Robotic and Structured Light Imaging Technologies for Harvesting and Defect Detection of Apples

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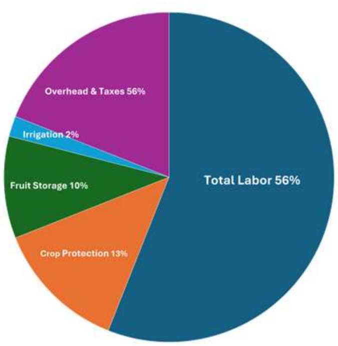
Background

- **Labor costs > 50%** in production of apples and other tree fruits in U.S.



(From Michigan Apple Committee, USA)

- **Harvesting Labor is the single largest cost** in apple production (~15%)

Harvest automation is thus urgently needed to alleviate rising costs and growing shortages of labor for apple and other tree fruits

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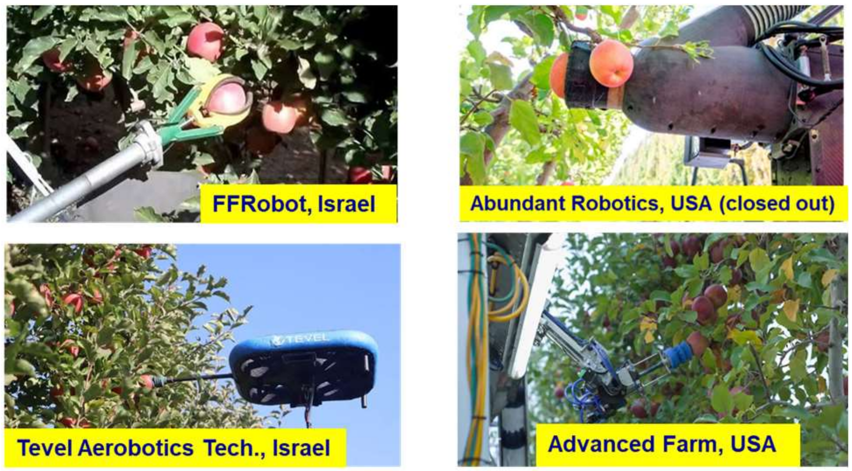
State-of-Art Harvesting Robots



Currently, robotic harvesting is not in commercial use because the technology is still short of meeting grower expectations in terms of performance, robustness, efficiency and cost.

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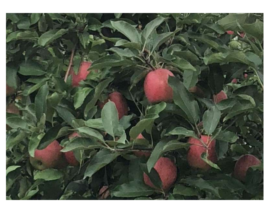
Challenges in Robotic Fruit Harvesting

- Fruit Detection & Localization

Fruit Clustering



Occlusion by Leaves & Branches

- End Effector for Fruit Picking

Difficult picking fruits in clusters and avoiding fruit damage

- Manipulator

Too slow with too many DOFs

Lack of dexterity with fewer DOFs

In summary, there still exist significant technological gaps in ***fruit detection and localization*** and ***manipulation/end effector designs*** for fast and dexterous picking of fruits in clusters and occluded by leaves and branches

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Goal and Contributions of Our Research

Goal:

Develop a commercially viable robotic harvesting system that is relatively simple and compact in design and yet dexterous and robust in fruit picking

Major Contributions:

- A new **perception module** for accurate fruit detection and localization
- A **dual-arm manipulator** with a common perception module and a centralized vacuum system to enhance harvest efficiency and cost effectiveness
- A **soft end effector** coupled with vacuum to enable quick and gentle picking of apples
- **Planning and control algorithms** for effective coordination of two robot arms for apple harvesting

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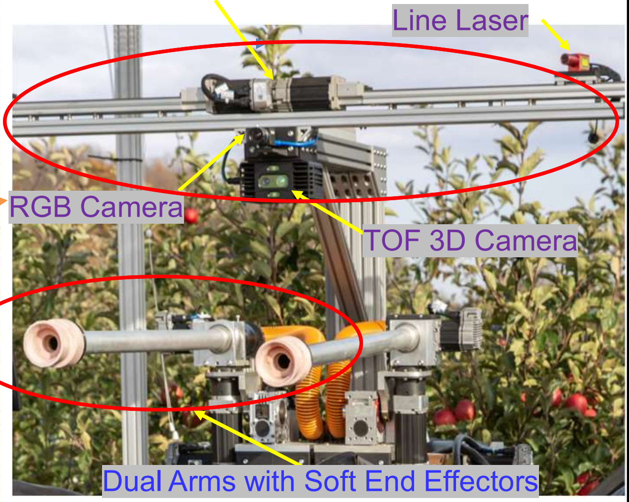
Overview of the Dual-Arm Harvesting Robot



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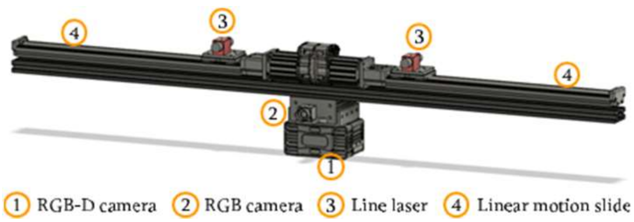
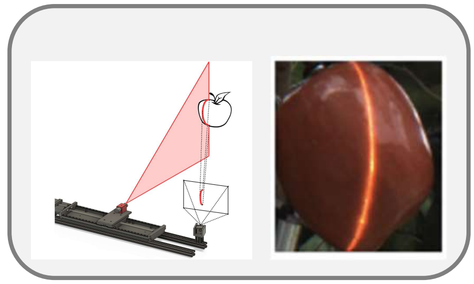
Perception Design



RGB-D Camera + ALACS



Laser Triangulation

Procedures:

- Obtain global fruit localization estimates in the workspace using RGB-D camera
- Determine the first apple to pick for each picking arm by the planning and control algorithm
- Refine the localization information for target fruits using ALACS
- Actuate the picking arm(s) to pick target fruits using the refined localization information

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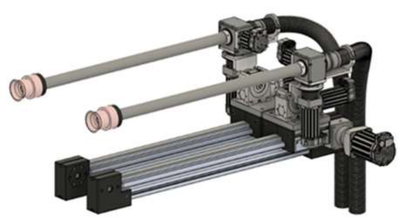
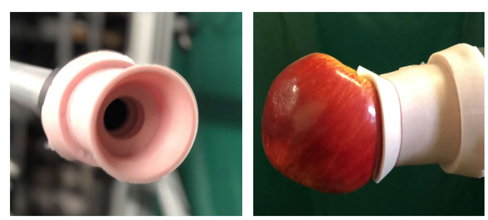
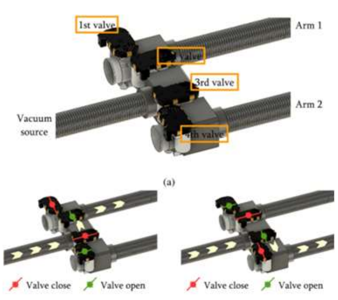
Manipulator and Soft End Effector



Four-DOF manipulator using a pan/tilt mechanism with a linear actuator plus a rotation mechanism



Soft end effector can accommodate fruits of different sizes and orientations, with fast and gentle gripping of target fruit within 12 mm distance



Centralized vacuum system to support two picking arms

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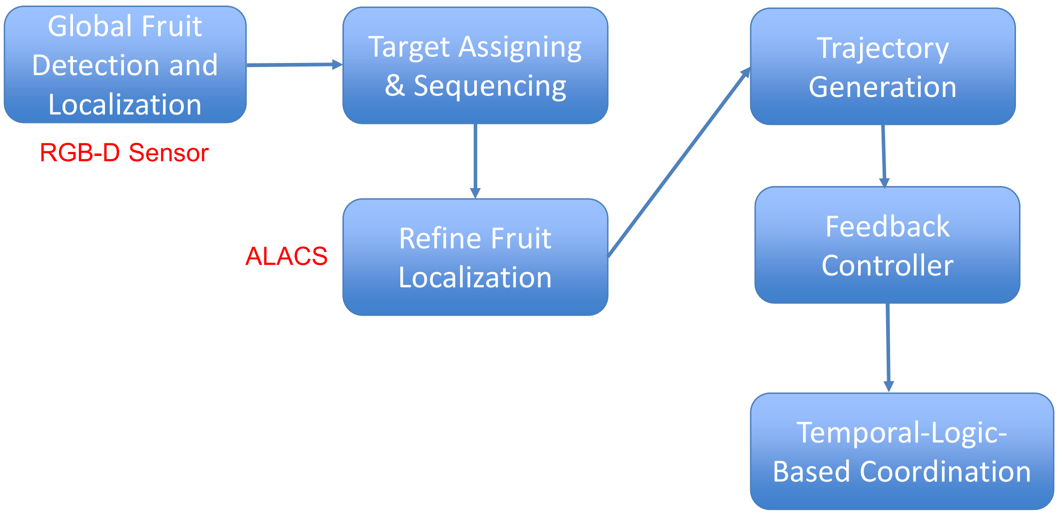
Planning and Control of Dual Arms for Fruit Picking



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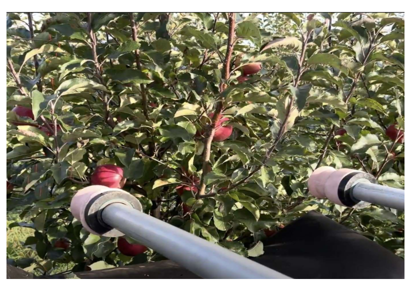
Field Evaluation – 2023 Harvest Season

- **Orchard Tests: MSU Plant Pathology Research Center, East Lansing, MI**



Challenging tree structures with heavy occlusions by leaves and branches

- **Evaluation Results:**
  - **Harvesting rate**: 60% (**Goal**: 80% harvesting rate)
  - **Picking speed**: 3 s to 6 s per fruit (**Goal**: 2-3 seconds per fruit)
  - **Harvesting efficiency improvement** (compared to 1-arm robot): 9% to 34% (**Goal**: 60% to 80%)
  - **Failed picks**: 50% due to picking or branch occlusion and 43% due to perception (leaves) error caused by heavy leaf occlusion

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Dual-Arm Apple Harvesting Robot

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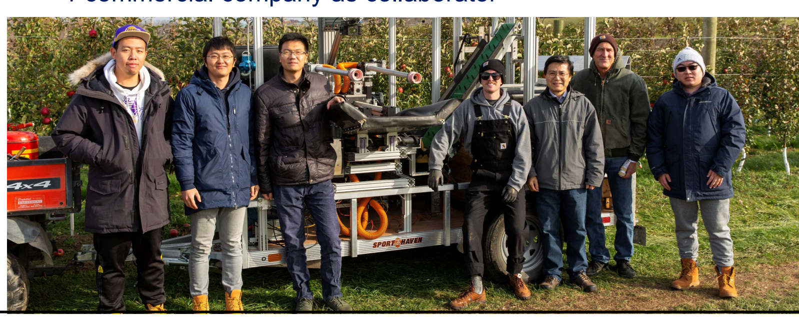
Our Research Team

Project Leaders: **Dr. Renfu Lu**, Research Ag Engineer & Research Leader, USDA-ARS
Dr. Zhaojian Li, Red Cedar Distinguished Associate Professor, Mechanical Engineering, Michigan State University (MSU)

Team Members: **Dr. Kaixiang Zhang,** Assistant Professor (fixed term), Mechanical Engineering, MSU
4 Ph.D. students in Electrical & Computer Engineering, Mechanical Engineering
1 M.S. student in Mechanical Engineering
2 undergraduate student in Biosystems Engineering, Computer Science & Engineering
1 commercial company as collaborator



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Next Phase of Research and Extension Plan

USDA-NIFA Specialty Crop Research Initiative (SCRI) Program Grant (2023-2027)

Goal: Developing an Automated and Integrated Mobile System (AIMS) for Apple Harvesting and In-field Sorting

Website: https://sites.google.com/view/aimsforapples/home

Plan for 2024: Test and demonstrate our new version of the harvesting robot in commercial orchards in Sparta and Hart, Michigan

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Development of an Online Structured-light Imaging (SLI) System for Defects Detection of Horticultural Products

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Defects of Apples

- **External**

Bitter pit | Superficial scald | Sunburn | Lenticel breakdown | Skin russeting

- **Internal**

Watercore | Soggy breakdown | Flesh browning

- **Bruising**

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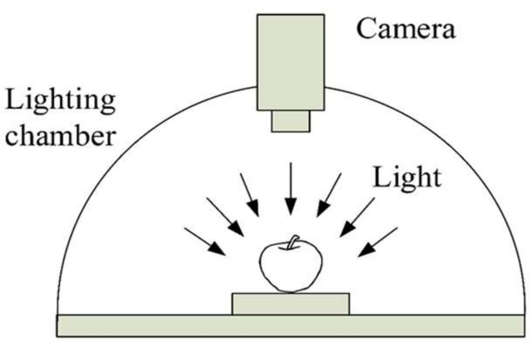
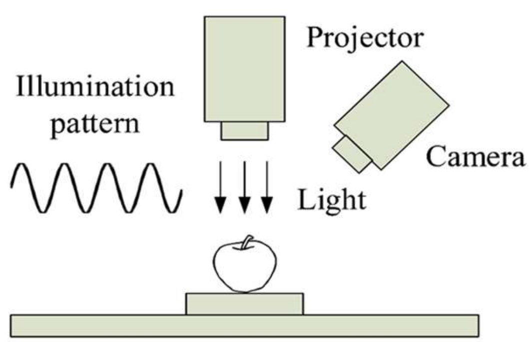
Conventional and Structured-Light Imaging Techniques



Uniform illumination



Structured illumination

Conventional Imaging with Uniform Illumination

Imaging With Structured Light

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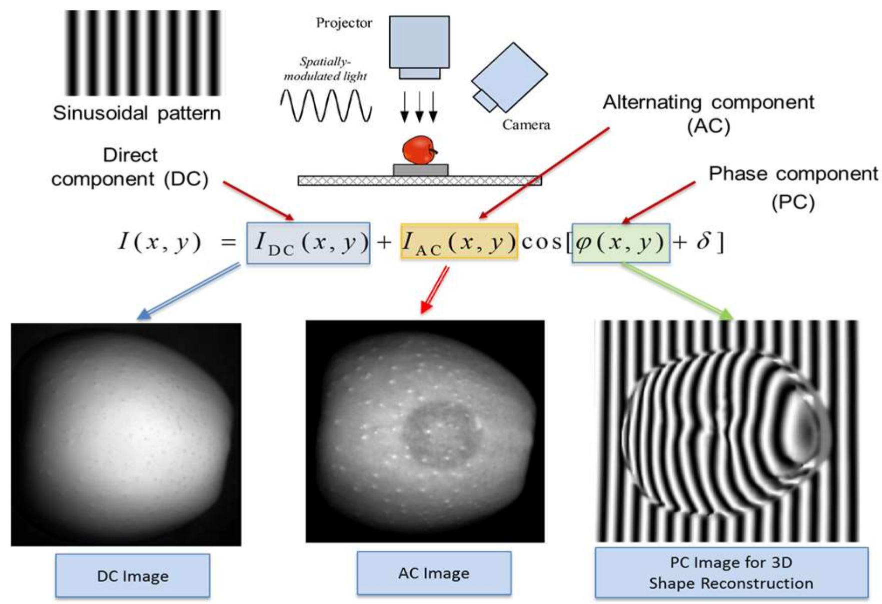
Principle of Structured-light Imaging (SLI)



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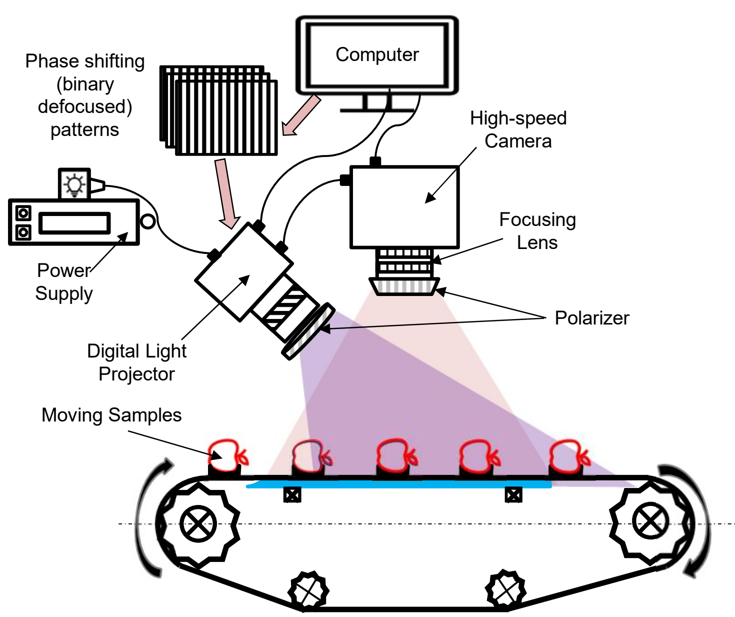
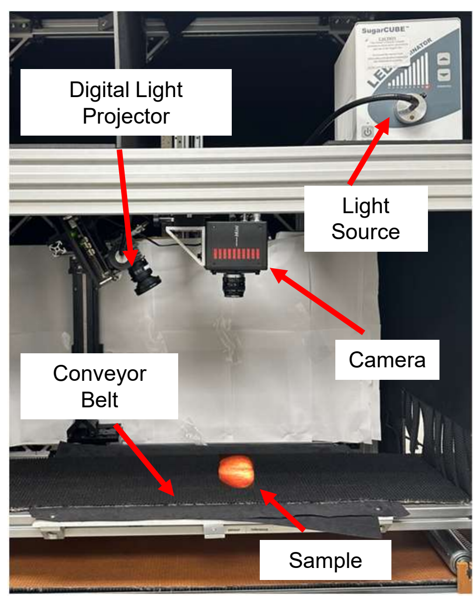
Online Structured-Light Imaging System





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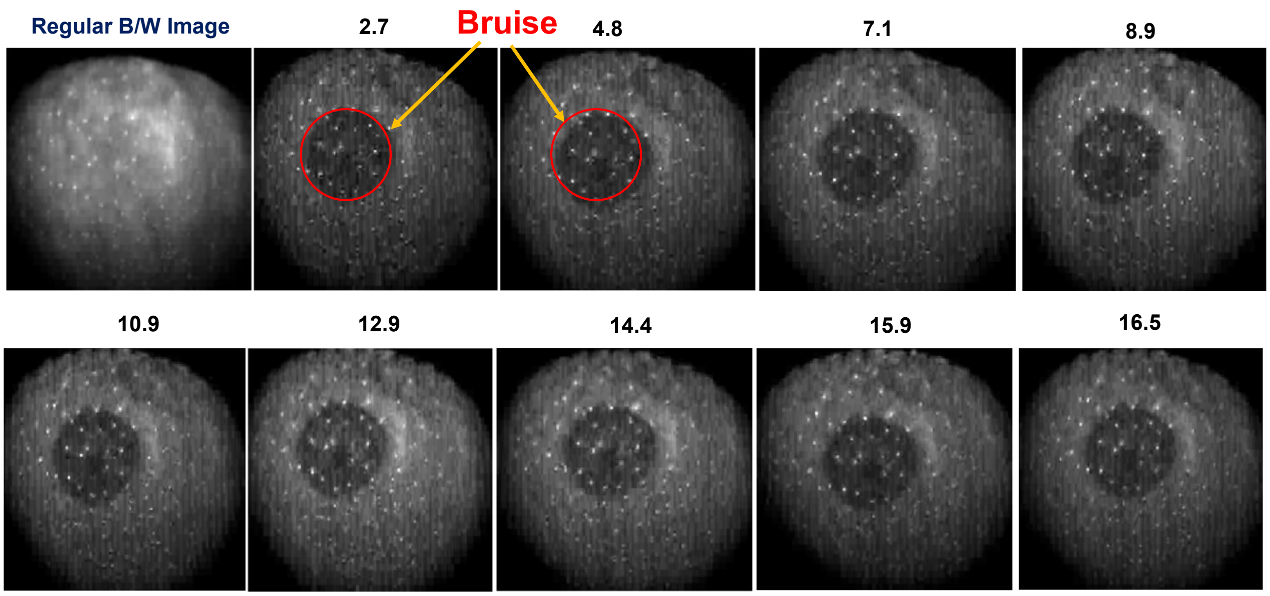
Real-Time Bruise Detection at Different Belt Speeds (inches per second)



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Summary

- We have demonstrated that the structured light imaging technique can be implemented for online detection of defects like bruises on apples.
- High quality images were obtained for the conveyor speeds of up to 10 inches/second, with the potential for running at up to 16 inches/second conveyor speed.
- Structured light imaging has potential for providing enhanced capabilities for online detection of fruit defects, which are difficult to detect by conventional imaging techniques.

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