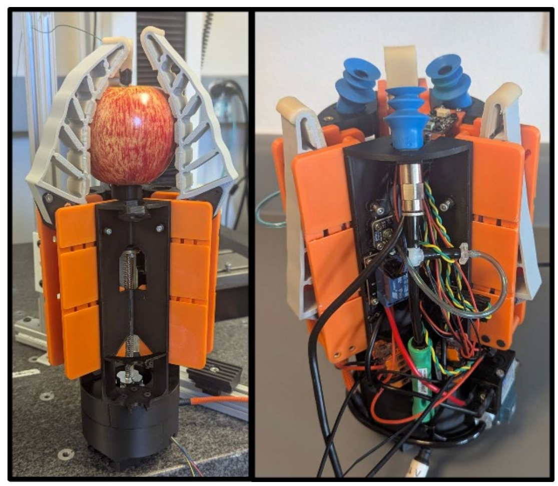


Figure 4. Fin-ray gripper with fingers extended (left) and fingers retracted (right).

<u>Objective 2: Design sensor fusion and control algorithms (OSU lead, WUR participant)</u>: While Objective 1 focuses on hardware design, in Objective 2 we are developing algorithms to fuse multiple sensor streams to align the gripper, evaluate grasp quality, and determine an optimal pick direction. We have broken Objective 2 into three tasks.

Task 1 – Precision alignment using visual plus depth feedback: Using the single-mode gripper, we perform fine alignment of the end effector by combining visual feedback with depth sensing from a Time-of-Flight (TOF) sensor. The TOF sensor provides accurate distance measurements along the z-axis, while the flexible "whisker" bend sensors give feedback for centering in the x and y directions. The approach begins with coarse alignment from the vision system, which is then refined using sensor feedback. As the gripper nears the fruit, the TOF readings stabilize (indicating proximity to the suction point), and the whisker sensors confirm lateral centering. Finally, the gripper performs a small varying lateral and angular motion for fine-tune positioning when initiating suction (see Task 2).

Task 2 – Measuring grip/grasp quality and stem orientation: To assess grasp quality, we use in-line pressure sensors to monitor vacuum level in real time. Based on data from previous picks, we established a pressure threshold corresponding to a reliable seal and successful grasp. When the measured vacuum reaches or exceeds this threshold, the system confirms a valid grip and proceeds to the picking phase. If the pressure remains below the threshold, the gripper performs small lateral and angular adjustments to search for a better seal before retrying. This process also provides indirect information about stem orientation and contact stability.

Task 3 – Intelligent pick directions: We developed two controllers for closed-loop picking motion generation. Both controllers use a non-linear admittance function to transform a measured force at the wrist into a commanded end-effector velocity. This commanded velocity is then passed to a low-level velocity controller for control of the robot arm. We benchmarked these controllers against an open-loop linear pull, in which the robot arbitrarily pulls back along the plane normal of the palm of the end-effector. Our goal was to understand the difference in picking controller performance across a wide range of possible scenarios. In order to conduct a large number of experiments, and in order to separate the effects of controller type, plant stiffness, and plant geometry, we performed 396 trials using our indoor proxy orchard testbed. We found that plant geometry had a significant effect on simulated plant damage rate, with more orthogonal geometry being more favorable (less damage). Moreover, while the linear pull resulted in an overall spur break rate of 45%, the two closed-loop controllers achieved reduced rates of 39% and 12%, respectively.

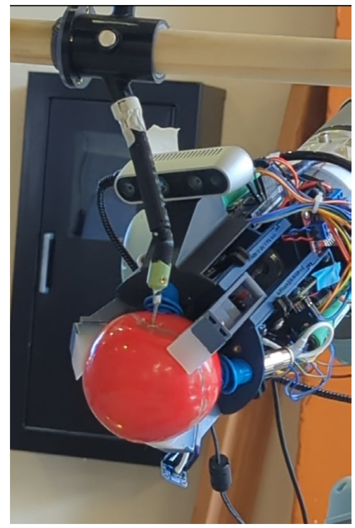


Figure 5. Studying force-based pick motions in the lab.

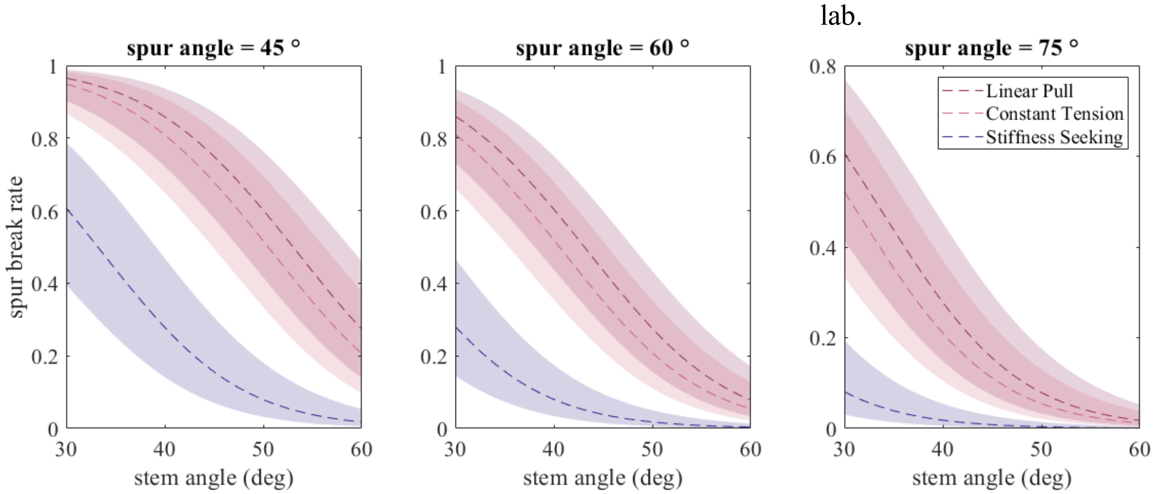


Figure 6. Predicted spur break rate by controller and plant geometry.

<u>**Objective 3: Integrated field trials (WUR lead, OSU participant)**</u>**:** The main objective during the third harvest season of the project (Fall 2025) was to compare the three grippers and evaluate our new sensors and controllers. We conducted experiments at a Yakima Valley Orchards Envy block (Prosser, WA) in late October (Figure 7). Results from the field studies were not available at the time of report submission but will be presented at the annual research review.

Figure 7. Photos from field trials in Prosser, WA (October 28-30, 2025).

Project dissemination and stakeholder involvement: The team presented project outcomes at several tree fruit industry events over the past year, including:

- In the Netherlands, WUR has presented the sensorized gripper design on different occasions to interested machine manufacturers. The Dutch companies Munckhof and RIWO, which are involved in an ongoing robotic apple harvesting project (UC5 Apple Picking Robot - NXTGEN Hightech), have confirmed that the integration of close range sensors next to camera sensors is very important to increase the current picking success rate of the robot. Inspired by our project, Munckhof has started to integrate such sensors into their suction cup. The first prototypes have already been built and tested.
- OSU hosted members from the WTFRC Board and Technology Committee for an 'Innovation Exchange' in Corvallis, OR (March 2025).
- OSU discussed the harvesting project and demonstrated the robotic system for a visiting group of national journalists in September 2025.
- Co-PIs Jochem Hemming and Menno Sytsma presented a seminar on robotic harvesting to growers and researchers at WSU CPAAS in October 2025.
- The project team presented five research papers – based on results from this project – at the IFAC Conference on Sensing, Control, and Automation Technologies for Agriculture (Davis, CA) in August 2025:
    - J. Hemming, N. van Damme, M. Sytsma, R. van de Ven, G. Kootstra, and J.R. Davidson, "Multi-sensor vacuum gripper for closed-loop grasp in robotic apple harvesting," *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.
    - M. Cravetz and J.R. Davidson, "Abscission joint localization during robotic fruit harvesting using force sensing," *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.
    - M. Rosette, K. Nave, E. Yong, C.M. Grimm, and J.R. Davidson, "Increasing fruit reachability in semi-structured orchards with tree templates," *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.
    - A. Velasquez, O. Gehrke, C. Grimm, and J.R. Davidson, "Air-pressure-guided servoing for robotic grasping with multi-cup suction grippers," *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.
    - E. Krueger, O. Gehrke, M. Cravetz, M. Sytsma, J. Hemming, and J.R. Davidson, "Detecting apple abscission during robotic harvesting with force and pressure sensing," *AgriControl 2025: 8th IFAC Conf. on Sensing, Control, and Automation Technologies for Agriculture*.

Proposal Title:

Training Vision Systems to Detect Little Cherry Disease in Orchards

Report Type: Continuing Project Report

Primary PI: **Charlie Wu**
Organization: Orchard Robotics
Telephone: +1 (607) 269-8838
Email: charlie@orchard-robotics.com
Address: 1522 Western Ave
Address 2: STE 24269
City/State/Zip: Seattle, WA 98101

Co-PI 2: Dr. Scott Harper
Organization: Washington State University
Telephone: +1 (509) 786-9230
Email: scott.harper@wsu.edu
Address: 24106 North Bunn Road
City/State/Zip: Prosser, WA 99350

Cooperators: Suzanne Bishop (Allan Bros., Inc.) Garrett Bishop (G.S. Long Co., Inc.) Tobin Northfield (Washington State University), Corina Serban (Washington State University Extension)

Project Duration: 2-Year

Total Project Request for Year 1 Funding: $ 54,321.00
Total Project Request for Year 2 Funding: $ 15,314.00

Other related/associated funding sources: None

WTFRC Collaborative Costs: None

Budget 1
Primary PI: Charlie Wu
Organization Name: Orchard Robotics
Contract Administrator: Charlie Wu
Telephone: +1 (509) 239-1598
Contract administrator email address: charlie@orchard-robotics.com

Item	**2025**	**2026**
Salaries[1]	$35,000.00	
Benefits		
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies		
Travel		
Plot Fees		
Miscellaneous[2]	$5,000.00	
Total	$40,000.00	$0.00

Footnotes:
[1] The total cost of engineering salaries for data labeling from Orchard Robotics is estimated to be at least $75,000 during 2025. The project's listed expense will likely cover about 1/3 of the total cost of the engineering salaries, and Orchard Robotics will contribute the remainder (at least 2/3) of the total cost required to get the features and results built out fully.
[2] Machine Learning Training Server

Budget 2
Co PI 2: Dr. Scott Harper
Organization Name: Washington State University
Contract Administrator: Stacy Mondy
Telephone: +1 (509) 335-2885
Contract administrator email address: arcgrants@wsu.edu

Item	**2025**	**2026**
Salaries	$5,416.00	$5,632.67
Benefits	$1,905.00	$1,981.33
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies	$7,000.00	$7,700.00
Travel		
Plot Fees		
Miscellaneous		
Total	$14,321.00	$15,314.00

Footnotes: Postdoctoral associate at 0.083 FTE

OBJECTIVES
While research is underway for long-term solutions to Little Cherry Disease (LCD), growers are eager for near-term solutions. This project evaluates vision systems to improve our toolbox. The intended result is a tool growers can use to more quickly and reliably capture cherry size and color distribution within the tree. This would reduce time by focusing trained scouts and sampling where it's most needed and aid growers in seamlessly developing reliable maps without human error. In evaluating the spread of disease by visualizing trees with symptoms and accounting for removed trees, growers would gain confidence in determining the best management plan for tree removal and replant strategies.

2025

1. Develop and train computer vision and machine learning models capable of:
    a. Accurately sizing and color grading cherries on varying cherry orchard configurations.
    b. Identifying specific trees showing symptoms of LCD
    (Considers Technology Project Priorities 2, 3,5 & 8)

2. Determine how many days before harvest LCD symptoms can be detected by the Orchard Vision System.

3. Manually scout and compare to model results to validate vision system outputs and collect training data for improving the LCD detection statistical machine learning model.

Spring 2025	Summer 2025	Fall 2025	Winter 2025
Project Planning	LCD Scanning	Entering of Visual Ground truth Data	Machine Learning
Block Selection	Ground Truthing	Cherry Scans Uploaded and Reviewed	2026 Project Improvement Planning
Set Up Scans	Virus Sample Collection	Collecting of lat/long coordinates for sample trees	
	Postharvest Scanning	Tree Removal Scanning	

2026

4. Demonstrate higher scouting efficiency by increasing the Key Performance Indicator (KPI) of scouted acres/hour (sa/hr) using established machine learning models (Figure 5).

5. Develop automatic map creation methods to quickly enable actions such as:
    a. Infer which trees are candidates for removal vs those that need more investigation.
    b. Determine count of missing trees due to previous tree removal
    c. How many trees are non-bearing (e.g. replant trees)
    d. How many trees are weak from other pathogens (not LCD)

6. Continue training the machine learning model against confounding factors common in cherry orchards, resulting in similar symptoms such as June drop, tree age, variations in soil and topography, excessive crop load, and other cherry diseases.

7. Participate in grower educational events or conferences to demonstrate camera use, user interface, and mapping features.

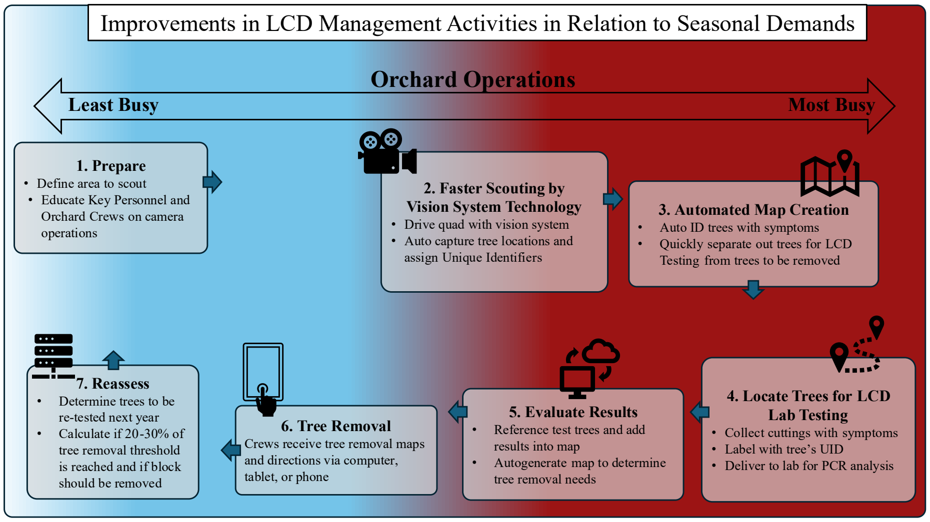


Figure 1: How vision systems can improve the workflow of LCD management activities

SIGNIFICANT FINDINGS

- Ground Truthing Data and Lab qPCR Results:
  - The Ground Truthing Data is matching the Lab qPCR results very well with notable decreases in Ct values (corresponding with high concentrations of LCD pathogens) as visual severity grading increased, especially between slight (2-4 single symptomatic spurs) and low (<20% symptomatic) severity grades which will help the machine learning algorithm to better understand the limits of human visual detection of LCD verses pathogen presence in the orchards.

- Tree Detection and Position:
  - The machine learning model for detecting cherry trees improved with increased data from subsequent scans. Tree positions in some orchards were not as well captured as others early in the season. With every scan and iteration of the scans the machine learning models learned how to better identify trees.

- Training Systems:
  - Y and V trellis systems:
    The benefit of formally trained canopies is branch structures and fruiting sites are more organized and easier for the camera to detect. One downside of trellis systems is post and wires can sometimes cause interference with GPS signals and tree positions can be harder to capture.
  - Free Standing Training Systems:
  - With row spacing farther apart and less trellis poles and wires interfering with GPS signals, there could be more accurate tree location information earlier on. However, with less organization of branches, more fruiting branches grow into the drive rows, leading to higher risk of fruit occlusion in these training systems.
  - Starting the season off with scans, when the trees are still dormant may be required to achieve high accuracy of row and tree positions.

METHODS

Site Selection

We identified five different cherry orchards and scanned 5-10 acres in each block. The strategy for site selection allowed for detailed ground truthing and thorough machine learning model training in the first year. We strategized to select blocks with V-Trellis, Y Trellis, and Free Standing cherry training systems so the robustness of the model can accommodate a variety of cherry orchard configurations throughout the Pacific Northwest. The varieties in the selected blocks were Coral Champagne, Skeena, and Sweetheart (Table 1). We decided on these blocks because of the varietal significance in the cherry market, their susceptibility to LCD and distinct expression of symptoms. Differences in location and variety also distribute the workload with staggard harvest windows ranging from mid-June to mid-July.

Table 1: Parameters of selected orchard and block configuration

Orchard ID	Variety	Configuration	Row Spacing	Tree Spacing	Acres	Pollenizer
Sunnyside	Coral Champagne	Y-Trellis	13’	7’	5.6	Bing
Mattawa	Skeena	Y-Trellis	12’	5’	4.8	n/a
Naches	Organic Sweetheart	V Trellis	13’	6’	5	n/a
West Valley	Skeena	Free Standing	16’	10’	9.6	n/a

Camera Set up and Scanning

Understanding the growers’ need for early LCD detection, we targeted three time frames before expected harvest to evaluate the vision system’s capacity for earlier LCD detection:

1. 7-10 days before harvest
2. 4-6 days before harvest
3. 1-3 days before harvest

On June 4th a test scan was conducted at the Naches site to determine optimum camera positioning for subsequent project scans. Actual scanning, sample collection and harvest dates are outlined in Table 2.

Table 2: Actual scanning, sample collection and harvest dates by orchard

Orchard ID	7-10 DBH Scan	4-6 DBH Scan	1-3 DBH Scan	Sample Collections	Actual Harvest	Postharvest Scan
Sunnyside-*Coral Champagne*		June 9	June 12	June 25-26	Jun 13-15	June 18, 23rd
Sunnyside-*Bing*	June 9	June 12	June 18	June 25-26	June 19	June 23rd
Mattawa	June 20	June 24	June 27	June 28-29	June 30	July 9
Naches	July 4	July 8	July 11	July 12	July 13	July 17
West Valley	June 20	June 23	June 26	June 24,26	June 30	July 3

Ground Truthing & Validation

The fundamental way to "teach" LCD detection statistical machine learning models is to double check the model predictions against real life incidences for both infected and non-infected trees. This practice of ground truthing was conducted on 6-10 sections in each of the orchard sites chosen for this study (Figure 2).

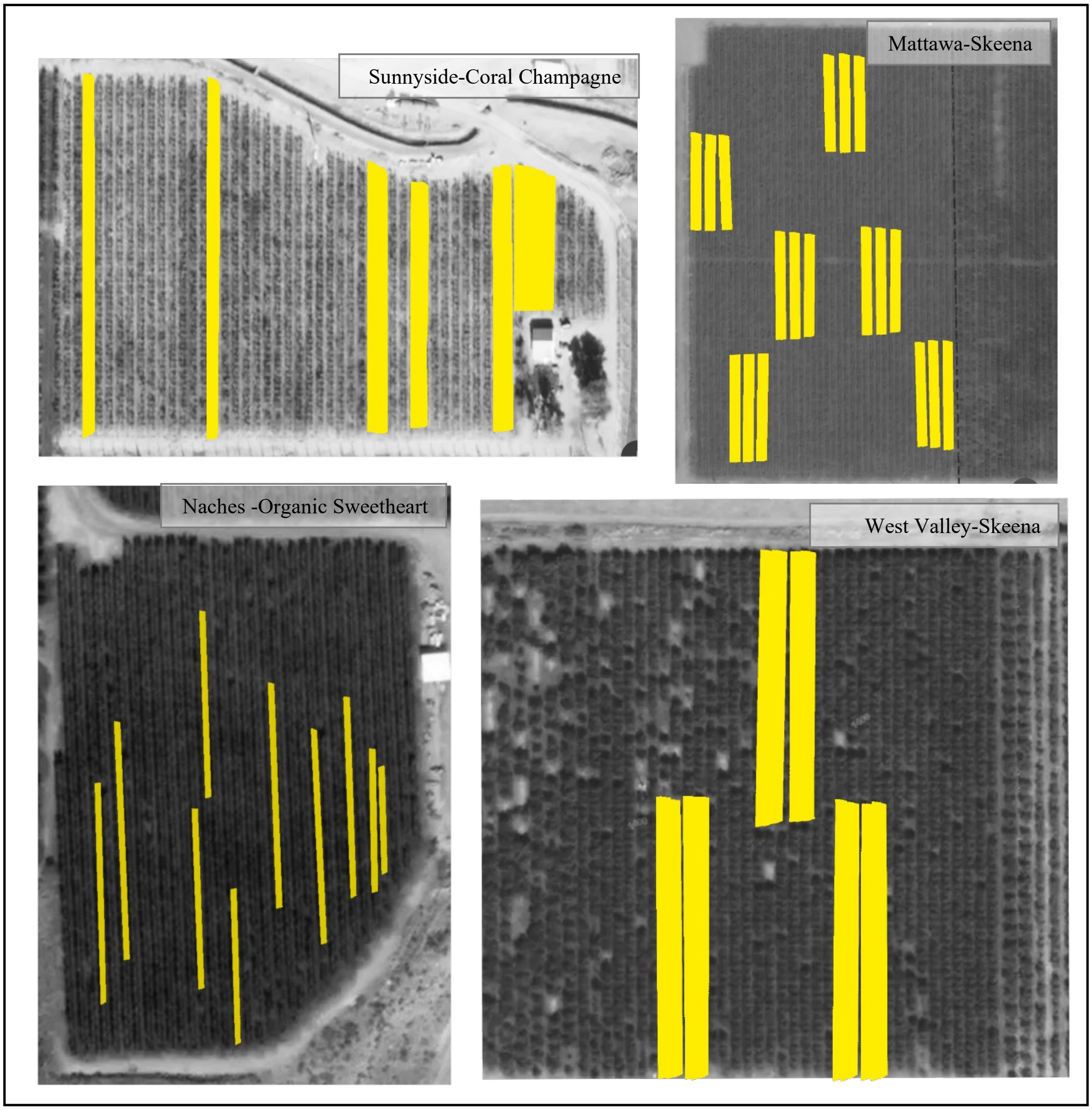


Figure 2: Overview of ground truthing zones within each orchard.

Within each section, 30-100 trees were visually evaluated for LCD incidence for a total of 410-555 trees per orchard site. LCD scouting for incidence and severity occurred at the same time as scanning for 7-10 days and 1-3 days before harvest according to the severity scales described in Table 3. The Sunnyside block's main commercial variety was Coral Champagne with pollenizers planted as every other tree, every fourth row. Due to the differences in harvest timings, additional scans and ground truthing occurred to accommodate later ripening fruit.

Table 3: Total number of trees with human visual ground truthing for each orchard

Orchard ID	Ground Truth Sections	Avg. Trees per section	Total Trees
Sunnyside	6	78	471
Coral Champagne	6	57	347
Bing	6	21	124
Mattawa	6	92	555
Naches	10	41	410
West Valley	6	70	420

After the 1-3 DBH scan and ground truthing, trees were chosen for qPCR/RT-qPCR confirmation on LCD disease severity and we marked with flagging tape corresponding to the disease severity category they were in. Upon sampling, specifics of which tree quadrant and limb was recorded to assist with Machine Learning Algorithms. Limbs from where actual sample were taken were marked with zip-ties for later collection dates if needed. Samples were collected and sent to the Harper Lab at WSU-IAREC for qPCR confirmation of positive and negative trees by using current, validated methodology. The samples were tested for the X-disease phytoplasma ('*Candidatus* Phytoplasma pruni'), little cherry virus 1 (LChV-1) and little cherry virus-2 (LChV-2). The samples were also tested for prune dwarf virus (PDV) and prunus necrotic ringspot virus (PNRSV) as these cherry viruses can impact fruit size and color as well. We collected samples from 4 trees in each visual LCD severity level grouping for a combined total of 24 sampled trees per orchard site. However, because of varying degrees of pathogen progression in the orchards, we found that in sites with samples of higher severity it was difficult to find trees completely free of symptoms and similarly, at sites with low severity there were fewer examples of higher severity. This led us to combine grades 0 (Good) and 0.5 (Questionable) together in one category similar to how 4 (Medium) and 5 (High) categories were combined.

Table 4: Severity scale for visually grading LCD symptom expression

Description	Annotations	Numerical Value	Lab Sample Count per Site
No Visual LCD Symptoms	Good (G)	0	4
Possible beginning of LCD Symptoms	Questionable (?)	0.5	4
Much smaller and lighter fruit on 1-2 spurs	Very Slight (VS)	1	4
True Visual LCD Symptoms on 2-4 spurs/limbs (less than 5% of tree)	Slight (S)	2	4
True Visual LCD Symptoms on 5-20% of tree	Low (L)	3	4
True Visual LCD Symptoms on 20-40% of tree	Medium (M)	4	4
True Visual LCD Symptoms on 40+% of tree	High (H)	5	
			Total 24

Table 5: Examples of observation notations used during ground truthing

Observation Descriptions	Annotations
Sick tree; maybe other pathogens invloved or other cause	Weak Tree (WT)
Removed Tree; Open Space; No Tree	Removed (R)
Replant Tree; non bearing	Replant Tree (RT)
Young Replant Tree; early fruit bearing years	Young Replant Tree (YRT)

After harvest, an additional postharvest scan was completed to provide another way to evaluate LCD incidence. We believe if growers are still experiencing time constraints just before harvest and miss preharvest scans, scanning just after harvest to detect how many trees had fruit that was left due to poor size and color, could provide another opportunity to quickly map the extreme cases of LCD incidence in their orchard.

In late summer and early fall, tree removal was observed in West Valley, Mattawa, and Naches, blocks. Ground truthing notes on tree removal and Lat/Long coordinates were collected for sample trees along with the range of cell phone GPS accuracy that might be used for general scouting purposes. This information will be used in the winter when machine learning algorithms will be developed.

RESULTS AND DISUCUSSION

Data from scans were uploaded into Orchard Robotics Operating System and Data visualization tool called FruitScope operating system. Figure 3 below illustrate the systems capabilities of tree identification and data representation for fruit count, fruit size, fruit hue, trunk spacing, and missing trees. When by hovering over specific data points, the user can view a snapshot from the scan for that particular tree and more detailed information associated with it. It is important to note these data are currently being reported from the platform originally being up for apples (during the 2024 season), but with support for cherries from the 2025 season, and from December 2025 to February 2026, Orchard Robotics' data engineering team will be developing more LCD-specific features for cherries into the platform to incorporate canopy area and color, size and color distributions per tree. Plans are to use ground truthing data to identify signals to find alarming distributions to flag specific trees with LCD. From this work heatmaps can be built to display specific LCD-ridden trees similar to the Red Leaf Disease heatmap for grapes which Orchard Robotics has created previously.

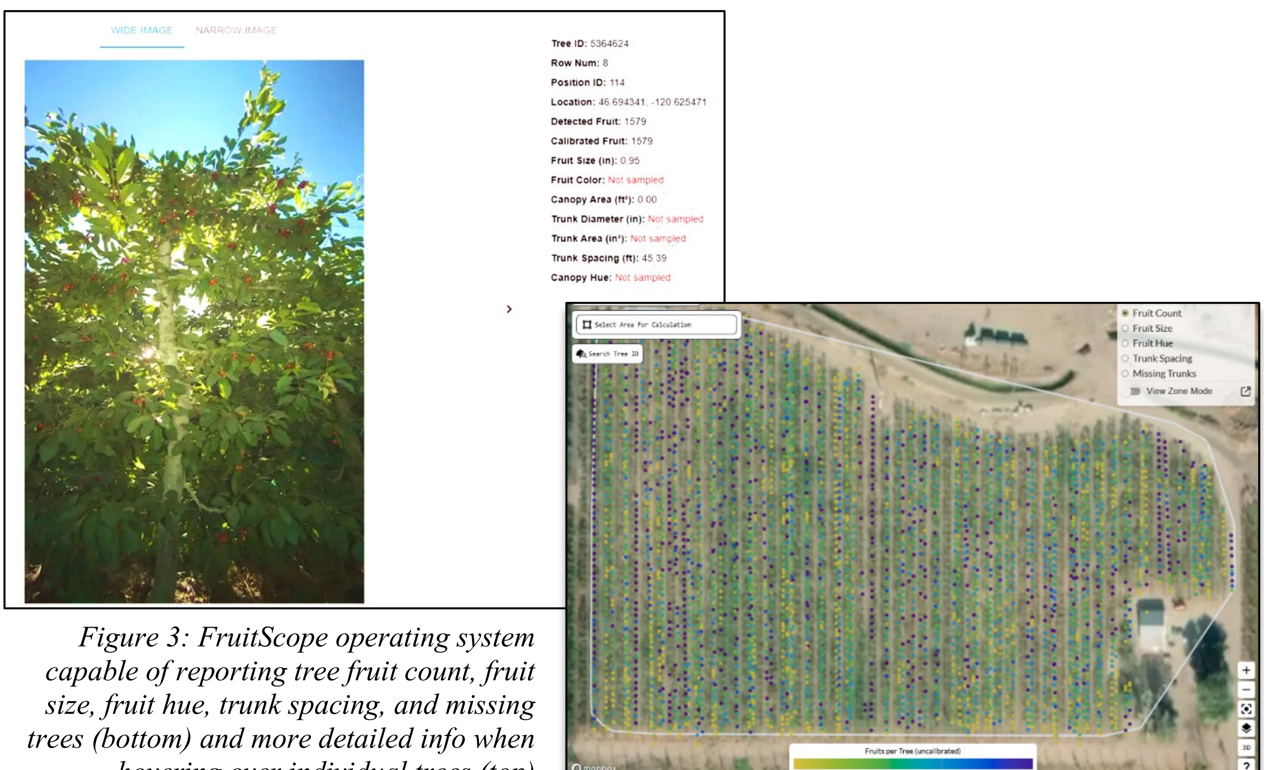
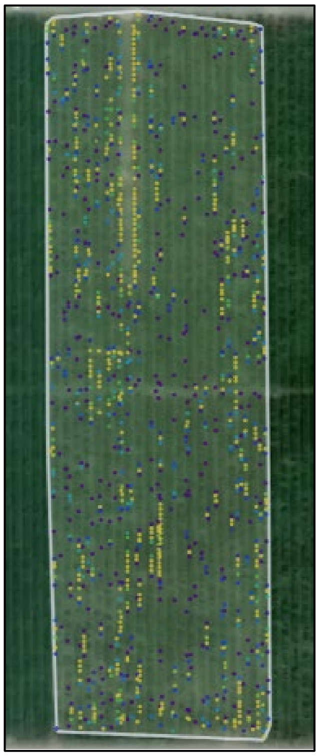
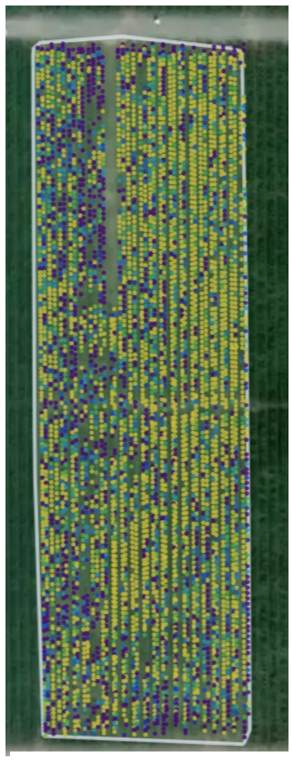


Figure 3: FruitScope operating system capable of reporting tree fruit count, fruit size, fruit hue, trunk spacing, and missing trees (bottom) and more detailed info when hovering over individual trees (top)

Figure 4 illustrates the problems dense trellis systems and canopy density can impose on GPS signals and accurately capturing tree location. However, as the season progressed machine learning for tree detection and GPS connections improved, accuracy also improved. We have determined that scanning needs to begin in February and March before leaf emergence for the highest accuracy of tree positions. This is critical for accurate comparison between the FruitScope operating system and ground truth mapping. Orchard Robotics is also upgrading camera hardware and data processing systems with better GPS for 2026.



Mattawa-Skeena
June 24, 2025



Mattawa-Skeena
July 9, 2025

Figure 4: These two heat maps represent fruit per tree on detected trees in Mattawa-Skeena orchard and illustrate how tree detection increased as the machine learning models improved from June to July.

Lab results from sample trees adds confidence to ground truthing data for machine learning algorithms when training to detect LCD symptom of smaller and lighter color fruit. Because LCD encompasses three pathogens including X-disease phytoplasma,'*Candidatus* Phytoplasma pruni'(XDP), little cherry virus 1 (LChV-1) and little cherry virus-2 (LChV-2), there can be variances symptomatic depending on individual or dual expression. LChV-1 was not found in any sample at any orchard in this study. In this study we were able to detect presence and absence of each pathogen, and the relative pathogen concentrations or each because of real-time qPCR methods and the corresponding Ct values. Lower Ct values indicate higher amounts of the targeted pathogen, while higher Ct values indicate lower amount of the targeted pathogen. When there is higher initial amounts of targeted pathogen DNA, less cycles (indicated by low Ct or Cq values) are required to reach detection thresholds.

Sunnyside-Coral Champagne had incidence of LCD throughout the block making it challenging to find trees completely free of symptoms. As depicted in Table 6, the Good & Questionable severity levels had higher Ct values indicating low infection levels while Low, Medium, and High had Ct values ranging from 17-22. For example, 20 Ct value is 1,000,000 copies of XDP while 34 Ct value is 100 copies. This is due to Ct values being represented on a log scale. The Bing pollenizers in the Sunnyside orchard had no trees of low severity (true visual symptoms on 5-20% of tree) as described below in Table 7.

Table 6: Lab qPCR results of sample trees by severity based on human visual grading

Sunnyside-Coral Champagne							
Human Visual Severity Grade	**Number of Collected Samples**	**Number of Positive XDP**	**Number of Positive LChV-2**	**Number of Both XDP + LChV-2**	**XDP** *(Avg Ct Value)*	**LChV-2** *(Avg Ct Value)*	**% LCD Positives**
Good & Questionable (0 & 0.5)	8	8	6	6	34	26	100%
Very Slight (1)	4	4	4	4	32	31	100%
Slight (2)	4	4	1	1	29	25	100%
Low (3)	4	4	2	2	17	22	100%
Medium & High (4 & 5)	5	5	3	3	19	20	100%

*Lower Ct values indicate higher amounts of the targeted pathogen, while higher Ct values indicate lower amount of the targeted pathogen.

Table 7: Lab qPCR results of sample trees by severity based on human visual grading

Sunnyside-Bing							
Human Visual Severity Grade	**Number of Collected Samples**	**Number of Positive XDP**	**Number of Positive LChV-2**	**Number of Both XDP + LChV-2**	**XDP** *(Avg Ct Value)*	**LChV-2** *(Avg Ct Value)*	**% LCD Positives**
Good & Questionable (0 & 0.5)	4	4	3	3	34	28	100%
Very Slight (1)	3	3	2	2	32	24	100%
Slight (2)	3	3	3	3	34	24	100%
Low (3)	0	n/a	n/a	n/a	n/a	n/a	n/a
Medium & High (4 & 5)	2	2	2	2	19	21	100%

*Lower Ct values indicate higher amounts of the targeted pathogen, while higher Ct values indicate lower amount of the targeted pathogen.

There was low LCD incidence in Mattawa-Skeena (Table 8). And provided good training for orchards with lower LCD occurrence. Many of the Very Slight and Slight trees had levels of prune dwarf virus (PDV) with an average of 28 Ct values. Some trees also had prunus necrotic ringspot virus (PNRSV). These viruses can also slightly reduce fruit size and in 2026 we will investigate their impact more on the machine learning algorithm. Only XDP was detected in Naches-Sweetheart (Table 9).

Table 8: Lab qPCR results of sample trees by severity based on human visual grading

Mattawa-Skeena							
Human Visual Severity Grade	**Number of Collected Samples**	**Number of Positive XDP**	**Number of Positive LChV-2**	**Number of Both XDP + LChV-2**	**XDP** *(Avg Ct Value)*	**LChV-2** *(Avg Ct Value)*	**% LCD Positives**
Good & Questionable (0 & 0.5)	9	1	0	0	38	n/a	11%
Very Slight (1)	4	0	0	0	n/a	n/a	0%
Slight (2)	4	1	0	0	38	n/a	25%
Low (3)	3	0	3	0	n/a	23	100%
Medium & High (4 & 5)	5	2	5	2	19	25	100%

*Lower Ct values indicate higher amounts of the targeted pathogen, while higher Ct values indicate lower amount of the targeted pathogen.

Table 9: Lab qPCR results of sample trees by severity based on human visual grading

Naches-Sweetheart							
Human Visual Severity Grade	**Number of Collected Samples**	**Number of Positive XDP**	**Number of Positive LChV-2**	**Number of Both XDP + LChV-2**	**XDP** *(Avg Ct Value)*	**LChV-2** *(Avg Ct Value)*	**% LCD Positives**
Good & Questionable (0 & 0.5)	9	9	0	0	33	n/a	100%
Very Slight (1)	4	3	0	0	32	n/a	75%
Slight (2)	4	4	0	0	25	n/a	100%
Low (3)	4	4	0	0	19	n/a	100%
Medium & High (4 & 5)	5	5	0	0	20	n/a	100%

*Lower Ct values indicate higher amounts of the targeted pathogen, while higher Ct values indicate lower amount of the targeted pathogen.

West Valley- Skeena is an older block that has and good mix of trees with XDP only, LChV-2 Only, and dual infection of XDP + LChV-2 (Table 10).

Table 10: Lab qPCR results of sample trees by severity based on human visual grading

West Valley-Skeena							
Human Visual Severity Grade	**Number of Collected Samples**	**Number of Positive XDP**	**Number of Positive LChV-2**	**Number of Both XDP + LChV-2**	**XDP** *(Avg Ct Value)*	**LChV-2** *(Avg Ct Value)*	**% LCD Positives**
Good & Questionable (0 & 0.5)	9	5	5	2	33	31	89%
Very Slight (1)	4	4	3	3	33	28	100%
Slight (2)	4	4	4	4	23	27	100%
Low (3)	4	4	1	1	21	35	100%
Medium & High (4 & 5)	4	4	1	1	20	20	100%

*Lower Ct values indicate higher amounts of the targeted pathogen, while higher Ct values indicate lower amount of the targeted pathogen.

Noted Improvements to Carry Into 2026:

- Starting the season off with scans, when the trees are still dormant may be required to achieve high accuracy of row and tree positions.

- Setting up cooperators with cameras and providing operational training rather solely relying on an Orchard Robotics field technician being deployed to perform the scanning will allow for more easier impromptu decision-making on scanning dates in relation to irrigation, spray applications, and harvest planning.

- Features Orchard Robotics will continue to develop in FruitScope operating System: Canopy Area, Color, Size and color distributions per tree, identifying signals to flag specific trees with LCD symptoms, Heatmap to display specific LCD infected trees similar to the disease heatmap for grapes.

- Upgraded camera system with better cameras and GPS for 2026. More testing and experimentation in terms of how those upgrades will improve the data quality but also how it should be mounted or configured to best view Cherries to detect LCD will need to be continued in 2026.

Project Title: New Strategies for Precision Plant Nutrient Application

Report Type: Continuing report Year 1

PI: Bernardita Sallato C.
Organization: Washington State University
Telephone: (509) 786-9205
Email: b.sallato@wsu.edu
Address: 24106 North Bunn Road
City/State/Zip: Prosser, WA 99350

Co-PI (2): Lav R. Khot
Organization: Washington State University
Telephone: (509) 786-9302
Email: lav.khot@wsu.edu
Address: 24106 North Bunn Road
City/State/Zip: Prosser, WA 99350

Co-PI (3): Jim McDougall
Organization: Outfield Technologies
Telephone: +44 7763 058842
Email: jim@outfieldtechnologies.com
Address:
City/State/Zip:

Cooperators: Steve Mantle (Innov8Ag), Agrocares, Croptix, North West Farm Management.

Total Project Request Year 1: $34744
Total Project Request Year 2: $14990
Total Project Request Year 3: $15245

Organization Name: Washington State University
Telephone: (509) 335-2885
Station Manager: Naidu Rayapati

Contract Administrator:
Email address: arcgrants@wsu.edu
Email address: naidu@wsu.edu

Item	**2025**	**2026**	**2027**
Salaries			
Benefits			
Wages[1]	5000	5000	5000
Benefits	500	500	500
Services	6144	6390	6645
Supplies[2]	2500	2500	2500
Travel	600	600	600
Miscellaneous			
Plot Fees			
Total	**14744**	**14990**	**15245**

Footnotes:
[1] Wages: hourly support for sample collection at $19/hour for 263 hours + 10% benefits
[3] Supplies: laboratory analyses of 64 soils @ $36/sample, 128 tissue, 32 fruitlet and 32 fruit @ $20 / sample.

Organization Name: Jim McDougall **Contract Administrator:**
Telephone: +44 7763 058842 **Email address: jim@outfieldtechnologies.com**

Item	**2025**	**2026**	**2027**
Salaries	20,000		
Benefits			
Wages[1]			
Benefits			
Services			
Supplies[2]			
Travel			
Miscellaneous			
Plot Fees			
Total	**20,000**		

OBJECTIVES

Our specific focus within the 'smart orchard project' is to assess mapping technology for plant stress, soils, vigor and fruit quality, and testing methods for nutrient management.

1. **Validate tools to determine precision and variable nutrient demand.**

2. **Integrate layers of information to create prescription mapping for different nutrient requirements**

3. **Evaluate the impact of variable rate nutrient management**

SIGNIFICANT FINDINGS

- The SPAD chlorophyll meter showed a strong correlation (r = 0.76) with standard leaf N when there is a broad N range. SPAD meters can be a reliable tool if calibrated and when a range of nutrient statuses is represented.

- Both sites (Cosmic Crisp™ in Mattawa and Envy in Zillah) had adequate or above-recommended N levels, indicating no nutrient limitations under current management.

- Croptix™ and Agrocares™ sensor data were collected but results are pending, so field validation of these optical/spectral tools will continue into Year 2.

- Outfield's prescription maps were consistent with tree-level nutrient demand calculated by WSU team — in five of six sites, the difference was ≤2 g N per 5-tree panel. Only one site deviated significantly (22 g/panel).

- Tree-level N requirements varied tenfold (6–63 lbs/acre), demonstrating substantial within-block variability not visible under standard uniform management.

- Total N rate calculated at Mattawa orchard was similar (≈43–45 lbs/acre), when utilizing average demand or with precision site estimation. However, distributing nutrients spatially could reduce tree-to-tree variability and improve uniformity in the block.

METHODS

1. **Validate tools to determine precision and variable nutrient demand**

The study was conducted in Mattawa on a 27-acre Cosmic Crisp™ apple orchard on M9-Nic 29 rootstock, planted in 2020 (Figure 1), and in Zillah on an 8-acre Envy apple orchard on G.41 rootstock, planted in 2021 (Figure 2). The sites were managed by Columbia Farm Services and NWFM LLC, respectively.

At each site, eight distinct areas were identified, and within each area, five trees were selected for detailed characterization throughout the season (40 trees per block).

Initial evaluations included a complete soil analysis for texture, pH, electrical conductivity (E.C.), organic matter (O.M.), and available nutrients, following standard procedures for Western soils (Gavlak et al., 2005). Tree parameters measured for each selected tree included cluster count, fruit count, shoot and fruit growth, and fruit quality. Leaf nutrient samples were collected from each replicated tree and location at eight stages during the growing season.

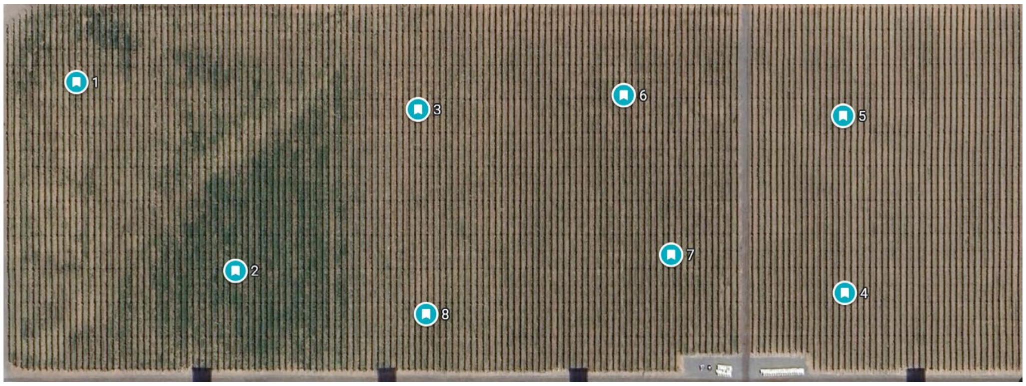


Figure 1. Site selection for 2025 Cosmic crisp™ apple orchard in Mattawa,WA.

Figure 2. Site selection for 2025 'Envy' Smart Orchard test bed in Zillah,WA.

Each composite sample was divided into two subsamples. One subsample was analyzed for nitrogen and chlorophyll content using an optical **SPAD meter (GYJ-A)** and then sent to Soil Test Laboratory (Moses Lake, WA) for standard nutrient analysis. The second subsample was sent to **Croptix™** for sap and nutrient analysis (Figure 3a).

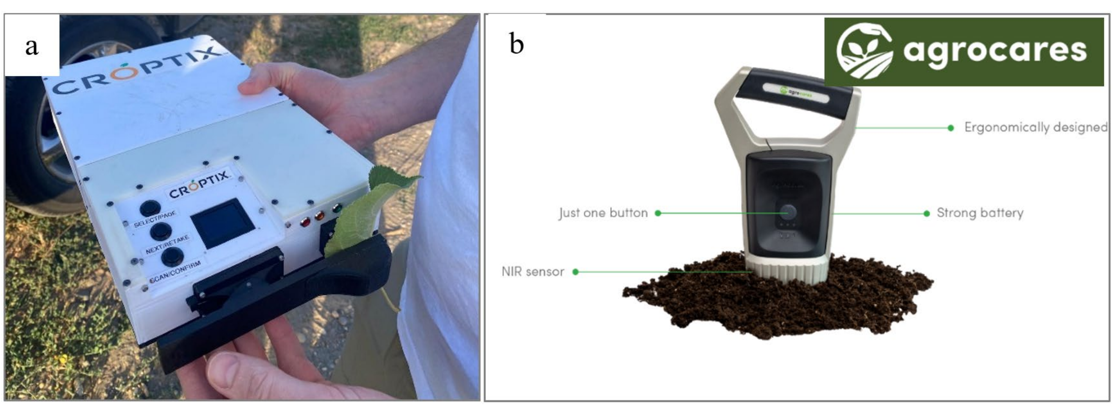


Figure 3. Hand held spectrophotometers used for nutrient assessment; a) **Croptix™** is a spectrophotometer, and b) **Agrocares** measures near-infrared (NIR) in leaf, fruit and soil matrix.

Data from each location were analyzed to characterize block-level variability. Nitrogen levels measured with the SPAD meter were compared with standard leaf and sap N values. Data from Croptix™ and Agrocares™ (Figure 3b) technologies have not yet been received and will be reported in Year 2.

2. **Integrate layers of information to create prescription mapping for different nutrient requirements**

Multiple technologies were used at each site to evaluate orchard variability, including Innov8.Ag with Green Atlas and SoilOptix, Vivid Machines, Orchard Robotics, Aurea Imaging, Aerobotics, and aerial mapping through Tyton Aviation with Outfield Technologies and Precision AgriTech. These platforms provided spatial data for estimating crop parameters such as blossom count, fruit size, and fruit count (see Khot's report for details).

Tyton Aviation and Outfield Technologies used an unmanned aerial vehicle (Mavic 3 Enterprise Multispectral, DJI Technologies) equipped with integrated RGB and multispectral sensors (green, red, red-edge, and near-infrared). Flights were conducted at an altitude of 7.6 m AGL and a forward speed of 5 m/s, with a 45° sensor orientation to capture a complete side view of the tree canopy. Multiple campaigns were conducted throughout the season to monitor crop development.

Both orchards had sufficient or high nutrient supply based on soil analyses and adequate to high leaf nutrient levels according to standard tests. Therefore, nutrient application rates were calculated using theoretical crop demand (Sallato et al., 2019). Although nutrient efficiency should be adjusted based on soil texture, both sites showed similar conditions (sandy soils in Mattawa and silt loam in Zillah). Consequently, a single efficiency factor was assumed for each block.

3. **Evaluate the impact of variable rate nutrient management**

During 2025, efforts focused on understanding natural variability in nutrient demand at both the individual tree and 5-tree panel levels. These data were used to estimate site-specific nutrient rates across the blocks.

In Year 2, variable-rate applications will be implemented using either precision sprayer technology (if available) or manual applications as proof of concept to evaluate system performance.

RESULTS AND DISCUSSION

1. **Validate tools to determine precision and variable nutrient demand**

Leaf nutrient levels in Mattawa were within or above recommended ranges for apple (Righetti et al., 1990; Silva and Rodríguez, 1995) (Figure 4). Similarly, in the Zillah Envy block, leaf nitrogen levels were within or above recommended values across all sites (Figure 5).

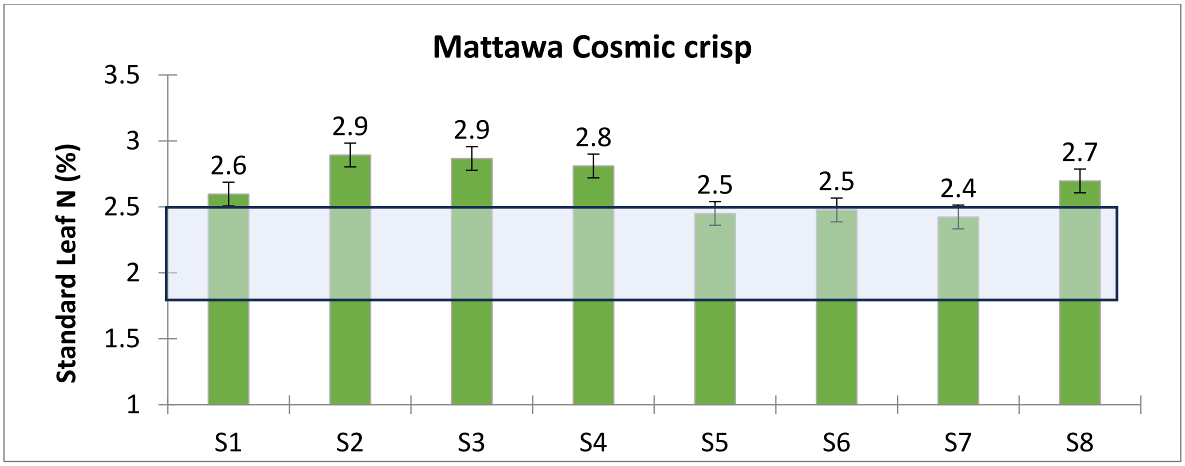


Figure 4. Leaf N levels in Mattawa apple orchard sites. Overlayed box reflects recommended N ranges for apples (Sallato et al. 2019)

Similarly in Zillah Envy block, leaf N levels were within or above N levels in all sites Figure 5

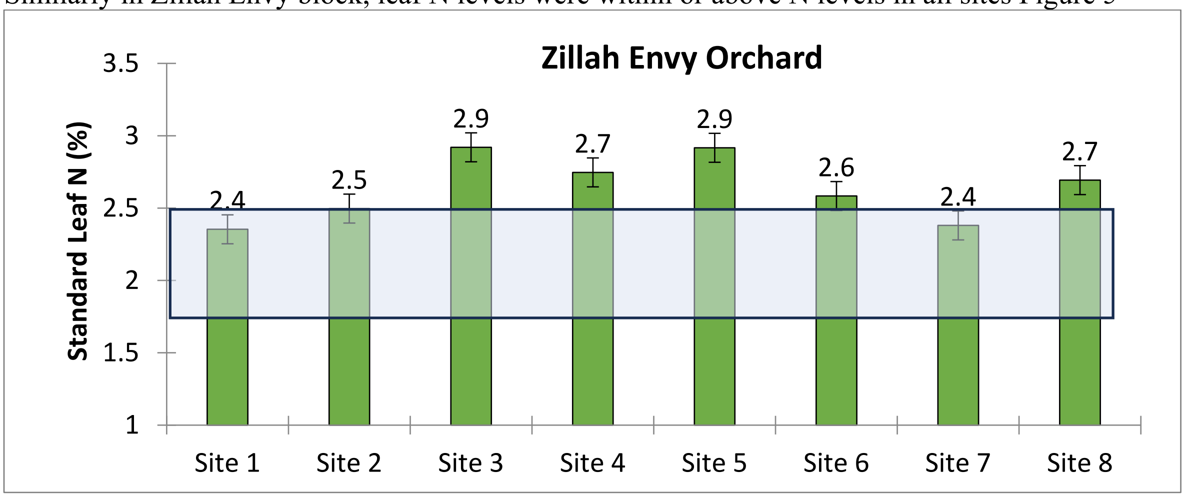


Figure 5. Leaf N levels in Zillah apple orchard sites. Overlayed box reflects recommended N ranges for apples (Sallato et al. 2019)

No significant correlation was found between SPAD readings and standard leaf N values when data from both sites were combined ($r = 0.15$, $p > 0.05$) (Figure 6a). Because both orchards had sufficient N and limited variability, additional datasets from orchards with known N deficiencies were included. When this broader dataset was analyzed, a strong positive correlation was observed between SPAD and laboratory N values ($r = 0.76$) (Figure 6b).

Although the SPAD meter tended to underestimate actual N concentrations, the results indicate that, with proper calibration, it can serve as an economical and rapid tool for assessing relative differences in leaf N status across large orchard areas.

Six sampling campaigns were conducted for Croptix™ analysis and two for Agrocares™, but results from both services are still pending.

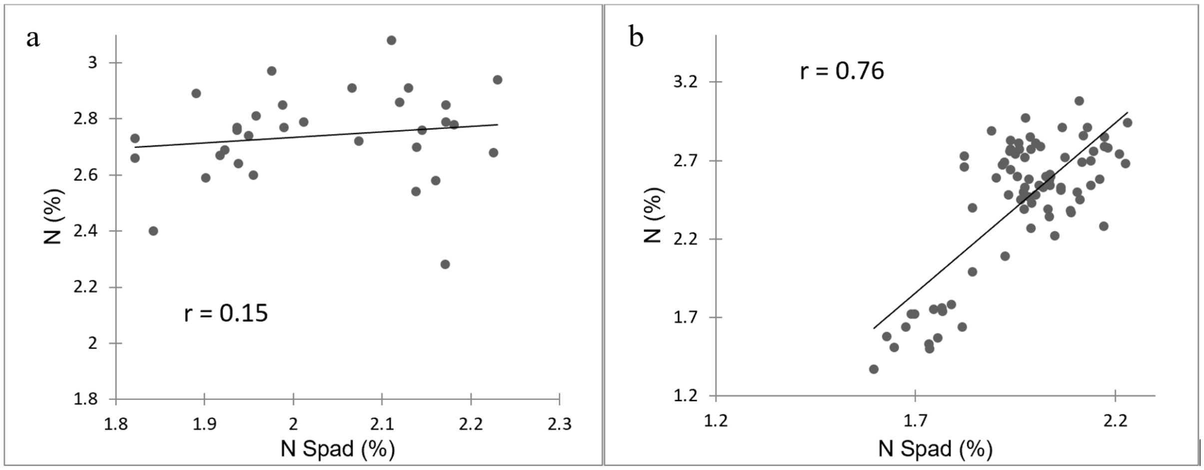


Figure 6. Pearson correlation between leaf standard N concentration and Spad N concentration in the two smart orchard sites (a) and when including other apple orchards with know N deficiency (b)

We conducted six sampling campaigns for Croptix ™ sample analysis and two campaigns for Agrocares. We have not received the results from either services.

1. **Integrate layers of information to create prescription mapping for different nutrient requirements**

Outfield Technologies generated nutrient prescription maps following WSU guidelines, which can be modified to match different nutrient management strategies. Rates were calculated according to the methodology proposed by Sallato et al. (2019) for Washington apple orchards. When soil and leaf nutrient levels are within the adequate range, nutrient application equals fruit demand minus soil supply.

Nitrogen prescription maps were produced for both orchards (Mattawa and Zillah) (Figure 7). The nutrient demand for each monitored site was calculated individually and compared to the prescribed rates. The calculated amounts matched prescription ranges in three of six sites; two sites underestimated rates by only 2 g per panel, and one site by 22 g per panel.

Tree-level N demand averaged 11.9 g per tree, equivalent to approximately 31.9 lbs/acre, with values ranging from 6 lbs/acre in low-cropping trees to 63.1 lbs/acre in high-cropping trees. When data were aggregated by panel (five trees), within-panel variability was generally low, except at sites 2 and 6 (Table 1).

The total N rate estimated from average tree yield was approximately 855.7 lbs per block (45 lbs/acre). When calculated from individual site demand, the total N was 835 lbs per block (43 lbs/acre). Although total applied N differed only slightly, redistributing N based on tree- or panel-specific needs could reduce within-orchard variability and improve overall efficiency.

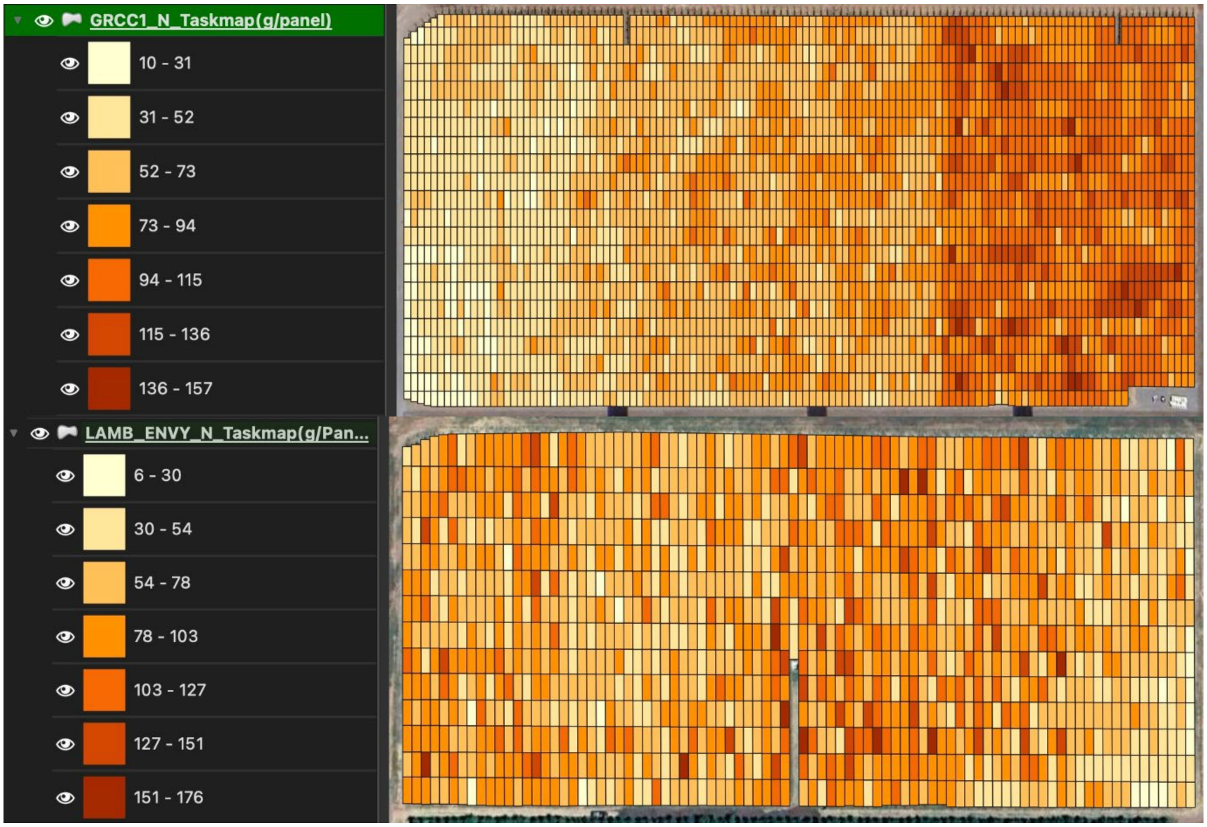


Figure 7. Nitrogen prescription map for a) 19 acre Mattawa Cosmic crisp orchard and b) 8 acre Zillah Envy orchard. Each panel corresponds to aprox 5 trees.

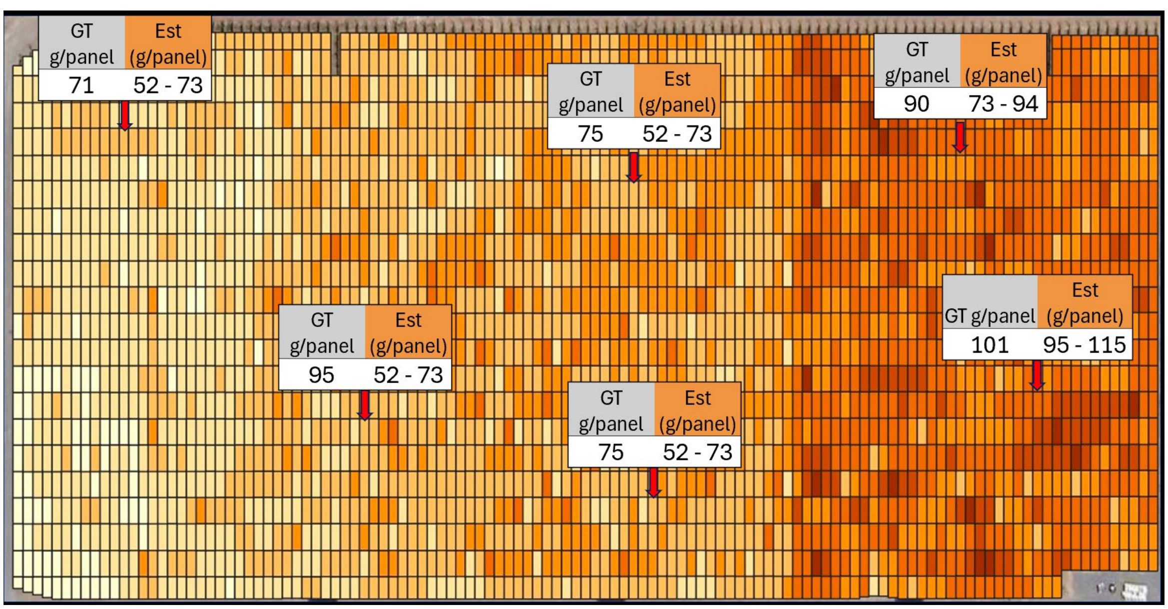


Figure 8. Prescriptive N rate map comparison between calculated rate (WSU) in gray and the estimated rate range by Outfield in orange for Mattawa orchard.

Table 1. Nitrogen rate determined for a panel of five trees, calculated for each individual, and variability within a panel.

Site	N (g/panel)	Var (g/panel)
1	71	6.2
2	95	12.5
3	75	3.9
4	36	0.6
5	31	2.9
6	90	16.4
7	101	7.4
8	75	9.5

Years 2 and 3 will focus on implementing variable-rate nutrient management and monitoring tree response and orchard variability.

Two field days were held in 2025—Precision and Automated Irrigation Systems (July 25) and Precision Crop Load Management and Automation Technologies (August 3)—reaching more than 200 participants. The test beds also hosted visits from national (CA Board) and international groups (Polish, South African, and Chilean growers and technology representatives). Preliminary findings were shared through the AgAID internship program by Negar Agah and Dayanara Mendoza. Continued outreach and collaboration are planned for Years 2 and 3.

Polish fruit growers were among the 125 people who checked out precision irrigation and heat management tools and ideas on July 25 at the Washington State University Smart Orchard field day near Mattawa. Organizers will host another field day at a different Smart Orchard location on Aug. 1 near Zillah. (TJ Mullinax/Good Fruit Grower)

Project Title: Low-Cost, Reliable Soft Arm for Robotic Tree Fruit Operation Phase II

Report Type: No-cost extension Project Report

Primary PI: Ming Luo
Organization: Washington State University, School of Mechanical and Material Engineering
Telephone: 509-335-4034
Email: ming.luo@wsu.edu
Address: Sloan 211
Address 2: 405 NE Spokane st
City/State/Zip: Pullman, WA 99163

Co-PI 2: Manoj Karkee
Organization: Biological and Environmental Engineering
Telephone: 607-255-4162
Email: mk2684@cornell.edu
Address: 308 Riley-Robb Hall
Address 2: 111 Wing Dr
City/State/Zip: Ithaca, NY 14853

CO-PI 3: Matthew Whiting
Organization: Washington State University, Center for Prec. & Automated Ag. Systems (WSU CPAAS)
Telephone: 509-786-9260
Email: mdwhiting@wsu.edu
Address: 24106 N Bunn Rd
Address 2:
City/State/Zip: Prosser, WA 99350

Cooperators: Dave Allan, Allan Brothers Fruits
Project Duration: 2-Year

Total Project Request for Year 1 Funding: $ 106,029
Total Project Request for Year 2 Funding: $ 110,010

Other related/associated funding sources: None
Funding Duration:
Amount:
Agency Name:
Notes:
WTFRC Collaborative Costs: None
Budget 1
Primary PI: Ming Luo
Organization Name: Washington State University

Contract Administrator: Anastasia Mondy
Telephone: (916) 897-1960
Contract administrator email address: arcgrants@wsu.edu
Station Manager/Supervisor:
Station manager/supervisor email address:

Item	**2023**	**2024**	**2025**
Salaries	$51,618.00	$53,683.00	
Benefits	$9,718.00	$10,106.00	
Wages	$23,314.00	$24,246.00	
Benefits	$2,379.00	$2,475.00	
RCA Room Rental			
Shipping			
Supplies	$8,500.00	$8,500.00	
Travel	$10,500.00	$11,000.00	
Plot Fees			
Miscellaneous			
Total	$106,029.00	$110,010.00	$0.00

Footnotes:

Abstract:
This year, our single soft-growing manipulator successfully achieved single-apple harvesting using an onboard perception system and a soft gripper in a lab environment. We also tested its functionality for multi-apple picking from different depths and planar arrangements, as well as with a moving tree, to prepare for field studies. During the October apple harvesting season, our robot was able to automatically pick several single apples, which is promising since this was our first field trial. We have also identified areas for improvement to further enhance its functionality in future field studies.

Key Words:
Soft growing robot; Lab environment; Field trail;

Objectives:

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

The objective was achieved last year. Here is the current performance of our robot.

Our current achievement:

- Length: Can extend up to 2.46 ft reliably with a high degree of control.
- Speed: Manipulator displays 1.24 ft/s growing speed and 0.86 ft/s retraction speed at 8 and 3 psi of pressure respectively. We have observed that higher pressures and airflow rates result in dramatically faster extension speeds. Currently, the speed is limited by the airflow rate and the free spin speed of the central motor.
- Targeting Speed: The manipulator can reach and pick a desired apple within approximately 30 seconds, including the time to drop off the apple and reset.
- Payload: 2.39 lbs. payload at 10 psi pressure input while at the max arm length. This payload includes the weight of the tip mount, soft-gripper, and fruit. With the tip mount and gripper being under 1.75 lbs., there is sufficient payload to carry an apple under 0.64 lbs.

- Workspace: One RealSense D456 camera is able to detect 3D position in 6 by 3 ft range at a 3 ft depth with a high degree of accuracy. Our robot's optimal workspace has a spherical sector shape with a radius of 2.5 ft and 60 degrees of actuation in the 2D plane, providing a total workspace volume of 22.46 ft^3.
- Pressure Reliability: The maximum input pressure of our fabric material's sealing is above 20 psi, and 5-10 psi is our operation pressure range since it displays adequate payload and control properties. In addition, there is a pressure relief valve to reduce the risk of pressure overloading.
- System Reliability: The system can operate for prolonged periods of time, >3 hours, without noticeable changes in control performance or degradation due to the system design in both lab and outdoor environments.
- R&D cost: The current prototyping cost ($) of a single manipulator is five times less than a commercially available rigid manipulator. The estimated cost is approximately $5,500, which is broken down into $574 for materials, $547 for manufacturing, $3,500 for electronics, and $879 for other mechanical components. The most expensive part is the central motor, which costs $1,117. Due to the urgent timeline, we purchased expensive and powerful motors and pressure regulators to verify our system first. We believe we can find alternative items when system verification is done, and the overall cost will be approximately $3000 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).

The objective was achieved last year. Here is the current performance of our robot.

Our current achievement:

- Machine Vision Model: The current YOLOv8 model trained on the images of apples taken in the Allan Bros Orchards in Prosser, WA with the local and global cameras mounted on the soft robotic manipulator has an apple detection accuracy of 98%.
- Image Based Visual Servoing (IBVS): Two cameras are used to estimate the real time positions of the end-effector and detected apples using a QR code mounted onto the end-effector and the machine vision model respectively. The global camera uses eye-on-hand configuration of visual servoing while the local camera uses eye-in-hand configuration to manipulate the end effector on the end goal.
- Image-Based Localization: The cross image-based localization used to find the end-effector position utilizes images from both local and global cameras to detect apples, find correlated apples, and determine the displacement between camera frames with some level of distortion between images to determine end-effector location. The vision system is flexible for various requirements in its application.
- Image-Based Teleoperation: The two camera vision system is capable of guiding the soft-gripper to desired apples within the system's workspace utilizing a low-complexity controller.
- Gripper Efficacy: The soft gripper with a thermoplastic polyurethane (TPU) 3D-printed endoskeleton can grasp apples without causing damage to the fruit. Prior versions of this gripper end-effector have achieved successful pick rates of 87% in a field test during the 2023 harvesting season.
- Gripper Design: A secondary motor and gear system allows the entire gripper to twist, simulating the twisting motion of a human worker.
- Gripper Weight: The gripper is lightweight at 1.10 lbs. and can be mounted to the soft manipulator arm without exceeding the payload limit.
- Gripper Cost: Given the current design that does not require costly sensors, the price of one soft gripper unit stands at approximately $120.

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

This year we focus on the system integration and verification of the robot with on board-perception and gripper in both simulated lab environment and field environment

Our current achievement:

- Our robot is fully functional for picking apples (including single apples on the same plane, at varying depths, and some apple clusters) in a lab-simulated environment.
- Our robot can pick single apples from V-trellis entry trees and drop them into the collection bin.

Overall progress

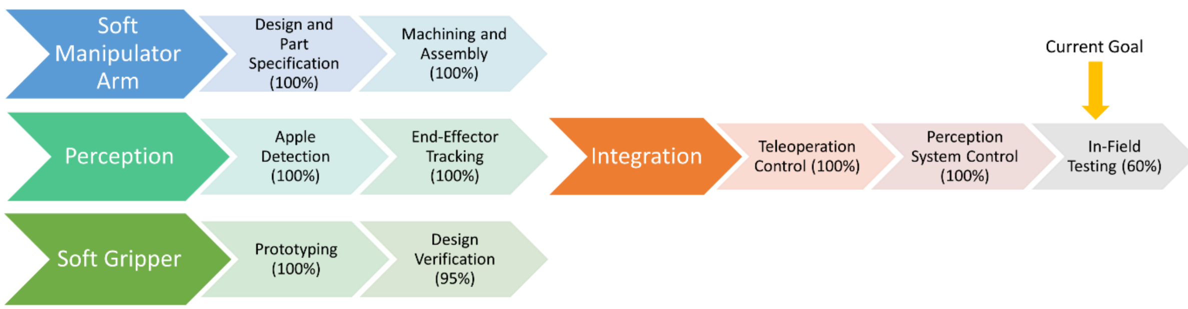


Figure 1. Goals vs. current progress.

Significant Findings:

Objective#3:

- From both lab and field studies, we found that our robot's motion with payload, perception, and gripper operation did not exhibit any significant errors. This allowed our first year of field testing to successfully grip some apples. We now have a clear plan to further improve our system design to achieve a higher success rate and faster harvesting speed, with enhancements in both hardware and software.

Methods:

Objective#3:

Camera and soft gripper integration: As shown in Figure 2, there are two cameras on the system. One is located at the pressure enclosure and can view all apples in the robot's workspace. It determines which apples should be harvested first based on their distance from the end effector. The second is a mini camera on the palm, which guides the robot's end effector toward the desired apples. Our next-generation soft gripper design, which adds an additional servo to achieve twisting motion, making it easier to detach apples from the branch.

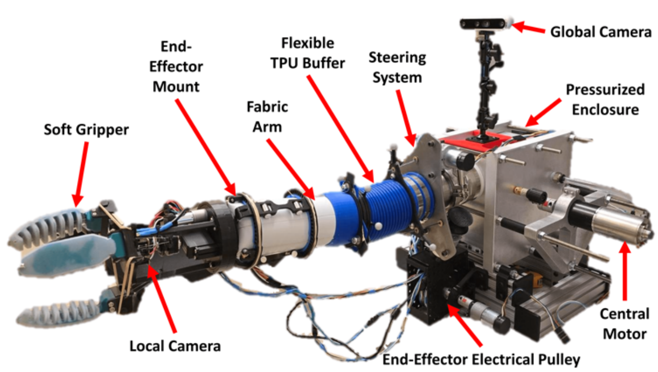


Figure.2 System integration with gripper and cameras.

Results and Discussion:

Objective#3:

Simulated Lab Environment: Figure 3 shows the experimental setup for lab testing. We used magnets to attach apples to the tree branches.

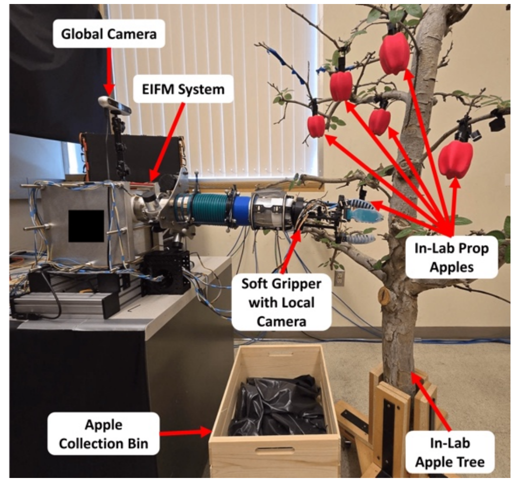


Figure.3 Lab set up

For single-apple picking, we placed four apples near the corners of the robot's workspace, as shown in the figure.4. The robot was tasked to pick these four apples three times, and all apples were successfully harvested. The average time from starting the pick to dropping the apple into the bin was approximately 24 seconds. These four apples' positions ranged from 2.2 ft to 2.4 ft away from the robot's center.

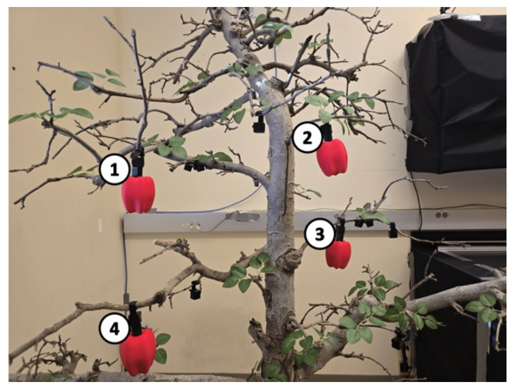


Figure.4 Single apple picking set up

For multi-apple picking, we set up three case studies, including planar, varying depth, and clusters, as shown in Figure 5. Each test was run three times. In most cases, one apple was dropped due to an unexpected error where the robot's finger pushed the apple away because the perception system could not fully detect the apple's center. The time for picking each apple varied from 20 to 40 seconds, depending on the distance, with apple clusters taking the longest.

We also tested the robot while the tree was moving, simulating a mobile robot carrying the system for apple harvesting. All apples were successfully harvested, with an average harvesting time of 30 seconds per apple.

The harvesting speed is limited by the robot's linear motion and the adjustments made when the gripper closes on the apples. This can be improved through future enhancements in perception and controller design.

(a) **(b)** **(c)**

Figure.5 Multi apple picking set up including (a) Planar, (b) Varying Depth, (c) Cluster

In field Study: We deployed our robot system in the Allan Brothers Orchard around mid-October. The trees the system was tested on were the Envy variety vertical V-trellises. We integrated the power source, pneumatic compressor, and mobile platform. From our observations, the robot is able to position the gripper so that the palm can touch the apple without issues, although the motion is slow, something that can be improved in the future since this was our first demo. The main issue is that the apple easily slides from the palm. We tried adding more twisting motion, which helped significantly. Figure 6 shows one successful picking case. Another concern is that the TPU material used for the exoskeleton may not be stiff enough to securely hold the apple, so we are working on adding more rigid material to the fingers to improve grip.

Figure.6 In the field study, one successful case involved the entire process: initialization, approaching, twisting, detaching, retracting, and dropping.

Executive Summary:

One of the major challenges facing Washington State tree fruit growers is sourcing adequate labor for critical operations such as harvesting and pruning. To address this issue, many growers and organizations have invested in the development of labor-saving technologies, including robotics. In particular, there has been significant interest in research and implementation of tree fruit harvesting and pruning robots. Our work contributes to this growing field by introducing a novel soft-growing manipulator platform for the orchard environment. Over three years of project development, our soft-growing manipulator has demonstrated the ability to automatically harvest apples in a variety of scenarios using onboard perception in a lab-simulated environment. Furthermore, our first field study has shown the potential to achieve a multi-compact robotic solution capable of picking apples in approximately two seconds each, with low-cost machinery and maintenance that can be adopted by all growers.

Project Title: Insight into RDI on Apple Growth and Color Development
Report Type: Final Project Report

Primary PI: Andrew Bierer

Report is Forthcoming

Project Title: Stem Clipping for Automated Harvest

Report Type: Final Project Report

Primary PI: Mike Corsetto
Organization: Advanced Farm Technologies, Inc.
Telephone: (650) 218-6300
Email: mikec@advanced.farm
Address: 27993 Mace Blvd.
Address 2:
City/State/Zip: Davis, CA 95618

Co-PI 2: Avery Phimmasehn
Organization: Advanced Farm Technologies, Inc.
Telephone: (530) 405-6005
Email: avery@advanced.farm
Address: 27993 Mace Blvd.
Address 2:
City/State/Zip: Davis, CA 95618

CO-PI 3: Kyle Cobb
Organization: Advanced Farm Technologies, Inc.
Telephone: (530) 564-8444
Email: kyle@advanced.farm
Address: 27993 Mace Blvd.
Address 2:
City/State/Zip: Davis, CA 95618

Cooperators: N/A

Project Duration: 2-Year

Total Project Request for Year 1 Funding: $125,000
Total Project Request for Year 2 Funding: $125,000
Total Project Request for Year 3 Funding: N/A

Other related/associated funding sources: None

WTFRC Collaborative Costs: N/A

Budget 1
Primary PI: Mike Corsetto
Organization Name: Advanced Farm Technologies, Inc.

Contract Administrator: Kyle Cobb
Telephone: +1 (530) 564-8444
Contract administrator email address: kyle@advanced.farm

Item	2025	2026	
Salaries	$115,000.00	$115,000.00	
Benefits			
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies	$5,000.00	$5,000.00	
Travel	$5,000.00	$5,000.00	
Plot Fees			
Miscellaneous			
Total	$125,000.00	$125,000.00	

Justification

With support from industry partners and the WTFRC, advanced.farm started developing an automated apple harvester in 2021. After basic field studies in 2021, our robots picked their first apple in the 2022 season, and have since picked hundreds of thousands of apples in Washington. For the first time ever, robotic apple harvest now seems within reach. With this in mind, we now look to the next frontier of technical challenges that will enhance robot performance, improve fruit quality and lower cost.

Up to this point, we have focused on de-risking tech around gently picking and conveying an apple. However, when our robots pick apples of varieties that require stem clipping, this task is performed by a human standing on the machine. This is not a sustainable approach long term as we aim to reduce cost and scale operations. We also do not believe that growers will accept no stem clipping given the increased damage it will cause in the final packout.

After studying precedents, few, if any, tools exist to automate stem clipping. The task is mostly performed with basic scissors in the field as part of manual harvest. To that end, we propose a new R&D project supported by the Commission to develop a stem clipping mechanism that would enable automated harvesting in line with the timelines we expect for commercial release of the robotic harvester overall. Benefits and goals of this project would include:

- The ability for a robotic harvester to pick more varieties of apples without the need of an operator on a machine. Robots are now picking so fast that a single person cannot keep up with the workflow of one machine. Unit economics studies show that we (and others) will actually need to remove the person entirely from a machine to scale operations cost effectively.
- Improving the quality and value of the packout, both directly and indirectly: by removing stems, we will directly reduce the puncture and bruising damage in a bin. Automated stem removal will also open up new opportunities for in-field cull sorting, especially if the stem removal is coupled with a vision system (which may itself be a part of the mechanism).

At the end of the 2024 season, we collected data to facilitate the design direction of this project. For example, in a test informed by grower partners, we looked at puncture damage on three samples of 100 Pink Lady apples, picked fresh from the orchard. The goal was to understand if a “flush cut” stem would produce more or less damage than an apple with a stem clipped below the bowl of the apple (i.e. traditional stem clipping). Results are below.

% Puncture damage on sample of 100 apples

Apples with no clipped stem	Apples with clipped stem (flush cut)	Apples with clipped stem (traditional stem clippers)
6%	2%	3%

We believe a “flush cut” concept will be significantly easier to mechanize and automate. Given that these preliminary test results are promising, we will move forward to develop this solution.

We expect a prototype to be available in the 2025 season following detailed studies, with a second generation version integrated onto our robotic harvester by 2026. We are requesting funding to cover 1 full-time engineer plus materials.

Objectives

This project directly supports the primary stated objective of the 2025 WTFRC technology RFP, the automation of apple harvest.

Methods

We will perform R&D in three distinct phases:

First, we will do concept “sprints” wherein we test several ideas to understand the problems associated with automated stem clipping, and explore potential implementations. This will happen in Q1 2025.

Second, we will down-select a concept that we wish to bring to field trials. In field trials, we will test an advanced version of the chosen concept on un-clipped apples taken from a packhouse (i.e. Gala). This will happen in Q2 2025.

Third, we will take lessons from the field testing to develop a concept that can be integrated with a full harvester in time for the 2025 apple season. This will happen in Q3-Q4 2025.

Finally, we will repeat this cycle in 2026 using the learnings from the first year of the project to continue to move towards a commercial solution. The second year of the project will most likely involve making the solution more robust and reliable.

Literature review

We have reviewed the study by Ines Hanrahan titled *WA 38 Stem Punctures & Semi-commercial Packout in the 2017-18 Storage Season* to understand the financial impact of stem clipping. Given the expected 3% incremental damage saved by stem clipping, we consider this project worth pursuing.

Wood Removal Sprint

System Design Requirements

We recognized early on in the development of the automated apple harvester that sometimes when picking an apple, some amount of fruiting wood is pulled along with the apple. We developed better gripping and removal techniques, but still between 2-5% of apples came with fruiting wood. We needed a method to reliably remove this wood before the apples entered any sort of conveyance system. If an apple entered conveyance without attached wood removed, there was a high likelihood that the wood would be lodged into the conveyance system and damage adjacent or subsequent apples.

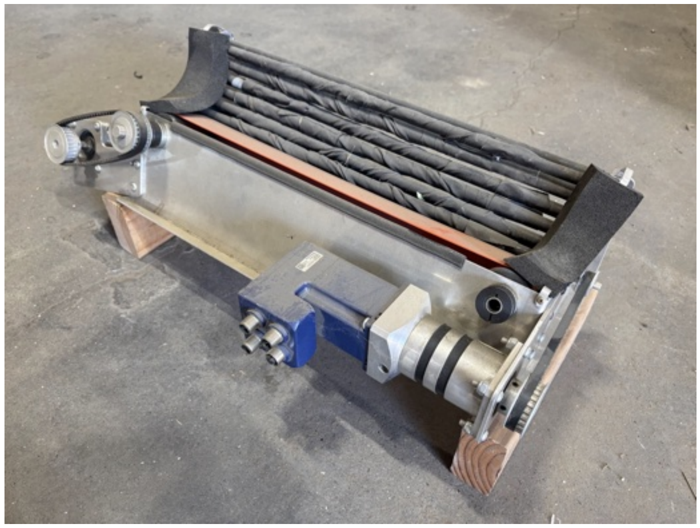
Due to these system requirements, we landed on a concept of wood removal that took apples directly after being picked, removed long wood/stems, and progressed the apple to the next step of conveyance. This system would need to support roughly one apple per second. We then sprinted on a few different systems that could achieve this goal:

Passive Scraper

Video: https://photos.app.goo.gl/XF6eCVACCrmAojg26

The passive scraper was the very first concept tested on removing fruiting wood from apples. This was a crude mock up that ultimately did not show consistency and was not pursued further.

Micro-roller + Belt picture and testing



Micro-roller + Belt Prototype Build

This system was designed to use multiple small rollers spinning in opposite directions to suck the fruiting wood through and off of the apple, while the large orange belt would progress the apple down the length of the system. While showing some promise, the apples did not consistently rotate, and would often “orbit” a standard axis, which proved problematic when trying to randomize the rolling to allow fruiting wood to be removed.

Auger Concept

Multiple Auger Prototypes

Video: https://photos.app.goo.gl/spgzur2Q9eGpJg1B6

The Auger concept went through many iterations, testing multiple shapes, profiles, pitches, and screw materials. Many solutions showed promise, but the smooth, ~3” pitch screws showed the most promise and moved into material choice selection and lifetime testing

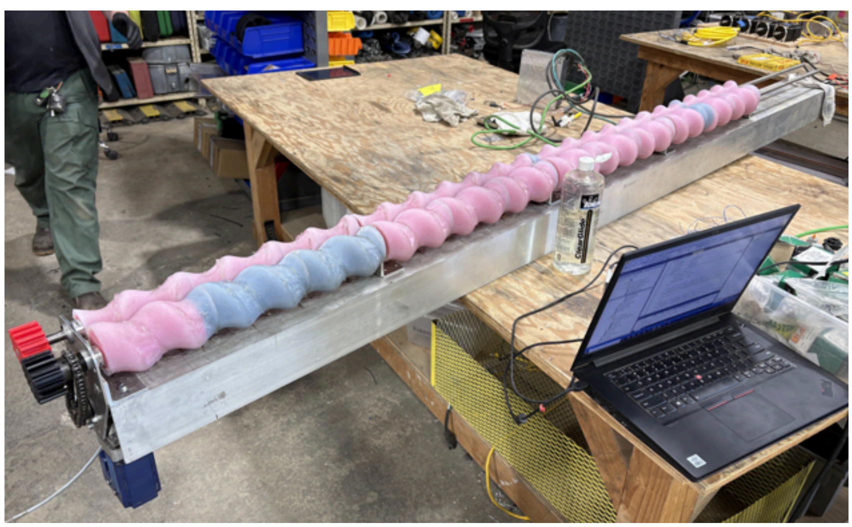
Auger Lifetime Testing

Lifetime Testing Setup and Results

Video: https://photos.app.goo.gl/cLDXrqPGZLQYbbe89

Before making a full-scale Auger (7ft long in our system design), we co-molded multiple types of silicone material onto 3D printed cores to test the durability of various durometer materials. We set up a system designed to recirculate apple-like objects and test the durability of the system across many apples. In the first picture above, you can see the results of multiple sections of overmold wearing off and failing, giving valuable insights into that design's durability. Other seconds on the roller still intact had ~¼" of overmold material, proving much more robust.

Auger Alpha Design



Full Build of Alpha Design

Video: https://photos.app.goo.gl/m3UwL3sc1SWEDbQi9

The Alpha Auger design that we landed on showed over 98% reliability in removing all fruiting wood from apples placed on the augers through testing on fresh apples in Washington and simulation apples in the lab. The design met the requirements for both conveying apples and removing fruiting wood reliably.

Stem Clipping Sprint

System Design Requirements

Stem clipping was the primary purpose of this research. Fully burdened, our apple harvester system design showed we could achieve pick rates of 9000 apples per hour across 12 robots. Humans can only reliably pick ~2000 apples per hour, so our harvester was going to quickly outpace the rate humans can clip on board the harvester.

We decided to divide the 12 robots into 6 separate apple conveyors, in an effort to keep apples in defined lanes and safer from potential damage. 6 lanes means that each lane needs to clip stems at a rate of ~1500 apples per hour, or one every ~2 seconds, in order to keep up with steady-state anticipated pick rates.

Buzz Chop Concept Picture, Testing and Video

Buzz Chop Clipping Prototype Build

Video: https://photos.app.goo.gl/1Zzfkiwc67H1a3Jh6

The buzz chop system was designed to have a cutting surface directly beneath a "grate" of sorts that kept the apple away from the blade. The attempt here was to create a simple mechanical system that the apple could roll across and trim its stem, without any additional features or automation. Ultimately, the stem clipping was unreliable, apples were damaged by the grate, and the stems were not clipped sufficiently to reduce damage in the bin.

Nose Clipper Concept

Nose Clipper Concept Build

The Nose Clipper concept relied on a spinning cutting bit, nestled within a curved guard, to reach into the stem well of the apple and clip the stem below the top of the stem well. While this worked decently well, indexing the apple into the correct location to clip the stem, without damaging the apple, proved difficult.

Counter Rotating Concept

Various Counter-Rotating Concept Parts

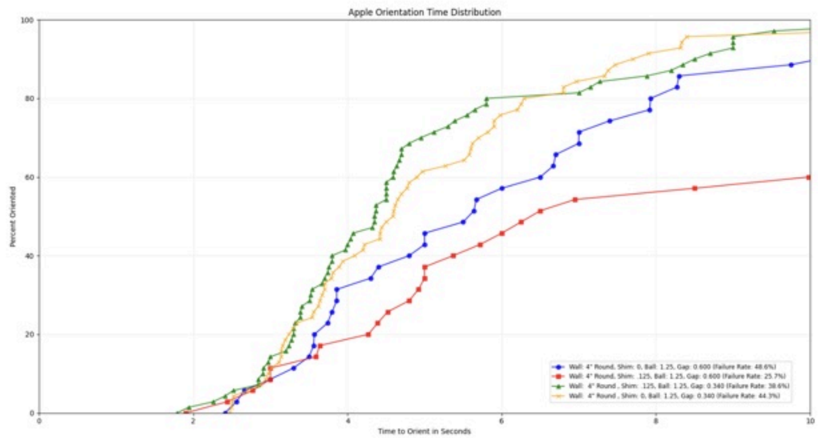
The concept sprint of the Stem Clipping project focused on refining the apple orientation and stem removal mechanisms for integration into the 2025 Alpha Harvester. The sprint explored multiple physical prototypes and test setups aimed at automating apple alignment and clipping with minimal damage. Early experiments centered on a vertical drop system using linear rails to test how apples centered when dropped onto whiskers and flat plates. These trials revealed that flat-plate balancing was more effective for achieving perpendicular orientation, capable of correcting up to 25° of apple tilt.

Early Iteration of Counter Rotating Concept, with Separately Driven Right/Left Rollers

Subsequent iterations combined the clipping and orienting processes into a unified module inspired "spinning apple clip" concept. Tests using dual drill-driven wheels simulated differential spinning to position stems between clippers for cutting. Adjustments included widening the stem gap (~0.3"), enlarging the inner ring to reduce catching, and experimenting with ring-based "lazy susan" rotation versus dual-wheel spin. However, interference from ring surfaces and inconsistent rotation prompted further exploration. Later designs incorporated TPU halves and O-ring friction surfaces, revealing that conical rollers outperformed flat ones in guiding apples smoothly without snagging stems.

Subsequent Iteration with Cutting Blades for Stem Clipping

The team conducted extensive A/B testing across variables such as wall slope (40°–90°), wheel diameter (≈1.25"), and inter-wheel gap (0.320–0.438"). Steeper and more vertical wall geometries improved both orientation reliability and "turntable" rotation effects, while smaller wheel gaps yielded more stable centering and spin performance. The optimal configuration featured a 4" round topper, 0.125" shim, 1.25" wheel, and 0.320" gap. Quantitative testing (≈50 runs per setup) confirmed higher orientation rates, though some apples became locked off-center. Damage assessments using Honeycrisp apples showed consistent bruising and scrape marks, emphasizing the need for softer wheel coatings (e.g., Dragon Skin silicone) and refined wheel geometry.

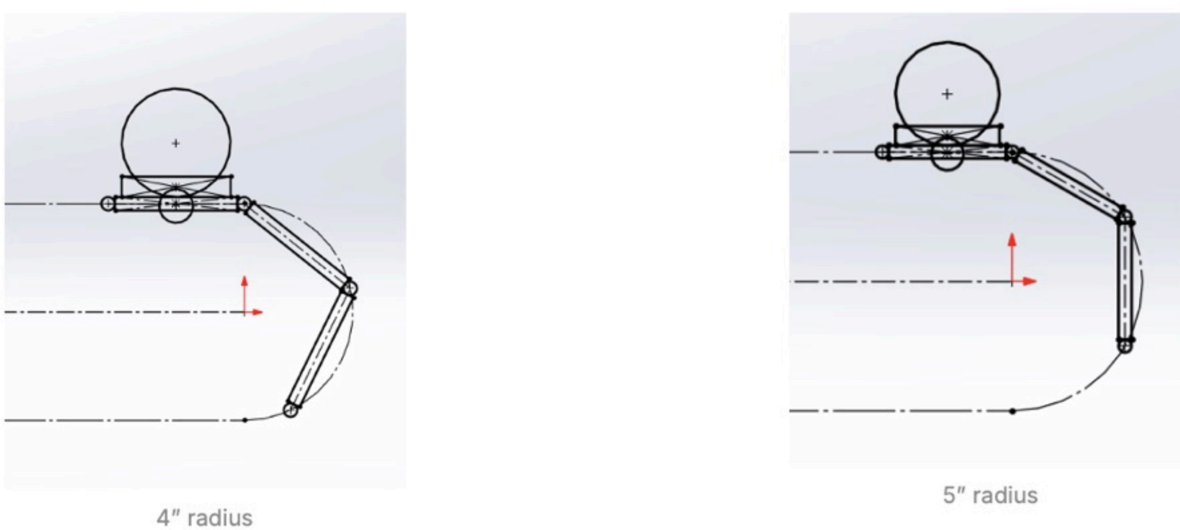


Test Results for Time to Apple Orientation for Various Pocket Geometries

Overall, the concept sprint produced valuable insights into mechanical parameters governing apple alignment, stem accessibility, and damage reduction. The team established a clear experimental foundation for merging the orientation and clipping systems in the next design phase.

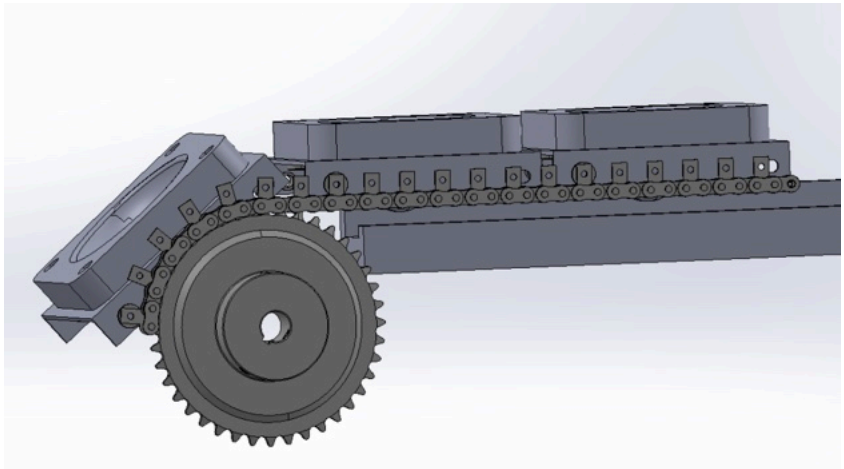
Counter Rotating Alpha Design

The Stem Clipper Benchtop Test Unit sprint marked a major step toward validating a functional single-lane prototype for automated apple stem clipping, forming part of the 2025 Alpha Harvester program. The project focused on designing and assembling a scalable test platform to evaluate mechanical clipping forces, chain-driven transport geometry, and cutter manufacturability. Early sketches modeled 4–5-inch conveyor radii, balancing mechanical clearance with under-deck volume, and explored configurations for integrating bowl walls above or within sheet metal assemblies.



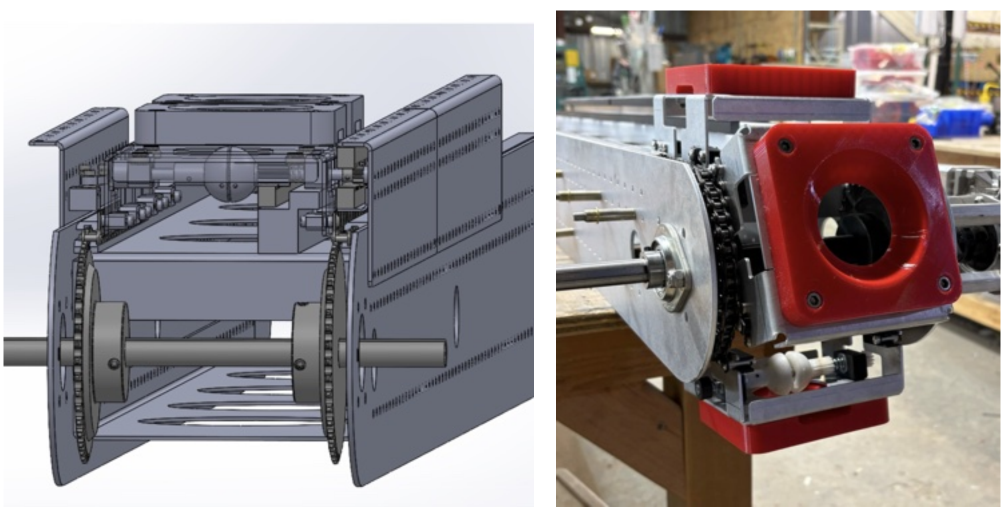
Layout Sketches for Various Alpha System Chain Pockets

The team iterated through multiple drive chain configurations (#35 and #40 ANSI) to optimize chain pitch, sprocket size, and pocket spacing for apple conveyance. A 40-tooth sprocket on a 60-inch span proved optimal for maintaining 26–30 slats with even chain length distribution. The #40 chain was ultimately favored for its higher working load and superior tolerance to misalignment compared to smaller chains. Plastic chain guides and pin-slot attachments were evaluated for smoother motion and easier assembly. Spring-assisted retract mechanisms and linear actuators were incorporated to automate the clipping motion, while mounting features and a benchtop superstructure were finalized in CAD for manufacturability.

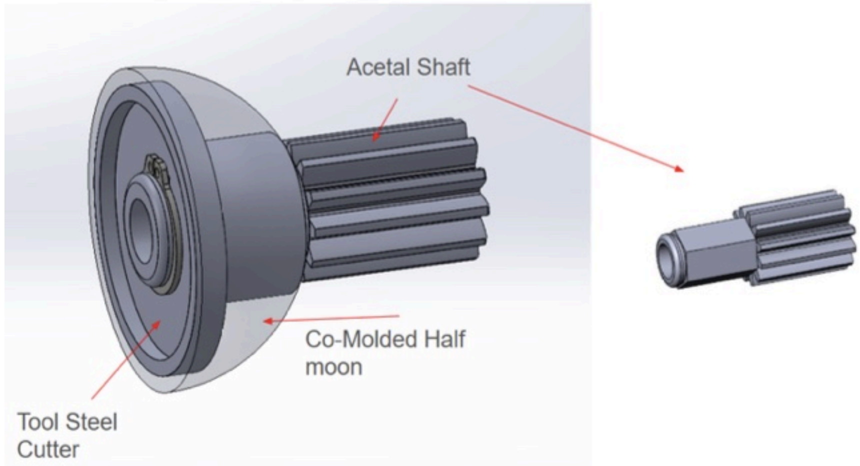


Early Design for Alpha Conveyance System

The clipper assembly was physically constructed and powered, revealing minor meshing issues in the rack drive but demonstrating full kinematic motion. Attention turned to the cutting subsystem, exploring cutter fabrication via involute gear cutters and testing cam-based and bearing-actuated clipping mechanisms. Formal testing measured cutting forces across different cutter geometries, using dial indicators to derive a spring constant. Measured stem-cutting forces averaged ~22 lbf, closely matching manual field clippers and confirming feasibility for automation. Shear-style cutters offered minimal additional benefit but validated force consistency across designs.



Clipper System CAD and Build Side by Side



Detail View of Clipper Roller, with Soft Co-Molded Rubber

Test Setup for Clipping Force Measurement

The completed benchtop system serves as a representative single-lane test platform for downstream automation and durability studies. It demonstrates integrated feeding, clipping, and stem disposal with wash-down capability while remaining scalable to multi-lane deployment.

Video: https://photos.app.goo.gl/qAPHKPCSPkkubSft8

Conclusions

The Wood Removal prototypes established a robust method for detaching fruiting wood from apples immediately after picking to prevent damage in downstream conveyance. Early trials with a passive scraper and micro-roller belt showed limited success, leading to the development of an auger-based system that reliably removed attached wood while moving apples along the line. Through extensive testing of auger shapes, materials, and wear resistance, the team identified a smooth, 3-inch pitch silicone-coated design as the most durable and effective, achieving over 98% wood removal efficiency in both lab and field tests.

The Stem Clipping Sprints focused on automating stem removal to keep pace with robotic harvesting rates far exceeding human capability. After testing several mechanical approaches, the counter-rotating and benchtop clipper systems emerged as viable solutions, integrating apple orientation and stem clipping at rates of one apple every two seconds. Iterative testing refined roller geometry, chain-driven transport, and clipping force mechanics, ultimately producing a prototype capable of clean, repeatable cuts using about 22 lbf of force, comparable to manual tools. Together, these systems form the foundation for fully automated apple preparation ahead of binning in the 2025 Alpha Harvester.

Project Title: Granny - image based analysis of fruit quality; TR-24-100A

Report Type: Final Project Report Year 2

Primary PI: Loren Honaas
Organization: USDA ARS TFRL
Telephone: 509.433.1143
Email: loren.honaas@usda.gov
Address: 1104 North Western Ave
Address 2:
City/State/Zip: Wenatchee, WA 98801

Co-PI 2: Stephen Ficklin
Organization: WSU Department of Horticulture
Telephone: 509.335.4295
Email: stephen.ficklin@wsu.edu
Address: PO Box 646414
Address 2:
City/State/Zip: Pullman, WA 99164

Co-PI 3: Dr. Huiting Zhang
Organization: WSU Department of Horticulture
Telephone: 509.335.4295
Email: huiting.zhang@wsu.edu
Address: PO Box 646414
Address 2:
City/State/Zip: Pullman, WA 99164
Cooperators: Allan Brothers Inc., Stemilt Growers LLC, WA Tree Fruit Research Commission, Dr. Carolina Torres (WSU TFREC), Dr. Rachel Leisso (USDA ARS TFRL), Hectre, Pomona Hort Innovation

Project Duration: 2-Year

Total Project Request for Year 1 Funding: $77,176
Total Project Request for Year 2 Funding: $73,944

Other related/associated funding sources:

Awarded:

Funding Duration: annual congressional appropriation
Amount: $85,000
Agency Name: USDA ARS
Notes: 3-year total $255,000: Personnel $180,000, Consumables/Supplies $30,000, Equipment (including computational resources): $45,000

Funding Duration: 2022-2024
Amount: $46,00
Agency Name: Washington Tree Fruit Research Commission (Award #AP-22-101A)

Notes: The high-performance compute node that was requested as part of a supplemental for the AP-22-101 will be utilized for this project, thus aside from a desktop computer for the postdoc in this budget, no other computing equipment is necessary.

Funding Duration: 2017-2022
Agency Name: US National Science Foundation (NSF) Award #1659300
Amount: $150,000
Notes: A portion of this award was used to fund 600 Terabytes of storage for execution of scientific workflows and storage of results. That infrastructure is still available and we will use that infrastructure for this project.

Budget 1
Primary PI: Loren Honaas
PI requests no funding

Budget 2
Co PI 2: Stephen Ficklin
Organization Name: WSU Department of Horticulture
Contract Administrator: Anastasia Mondy
Telephone: 509.335.6885
Contract administrator email address: anastasia.mondy@wsu.edu

Item	**2024**	**2025**
Salaries	$50,738.00	$52,768.00
Benefits	$18,438.00	$19,176.00
Wages		
Benefits		
RCA Room Rental		
Shipping		
Supplies[1]	$6,000.00	
Travel	$2,000.00	$2,000.00
Plot Fees		
Miscellaneous		
Total	$77,176.00	$73,944.00

Footnotes: [1]machine learning capable desktop computer, camera equipment, imaging station supplies, other minor consumables

Budget 3
Co PI 3: Huiting Zhang
Co-PI Budget is together with WSU's Budget #2 above.

Specific project objectives:
1) Build a stable version of Granny that includes a user-friendly starch rating module.
2) Provide a robust starch rating module for the industry.
3) Build a data set to train and test the software.
4) Provide outreach and training.

Significant findings, results, and milestones from 2025:
To provide some context, In 2025 we brought on a new programmer as our previous programmer left for graduate school. This new programmer required training and an onboarding period. The following organizes significant findings, results, and milestones as accomplishments we performed in order of the four stated objectives above.

1. *Build a stable version of Granny that includes a user-friendly starch rating module*
   a. ***Previously stated objectives for 2025***:
      i. Continue redesigning the software. Proper software design supports flexibility and reduces long-term maintenance costs. Taking the time now to do something correctly will save us headaches downstream. Our MVC framework design (as described below) is not yet complete and we will finish this in 2025.
      ii. To meet software robustness standards we will continue to add a complete suite of functional tests. This will ensure that as we make changes, we don't accidentally break what works between releases. It ensures the robustness of the software.
      iii. We will work to ensure the software can work on a Windows PC, currently, it only works on a Linux PC.
   b. ***What was accomplished***:
      i. <u>We met our goal of completing the software design</u>. While there is always room for improvement and expansion, we consider the software design at a stable and complete state. The primary design objective has been met that rater modules should be plug-and-play. Developers (either us, or industry partners) only need to focus on writing a new analysis and not worry about how to integrate their new tool. Granny utilizes a design approach termed Model-Viewer-Controller (MVC) which fully separates into modules (that can easily be swapped in-and-out and replaced) the data model, the user interface (viewer), and the controller (analysis modules). New modules are integrated automatically so long as the development protocols are followed. The protocols for creating new analysis are described in the Granny online documentation https://granny.readthedocs.io/en/dev/dev_guide/adding_analysis.html. While our original objective was to create starch rating modules, The MVC framework allows Granny to be **scalar** and **modular**. It is scalar in that new analysis modules or user interfaces can be easily added without major changes to the overall software. Moreover, Granny was designed to meet FAIR (Findable, Accessible, Interoperable and Reproducible) data standards in that the design facilitates the Interoperability and Reproducible parts of FAIR. Granny supports interoperability in that all starch rating arguments and parameters are fully exposed, documented, and have strict and well documented metadata describing the parameters.
      ii. <u>We will meet our goal of meeting robustness standards</u>**.** We have implemented a complete set of functional tests. These provide a battery of stress tests that we can use to check for problems with the software before we

make a release. In summary we have strong coverage of the underlying data types (parameters), good coverage of import and managing of Images and IO. We are missing some functional tests for our starch analysis module, but expect to have that completed by the time the project ends.

iii. We redirected efforts on the Windows interface. As reported last year, in 2024 we began working with Meg Staton's group at the University of Tennessee to build a web-front end Graphical User Interface (GUI) for Granny rather than a windows interface. This will allow Granny to be used more broadly across UNIX, MacOS and Windows-based computers. This work by the Staton team was separately funded by a USDA project but with close integration of our efforts.

2. *Provide a robust starch rating module for the industry.*
   a. ***Previously stated objectives for 2025***:
      i. While tests look great so far, we will continue testing partner images (WTFRC, Stemilt, AllanBros) to ensure consistent and quality rankings.
      ii. Granny currently converts its ratings into eight starch rating scales (e.g., Granny Smith, Jonagold, WA 38, etc.). We will be adding more starch rating scales.
   b. ***What was accomplished***:
      i. We continued to test images. Our team has continued to collect in-house images for the 2025 season and evaluate performance of Granny on those images. We have also tested images from the WTFRC WA 64 variety. Performance of rating continues to be good as in line with the results shown in Figure 6.
      ii. We will meet our goal of adding additional rating scales. With the onboarding of a new programmer, and the focus on finalizing program structure and robustness, we have not yet added additional starch rating scales. We will add some MSU scales that are not yet integrated. We will ask industry stakeholders to prioritize which scales they prefer. We will focus on varieties that are relative to Washington State.
3. *Build a data set to train and test the software.*
   a. ***Previously stated objectives for 2025***:
      i. We will continue to collect new tray images internally and with partners to improve training in image recognition and segmentation
      ii. We will continue to update our trained model files that are publicly available.
   b. ***What was accomplished***
      i. We continued to collect images: As already stated in section 2.b.i above, we have been collecting images in 2025
      ii. Updating of models: The deep learning model of Granny is used to segment fruit into individual images from an image of fruit on a tray. The work we have done in 2024 to build the model for image segmentation has performed extremely well in identifying fruit, and recent changes in Granny allow end-users greater control over how the model removes incorrect calls (happens rarely). Thus, we have not had a need to release an updated model during the 2025 season.
4. *Provide outreach and training*
   a. ***Previously stated objectives for 2025***:
      i. We will update the User's Guide to support use on a Windows PC.
      ii. We will work with partners to ensure online documentation meets their needs and expectations.

iii. We will support partners as they test Granny and work with us to improve the software.

b. What was accomplished

i. The User's Guide has been updated. As previously stated, we shifted from providing a PC based version of Granny to working with the Staton team to develop an online web-accessible version of Granny. We did not update the documentation for Windows support. However, we did add to the documentation a new section titled "Developer's Guide". This section walks developers (stakeholders with on-staff programmers) through the steps of adding their own analysis modules. Before the end of the project we will also be adding documentation for how stakeholders can write IO (Input/Output) modules such that they can integrate results from Granny into their own in-house databases.

ii. We have supported partners. We have checked-in with our industry partners during the year. Because the software is open-source and easily obtainable, several of our partners have downloaded and tested Granny within their own assessment environments. We have received feedback both regarding the functionality of Granny, as well as the GUI that was developed by the Staton lab. This feedback has allowed us to make some important changes they have requested such as the ability to change all analysis parameters, the ability to integrate, improvements to the data outputs. We are currently focused on reading hand-written or typed IDs on each try as requested.

5. Additional Accomplishments

a. WTFRC project cross integration:

i. *Integration with WTFRC project AP-22-101 "Towards next-generation maturity indices: apple biomarker discovery"*. During the summer of 2025, our student worker participated in a USDA funded Research and Extension Experience for Undergraduates (REEU). The goal of REEUs is to give undergraduate students exposure to research projects in an effort to encourage new scientists moving into graduate programs and careers in science. The student used Granny ratings to see if more granular and precise granny ratings would improve the machine learning (ML) models that are used to predict fruit maturity markers using gene expression data. Starch ratings from Granny were used as the expected values for predictions. Results showed that Granny performed as good as a single highly trained rater. Next steps are to test if Granny ratings perform better than a variety of human raters with varying levels of expertise. The hypothesis is that Granny will perform better.

ii. *Data-Driven Rating Scale for WA 64*. We have begun working with the WTFRC on a project to integrate Granny in a new WA 64 starch scale. Granny ratings show that human ratings are not linear. This integration of effort will hopefully yield new scales that are easier for humans to use.

b. Upgrading other rating modules: The objective for this project was to provide a starch rating module, and while this has been our primary focus, we also upgraded the other 3 additional rating modules that were part of Granny before this project, but which were not fully integrated into the new modular framework that this project supported. These include rating modules for percent superficial scald, pear color and blush in pears. The MVC framework we used to redesign Granny from its original state allowed for easy modular integration of these additional rating modules.

Activities for 2026 (If NCE): N/A

Methods

Development of the Granny Software

Granny began as a collection of efforts between the Loren Honaas (USDA), Stephen Ficklin (WSU), Carolina Torres (WSU), and Rachael Leisso (USDA) research programs. When we discovered we were collectively working on the development of software for rating different pome fruit quality traits using image processing and machine learning, we decided to combine our efforts into a single software package we called Granny (a nod to the Granny Smith apples we were using to rate superficial scald). A figure showing the workflow for how fruit rating occurs in Granny is shown in **Figure 1**. Our collective efforts yielded a set of software code, written by each of our different groups that included Python, Java, and ImageJ code. They were sandwiched together to form a single Granny software package. Recently, we published a manuscript (listed in the significant findings section) in the *Plant Direct* journal that describes this version of the Granny software. We referred to this as version 0.5 alpha (alpha meaning it is ready for testing but not production use).

While the 0.5 alpha version of Granny works, it was not optimal. The software needed a major rewrite to use a single programming language, and it needed a proper software design. Additionally, one of the software libraries we were using to identify fruit on a tray stopped being supported. Hence, the software needed a newer package for image recognition. Additionally, we needed to ensure that the software was delivering a high-quality robust starch rating module that could be used for industry applications and for research. Hence our request for this funded project. To meet the software development goals of the project we actively worked on each of these four specific areas:

1. conversion of the software to use a single unified programming language;
2. a complete redesign of the underlying infrastructure to support flexibility and ease of maintenance;
3. upgrade of the segmentation module of the software;
4. and development of a robust starch rating module.

First, we met the goal of consolidating the software into a single programming language. The current version of Granny is now written only in the Python programming language. Python was chosen because it is one of the most commonly used languages for machine learning and AI. Python also has ample image processing and data science modules available for programmers to use within their programs–that makes our job much easier. Python is also extremely popular with data scientists, software developers, and web developers, so it is an attractive language for finding competent programmers who want to learn and use it.

Second, we took the time to completely redesign the software. Version 0.5 alpha was simply a collection of cobbled-together programs. In contrast, our most recent version of Granny, version 1.0 alpha, is now designed in a modern Model-Viewer-Controller (MVC) style framework. This type of framework will support long-term flexibility because it fully separates the software into a plug-and-play type design where modules form the parts of the program that are responsible for the user interface (viewer), the way the software behaves (controller), and the way results are stored (model). This design will allow us to easily add new fruit rating modules, add new user interfaces, or change the way results are stored (e.g., to an in-house database) more easily. This redesign is quite far along, as we have already designed:

- the "viewers" (or interface) for interacting with Granny on the computer terminal (a text-based interface–not yet a graphical interface);
- the "controllers" (or analytical modules) for the rating of fruit that include modules for rating apple starch clearing, pear color, pear blush, and percent superficial scald;
- and the "models" to internally represent results and store them in files on the computer that can be easily opened with a text editor or Excel.

The code for Granny can be found online in an open repository at https://github.com/SystemsGenetics/granny (see **Figure 2**). To manage the Granny source code we use a tool called Git (https://git-scm.com/) and an online repository called GitHub (https://github.com/), which allows multiple programmers to work on the same software code without stepping on each other's toes. It also allows anyone who has programming experience to see how we have designed the code, and contribute back their own changes for review if they would like to be involved in our open-source software development.

One additional long-term benefit of our MVC design is that we now have an Application Programming Interface (API). An API is a set of written instructions and a set of programming "hooks" that allows anyone with programming skills to write their own plugins! We have written such an API. The API documentation is currently found online in the "Developer's Guide" at https://granny.readthedocs.io/en/dev/dev_guide/index.html. The objective here is that because the software is open-source anyone can add to it, including our industry partners who may have sufficient in-house computing experience to do so. This will allow for custom proprietary modules if needed.

Third, we have completed upgrading the segmentation module of Granny. This is the module that identifies fruit on a tray. It first identifies fruit and then "segments" the tray image into individual fruit images. This module requires the use of AI. We previously used the Mask R-CNN package to identify fruits and fruit cross sections on a tray. The Mask R-CNN package is an AI tool that must be trained to recognize objects. It learns to recognize fruit by repeatedly giving it images of the fruit and correcting it when it makes mistakes. Over time, it learns to properly identify fruit. This method was used in the 0.5 alpha version of Granny. However, the package has not been updated and newer versions of Python do not properly support it. Instead, we switched to using the You Only Look Once (YOLO) package which is actively supported and provides the same functionality. Converting to YOLO took some time, but the current version of Granny now fully supports the identification of apples, apple cross-sections, and pears using this tool. The trained models are freely available on the Open Science Framework (OSF) repository for download (and automatically retrieved by Granny) here: https://osf.io/4jxy5/.

Fourth, we have upgraded the starch rating module of Granny to use the new infrastructure just described. The results of the rating module are shown in the results section below. The starch rating module currently rates starch by providing a percentage of staining on the apple cross-section. This is different from the starch card ratings we are typically used to using which are subjectively determined using the human eye. However, to help understand how Granny ratings compare to the starch cards, the Granny results are converted to an approximate starch-card rating that is closest to each of the starch rating cards. While we were not expected to upgrade the other rating modules, we did also upgrade the ratings for percent superficial scald in apples, pear color and blush in pears.

During the second year of the project we worked to improve the robustness of the software, to ensure it can be used in a production setting. This involved the development of functional testing. Essentially, functional testing is a separate program that we write that is only designed to stress-test Granny. It provides valid and invalid input and makes sure that every aspect of the software, including the internal parts that the user does not see, responds as expected. This is extremely important because programmers make mistakes and sometimes in the process of adding a new feature or fixing a reported bug they inadvertently break something else. Functional testing is performed every time a programmer adds new code to Granny and it checks to make sure nothing breaks and results will always be consistent. We needed such testing to make sure that the starch ratings are robust across all of the versions of Granny that are released. Granny now includes a suite of functional testing, with more forthcoming. Writing of functional tests is an ongoing effort and is never completed, but we have a very strong base that ensures core robustness in the software.

Towards Robust Starch Ratings
In order to further evaluate the accuracy of the starch-rating function of Granny, we have worked with partners to generate a testing dataset that consists of images of real-world samples that have accompanying physiological data - namely starch ratings by human technicians. In the first year of the project, we processed the images with Granny to produce digital starch ratings and then compare the results via linear regression (i.e., granny vs. humans). We analyzed 245 images of trays of 'Envy' apples and 59 images of trays of 'Honeycrisp' apples that were provided by Austin Wilson (Allan Brothers Inc.). There were typically 25 apples per tray in each image. Starch ratings of 'Envy' apples (n=4825) were classified according to the Enza starch scale, and ratings of 'Honeycrisp' apples were classified according to the 'Honeycrisp' starch scale (n=750). Both the human ratings and granny ratings of the fruit were averaged across the tray. The tray averages were subject to linear regression analysis, Pearson's R was calculated.

Outreach and Training
To ensure that Granny is accessible to anyone, we have created a user-friendly User's Guide that is freely available online. This User's Guide walks users step-by-step through the process of rating fruit using Granny. We also provide example images that a user can use to test Granny before experimenting with their own images. We use a popular Read the Docs format for creating these documents. One benefit of this is that the documentation is freely available online, and anyone can provide suggestions for changes if they see a typo or want to suggest clearer language. The User's Guide can be found here: https://granny.readthedocs.io/ (see **Figure 3**).

As part of our outreach efforts, we have worked with our industry partners to develop an imaging station design. The design instructions for the imaging station are available in the online User's Guide. We have also created a template mat used to organize items needed by Granny. The mat provides instructions for where to place the tray, where to place a color card for calibration of the image processing, and a place for sample information notes. An image of the template within an image station can be seen in **Figure 4**. An example of the template mat being used within an imaging station can be seen in the demo image of the User's Guide screenshot of **Figure 3**.

Results and Discussion

Granny accurately rates starch clearing
In the Nguyen et al. 2024 manuscript cited in the "Significant findings/results from 2024" section, we provided an initial analysis of the starch rating module using 38 fruit images. To demonstrate further the analysis of Granny's starch rating function using the newly rewritten Granny v1.0 alpha, we performed a more in-depth analysis using the 245 'Envy' apple tray images and 59 'Honeycrisp' apple tray images that we obtained from our partners. The starch rating analysis in Granny consists of 3 key steps: fruit identification, image segmentation, and calculation of the percent starch clearing in each fruit sub-image (see **Figure 1 panel D2**). Granny provides a rating of 0 to 1 indicating the percentage of starch clearing on each cross-section of the apple, where 0 indicates no starch clearing and 1 indicates complete clearing. For each tray, an average starch clearing percentage is calculated. Lastly,

Granny converts its rating into a starch-card value appropriate for several commonly used starch cards. In this case, the Envy and Honeycrisp starch cards were used. This conversion is provided to help users better conceptualize the rating and to allow us to perform comparisons. We expect that the Granny rating from 0 to 1 is more accurate than the converted rating. The main goal of our tests was to see if Granny produced similar starch ratings to humans in a real-world setting. The results for 'Envy' apple trays are plotted in **Figure 5**. Results showed a high degree of correlation between human ratings and the ratings provided by Granny (R^2=0.64). The analysis of 'Honeycrisp' apples (not shown) exhibited a similar result (R^2=0.61). These tests showed that Granny is accurate and that Granny seems to slightly overestimate the degree of starch clearing when compared to human ratings. Because there is a strong correlation between human ratings and Granny ratings, future calibration of the software will be straightforward.

USDA AI Innovation Fund Award to support the development of user interface

During the project period, we received additional support from USDA to develop a graphical user interface (GUI) for Granny. In lieu of creating a Windows interface (as was an objective for 2025), we felt an online interface that would make Granny accessible in the lab or the field would provide greater flexibility. Briefly, along with new collaborator Dr. Meg Staton from the University of Tennessee at Knoxville, we developed a simple user interface for the starch rating function of Granny. Her team are experts in development of citizen science mobile and web-based applications. The current version of Granny uses a command line interface (commands given to the software in text form), and this graphical version will always remain available. The command-line version is especially useful in research applications. However, the new GUI is now available for testing, has been demonstrated to industry partners in August of 2025, with requests for feedback, and makes Granny easier to use in a commercial setting. Our design concept for the GUI is shown in **Figure 6**.

Figures

Figure 1. Granny key functions, adapted from Nguyen et al 2024. Granny performs four steps to process an image and provide a rating. (a) First, images of fruit trays are provided as input (apple or pear). (b) Second, individual fruits are detected on the tray. The figure shows individual fruits colored differently to show how they are identified. (c) Third, each fruit is segmented into individual fruit images. (d) Fourth, ratings are performed including detection and scoring of D1) superficial scald, D2) starch content, D3) pear peel color, and D4) pear blush percentage.

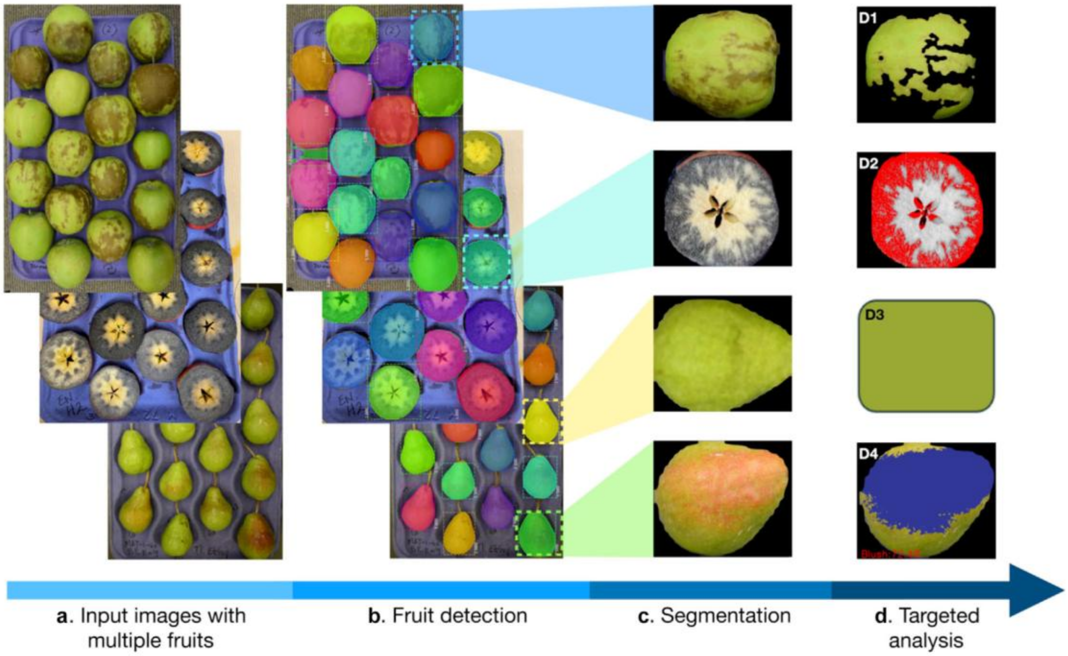


Figure 2. Granny Source Code Repository. The following is a screenshot of the Granny software source code repository on GitHub at https://github.com/SystemsGenetics/granny.

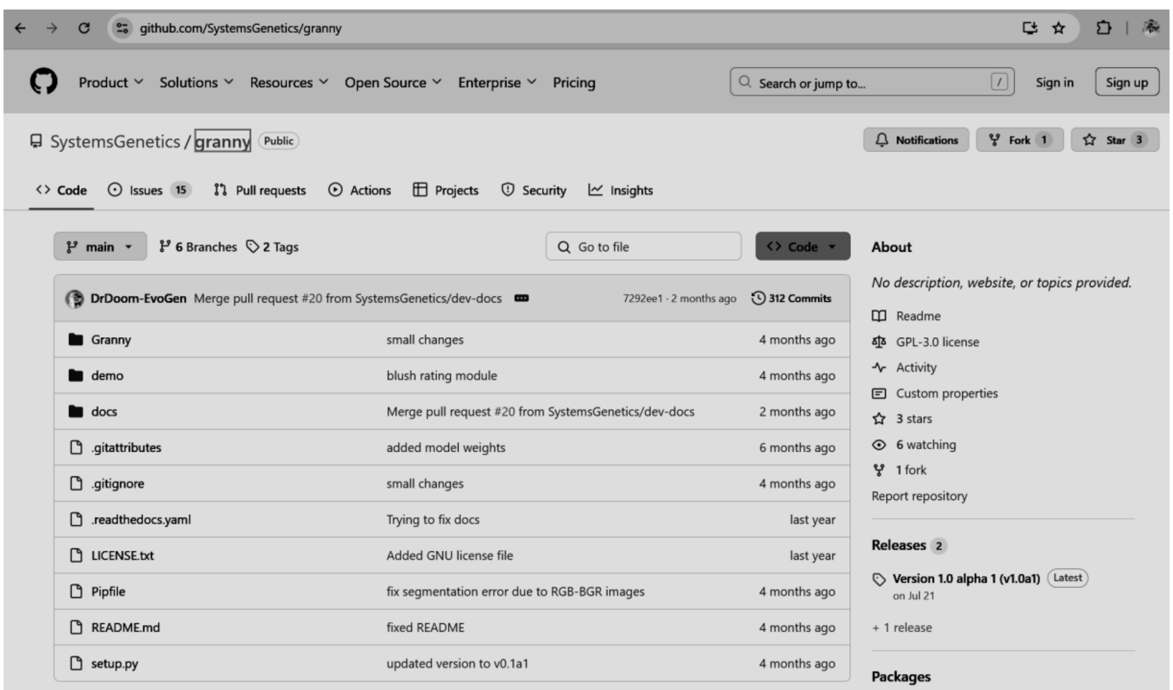


Figure 3. A screenshot of the Granny User's Guide showing the instruction page for rating starch. Available at https://granny.readthedocs.io/.

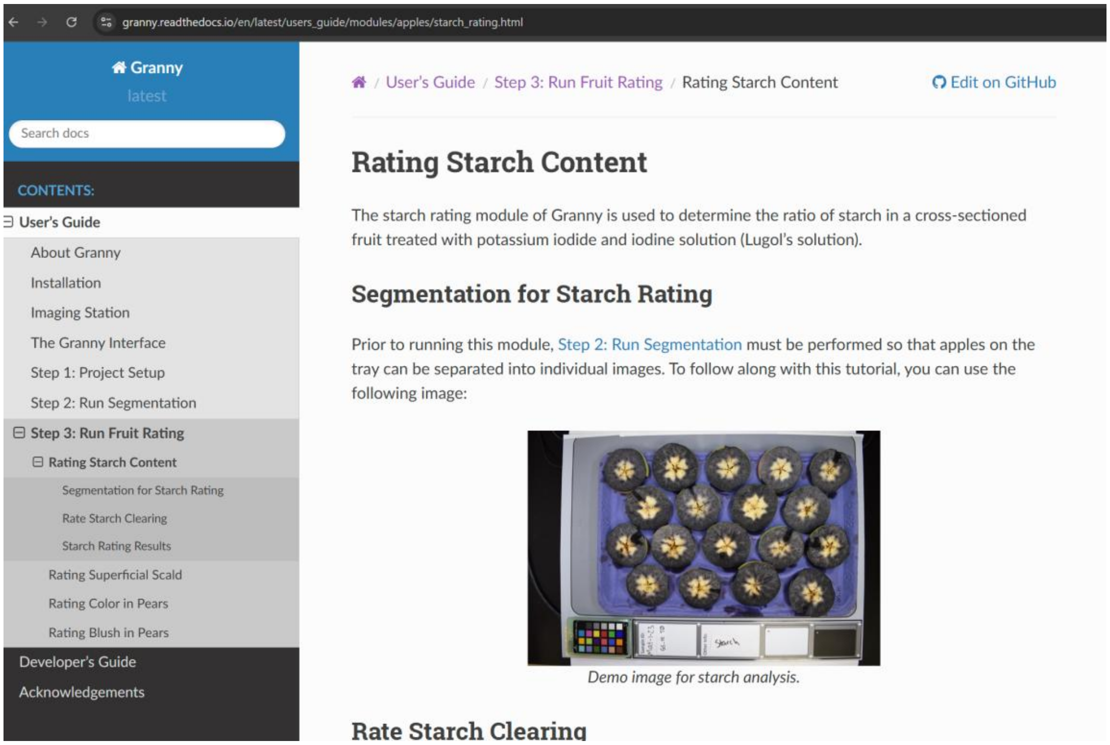


Figure 4. The Granny Imaging Template Mat. The design for the imaging station and the template mat are described in the Granny User's Guide. The image shows the template mat which indicates where the tray should be positioned, where a color card should be positioned, and an area for sample information.

Figure 5. Analysis of commercial samples shows high accuracy. Average starch ratings of 245 Envy apple tray images are plotted in the full figure where human technician ratings are represented with circles and Granny's ratings of the same trays are shown as triangles. The 245 tray images are ordered on the x-axis using the percentage of the cross-section not stained by starch that Granny produced (the lowest on the left). For comparison, the actual

value plotted is the Granny rating converted to a starch card value. A strong linear correlation is observed between human and Granny's ratings as is shown in the plot on the lower right corner.

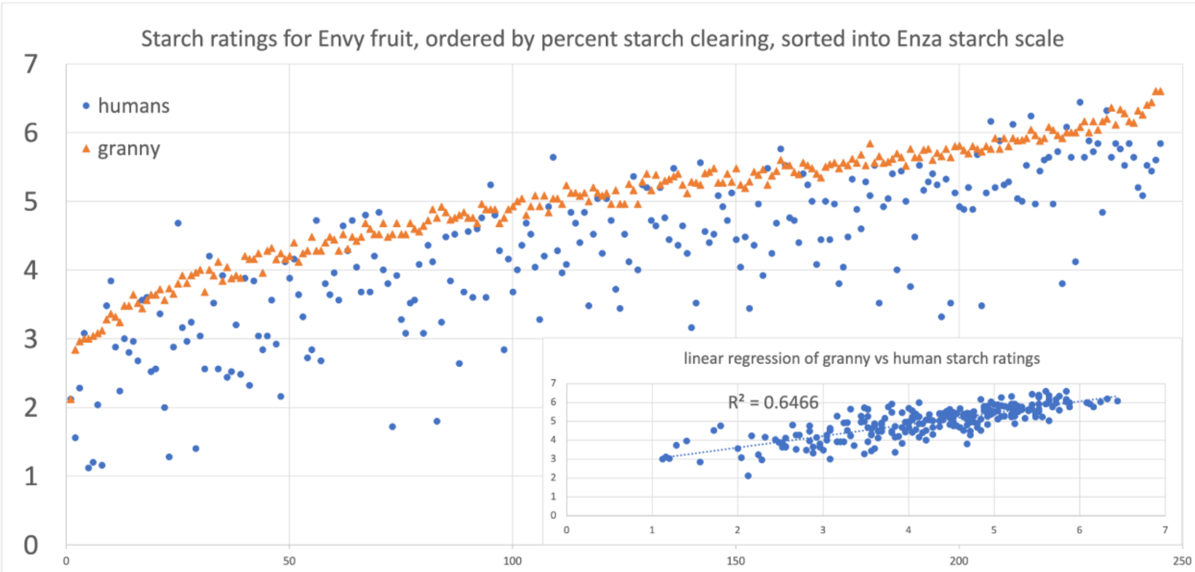


Figure 6. User interface concept. We have designed a graphic user interface (GUI) with Dr. Meg Staton's research group. Once an image is uploaded and processed by the GUI, users can review the image and the fruit detection results, verify the Samples ID, select the reference starch scale, and the software produces a summary graph and tray-level statistics.

Executive Summary

Project title: *Granny – Image-based Analysis of Fruit Quality; TR-24-100A*
Key words: image-based phenotyping, starch rating, fruit maturity, machine learning, fruit quality

Abstract

This project delivered an important advancement in automated image-based fruit quality assessment software. *Granny*, an open-source platform originally developed to rate superficial scald, has now been fully re-engineered into a modern, modular system capable of robust and reproducible apple starch clearing evaluation. Across the two-year period, the project team completed a full rewrite of the pre-existing disjoint software into a single unified Python package, implemented a modular expansible software framework, and integrated a modern deep-learning model for identification and segmentation of individual fruit on a tray. The primary objective of this project was to deliver a starch-rating module that provides granular and consistent ratings, avoiding the pitfalls of human rater bias. Additional rating modules for superficial scald, pear color, and pear blush were also upgraded and integrated. Extensive functional testing ensures reliability across future versions. Image-based starch ratings produced by Granny correlate strongly with human rater assessments across commercial samples of 'Envy' and 'Honeycrisp' fruit. Its design allows industry users and researchers to expand its capabilities by integrating custom analysis modules and database systems.

Industry collaboration was central to success. Growers and packers provided images for training and validation, and several partners tested the software in their internal workflows. User documentation and developer guides were substantially enhanced, and design support was provided for imaging stations and tray-layout templates. A new graphical web interface—supported by a supplemental USDA award and developed in collaboration with the University of Tennessee—extends access to Windows, macOS, and field-use environments without requiring installation.

This work provides to researchers and the industry, objective, standardized, and scalable fruit maturity measures and provides a flexible platform for additional trait-rating modules.

Leveraged Funding Summary

Over the life of the project, development was supported by funding from:

- All funds from the Washington Tree Fruit Research Commission for this proposal.
- Additional funds leveraged to support the development of Granny:
  - USDA ARS AI Innovation Fund to support creation of a graphical user interface for Granny.
  - Data storage equipment from the National Science Foundation (NSF) purchased for a previous project that ended prior to this award was used to support development and testing of Granny.
  - Funds from a USDA Research and Extension Experience for Undergraduate (REEU) supported purchase of a high-performance workstation for the student programmer.

Combined leveraged support exceeded $400,000, providing computing infrastructure, programming support, and user-interface development to enhance outcomes beyond the base award.

Project Title: The Next Fruit 4.0

PI: Peter Frans de Jong		Co-PI (2):
Organization:	Wageningen University & Research	Organization:
Telephone:	+31 4884 73744 (voicemail) +31 (0)6 30475029 (SMS/Whatsapp)	Telephone:
Email:	peterfrans.dejong@wur.nl	Email:
Address:	Lingewal 1,	Address:
Address 2:	Droevendaalsesteeg 4,	Address 2:
City/State/Zip:	Randwijk, Gelderland, 6668 LA	City/State/Zip:
City/State/Zip2:	Wageningen, Gelderland, 6708 PB	

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 Agriculture, Nature and Food Quality

Notes: Total project size is 3,156k€ for 4 years, half is paid by the Dutch Ministry of Agriculture, Nature and Food Quality and 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	2024-mid 2025
Salaries	$54,000	$54,000	$54,000	$54,000
Benefits				
Wages				
Benefits				
Equipment	$5,000	$5,000	$5,000	$5,000
Supplies				
Travel				
Miscellaneous				
Plot Fees				
Total	$59,000	$59,000	$59,000	$59,000

Executive Summary The Next Fruit 4.0

The object is to make fruit cultivation more efficient, intelligent, sustainable, and future-proof. A crucial step is to be able to monitor, manage, and to act at the level of individual trees with the help of smart technology. The **first example** is the development of a precision sprayer that can spray at a nozzle level with sensors that detect the volume of the trees. Two prototypes were build and one is commercially available for growers. A later add-on are RGB camera's that can detect pests and diseases. For the detection of fruit tree canker the first algorithm was developed. Precision spraying during fruit thinning showed that aiming the trees with a high number of flowers gave the best effects on return bloom and that orchards will become more uniform. The **second example** is the development and or tests of sensor platforms that can detects blossoms and tree positions in the orchard or a platform that can examine the fruit quality of a storage bin. Specially for pear an algorithm was developed to measure the size. Colour measurements will follow in a follow-up project. The **third example** is the use of a non-destructive sensor to measure fruit quality like firmness and brix. The Fresco sensor showed reliable outcomes for both firmness as brix. And finally the **fourth example** is the build of end effectors for picking and pruning to make robots multifunctional. The first end effector to pick pears was made and tested with success in the field. This winter red currant plants will be pruned with the pruning end effector.

Objectives overall project
Making fruit cultivation more efficient, intelligent, sustainable, and future-proof requires us to be able to monitor, manage, and act 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 case studies. 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.

Results of the projects are presented per case study.

Case study: Precision sprayer

Objectives on building precision sprayer
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
- Both prototypes were tested in the field.
- Munckhof is already selling the sprayer developed in this project to the first customers.
- Factors that influence successful market introduction focus on compatibility (brand-independent integration), plug-and-play (simple operation), and techniques that allow growers to be independent.

Methods
The project concentrated on:

- Building 2 prototype sprayers with Pulse Width Modulated nozzles together with the manufacturers KWH and Munchhof.
- Building an improved sensor platform for the sprayers with LIDAR and GPS.
- Processing data into usable data for spray decisions at nozzle level based on tree volume.
- Tested the sprayers on leaf deposition and also on savings on spray volume.

Results and Discussion
In practice, the most important benefit is that in the future fewer spray volume will be needed to achieve the same result and that emissions to the environment will be further limited. The LIDAR scanners that make this possible are placed at the front of the sprayer. They determine the tree volume and gaps while driving. Both spray systems use PWM (Pulse Width Modulation) technology to vary the amount of spray liquid. This is done by changing the length of those pulses. Based on the tree volume an algorithm determines the amount of spraying liquid for each nozzle. Munckhof build their own algorithm and KWH used an algorithm developed in this project by Wageningen University & Research.

At the end of the project both sprayers were working and were tested in the orchard. The deposition on the leaves with the use of the sensors turned on were as good as when the sprayer did not use the sensors. If the deposition was not as good, it would have meant that the nozzles sprayed too late. The savings were around 15% in summer, during spring this can be better. Also the settings are very conservative so it will not miss anything. The optimum settings still need to be determined. Also the PWM nozzles are set to be turned on or off, in other words they spray at 100% capacity or 0%. In a future project the sprayer will be able to spray a lower amount (between 0-100%) if the density of leaves is less. In that way, more spraying product can be saved.

Below 2 pictures of the sprayers, one in the field during tests and one during installation of the components.

Objectives work on economic validation and innovation adoption
Within this work package work is also done on the economic validation and innovation adoption of a precision sprayer. This research clarified the factors that influence successful market introduction. This includes, on the one hand, economic feasibility and, on the other, factors that can drive or hinder the implementation and/or user acceptance of technological innovations for fruit growing.

Methods
The preconditions for faster practical adoption of new precision technologies were examined. The focus is on which factors influence the purchase of a precision sprayer or the use of precision features on the sprayer. Interviews were conducted with growers, advisors, dealers, manufacturers, and/or developers. The questions are based on the Behaviour Change Wheel method (see figure below).

This allows us to:

- Conduct a behavioural analysis: which behavioural characteristics play a role in the use or non-use of the precision sprayer?
- Diagnose what needs to change.
- Identify which interventions are likely to bring about behavioural changes.

Results and Discussion

The following interventions can help accelerate the adoption of precision spraying techniques. Work with growers as ambassadors and role models. A success story told by a grower is the most convincing. As developers, **focus on compatibility** (brand-independent integration), **plug-and-play** (simple operation), and techniques that **allow growers to be independent** from other companies like in the case of hiring a drone pilot to scan the orchard versus having a sensor platform on their own so they can scan any time they want.

A recommendation at the system level is to develop a shared strategy and vision for the sector, focusing on "it is important for health and the environment that we reduce crop protection options, and precision farming is the way to make this possible and thus the future." The second recommendation is to adapt legislation to the possibilities of precision farming. Legislation currently lags behind the possibilities of precision farming (for example: adjusting the maximum number of applications per plot per year to the maximum amount of permitted pesticides per plot per year).

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

- Trunk detection to get the GPS locations for individual trees.
- Detection method to detect fruit tree canker and apple blossom weevil
- Proof of principle was demonstrated for automated detection of pear in top layer of storage bins.
- Experiments were done to develop a thinning decision support system for Conference pear.
- Field trial on blossom and fruit thinning showed that precision spraying on trees with a high amount of flowers is the most effective strategy to make the orchard more uniform. Stimulating trees with a low number of flowers is less effective.

GPS position of trees

Methods

In this part of the research, sensor platforms of Aurea Imaging and AgroWizard were used to see if they are able to detect the GPS position of trees. This is relevant if orchards were not planted with GPS and the grower wants to use precision fruit thinning.
The sensor platform of Agrowizard is mounted on a quad and scans the trunks. Combined with the GPS and an algorithm it determines the GPS position of the trees (picture below with setup).
The system of Aurea Imaging is mounted on the top of the tractor. The camera's face downwards to scan the trees but also the trunks during winter time. During the summer, this is not possible.
With Agrowizard system 6 orchards were scanned with 86-162 trees per orchard and with the Aurea Imaging setup, 2 orchards with 64-96 trees. Outcomes were compared with GPS measurements done with a handheld RTK-GPS.

Results and Discussion

The Agrowizard system could determine 69% of the trees position within an error margin of less than 10 cm (~ 4 inches). With a higher error margin of 20 cm, 92% of the trees could be determined. An error margin of 20 cm (~ 8 inches is found to be enough for most of the growers to use precision fruit thinning.
The Aurea Imaging system found 47% of trees within the 10cm error of margin and 89% within the 20cm error of margin.
For both system the challenges were orchards with slanting trees or with interfering elements like nets to protect the trees against wildlife damage. Aurea Imaging will have an option in the future to position their sensor platform to a lower position in order to be able to detect the trunks in a better way. But with those 2 systems, it is now possible for growers to start using precision spraying in older orchards. The same camera

systems can be used for other things as well, like detection of blossoms, fruits and diseases. In the project algorithms to detect the disease fruit tree canker and the pests apple blossom weevil were developed. Further development is still needed to be able to use the algorithms on a commercial level.

Image processing photos storage bin

Methods

Within the project, WUR was developing image processing in which the size distribution of the pear is initially determined from photos of the storage bin. In subsequent steps, other quality aspects can also be analysed, such as fruit shape, colour and certain damages. For the size measurement specific points in the shape are now detected. This concerns the stem and nose position and the widest point of the fruit to determine the diameter. Several steps are required to validate the data. First, it must be determined how reliable the size measurement for the detected pears is and then it must be determined how well this size distribution corresponds to the entire storage bin or the entire batch.

Results and discussion

The performance of the various AI models (developed in 2023 and optimized in 2024) and combination of models were tested on pears. The maximum deviation in size was determined, for both size and weight. The best model for size had a deviation of deviation 3.8 mm (0.15 inch) , while another model was better to determine fruit weight (deviation 24.8 grams/ 0.055 pounds). The image processing model is running on a trial basis at the project partner Bodata. The goal is to bundle the collected information into a quality report. We are currently discussing with the consortium partners involved how the analyses can be incorporated into daily practice. Preparations are also being made for market introduction.

Because there is little time during the harvest to photograph each storage bin by hand, it was suggested that it would be practical to drive a picking train under a gate where the photos could be taken automatically. By then linking the photo to this storage bin via an RFID chip, it will be possible to quickly gain insight of a complete batch.

A test setup was tested at the experimental orchard Randwijk during a harvest period. As soon as a storage bin passes the camera, a photo is automatically taken and the RFID chip is scanned. To ensure consistent photo quality, it was decided to shield the portal from daylight and artificially illuminate it with construction lights. To minimize motion blur in the photo, the picking train had to pass in the lowest gear. Integration with RFID stickers turned out to work fine. There are still some points that require attention, such as fruit brilliance and colour correction. The latest insight is that growers prefer a setup on a forklift. This idea will be examined in another project.

Precision thinning

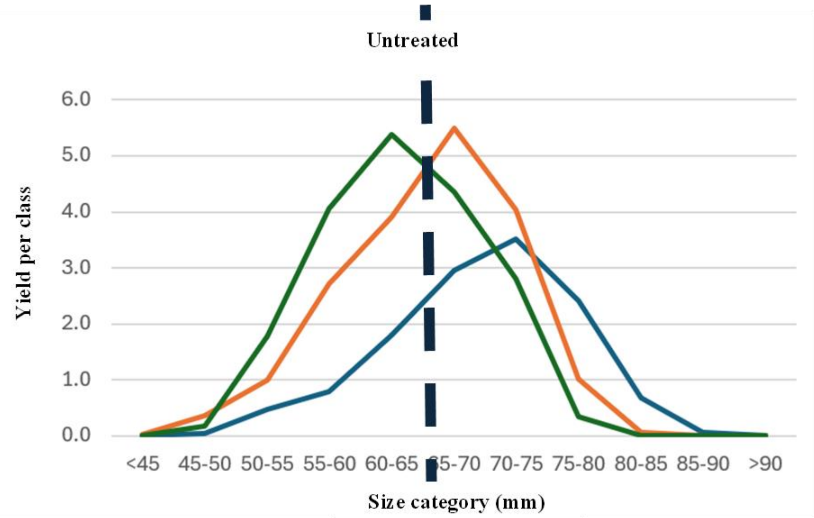
Methods

Extensive thinning tests were done at the Experimental orchard in Randwijk on Elstar apple and Conference pear during the course of the project. Different thinning treatments were done with a

focus the product Brevis. Those treatments were done *on the whole* orchards or *based on a task map* and compared with *an untreated* orchard. In the task map the trees with a high amount of flower clusters got the strongest thinning treatment, the middle group of trees got the standard treatment and the trees with a low amount of flowers got nothing.
Counting was carried out at three times, namely at the end of June (end of June drop), in July (hand thinning) and in August (just before harvest). Just before harvest, a random fruit size measurement was also carried out in all treatments.

Results and discussion
Precision thinning in the Elstar apple variety has several advantages: 1) avoiding chemical thinning in the lowest flowering class prevents yield loss, 2) a significant reduction in the required manual thinning when thinning according to the task map is possible, particularly in the highest flowering classes, 3) in the case of a high flower cluster numbers, overthinning is less likely to occur.
By applying precision thinning according to the task map, each flowering class can be given the optimal thinning strategy, making it easier to achieve the target number fruits/tree in more trees; the orchard becomes more uniform and alternate bearing in the following year is prevented.

In Conference pear, applying fruit thinning in the "high" flowering category results in a reduction in the number of fruit per tree, and gave a higher average fruit weight, resulting in a comparable net yield in kg. This can reduce the labour required for hand thinning and harvesting.
In the figure below the effect of precision spraying is clearly demonstrated. In the untreated block the different categories of trees from low to high numbers of flowers, show a different size distribution at harvest time. In the case of the orchard were each category got another treatment the size distribution is uniform.



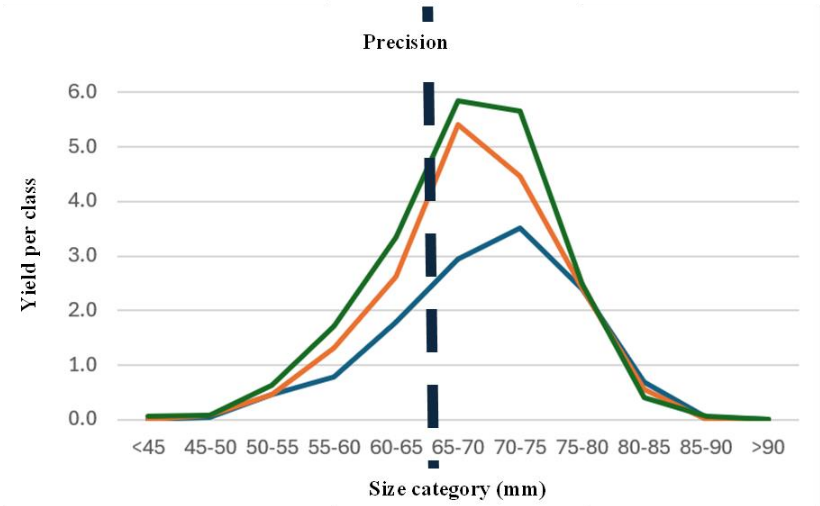


Figure: blue line: low amount of flowers, orange: normal amount, green: high amount of flowers.

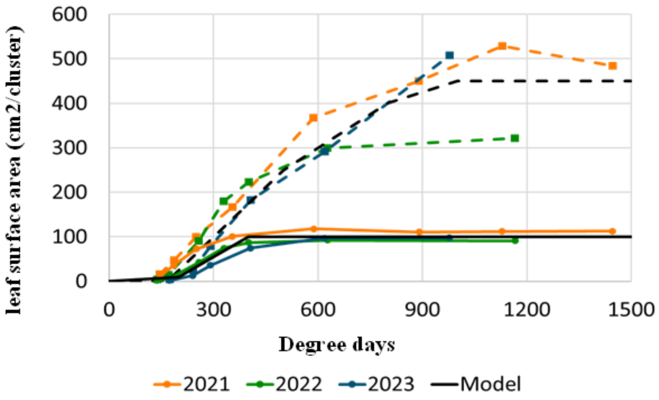
Develop crop growth model

Methods

Within this work package, Delphy is working on developing a crop growth model for pear (Conference). The aim is to predict the June drop and the final fruit numbers for Conference pear. Many counts and measurements were again carried out in various tests from 2021-2024. In addition to validating the model, work has been done to collect information about the course of the June drop and the factors that influence it on 3 different pear orchards.

Results and Discussion

It was found that it is possible to determine the leaf development based on degree days as is shown in the figure below. It was also found that the chance of a fruit drop is determined by the relative growth of the growth of the pear. This can be described by formulas. The measurements are plotted in the figure below. Camera systems with the right resolution could in the future follow the growth of pears and predict the fruit drop in a better way.



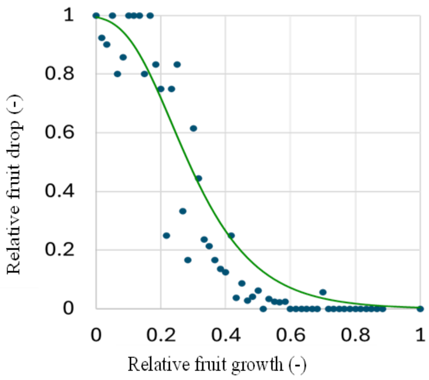


Figure: Development of cluster leaves (solid lines) and shoots (dotted lines) in 2021-2023.

The probability of a pear falling or remaining stuck depends on its relative growth. Example: May 2022.

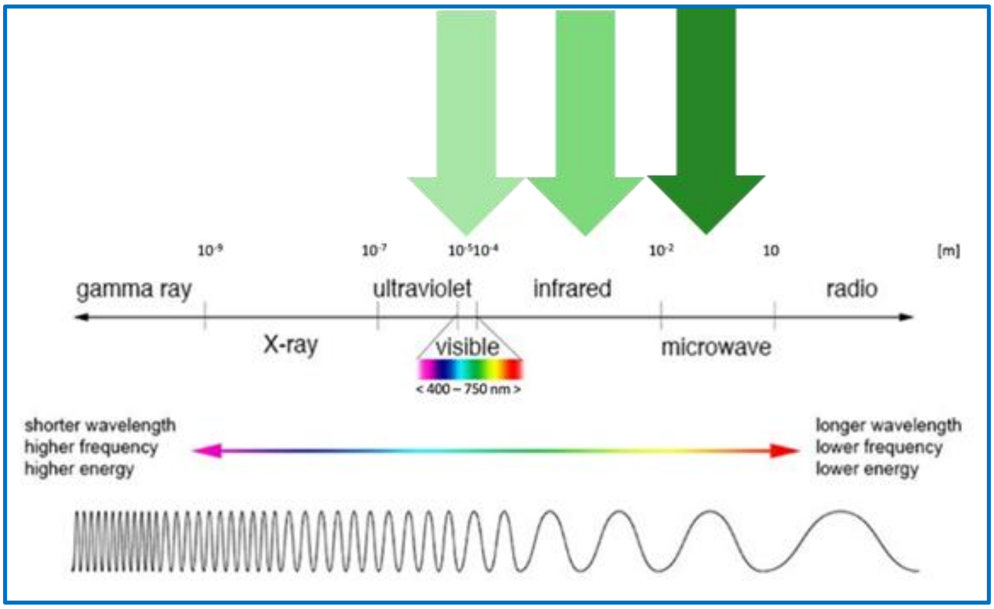
Case study: Cool data

Objectives

This project investigated two techniques for non-destructively measuring the internal fruit quality of Conference pears. Both utilize electromagnetic waves from the invisible part of the spectrum. Kubota investigated the application of Near Infrared (NIR) technology, while Vertigo investigated the application of Microwave technology.

Significant Findings

- It was possible to measure the Brix with both systems but measuring the firmness was only possible with the Fresco scanner from Vertigo.



Methods

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.

Common quality assessment

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

Non-destructive 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 project partner Kubota decided to pause the further development of the NIR hand held sensor. Therefor the focus was on Fresco sensor from Vertigo.

Companies were visited in the most important Conference growing regions (Limburg, Zeeland, the Betuwe, Utrecht, Flevoland, North Holland and the Belgian fruit region). In some cases, the storage boxes were labelled so that they can be reanalysed as soon as they leave storage. Fruits from each batch were collected and stored in parallel at WUR Randwijk. Photo material and data about firmness and sugar content are added to the Agromanager database as much as possible. Agromanager is data platform for fruit growers where all data can be collected and analysed by the grower.

Results and Discussion

Both Kubota and Vertigo meters are suitable for non-destructively measuring Conference Brix. The Vertigo meter (Fresco) is suitable for non-destructively measuring Conference firmness. Although the Brix is easier than the firmness. The nice thing about the hand held sensor is that multiple measurements can be taken to get a better average firmness value. In consultation with Vertigo, a plan is being developed to launch the Fresco.

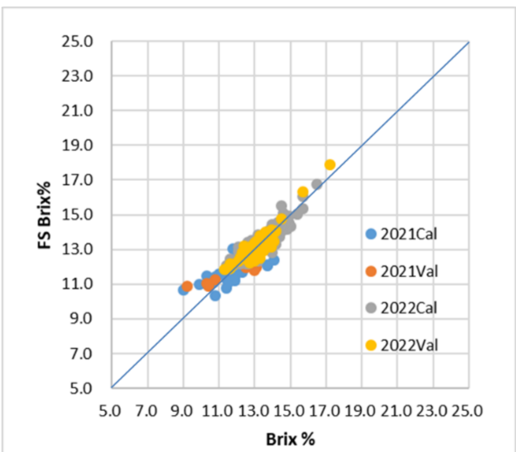


Figure: on y-axis predicted Brix value and on the x-axis the measured ground truth data of Brix.

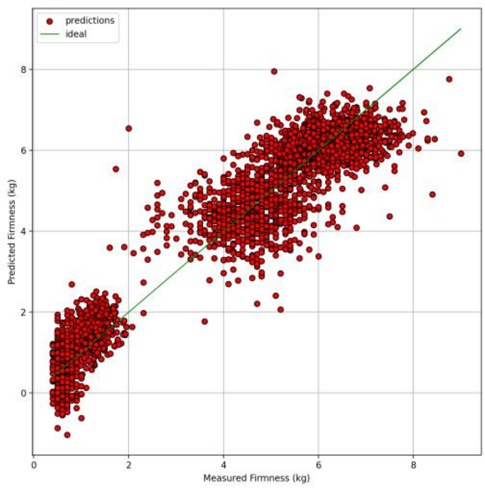


Figure: on y-axis predicted firmness value an
on the x-axis the measured ground truth data
firmness.

Case Multifunctional robot

Objectives

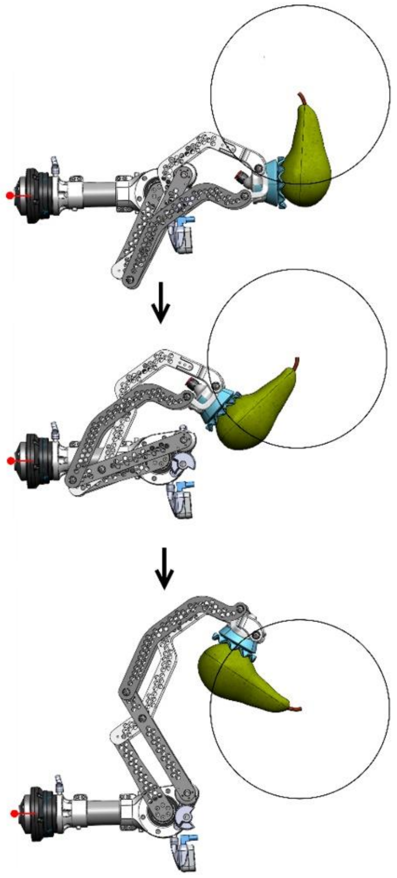
The main objective of the multifunctional robot case is to expand the functionality of existing orchard robots and of orchard robots currently under development in parallel research projects. The focus of the work is on two topics, namely the development of a sensing system and a gripper for picking 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

- Detection system developed for robotic harvesting pear to detect the position but also the orientation and some other key points of the fruit.
- Prototype gripper that can do the required motion to detach a pear from a tree which is significantly different from that to detach an apple.
- Extensive knowledge and expertise on automatic pruning and fruit harvesting is exchanged with Washington State University and Oregon State University. Close cooperation and knowledge exchange between Dutch and US researchers is of mutual benefit.
- A prototype gripper for pruning is developed and tested on red currant.

Methods

When harvesting by hand, the pear is often lifted perpendicular to the stem, causing the pear to detach from the tree during the natural separation of the stem. The new pear gripper concept uses the same motion. A soft silicone suction cup uses a vacuum pump to grip the pear. The key innovation of the pear gripper lies in the lifting motion that is integrated into the gripper mechanism. This means the robot arm no longer has to perform this motion itself. This increases the picking speed and reduces the risk of collision between the robot arm and the tree.



A small stereo vision camera attached to the gripper detects and locates ripe pears. This information is passed to the control software, which calculates the correct path for the robot arm to grasp and pick the pear.

To detect the pear and estimate its grasp point, Deep-Learning Keypoint R-CNN is used. This algorithm is a region-based convolutional neural network (R-CNN) that can simultaneously detect the object (the pear) and the grasp point (a point on the pear) in an image. Not only the position of the pear but also the grasp point can be learned end-to-end using hand-labeled training images.

The robotic arm systematically moves the gripper with the camera along a preset search frame approximately 20-30 cm from the tree. Upon detection, the pear is harvested immediately. If multiple pears are detected in a single frame, the pear closest to the robotic arm is picked first, as this is generally the easiest to reach.

Results and Discussion

During the harvest period in September 2023, WUR conducted experiments with this setup at the experimental fruit research station Randwijk to harvest Conference pears. The results are convincing: the robot can detect and harvest pears without damaging them. The tests in the orchard provided valuable insights into what works well and what can be improved on the gripper. For example, some fruits are difficult to reach, and the lifting mechanism only works optimally for a predetermined fruit size. Furthermore, the robot does not yet detect obstacles, such as branches or crop wires. This can be risky for both the tree and the robot. The gripper is therefore not yet ready for practical introduction, but it is an important piece of the puzzle for the development of future robots for fruit growing.

Photo 1 Robot setup in orchard

Photo 2 Gripper with suction cap

Pruning red currant bushes

Methods

The main challenge in the end-effector for pruning lies in the sensors responsible for determining the correct pruning positions. Electric battery-powered pruning shears for manual pruning have developed into robust systems over the years. For this reason, it was decided to use an existing pruning tool (Makita DUP361ZN) and modify it so that it could be controlled by the robot. This pruning shear is capable of cutting branches with a diameter of up to 33 mm. To operate this tool safely, a digital output signal from the robot was converted into a mechanical input to actuate the lever in the tool. This was achieved using a coil with an electromagnet. To accommodate this additional component and enable mounting on the robot flange, a new 3D-printed housing was designed. The power for cutting is supplied by two 18V 5.0Ah batteries. These can cut over 70,000 times on a single charge.

The camera system's task is to determine which branch the robot should prune, and where. In addition to colour information, this requires 3D information. A stereo camera (Intel RealSense D405) is mounted on the end-effector for this purpose. This small and lightweight camera (4.2 cm × 4.2 cm × 2.3 cm; 60 g) provides colour and 3D images between 7 cm and 50 cm. This makes the camera suitable for detecting detailed features or improving target position estimation based on additional sensors on the robot. The completed prototype of the pruning end-effector is shown below. Linux and the Robot Operating System (ROS2) are used to control the end-effector, the camera, and the robot.

Conclusion and discussion

Experiments in the lab and outdoors with redcurrant have confirmed that it is possible to prune branches using a robot arm and this end-effector. The prototype end-effector for pruning meets the wishes and requirements defined in the project. In addition to pruning redcurrants, this prototype can also be used to prune large fruit. The prototype does not yet meet all the requirements of a commercial product, such as watertightness. The biggest challenge for robotic pruning is not the pruning shears themselves, but sensors and algorithms for detecting the correct pruning positions.