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EFFORTS TOWARDS EFFECTIVE ROBOTIC STRAWBERRY HARVESTING

by *Zixuan He*
Washington State University -United States; zixuan.he2@wsu.edu,24106 N Bunn Road, Prosser WA 99350, United States

Extended Abstract

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1. Introduction of Research

The need for sustainable and efficient agricultural practices has led to a global shift towards robotic technologies in farming, addressing labor shortages and minimizing crop inputs, while increasing yield and quality of fresh produce. Robotic solutions are particularly crucial for labor-intensive tasks like fruit harvesting, where manual labor is costly and often insufficient. This dissertation focuses on enhancing robotic strawberry harvesting systems for open-field conditions, aiming to optimize detection and localization of strawberries, determine their pickability, and address occlusion challenges during harvesting. The research objectives include developing precise detection models for varying maturity levels, integrating deep learning networks for improved accuracy and occlusion handling, and investigating innovative robotic manipulation systems. Through this research, advancements in machine vision and manipulation techniques are sought to enhance the efficiency and viability of robotic harvesting systems, contributing to the long-term sustainability of the strawberry industry.

2. A Brief Review of Robotic Strawberry Harvesting Technologies

The field of agricultural robotics is on the verge of a transformative breakthrough, aiming to fully automate agricultural production by merging cutting-edge Artificial Intelligence (AI) and information technology, intelligent machinery, and plant canopy management techniques, among others. Ongoing research and development efforts have tackled the unique challenges of selective, robotic harvesting across various types of fruit and vegetable crops. These efforts are aimed at enhancing the efficiency and reliability of robotic systems, thereby reducing labor use and costs, increasing productivity, and increasing the quality of harvested produce. This review explores the state of robotic strawberry harvesting (including relevant studies from other crops), and describes sub-systems such as the machine vision system, manipulator, end-effector, and related path-planning and control techniques. Specific platforms for robotic harvesting of strawberries and other crops are highlighted, along with their success rates and challenges. The review also underscores the importance of effective path planning and end-effector design. Last but not least, innovative solutions for addressing occlusions within strawberry canopies are discussed, as they pose significant challenges for both fruit detection and picking.

3. Real-time Strawberry Detection Based on Improved YOLOv5s Architecture in Open-field Enviornment

Strawberry detection is one of the crucial steps during vision-guided robotic harvesting, which provides the precise location, pose, and maturity of the fruit to the manipulation system for picking. False detection and/or localization of strawberries with varying maturity levels result in poor performance of robotic picking, picking of immature fruit, and/or fruit injury during robotic harvesting. This study proposed a YOLOv5-based custom object detection model to detect strawberries in an outdoor environment. The original architecture of the YOLOv5s was modified by replacing the C3 module with the C2f module in the backbone network, which provided a better feature gradient flow. Secondly, the Spatial Pyramid Pooling Fast in the final layer of the backbone network of YOLOv5s was combined with Cross Stage Partial Net to improve the generalization ability over the strawberry dataset in this study. The proposed architecture was named YOLOv5s-Straw. The RGB images dataset of the strawberry canopy with three maturity classes (immature, nearly mature, and mature) was collected in open-field environment and augmented through a series of operations including brightness reduction, brightness increase, and introductiono of noise. To verify the superiority of the proposed method for strawberry detection in open-field environment, four competitive detection models (YOLOv3-tiny, YOLOv5s, YOLOv5s-C2f, and YOLOv8s) were trained, and tested under the same computational environment and compared with YOLOv5s-Straw. The results showed that the highest mean average precision (mAP) of 80.3% was achieved using the proposed architecture whereas the same achieved with YOLOv3-tiny, YOLOv5s, YOLOv5s-C2f, and YOLOv8s were 73.4%, 77.8%, 79.8%, 79.3%, respectively. Specifically, the average precision of YOLOv5s-Straw was 82.1% in the immature class, 73.5% in the nearly mature class, and 86.6% in the mature class, which were 2.3% and 3.7% higher than that of the latest YOLOv8s, respectively for mature and immature classes. The proposed model was lighter and faster with 8.6×10^6 network parameters and an inference speed of 18 ms per image compared with YOLOv8s model which had an inference speed of 21.0 ms and parameters of 11.1×10^6. The proposed model showed strong potential for providing accurate positions of mature strawberries for developing an effective strawberry harvesting system in an outdoor environment.

4. Machine Vision System for Detectiong Pickable Strawberries in Field Conditions Using a Two-step Deep Learning Model

As discussed above, accurate and efficient vision system is essential to develop a robotic strawberry harvesting system as an alternative to manual harvesting methods. Advancing on the previous version of the vision system, a novel two-step deep learning model consisting of a modified YOLOv8s and a YOLOv5s-cls was developed to accomplish strawberry detection and pickability classification (*Figure 1*). Firstly, the YOLOv8s was enhanced by incorporating C3x modules and an additional head network structure, specifically tailored for accurate strawberry detection. To further improve training performance, the α-IOU (intersection over union) technique was integrated. Subsequently, the YOLOv5s-cls model was utilized to classify the detected mature strawberries to determine their suitability for picking. Performance evaluations showed that the modifyied YOLOv8 model with C3x modules, additional head network for small object detection, and new αIoU loss function in the training process performed the best among the tested models achieving the highest Average Precision (AP) of 84.2% for immature, 77.8% for nearly mature, and 87.8% for mature strawberry classes, along with the highest mAP of 83.2%. Overall, this modified model achieved a 2.5% improvement in mAP compared to the same achieved by the original YOLOv8s model. Despite a slightly slower inference speed of 8.6 ms per image, this modified model maintains real-time capability, making it an optimal choice for strawberry detection. Additionally, YOLOv5s-cls was identified as the preferred model for classifying mature strawberries into pickable and unpickable groups, offering a good inference speed of 2.8 ms per image and comparable accuracy with other models assessed including YOLOv8s-cls, ResNet 18, EfficientNet_b0, and EfficientNet_b1. Finally, the combined two-step model developed in this study was further evaluated in 10 different field scenarios from a completely different strawberry field that was not used in collecting data for model training and initial testing. This second stage evaluation showed that the machine vision system achieved an AP of 89.0%, 82.0%, and 90.0% in detecting strawberries in immature, nearly mature and mature classes while the classification accuracy was 100.0% in unpickable group and 95.0% in pickable group. The results showed that the developed two-step machine vision system has potential to improve the overall robotic harvesting system for strawberries grown in open-field conditions.

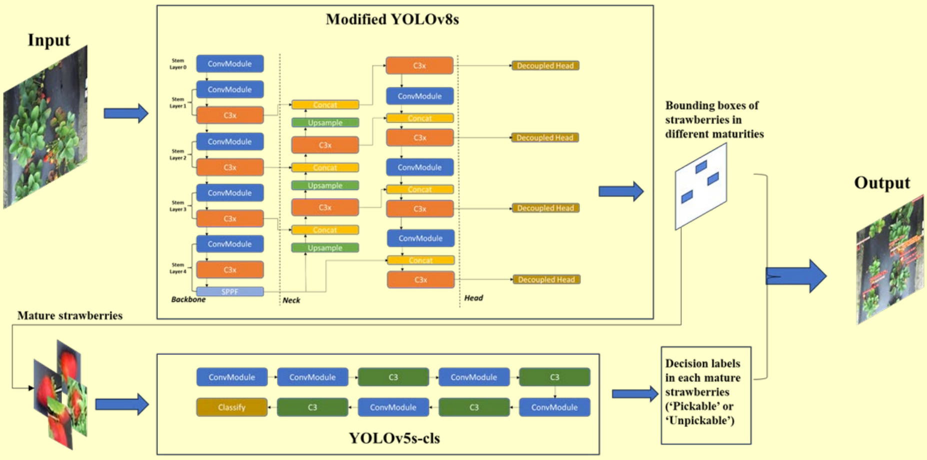

Figure 1. Workflow of the combined two-step vision model including strawberry detection and occlusion classification.

5. Improving Picking Efficiency under Occlusion: Desgin, Development, and Field evaluation of a Novel Robotic Strawberry Harvester

As mentioned before, robotic harvesting has long been seen as the potential alternative to manual harvesting in the strawberry industry. However, despite much progress made in the harvesting process from detection to picking, these technologies are not yet commercially viable. One of the limiting factors for increased performance and practical adoptability is fruit occlusion in canopies, particularly in the open-field environments. There has been only limited studies on active occlusion handling/removal techniques during robotic picking. This paper presents the development and evaluation of an innovative strawberry harvesting robot (*Figure 2*) focusing on occlusion handling using vision-based occlusion detection and a novel end-effector design equipment with a fan to blow away leaves (*Figure 3*). The integrated robotic system included a 6 DOF manipulator and was installed on a mobile platform for field evaluation. Based on the classification of detected strawberries ('not occluded' or 'occluded'), the robotic platform followed specific steps for directly picking the strawberries (if not occluded) or removing/dispersing the occlusion over the strawberries (if occluded) using the fan before picking them. The effectiveness of this harvesting robot was evaluated using multiple experiments in both the simulated field and a real outdoor field. The results showed that the vision system achieved a mean average precision (mAP) in strawberry detection of 80.7% and classification accuracy was 93.2%. Picking efficiency of the robot was enhanced substantially by the use of the fan system. In an outdoor strawberry field, the robot achieved a picking rate of 58.1% without fan system, which increased to 73.9% with the fan system (a 15.8% increase in fruit picking rate). It was found that the average processing time of machine vison system was 6.26 s and the overall average time to pick single strawberry with the fan system was 20.6s.

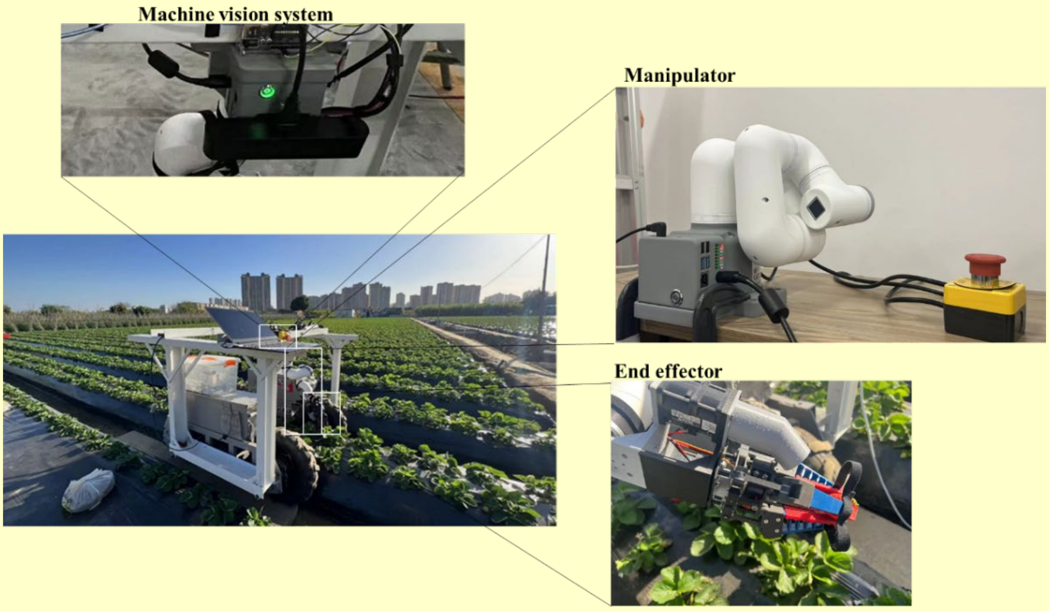

Figure 2. Robotic strawberry harvester including a machine vision system, manipulator, end-effector, and a ground platform.

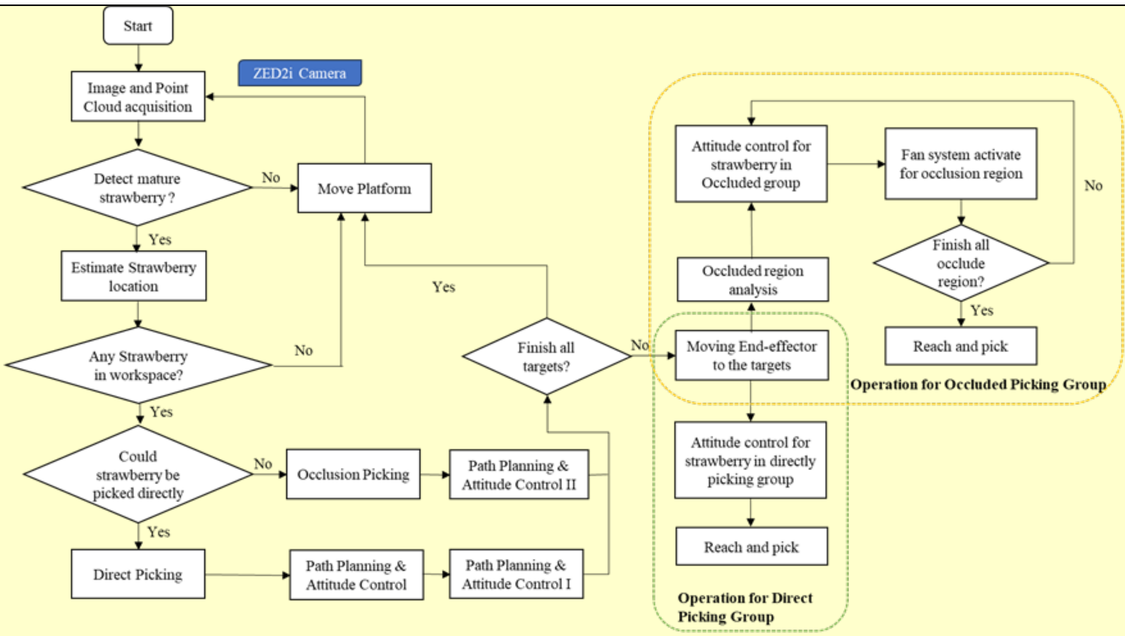

Figure 3. *Flowchart of the overall robotic harvesting process.*

6. General Conclusions and Recommandations

This research addressed the challenges posed by occlusion within strawberry canopies in open-field environments for robotic harvesting. Specifically, the study enhanced the machine vision system's performance for detecting strawberries of varying maturities, determined pickability of partially occluded strawberries, and implemented a mechanism for actively removing fruit occlusion during robotic picking. Results show that modified YOLOv5 and YOLOv8 models achieve high accuracy and computational efficiency in strawberry detection. Deep learning-based classification models accurately determined the pickability of strawberries. Additionally, integrating a fan system into the robotic harvester significantly improved picking success rates, especially in occluded environments. Recommendations for future research include further improving detection and classification models, exploring dynamic airflow analysis for occlusion handling, optimizing manipulator design for faster harvesting, and integrating the fan system into the detection process for enhanced visibility.

Final remarks concerning benchmarks and strengths for the the Pellizzi Prize 2024

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This dissertation pioneered advancements in robotic strawberry harvesting, particularly targeting the challenges of occlusion in open-field production environments. The research introduced novel solutions across machine vision, classification, and robotic manipulation sub-systems. Leveraging modified YOLOv5 and YOLOv8 models, the vision system achieved high accuracy and real-time performance in strawberry detection and localization. The integration of a two-step deep learning model accurately determined pickability of fruit based on extent and type of occlusion, while a novel robotic harvester equipped with a fan system demonstrated significant improvements in picking efficiency under occlusion. These findings demonstrated the potential of this innovative system to enhance efficiency and precision in robotic strawberry harvesting thus increasing the practical adoptability of such systems. The research also identified areas for future innovation including dynamic occlusion handling.