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[F] PhD Extended Abstract Form *(Please select the Calibri 10 typeface)*

Study of Canopy-Machine Interaction in Mass Mechanical Harvest of Fresh Market Apples

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Extended Abstract

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1. Chapter 1 [Introduction]

Fresh market apples comprise one of the most important high-value agricultural products in the U.S. and the number one agricultural commodity in Washington State. About 120,000 ha of apple are harvested each year nationally, and ~80,000 ha come from Washington State. Traditionally, apple harvesting requires a large workforce in a small harvesting window. Given a huge production volume requiring high labor demand coupled with decreasing labor availability and unreliable sources of this labor force, apple growers around the country are facing an increasingly challenging situation to hire and keep skilled harvest laborers. Mechanized/automated solutions, therefore, need to be developed to relieve the rising issue of the aging farm population and the related labor shortage faced by farmers in the U.S. and around the world. This research was endeavored to improve the efficiency of the mass mechanical harvesting system for fresh market apples by considering the two most important components of the overall system: crop canopy effects, and machine integration and automation. Therefore, it focused on studying machine-plant interactions using machine learning and precision canopy management techniques and investigating machine vision techniques (including deep learning) for automating shake-and-catch harvesting.

2. Chapter 2 [Mechanized and Automated Tree Fruit Harvesting]

The rapid development of the modern agricultural machinery has substantially advanced farming operations in recent years, and researchers and engineers are working on developing intelligent solutions to solve various challenging problems in production agriculture. There has been a particular emphasis in developing automation and robotic solutions for tree fruit crops because of the critical need of the industry that currently many production operations such as harvesting are completely manual. Despite these efforts, the progress in practically adopting smart, robotic solutions in tree fruit crops has been slow because of the large variation and complexity in the farming environment. In addition to fulfilling the important expectation of crop yield and quality improvements, the adoption of proper crop modifications could also be one of the critical ways to facilitate further advancement and adoption of mechanization and automation solutions in agriculture.

3. Chapter 3 [Determination of Key Canopy Parameters for Mass Mechanical Apple Harvesting Using Supervised Machine Learning and Principal Component Analysis]

A mass mechanical harvest approach to apple harvest offers an alternative and promising solution. In addition to harvester design elements, it is important to understand the key canopy parameters of apple trees as they are closely integrated and interact with each other during the harvest process. In this study, the impact of 11 canopy parameters on mechanical harvesting were investigated for vertically trained 'Scifresh' and V-trellised 'Envy' trees during the harvesting trials. A supervised machine learning algorithm with weighted k-nearest neighbors was adopted to analyze the canopy datasets. Overall, 2,678 ground-truth data points were classified into two binary classes of fruit removal status: "mechanically harvested" and "mechanically unharvested" apples. For the training dataset (85%), the adopted algorithm achieved overall prediction accuracies of 76–92% and 62–74% for 'Scifresh' and 'Envy'. With the remaining 15% dataset, the overall test accuracies were 81–91% on 'Scifresh' but only 36–79% on 'Envy'. The principal components analysis was adopted to determine the key canopy parameters by calculating the coefficients of principal components. The PC1–PC5 explained at least 80% of the data variance. By assuming a coefficient greater than 0.5 as being highly relevant, fruit load per branch, branch basal diameter, and shoot length were the most relevant among all. These results provide guidance for growers in canopy management that could improve efficiency of a mechanical harvesting system.

4. Chapter 4 [A Precision Pruning Strategy for Improving Efficiency of Vibratory Mechanical Harvesting of Apples]

This transdisciplinary studies on mechanical harvest systems for apples have shown that fruit removal efficiency (FRE) with a vibratory system can be improved with precision canopy management. In this study, the effect of precision pruning strategies on FRE was evaluated in two groups (106 and 107) of randomly selected horizontal branches of 'Scifresh/M.9' apple trees in a commercial orchard. Fruiting lateral branches were pruned to either shorter than 15 cm (G1) or 23 cm (G2). Harvest tests were conducted using a shake-and-catch harvester prototype developed by Washington State University with a fixed vibrating frequency of 20 Hz and shaking duration of 5 s. FRE for branches treated with G1 was significantly higher (91%) than FRE for branches treated with G2 (81%). A negative relationship between FRE and lateral shoot length was recorded. FRE was up to 98% when shoots were shorter than 5 cm, and FRE was only 56% for shoots of 25 cm or longer. A shoot diameter-to-length index (S-index) was developed to better understand the effect of shoot size on FRE. FRE was as high as 98% when the S-index was greater than 0.15. In addition, mechanically harvested fruit quality was assessed by categorizing the fruit into Extra Fancy, Fancy, and Downgrade fresh market classes based on USDA standards; however, no significant difference was found between the two treated groups. These results suggest that pruning lateral fruiting branches to less than 15 cm or to an S-index greater than 0.03 is required to achieve FRE of 85% with no negative impacts on fruit quality.

5. Chapter 5 [Field Evaluation of Targeted Shake-and-Catch Harvesting Technologies for Fresh Market Apple]

This study was to evaluate the developed system through analyzing fruit harvest efficiency and fruit quality under three shaking methods, i.e., continuous non-linear, continuous linear, and intermittent linear shaking, on up to six apple cultivars trained to formal tree architectures. Results revealed that intermittent linear shaking achieved 90% of fruit removal efficiency on 'Scifresh' cultivar, while the continuous linear shaking achieved 63% on 'Gala'. This study also compared three vibratory harvest systems: a hand-held system, a hydraulically driven system, and a semi-automated hydraulic harvest system. The semi-automated harvest system achieved the highest fruit removal efficiency (90%), followed by the hand-held (87%) and hydraulic systems (84%), mainly attributing to the different shaking methods employed. However, the differences were statistically insignificant. Fruit catching efficiency varied among systems with the hand-held achieving the highest (97%), followed by the hydraulic (91%) and the semi-automated systems (88%). Among all three tested technologies, the developed prototype of semi-automated system achieved the highest level of mechanization, as well as the fruit removal efficiency and best fruit quality. As the semi-automated system did not yet include the auto-positioning function, it would take about eight times longer (~103 s) to position its shaker head than the actual shaking time (~13 s), which suggests that a fully automated system would be desirable in the future for further increasing the productivity. This study showed that the shake-and-catch approach has a high potential for practical adoption in harvesting fresh-market apples.

6. Chapter 6 [Computer Vision Based Tree Trunk and Branch Identification and Shaking Points Detection in Dense-Foliage Canopy for Mechanical Harvesting of Apples]

Mechanical harvesting solutions have become necessary for addressing the challenge. As one of the major challenges in shake-and-catch harvest was to position the shaking end-effector and the catching device at appropriate locations within tree canopies, a vision system has been used for automatically and accurately identifying desired canopy locations. Convolutional neural networks (CNNs)-based semantic segmentation was utilized to identify the tree trunks and branches for supporting mass mechanical harvesting of apples. There were three CNN architectures employed in this study including i) Deeplab v3+ ResNet-18, ii) VGG-16, and iii) VGG-19. Four pixel-classes were pre-defined as 'branches', 'trunks', 'apples', and 'leaves' to segment the tree canopies with varying foliage density. Specifically, three density levels, light, medium, and high densities, were considered, which represented the entire population of canopy layouts of formal apple tree architectures. In total, a dataset of 674 'Fuji' images were collected, which were then divided into 70%, 15%, and 15% respectively for network training, validating, and testing. Training results showed that ResNet-18 outperformed VGGs in identifying tree branches and trunks based on all three evaluation measures (i.e., per-class accuracy (PcA), intersection over union (IoU), and boundary-F1 score (BFScore)). PcA of 97%, IoU of 0.69, and BFScore of 0.89 were achieved by ResNet-18 with full image resolution. In terms of the targeted class of 'branches', IoU of up to 0.40, and BFScore of 0.82 were obtained by the same network, indicating good overlaps between predictions and ground-truth data, and satisfactory preservations of the object boundary information. The selected ResNet-18 was further evaluated for its robustness with a set of test canopy images: light density of 'Pink Lady', high density of 'Envy' and 'Scifresh'. Results showed that IoU of 0.41 and 0.62, and BF score of 0.71 and 0.86 were achieved respectively for 'branches' and 'trunks' on a per class basis. These results were achieved with one of the highest density canopies of 'Scifresh'. Finally, suitable shaking points near branch bases were estimated. It was found that 72% of them were deemed "good" in performance comparing to manual selections.

Final remarks concerning the competition benchmarks and strength points

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[Chapter 7] This research aimed at creating a benchmarked knowledgebase for maximizing the efficiency of a vibratory shake-and-catch harvesting system for the mass harvest of fresh market apples. It was focused on gaining an understanding on canopy-machine interactions for supporting the creation of machine-operation-friendly canopy management strategies and the optimization and automation of shake-and-catch harvest systems design to achieve a highest possible overall harvest efficiency.