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United States Department of Agriculture
Project Initiation

Project Data for Accession Number 1029004

Project Title

Robotic Blossom Thinning in Tree Fruit Crops with a Novel, Soft Growing Manipulator

Project Details

Sponsoring Institution National Institute of Food and Agriculture	**Project Status** COMPLETE
Funding Source NIFA Non Formula	**Grant Year** 2022
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Non Technical Summary

The production of our nation's high-value tree fruit crops requires a large, semi-skilled workforce for intense periods. One of the most labor-intensive activities is flower thinning - a critical annual operation required to optimize fruit yield and quality. Mechanical and chemical thinning machines/systems are available, but cannot permit selective thinning, lack necessary precision and efficacy, and are being abandoned for manual approaches at great expense. Increasingly, US tree fruit growers are adopting manual flower thinning due to its precision. As we continue to face the challenge of decreasing availability and increasing cost of farm labor, the development of robots able to perform labor-intensive orchard operations will play a critical role in its long-term sustainability. The overall goal of this proposal is to develop a prototype robotic system for flower/flower cluster thinning utilizing a fast, soft-growing manipulator. Specifically, the following objectives are pursued. i. Develop a fast and precise machine vision system for blossom detection and localization; ii. Design and implement low-cost, soft growing manipulation for flower thinning; and iii.

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Integrate thinning end-effector and vision systems with soft manipulator, and evaluate the thinning robot in commercial orchards.Our prototype development and field validation work with commercial growers is expected to provide sufficient information for companies (e.g. collaborator FFRobotics) to develop and commercialize a robotic flower thinning system. Commercial adoption of this technology will substantially decrease farmers' dependence on and cost of labor while increasing the yield and quality of fruit crops, thus helping ensure long-term sustainability of the industry.

Animal Health Component

Animal Health Component: 0%

Research Effort Categories

Basic	20%
Applied	40%
Developmental	40%

Classification

Knowledge Area (KA)	Subject of Investigation (SOI)	Field of Science (FOS)	Percent
205	1110	1020	35%
402	1110	2020	65%

Knowledge Area

[205] Plant Management Systems

[402] Engineering Systems and Equipment

Subject Of Investigation

[1110] Apple

Field Of Science

[1020] Physiology

[2020] Engineering

Keywords

Flower thinning, flower detection, modern orchards, soft robot, thinning end-effectors

Goals / Objectives

The US fruit industry is an important component of the nation's agricultural sector representing about 10% (~$20 billion) of all crop production. Production of these high-value tree fruit crops requires a large, semi-skilled workforce for short, intensive periods during the year. One of the most labor-intensive orchard activities is blossom thinning, which involves selectively removing closely spaced flower clusters and/or flowers removing several individual flowers from within a cluster, so that only desired number of flowers are left for pollination. In addition, removing a portion of each tree's flowers during or prior to bloom works to minimize the biennial bearing of crop - a challenge that has plagued

tree fruit growers for generations.Growers deploy a variety of tactics to thin flowers - the tools range from chemical bloom thinners to tractor-driven mechanical string thinners, to, more recently, a return to the only reliable, selective thinning technique - removing flowers manually. These techniques, however, are non-selective, ineffective and/or labor-intensive. To address this challenge, it is crucial to develop automated/robotic thinning machines that can detect and precisely locate flowers in tree canopies and effectively remove the desired proportion of flowers from target locations.Automating flower thinning is a complex problem requiring high-resolution, fast sensing systems, effective end-effector techniques, and fast and low-cost manipulation. Researchers have developed conventional and deep-learning-based models to detect flower clusters in apple and cherry orchards. A limited number of studies have also attempted robotic flower thinning. However, these efforts lack the ability to accurately detect and locate flower clusters and count the number of flowers in those clusters (or estimate flower density), which is essential to make a decision on the location and extent of flower thinning. It is essential that flower detection models have a high computational speed for real-time, in-field operation. Past efforts have also not demonstrated the capability to precisely remove a proportion of flowers from target flower clusters. In addition, horticultural studies have established optimum fruit loads based on thinning to a wide range of fruit densities.Traditionally, robotic systems have been developed with the use of rigid manipulators (arms) that are limited by high cost and complexity, and low manipulation speed. Despite their compact, organized appearance, modern, narrow tree canopies also have obstructions to robotic operations such as trellis wires, tree trunks and branches. In such a situation, rigid manipulators can damage the obstructing objects and /or themselves. Soft manipulators composed of flexible or stretchable material demonstrate a great potential for addressing these challenges because their naturally compliant bodies can absorb contact forces compared to rigid manipulators. In addition, they possess greater flexibility, which improves their reach and access.In this project, we proposed to develop a robotic flower thinning system that relies on a fast and precise machine vision system and a novel, soft growing manipulator to improve the robustness, accuracy and speed, and reduce the complexity and cost so that robotic flower thinning can be practically applicable. When successful, adoption of such asystem will reduce the dependence on and cost of a dwindling manual labor supply, increase crop yield and quality, and improve long term-sustainability of tree fruit production systems across the nation. Specifically, the following are the objectives of this project.i. Develop a fast and precise machine vision system for blossom detection and localization in tree fruit crops,ii. Design and implement low-cost, soft growing manipulation, and an end-effector for flower thinning, andiii. Integrate thinning end-effector and vision systems with a soft manipulator and evaluate the thinning robot in commercial orchards.

Project Methods

Vision System: Localization and selective removal of an individual flower within a cluster are challenging for machine vision systems and require complex motion of the robotic arm and hand in constrained space, making the process complicated and time-consuming. The proposed machine vision pipeline consists of a sequence of supervised and unsupervised machine learning algorithms to localize flower clusters and estimate total number of flowers in each cluster. Attention-Based Fully Convolutional Neural Network (AFCNN) is proposed for flower spatial distribution and counting, followed by an unsupervised method to achieve precise cluster segmentation and count information. More than 1,000 color and 3D images will be captured using a low-cost RGB-D (Red, Green, Blue - Depth) camera (ZED Camera, Stereolabs Inc., San Francisco, CA) to train and test the model. ZED Camera was selected in this study as it has better resolution and improved performance in outdoor conditions compared to similar, consumer RGB-D cameras. Images will be collected in both day and nighttime conditions (LED lighting for nighttime imaging). All of these images will be manually annotated (budget allocated for summer students to be hired for this task), which is expected to improve the robustness and accuracy of the model in estimating number of flowers within individual clusters and delineating cluster boundaries.The proposed AFCNN model is an end-to-end attention-guided regression-based deep learning network to estimate the flower spatial distribution map (density map) without precise object detection. The density map provides the flower location and count information. The network requires only point annotation to identity object centers rather than comprehensive polygonal/bounding-box annotation of object boundaries, thus substantially reducing the number of hours needed to annotate training images, which allows for expanding the training dataset.Furthermore, to address the challenges due to varying lighting, exposure, and the

background objects and sky, the integration of a dual attention mechanism is proposed. A dual attention mechanism will be employed in both spatial and channel domains of the feature maps. The proposed dual attention mechanism, combining spatial and channel attention, is expected to highlight and integrate crucial features in spatial and channel dimensions while suppressing the non-relevant background information. The spatial attention module aggregates the features such that the features at each pixel location are computed as the weighted sum of features at all pixel locations. It increases the neural network receptive field from the local level to the global level highlighting similar features regardless of their spatial location. The channel attention module models the channel interdependencies and provides the contextual information in the channel dimension, highlighting channels with high feature information. Manipulator Fabrication: Compared to the existing soft growing manipulator, fabrication process will be improved to achieve desired speed and length. First, the length of the manipulator will be extended to 2 m so that it is able to reach even the furthest flowers. Second, the system will be designed to tolerate up to 20 psi (138 kPa), which is sufficient for performing various field operations outdoors. In addition, our target is to be able to achieve "one second reaching" speed. To match the 20 psi of air pressure, we will redesign and manufacture the base using metallic container, similar to a pressure cooker.End-effectors: Rotating string thinners have shown to be promising based on our preliminary work. A scaled-down version of commercial string thinner with rotating spindle configuration will be designed and evaluated for efficiency in robotic blossom thinning. The end-effector will be coupled to an electric motor (brushless DC gear motor - more efficient) via a special clamping system such that various configurations of end-effector could be connected and tested quickly and easily. Brushless DC gear motor (which has higher energy density) will be efficient to generate high speed and high torque while keeping end-effector weight (robot pay-load) low. Thinning efficiency will be evaluated in a field setting in different configurations by varying the length of the center spindle, number of strings, length of strings, spacing between the strings, speed of the electric motor, and end-effector approach direction to the flower cluster.System Integration and Evaluation: Once the machine vision system, and end-effectors and soft manipulator have been tested separately for their functionality, they will be integrated together for overall system evaluation in the lab and in the field environment using automated motion/path planning and control techniques. Collaboration with Avi Kahani and FFRobotics will be a key in system evaluation in the field conditions. Collaborator Kahani (FFRobotics) has strong expertise and extensive experience on developing and evaluating innovative robots, and is committed to provide necessary guidance to the research team.A universal adaptor will be developed and installed at the front end of the manipulator, which can carry any object less than 1 kg. Thinning end-effector like the string thinner operated by brushless motor will be integrated with the manipulator using the universal adaptor. Beside the flower thinning tool, a proximity sensor (e.g. mechanical limit switch) will also be installed at the end-effector of each manipulator to detect the object collision and completion of approach, along with the encoder feedback from center cable pulley system which will aid in the flower thinning process, since the global static vision sensor on the platform has a slow execution speed and the detection accuracy of the sensor regarding multi-targets decreases at longer distances.Once a single manipulator-end-effector system is integrated, it will be installed on an autonomous, mobile platform called WARTHOG (commercially available from clearpathrobotics.com; acquired by PD Karkee using other funds). The system will include one or more manipulators in each side of the mobile robotic platform, which can reach flowers for thinning in two adjacent rows of fruit trees simultaneously. One or more vision sensors (Zed Cameras) will also be mounted on each side of the mobile robotic platform, which will be used to take images for flower counting, cluster detection and estimation of 3D coordinates.A simulated apple orchard during bloom season will be created in PD Karkee's Lab to assess the system performance in the lab environment. This simulated environment includes a row of real apple trees collected from a commercial orchard and installed on a wooden platform. Artificial apple flowers will be installed using clips or magnets that can provide similar structure to apple flowers in orchards. The global vision system will be used to acquire images and estimate locations of the flower clusters that will be provided to the path planning system. The path planning system will then use the flower coordinates to provide optimal sequence and path to target flowers for thinning, which will be used by the manipulator control system to grow the soft manipulators to approach the target clusters from desired direction and actuate thinning end effector to remove all or a proportion of flower from each cluster as desired. As we are using growing manipulators, the path planning system was designed such that the thinning process starts with the closest flower cluster first and move to the next closest by another increment of manipulator growth. After finishing all flower thinning

within the field of view, the manipulators will be retracted and the machine will be moved to the next location for thinning.