Non-Destructive Plant Analysis Using Structure-from-Motion and a Cable-Driven Parallel Robot

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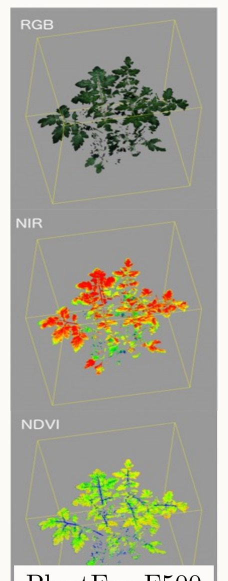
Background

Motivation	Farmers want **feedback** to understand how their plants are growing Researchers want **data** to develop plant growth models
Existing Methods	Cut down plant and send to lab for analysis Measuring biomass and nutrient content are **destructive** and **expensive**
Current Limitations	Researchers need *very* large sample sizes to compensate for **destructive loss** and **statistical variation** Cannot track a single plant over time since the first measurement is destructive
Proposed Solution	**Non-destructively** estimate **useful metrics** using robotics and computer vision

Prior Works (Non-Destructive)



PlantEye F500

Imaging Sensors

RGB Camera(s)
- Single Camera
- Stereo Camera
- Multi-camera rig

Depth Camera(s)
- IR-based depth (e.g. Kinect)
- Structured Light (non-IR)
- Time-of-flight (ToF)
- Light field (Plenoptic)

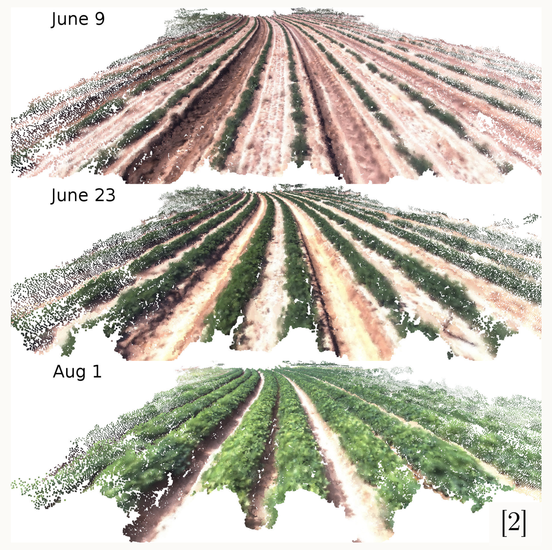
Multi-spectral Imaging
- IR (Thermal, NIR, VNIR)
  - ➢ Water, N, P, etc.
- UV
  - ➢ Disease, salt-stress
- Chlorophyll-Fluorescence
- Tomography (MRI, CT)
  - ➢ Hidden morphology

Limitations

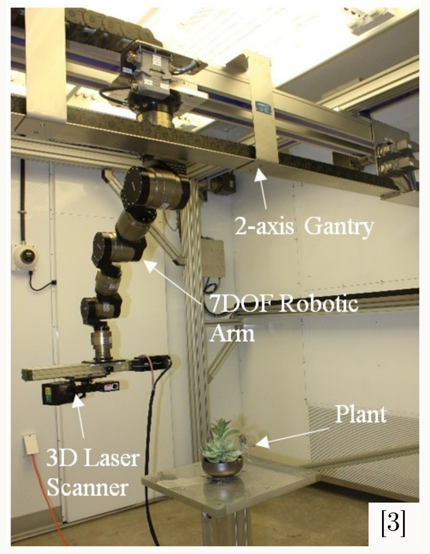
Current approaches exhibit a tradeoff between high-throughput phenotyping vs. high quality/resolution data. For example, [1] places imaging rigs on a push cart to achieve high-throughput, but produces 3D reconstructions of only individual leaves but not entire plants. Similarly, [2] uses a tractor for high-throughput, but produces coarse 3D reconstructions of entire plants insufficient to analyze plant morphology. Conversely, full-plant dense reconstruction approaches have not been shown in scalable, high-throughput settings (e.g. [3]).

Current approaches also struggle with leafy plants (e.g. lettuce)


[1]



[2]



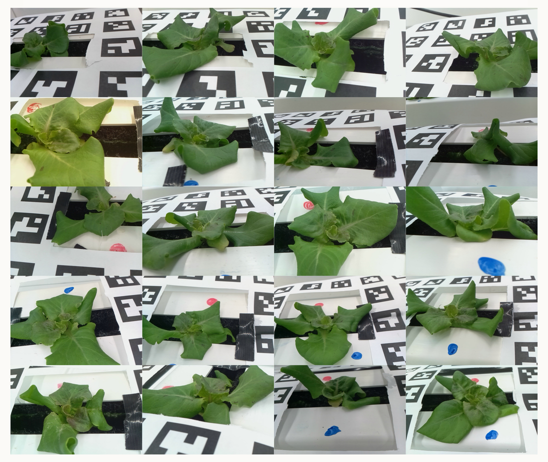
[3]

Objectives

1. Collect a publishable dataset
   - Collect a dataset of around 25 plants
   - Take around 150 photos of each plant from various angles
   - For all plants, measure:
     - Environmental Inputs
     - Wet Mass
     - Dry Mass
     - Nutrient Content (USDA lab testing)
   - Measure plants at multiple points in growth cycle (2x/week)
2. Implement baseline analysis algorithms
   - Attempt to estimate plant mass using photo data
   - 3 baselines:
     - 2D photo "count green pixels"
     - 3D Structure from Motion volume/surface area analysis
     - NeRF-based volume/surface area analysis
3. Evaluate
   - Evaluate algorithms using metrics such as:
     - Accuracy
     - Compute requirements
     - Reliability (e.g. plant-specific parameter tuning required)

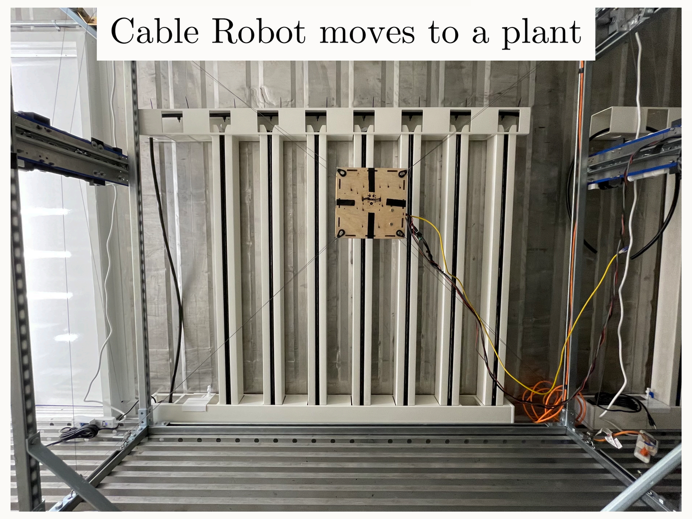
Top-down photos

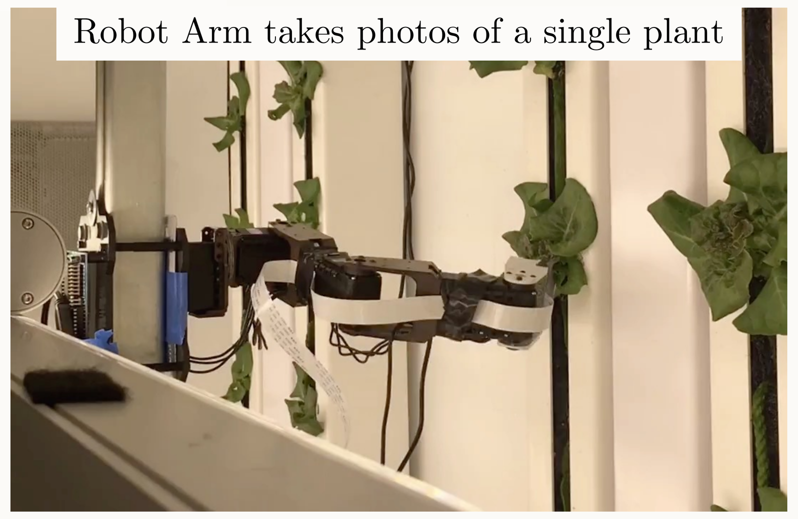
Select photos used for 3D reconstruction

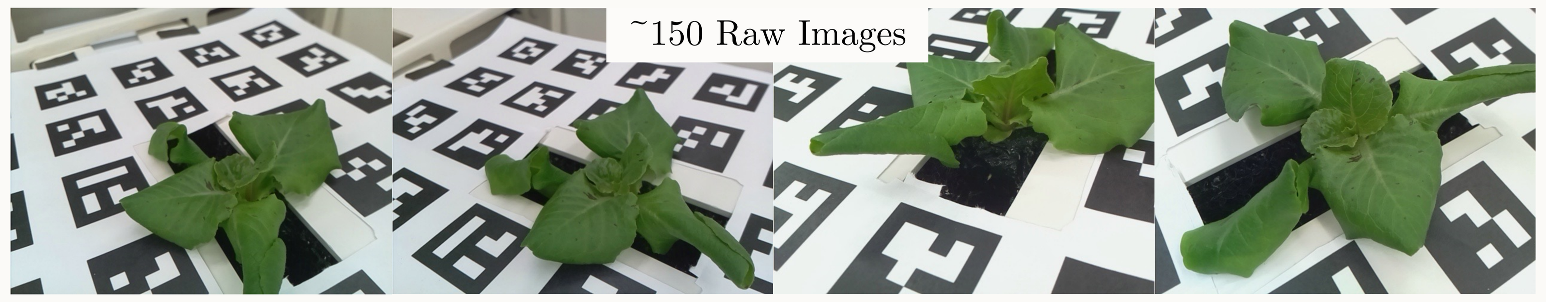


Proposed System Overview

Robotic Data Collection


Cable Robot moves to a plant


Robot Arm takes photos of a single plant

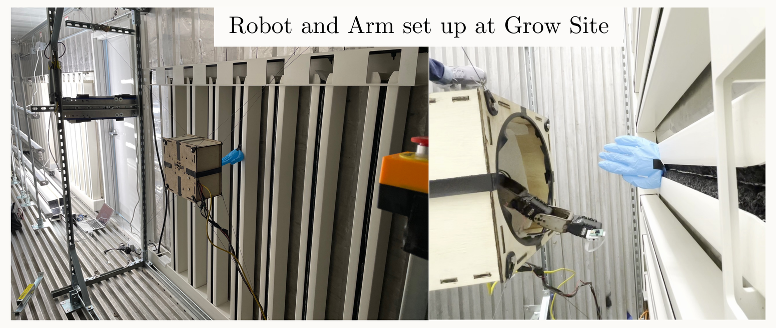

~150 Raw Images

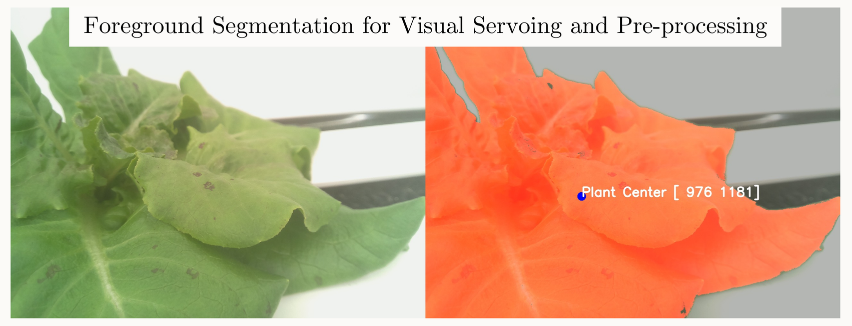
3D Reconstruction

Estimate Plant State
- Wet Mass
- Dry Mass
- % Nitrogen
- % Phosphorous
- ...

Preliminary Results

Robot Construction
- Cable Robot and Robot Arm have been built and integrated together
- Robot can autonomously move to an arbitrary plant and take photos

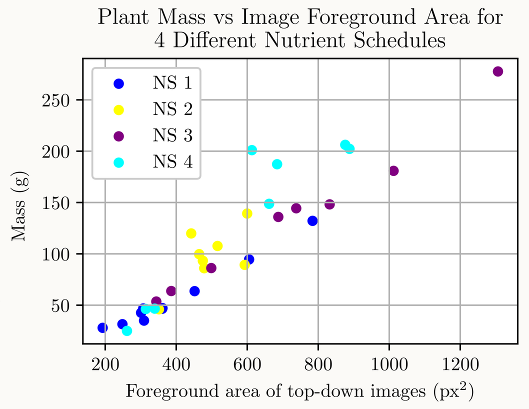

Robot and Arm set up at Grow Site



Foreground Segmentation for Visual Servoing and Pre-processing

Dataset Collection (all datasets contain plant masses and nutrient concentrations)
- 1 dataset w/ 2 photos (top-down and profile), 35 plants (70 photos)
- 1 dataset w/ 100-150 photos/plant, 20 plants, 3x/week for 4 weeks (~15000 photos) *without* using cable robot

Analysis
- 2D reconstruction baseline results
- Proof-of-concept 3D reconstructions
- Foreground segmentation for visual servoing and 3D reconstruction background removal



Expected Results

Robot Construction
- Visual Servoing to center the plant in each photo

Dataset Collection
- 1 dataset w/ 100-150 photos/plant, 24 plants, 3x/week for 4 weeks (~15000 photos) *with* using cable robot

Analysis
- High-quality SfM-based and NeRF-based dense 3D reconstructions
- Geometry and color analysis for mass and nutrient estimation

Future Work

Temporal Association: track plant growth over time by aligning 3D models across growth cycle
Plant Organ Segmentation: identify instances of each plant organ (e.g. leaves)
Plant Modelling: create a predictive model of plant growth dynamics
Model Predictive Control: Compute optimal fertilizer and environmental inputs to maximize crop yield
Multi-spectral Imaging: for improved nutrient content estimation

Selected References

[1] Y. Song, C. A. Glasbey, G. Polder, and G. W. A. M. van der Heijden, "Non-destructive automatic leaf area measurements by combining stereo and time-of-flight images," *IET Computer Vision*, vol. 8, no. 5, pp. 391– 403, 2014.
[2] J. Dong, J. G. Burnham, B. Boots, G. Rains and F. Dellaert, "4D crop monitoring: Spatio-temporal reconstruction for agriculture," *2017 IEEE International Conference on Robotics and Automation (ICRA)*, 2017, pp. 3878-3885, doi: 10.1109/ICRA.2017.7989447.
[3] A. Chaudhury et al., "Computer Vision Based Autonomous Robotic System for 3D Plant Growth Measurement," 2015 12th Conference on Computer and Robot Vision, 2015, pp. 290-296, doi: 10.1109/CRV.2015.45.