Awards issued prior to January 20, 2025, were funded under previous Administrations and may not reflect the priorities and policies of the current Administration.

United States Department of Agriculture
Project Initiation

Project Data for Accession Number 1034641

Project Title

Integrated Horticultural and Robotic Solutions for Labor Intensive Orchard Operations

Project Details

Sponsoring Institution National Institute of Food and Agriculture	**Project Status** ACTIVE
Funding Source NIFA Non Formula	**Grant Year** 2026
Grant No. 2026-51181-46280	**Cumulative Award Amt.** $5,835,164.00
Proposal No. 2025-08061	**Multistate No.** (N/A)
Project Start Date Jul 01, 2026	**Project End Date** Jun 30, 2030
Program Code [SCRI] Specialty Crop Research Initiative	

Project Director

Karkee, M.

Recipient Organization

CORNELL UNIVERSITY
341 PINE TREE RD
Ithaca, NEW YORK 148502820

Performing Department

(N/A)

Non Technical Summary

The U.S. tree fruit industry accounts for about 14% (~$22 billion) of all crop production and contributes >$100 billion to downstream economic activities. The long-term sustainability of this industry requires the automation of labor-intensive field operations. We intend to accomplish this with the development of an effective, affordable multi-purpose robotic system and precision canopy management strategies. We propose a socio-economics-driven, horticulture-aligned robotic solution through: i) analysis of the socio-economic impact of an integrated horticultural and robotic solution; ii) developing precision canopy management strategies; and iii) development of novel perception and actuation systems, and integrated multi-purpose robots. Our team includes economists, horticulturists, roboticists, and tree fruit industry partners. We are also partnered with a robotics company and will use their advanced platform to accelerate commercialization. We will validate the robustness of the system in commercial orchards, focusing on harvesting and thinning. By working at the intersection of social science, biology and technology, and with stakeholders, this project is

expected to yield practical integrated systems to automate tree fruit production operations. Commercial adoption of the proposed systems will dramatically reduce dependence on labor, reduce labor costs, enhance crop yield/quality, and improve long-term sustainability of the tree fruit industry, which addresses SCRI priority area 3: "Production Efficiency" and "New Innovation and Technologies". Specifically, this proposal directly addresses the SCRI priority on advancing "mechanization and automation to reduce the need for manual labor". In addition, our outreach/education activities will contribute to developing the next generation of scientists and practitioners to support the adoption of automation/robotics in agriculture.

Animal Health Component

Animal Health Component: 0%

Research Effort Categories

Basic	40%
Applied	40%
Developmental	20%

Classification

Knowledge Area (KA)	Subject of Investigation (SOI)	Field of Science (FOS)	Percent
402	1110	3010	10%
205	1110	2080	10%
205	1112	1020	10%
205	1110	1020	10%
402	1110	3080	10%
601	1110	3010	10%
402	1110	2080	10%
402	1112	2020	10%
402	1110	2020	20%

Knowledge Area

[402] Engineering Systems and Equipment

[205] Plant Management Systems

[601] Economics of Agricultural Production and Farm Management

Subject Of Investigation

[1110] Apple

[1112] Cherry

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Field Of Science

[3010] Economics

[2080] Mathematics and computer sciences

[1020] Physiology

[3080] Sociology

[2020] Engineering

Keywords

Socioeconomic analysis, Automation in Tree Fruit Crops, Canopy Mgmt, Multipurpose robotics, robotic thin

Goals / Objectives

As mentioned in the summary,labor-intensive operations such as pruning and harvestingaccountfor up to 40% of total production costs in the tree fruit crops, such as apples. Chronic labor shortages and increasing labor costs have forced growers to leave fruit unharvested, a problem worsened by declining migration to the USA. Although many farmers rely on the H2A visa program, it is costly, administratively burdensome, and fails to address long-term labor needs or hazardous working conditions in orchards. In response, industry groups have prioritized automation and robotics to reduce labor dependence, improve worker safety, and boost productivity. However, current robotic solutions still lack the speed, accuracy, usability, and affordability needed for commercial adoption. To address this challenge, our project innovates machine vision, end-effector, and manipulation technologies while simultaneously improving tree canopies to facilitate robotic operations, with a long-term goal to develop multi-purpose robots for tree fruit crops that would improve practical and economic viability. Specifically, we will pursue the following objectives: i. Define socio-economic drivers for integrated horticultural and robotic solutions for tree fruit farmers and analyze their impact.Hypothesis: The economic benefits of integrated robotic solutions will surpass their costs.ii. Optimize tree fruit orchard systems for efficient robot-tree interaction.Hypothesis: Utility and efficiency of robots will improve with strategic precision canopy management strategies.iii. Develop and evaluate a multi-purpose robotic system for tree fruit cropsHypothesis: Collaborative, multi-purpose human-robot system will allow efficient orchard operations and reduce labor use and production costs. iv. Broaden adoption and understanding to orchardists and external partners. Hypothesis:Using a multi-pronged outreach approach in collaboration with growers and advisory committee will improve the adoption of new solutions.

Project Methods

Objective 1: Define socio-economic drivers and analyze their impactThis objective uses a combination of quantitative and qualitative socio-economic methods to understand adoption drivers, profitability, and market impacts of multi-purpose orchard robotics. Behavioral analyses are conducted through structured grower surveys and discrete choice experiments administered to apple producers across major production states (e.g., WA, NY, MI, PA). Surveys are developed using established literature, stakeholder consultation, and focus groups, and include farm characteristics, orchard architecture, current labor practices, and grower risk preferences. Methods to mitigate hypothetical bias--such as cheap-talk scripts and certainty scales--are incorporated. Cost-benefit analyses are performed using partial budgeting frameworks that estimate changes in revenues and costs under multiple adoption scenarios, including robot ownership and Robot?as?a?Service (RaaS). These analyses are conducted at both per-acre and block scales and incorporate sensitivity testing on key parameters such as labor wages, robot speed, harvest efficiency, and damage rates. Market impact analyses employ national-level partial equilibrium models to evaluate how widespread adoption affects apple supply, prices, producer surplus, and consumer welfare, including dynamic replacement of orchard systems with robot-compatible architectures.Objective 2: Optimize tree fruit orchard systemsThis objective employs field experimentation, digital twins, and simulation to co-optimize horticultural practices with robotic requirements. Precision canopy management strategies are evaluated in commercial orchards to improve visibility and accessibility

in tree canopies to facilitate robotic operations while maintaining or enhancing yield and fruit quality. Replicated field trials will be used to compare conventional canopy management with treatments designed to improve robotic performance through targeted pruning, flower cluster thinning, and fruitlet thinning at different phenological stages. Harvest and thinning efficiency, fruit quality, tree vigor, and return bloom are measured to assess the performance. High-resolution 3D digital twins of trees are constructed using perception systems developed in Objective 3, enabling longitudinal tracking of canopy structure and management effects. These digital twins are integrated into physiology-based growth models to generate virtual orchards that simulate different canopy architectures and management strategies. Simulation experiments are used to evaluate robot reachability, task success, and interaction constraints across orchard designs, supporting rapid iteration of both horticultural and robotic design decisions.Objective 3: Develop and evaluate a multi?purpose robotic systemThis objective employs an integrated engineering, robotics, and field-evaluation approach to design, build, and validate a multi-purpose robotic system capable of performing essential labor-intensive orchard operations.Perception and Sensing Systems: The project develops a hierarchical perception framework that combines dormant season structural modeling with growing?season sensing to improve speed, accuracy, and robustness in complex orchard environments. Dormant season data are used to reconstruct detailed 3D models of tree structure, including trunks, primary branches, and trellis components, which serve as long-term structural priors. During the growing season, these structural models are aligned with real-time image and depth data to probabilistically estimate the location of occluded objects such as fruit, flower clusters, branches, posts, and wires. Low-cost camera systems are used to enable scalable deployment, and perception outputs support both real-time manipulation and longer-term data collection for decision support and horticultural analyses.Manipulator Design and Reachability Enhancement: To address limited reachability within dense and highly obstructed canopies, the project develops novel manipulator configurations that combine conventional linear arms with soft, growing robotic "wrist" extensions. These soft robotic wrists are designed to navigate around trellis wires, branches, and other obstacles, enabling access to fruit and flowers located deep within the canopy or behind permanent structures. The wrist design uses lightweight, low-cost materials and pneumatic actuation to add degrees of freedom without substantially increasing system complexity, weight, or cost.End-Effector Development for Harvesting and Thinning: Multiple modular end-effector designs are developed and evaluated for harvesting and flower thinning applications. For harvesting, the project investigates multi-modal grippers that combine suction, compliant fingers, and in-hand visual and tactile sensing to improve grasp reliability, reduce fruit damage, and enable closed-loop adjustments during pick execution. Alternative concepts, including soft everting grippers, are also developed to provide gentle yet firm fruit engagement across different fruit sizes and cluster configurations. For flower thinning, compact, lightweight end-effectors are designed to selectively remove flowers or flower clusters while minimizing unintended damage to neighboring structures.Closed-Loop Control and Human-Robot Collaboration: The robotic system incorporates visuo-tactile closed-loop control to improve manipulation accuracy under variable field conditions such as wind, canopy movement, and partial occlusion. In-hand cameras, tactile sensors, inertial measurement units, and wrist force sensing are combined to support real-time adjustment of end-effector position, orientation, and detachment forces. In parallel, the project develops dynamic scheduling and planning algorithms that enable coordination between robotic arms and available human labor.System Integration and Modular Architecture: System integration occurs in staged phases. First, newly developed perception, manipulation, and end-effector components are integrated into an existing commercial apple harvesting platform to extend its single-task functionality into a multi-purpose system. In parallel, a modular "mast-based" robotic architecture is developed to support broader adoptability across orchard sizes, row spacing, and canopy architectures.Laboratory Testing and Field Evaluation: Robotic components and integrated systems are evaluated through a combination of laboratory experiments and multi?state field trials conducted in commercial orchards. Performance metrics include task success rates, operational speed, fruit or flower damage, and robot-tree collisions.Objective 4: Broadening adoption and understandingThis objective uses extension, education, and stakeholder engagement methods to promote adoption, workforce development, and feedback-driven refinement of project outputs. A multi-pronged outreach strategy is implemented in collaboration with growers, extension educators, consultants, and industry partners. Methods include personnel development through graduate and undergraduate training, internships, and train-the-trainer programs for extension professionals. Durable products such as technical manuals, extension publications, economic bulletins, videos, and podcasts are produced and

disseminated through established industry and extension channels in English and Spanish. Workshops, field demonstrations, webinars, and conference presentations are conducted in partnership with commercial orchards and existing ag-technology initiatives. Stakeholder listening sessions, surveys, and interviews are used to assess knowledge gains, adoption intent, and barriers to implementation. A national certification framework is piloted to define workforce standards for automated orchard operations. Continuous feedback from outreach activities is integrated into research objectives to improve technical relevance and adoption potential.