Robotic Technologies for Automated High-throughput Plant Phenotyping

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Agenda

1. Machine Vision Systems
   - Automated Plant Population and Interplant Spacing Sensing
   - Plant 3D Reconstruction and Characterization under Indoor and Outdoor Conditions
2. Mobile Robotic Platforms

I. Machine Vision Systems

1) 2D Color Video and Sequential Images
2) Stereo 3D Imaging
3) Time-of-Flight (ToF) of Light 3D Imaging

Manual population and spacing data collection

Labor intensive, time consuming, error-prone

Seed germination and survival, yield trials

http://www.firstseedtests.com/data3/images/3stand_counting_crew.jpg

http://farmlandforecast.colvin-co.com

http://www.agweb.com/the-knirks/

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Corn plant identification
- some of the challenges

– Intertwined Leaves

– a weed interference, damaged plants

– Double plants, plants in the background

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1) 2D color video and sequential imaging

Challenges in lighting conditions, real-time processing

Real-time mosaicking
- a "long" panorama image of a crop row

Examples of real-time crop row reconstruction

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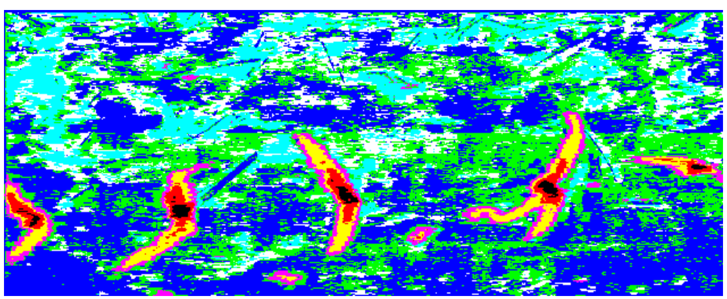
Color image processing for stem center identification

Original

$$\begin{bmatrix} EG \\ RB \end{bmatrix} = \begin{bmatrix} \frac{-1}{\sqrt{6}} & \frac{2}{\sqrt{6}} & \frac{-1}{\sqrt{6}} \\ \frac{1}{\sqrt{2}} & 0 & \frac{-1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Color Transformation



K-Mean clustering

Bayes classification

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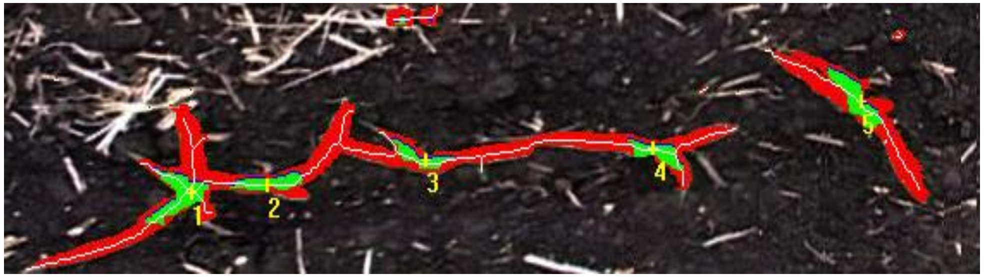
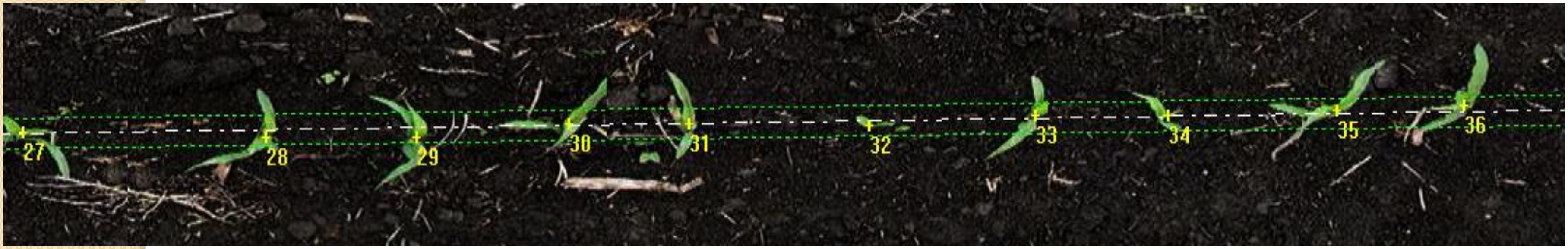
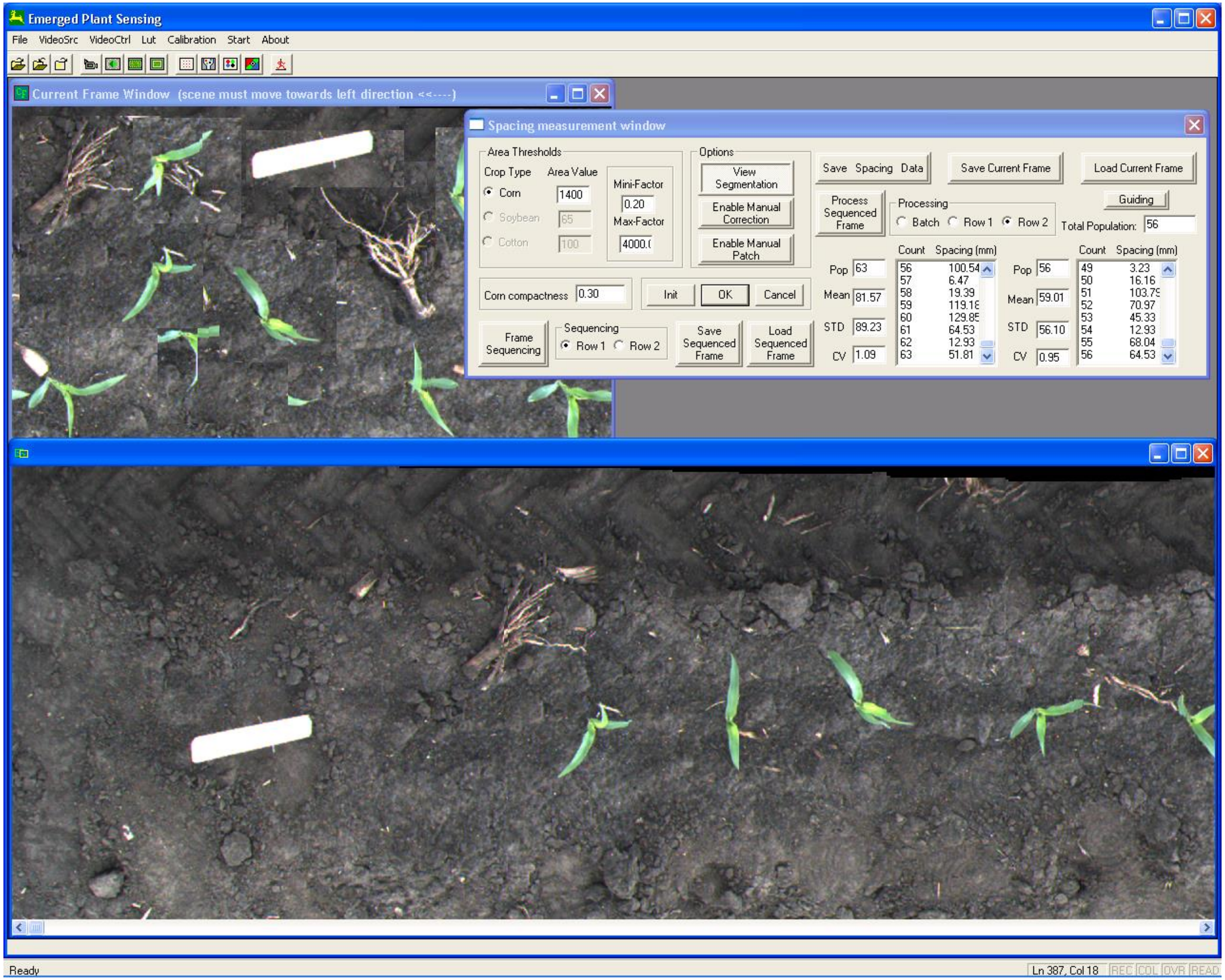
Robust crop row center-line fitting
- excluding small weed plants





Plant Identification and Spacing Measurement

Software Interface



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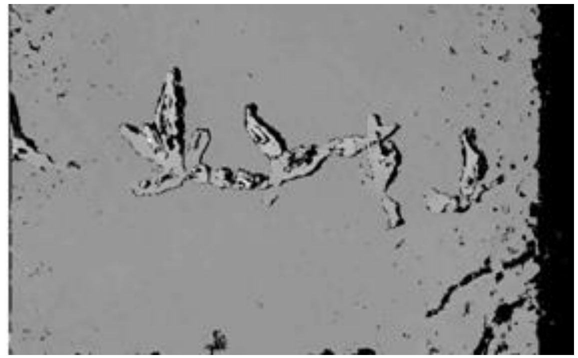
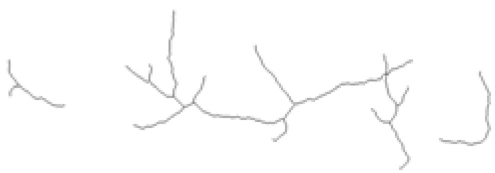
Conclusions on 2D imaging

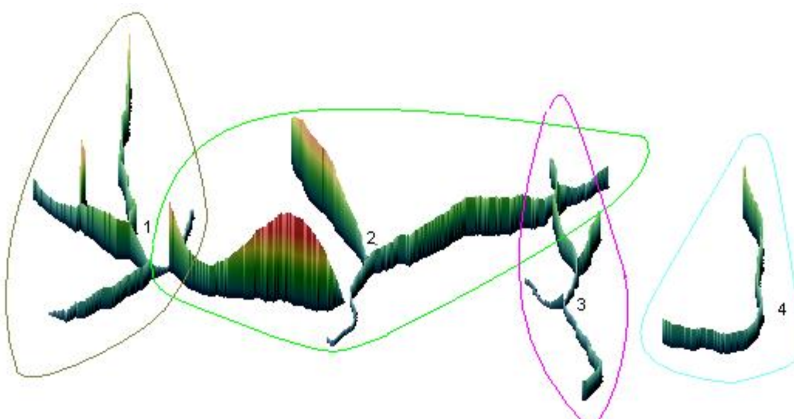
- Plus:
  - Reliable mosaicking and identification for corn plants between V2 and V3 (partly V4).
  - Allow error checking and manual recording.
- Delta:
  - Cannot deal with larger plants.
  - Rely on good color sensor and ideal lighting.
  - Cannot work under direct sunlight.

2) Stereo Vision system

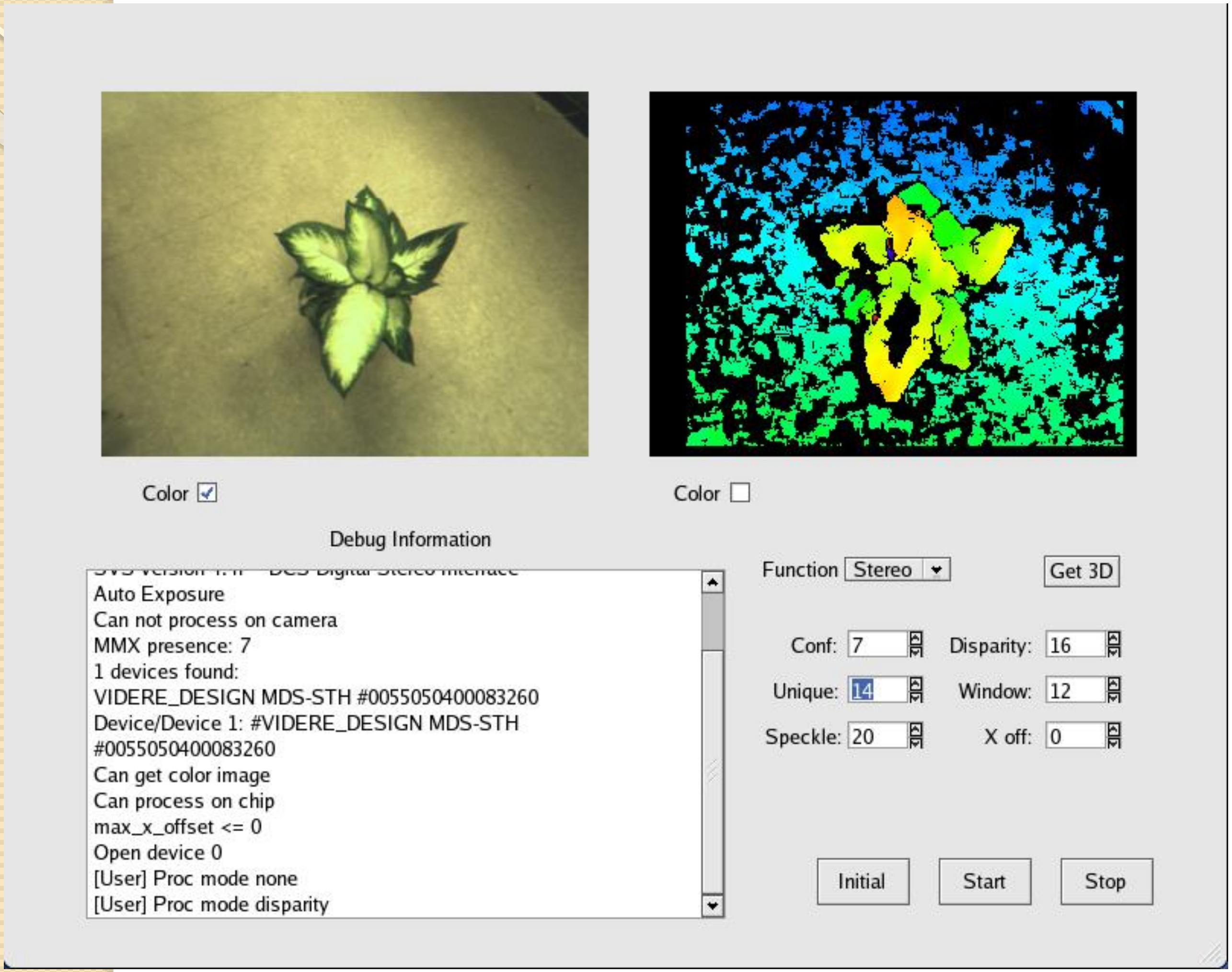




Real-time Stereo-On-a-Chip

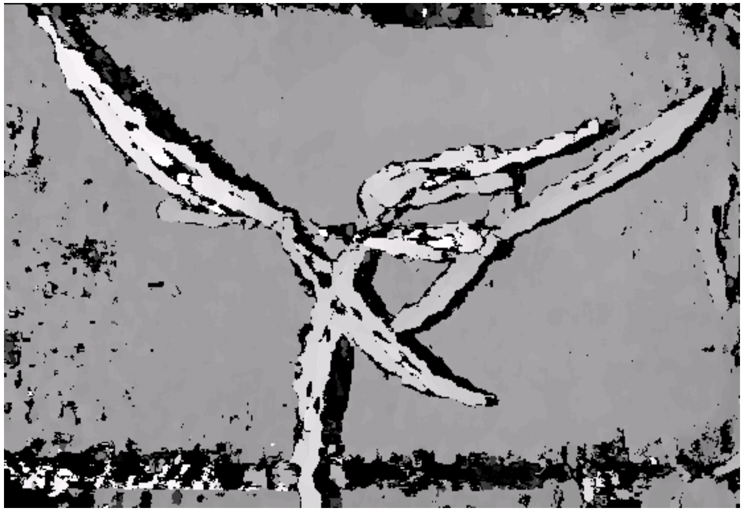


Graphical User Interface

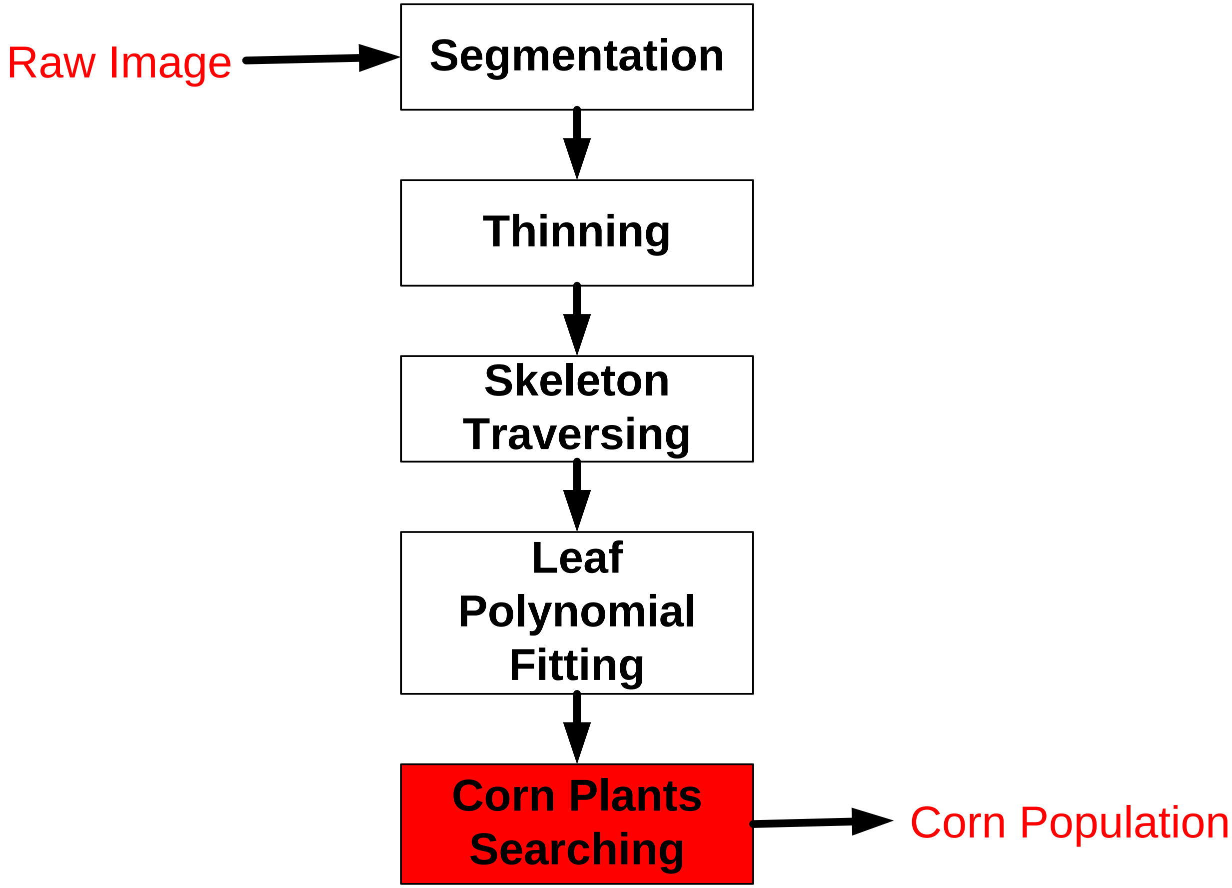


Videre Stereo-On-a-Chip color camera

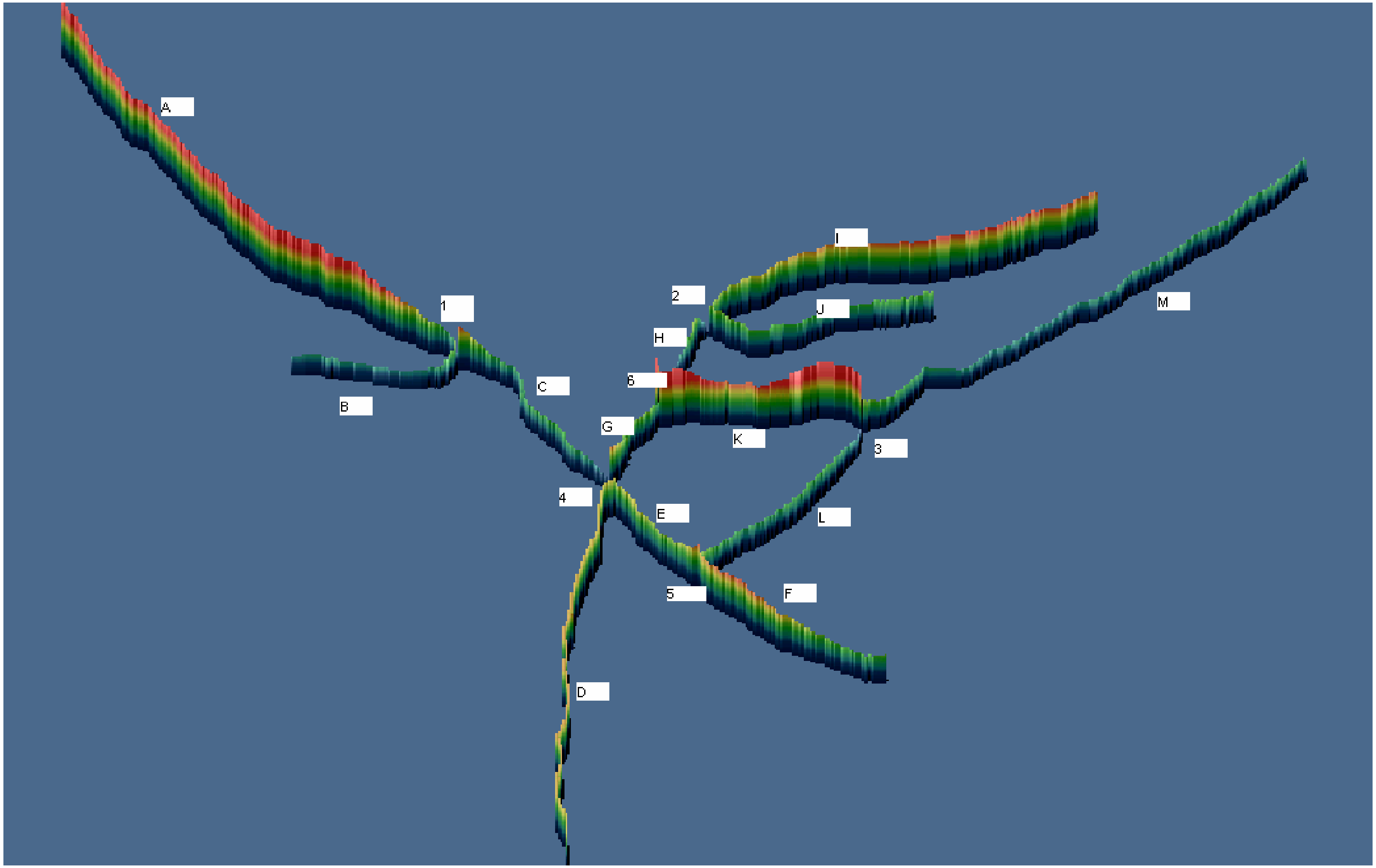
A Complicated Example



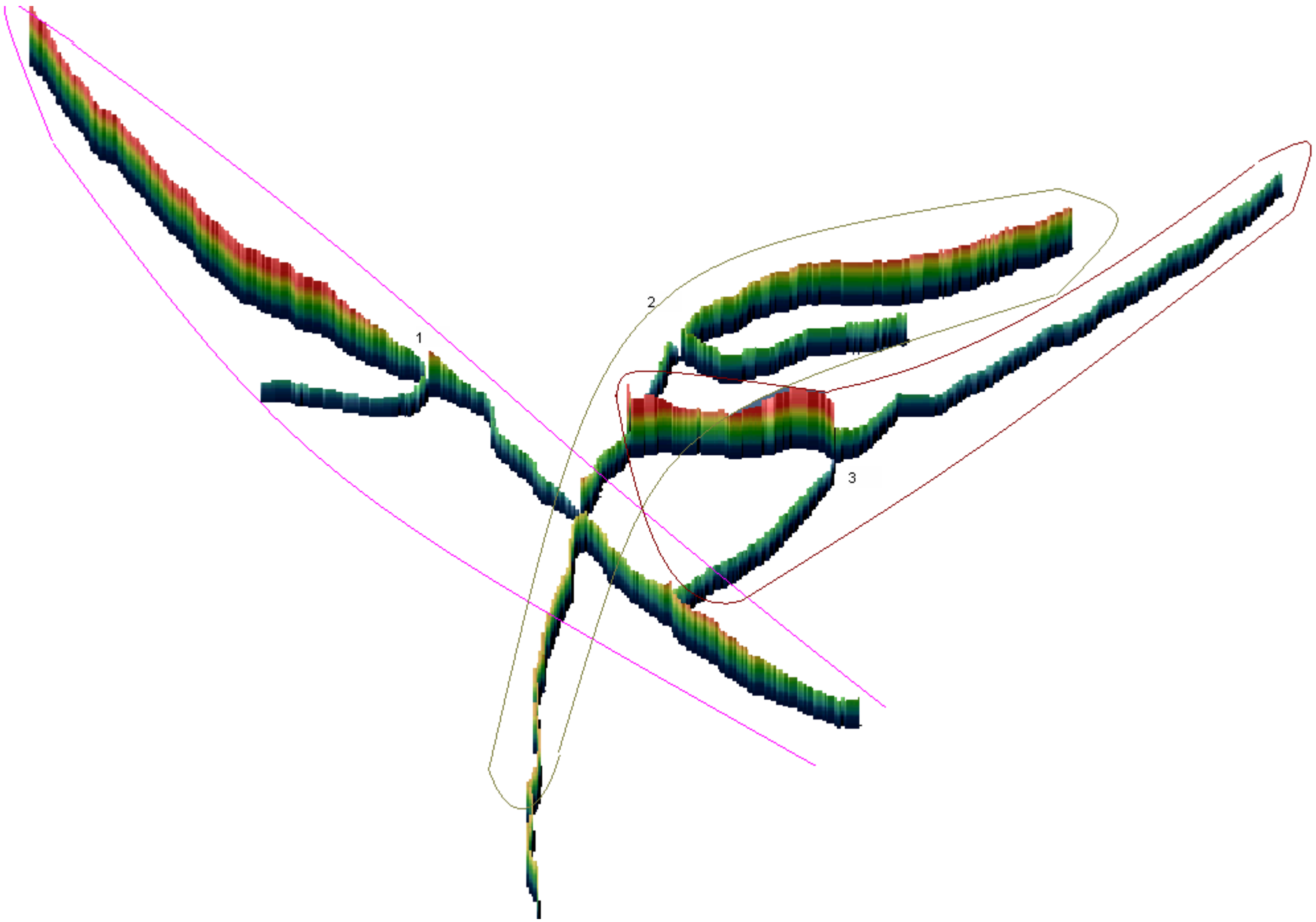
Method Overview



Skeletonization and leaf & intersection code lists



Result of identified stem centers



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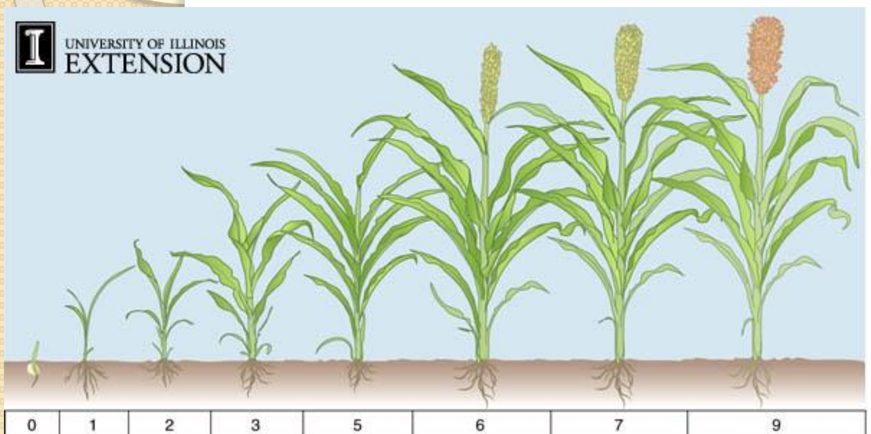
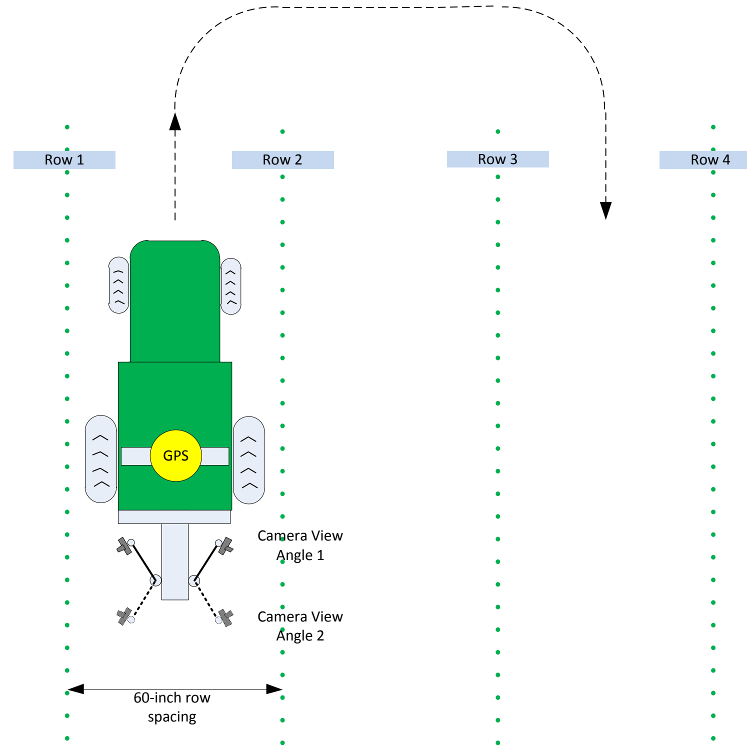
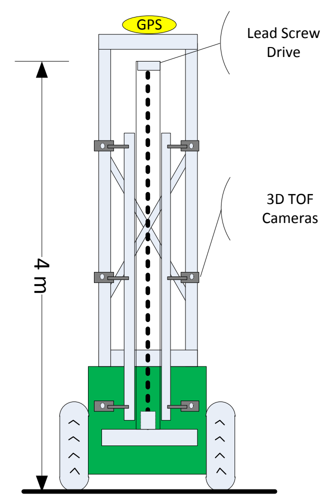
Robotic Phenotyping – Sorghum Biomass Traits



Top-View



Back-View



Genetic architecture of sorghum biomass yield-associated traits identified using high-throughput, field-based phenotyping technologies

PI: Patrick Schnable
Co-PIs: Maria Salas Fernandez, Lie Tang
Sponsors: USDA, DOE

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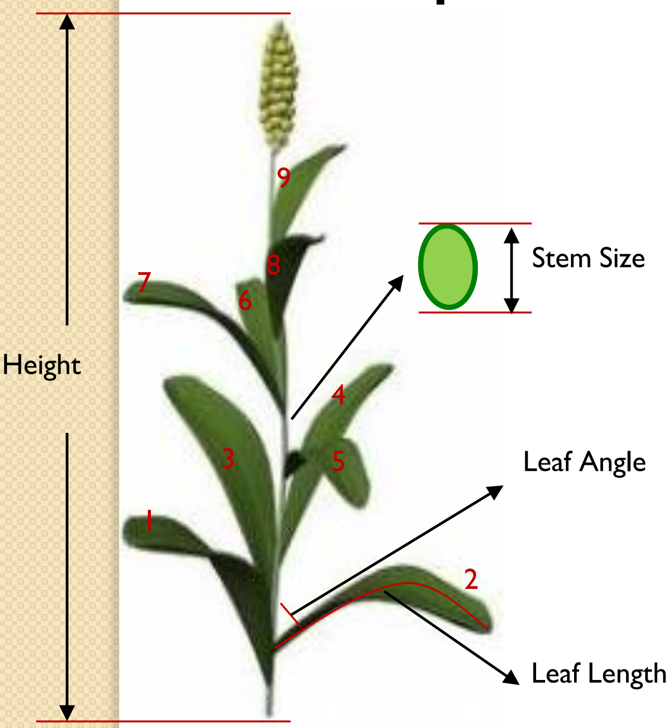
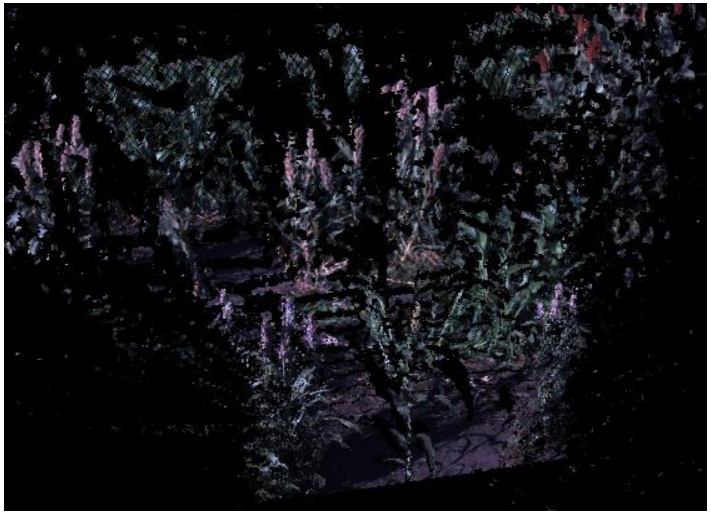
- Stereoscopic sensing
- Robot platform



Stereo camera

Image pair

Point cloud



Robotic platform - PhenoBot

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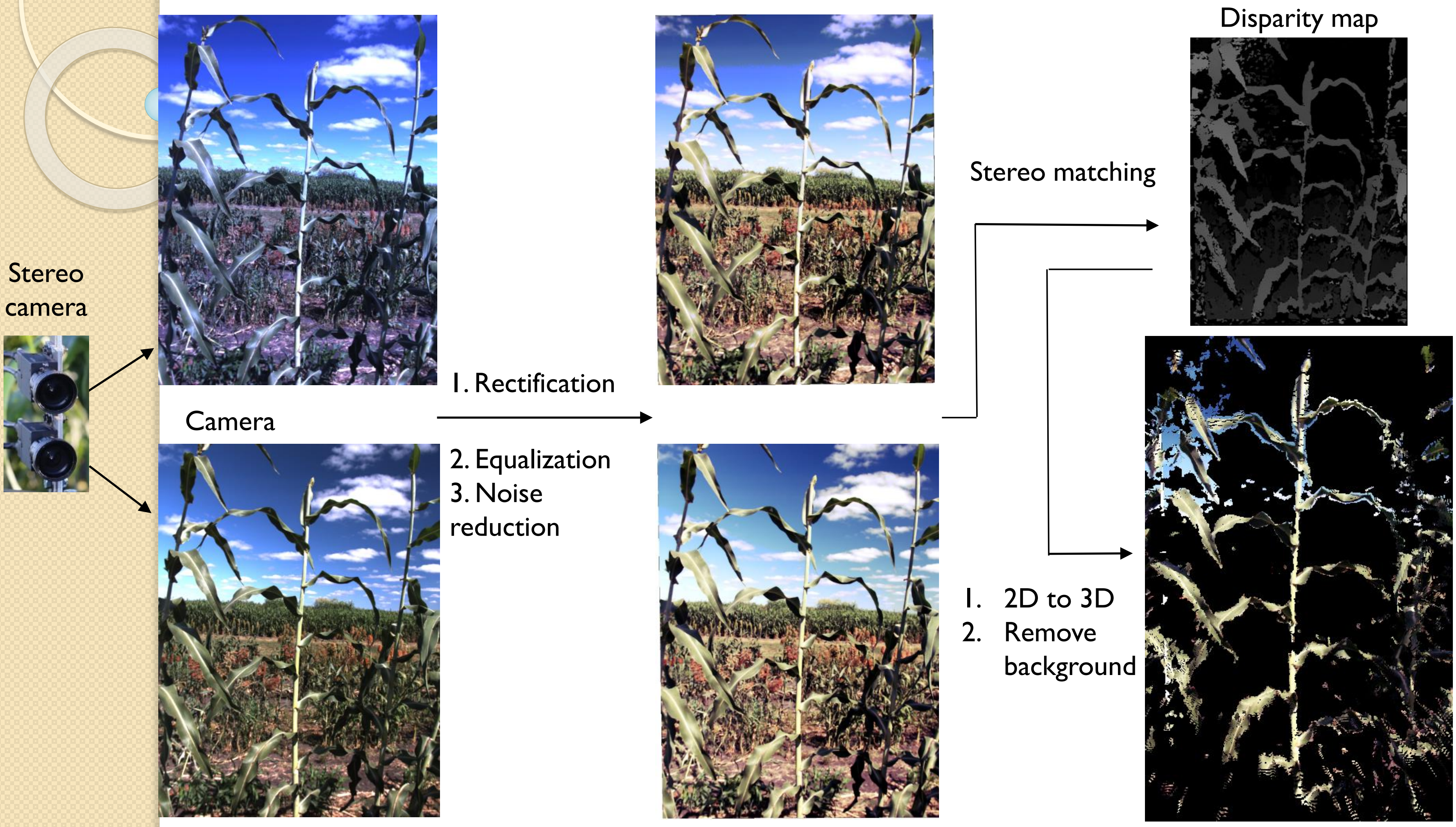
Video on scouting short plants

Video on scouting tall plants



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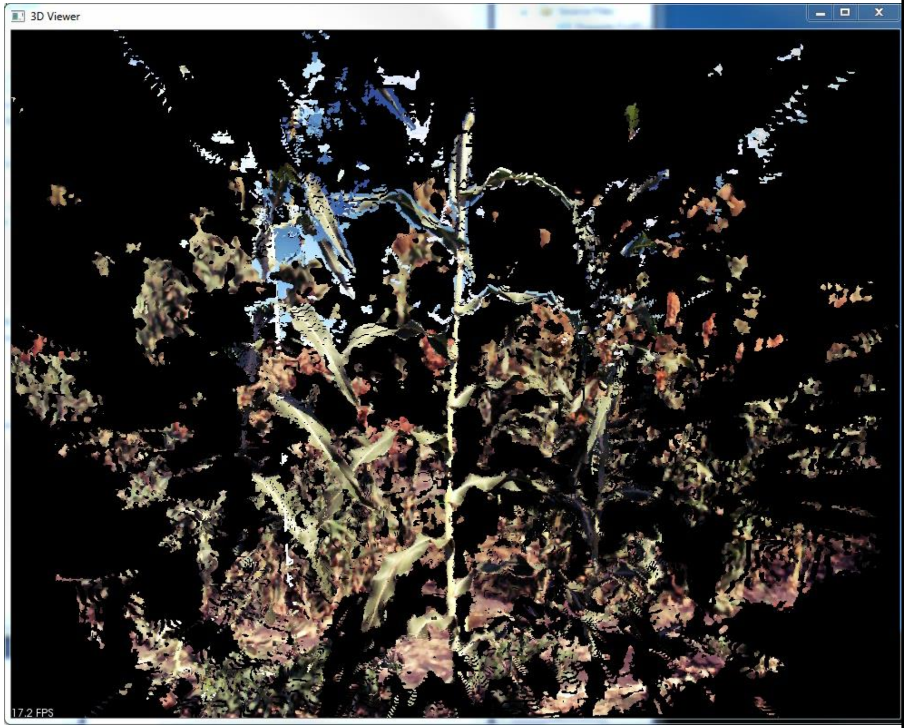
3D point-cloud



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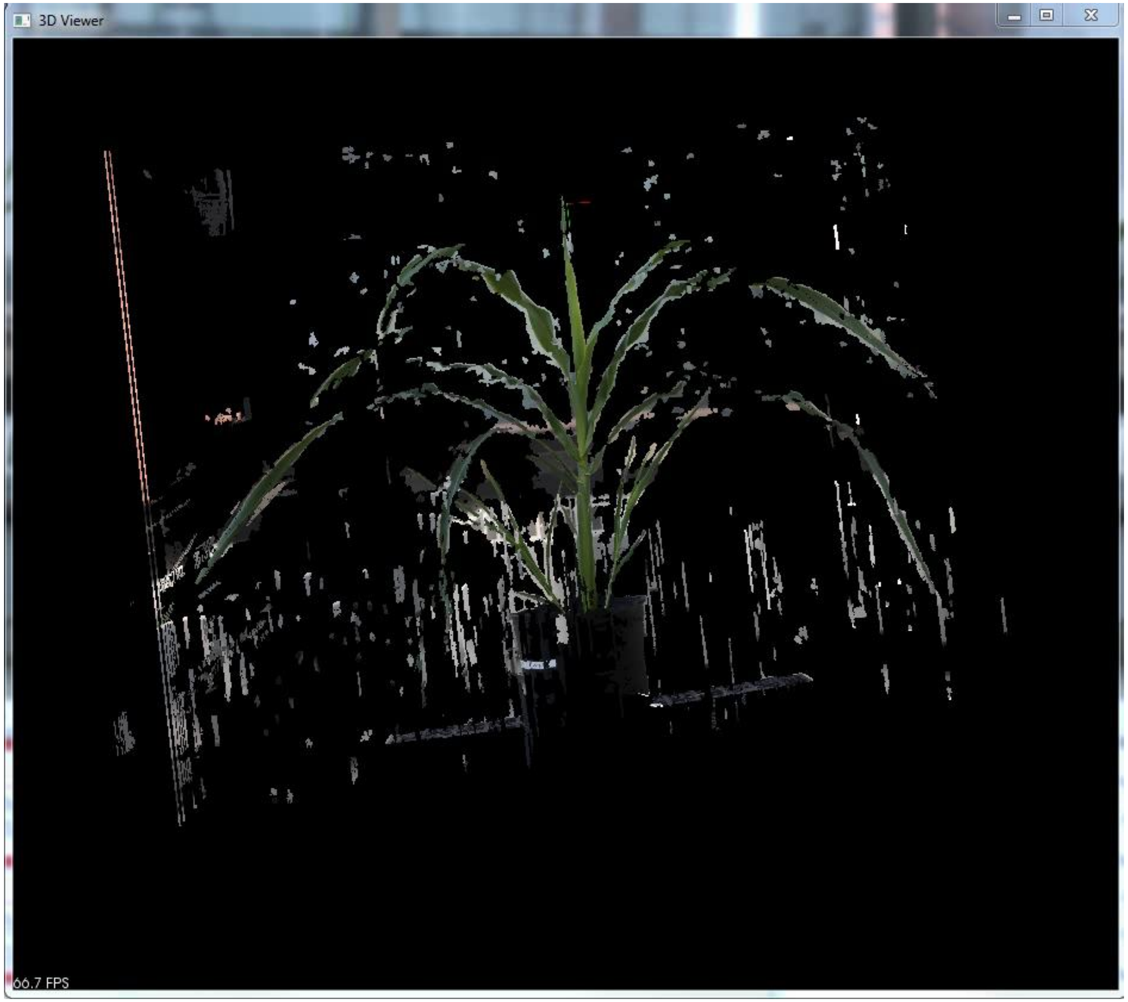
3D point-cloud with higher image resolution

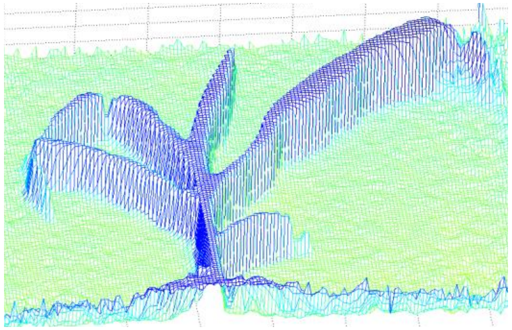


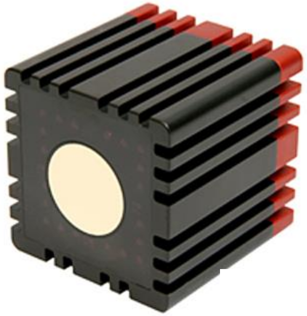
Need a clean segmentation at the first place.

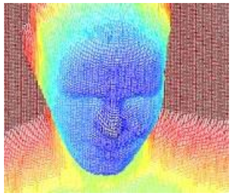
Conclusions on stereo imaging

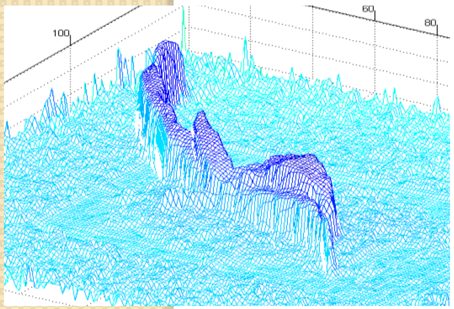
- Plus:
  - Utilization of depth information enables segmenting of individual plants.
  - High resolution and low-cost sensors are available.
- Delta:
  - The depth data generated by stereo head is often noisy and inaccurate.
  - Direct sunlight and variable lighting still impose challenges.
  - High computational cost for more sophisticated algorithms.

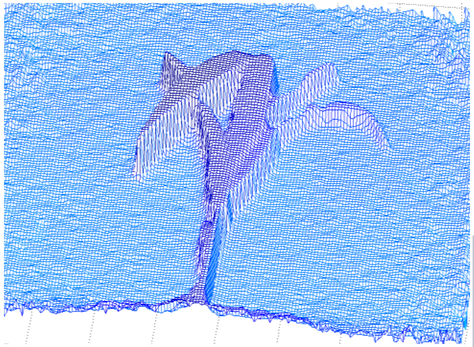
3) Time-of-Flight (ToF) of Light 3D imaging

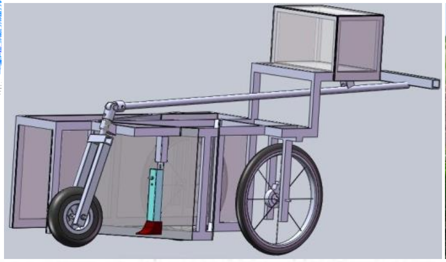


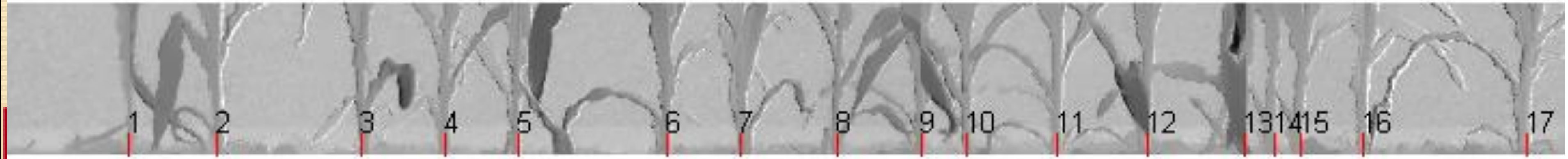






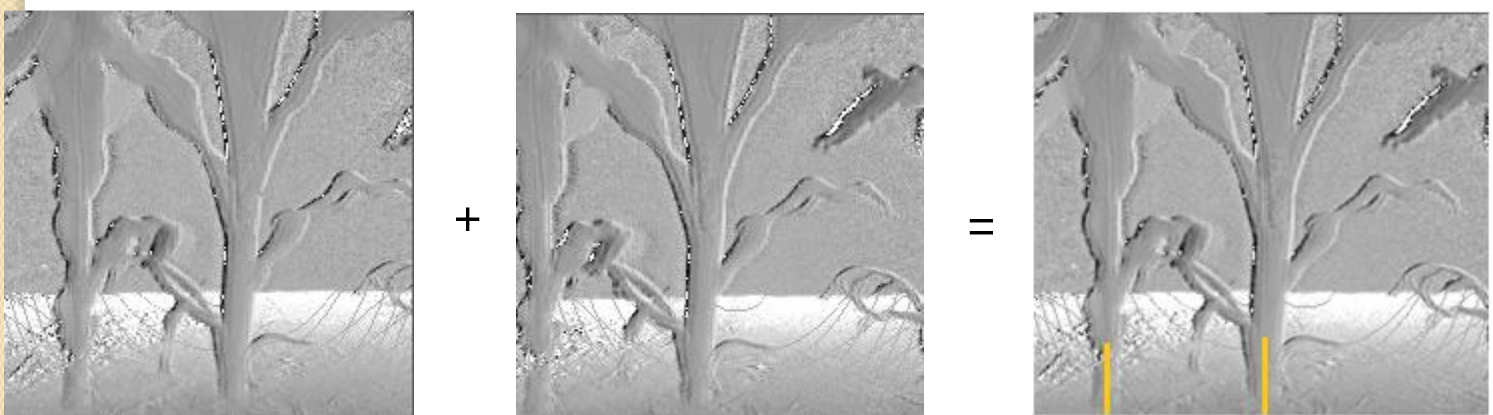






Data Processing

Stem matching & image mosaicking



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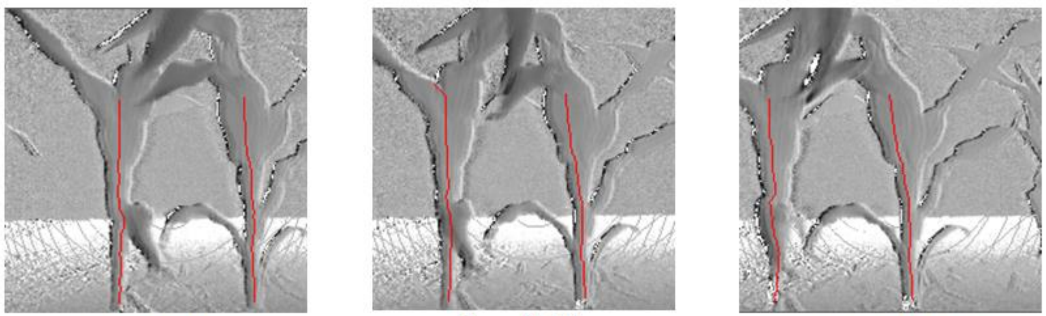
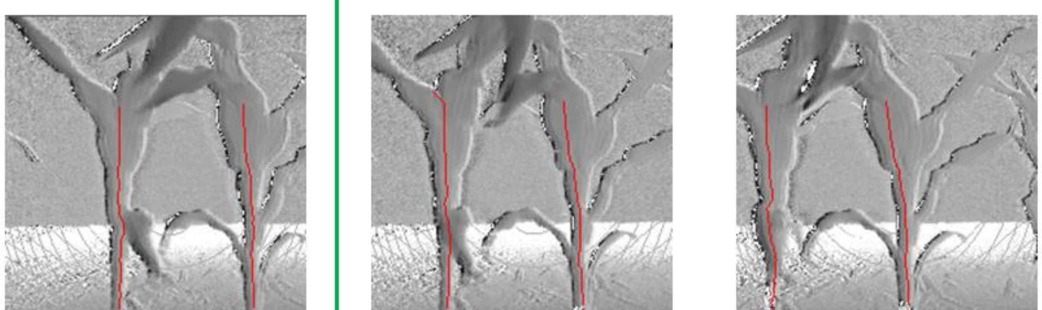
Inter-plant Spacing Sensing

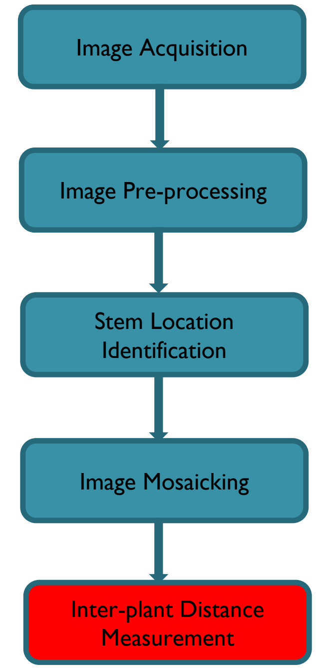
- Inter-plant distance measurement



$S_{d_1} = 6.32$ | $S_{d_2} = 10.87$ | $S_{d_3} = 4070.37$



$S_{d_1} = 6.32$, d_1=20.09 cm | $S_{d_2} = 10.87$, d_2=20.38 cm | $S_{d_3} = 4070.37$, d_3=26.41 cm



Manually measured distance was 20.21 cm.

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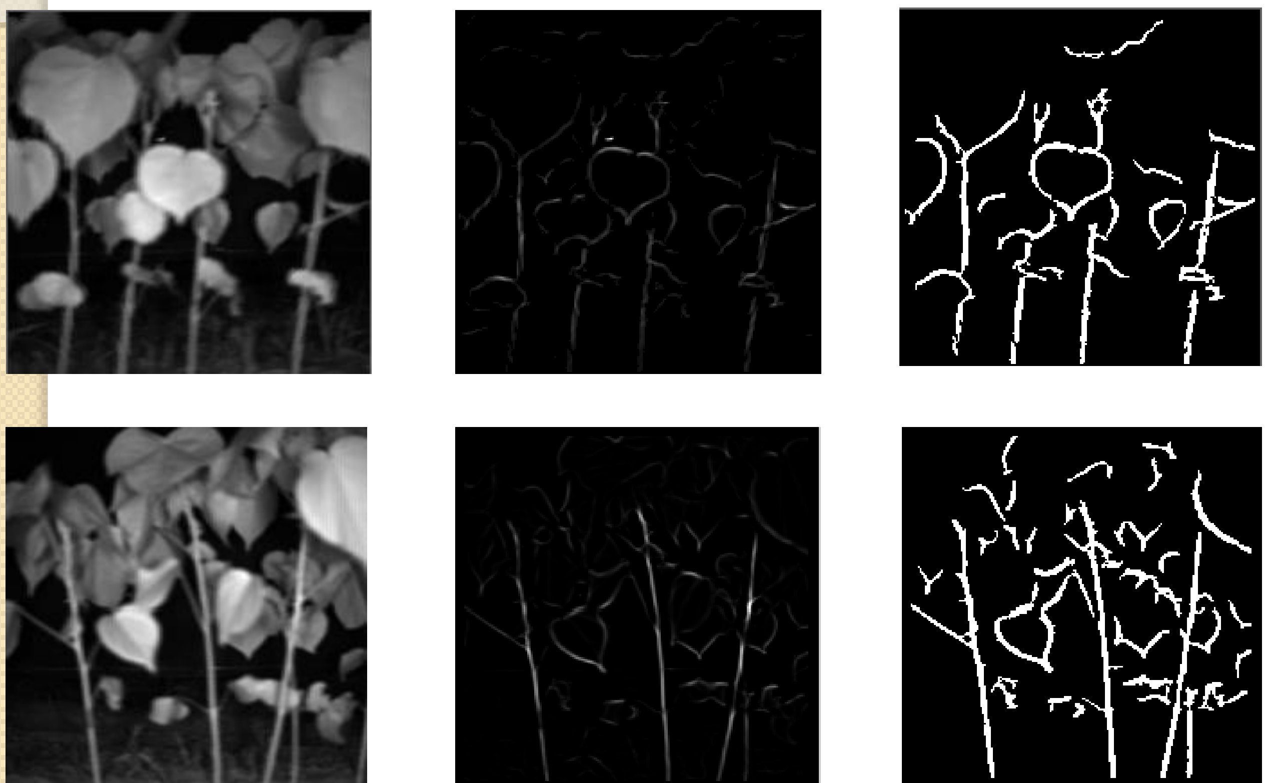
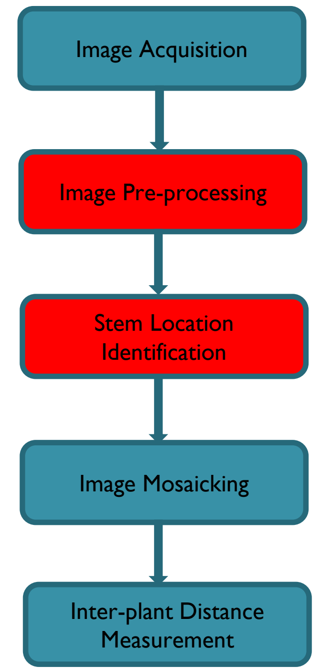
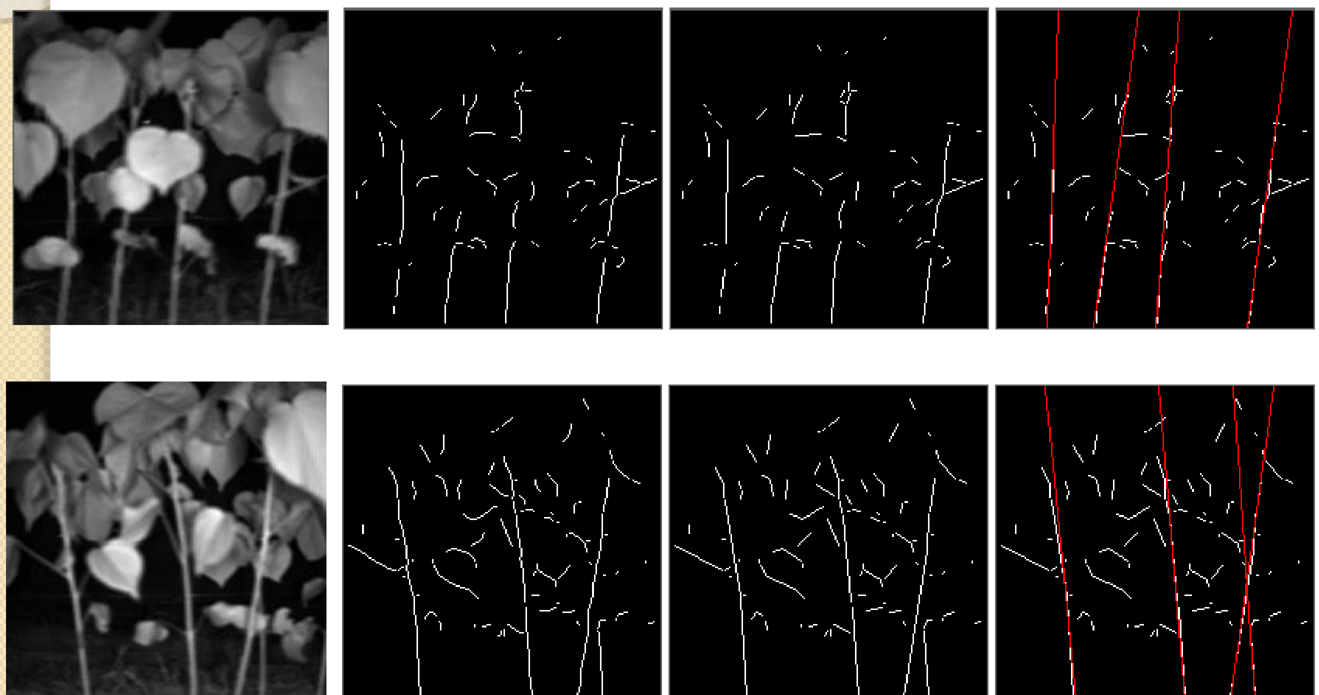
Cotton plant stem detection



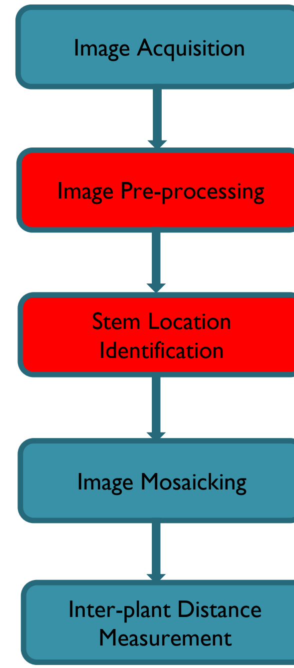
amplitude image | "vesselness" measure | "vesselness" filtered



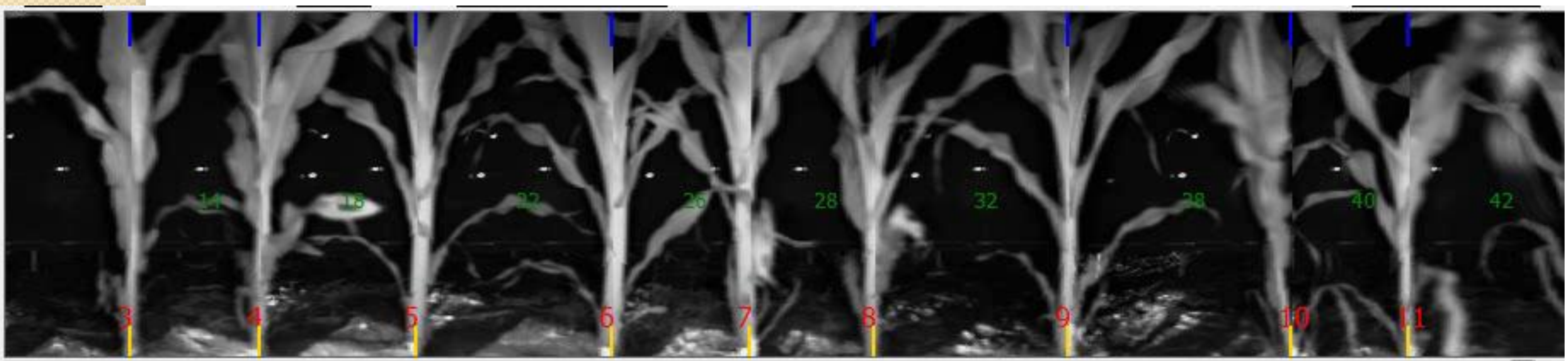
Cotton plant stem detection



amplitude image | center pixels | line fitting | Hough lines



Software Demo



Good news: a new stand analyzer has been developed

1) Analyzes crop stands in real-time (> 5 mph) and under any lighting conditions.
2) Works for corn plants from V2 – V9 (~7-8" and above). Potential to measure and count other crops.
3) Measures population, interplant spacing, and estimate stem diameter simultaneously.
4) Measure multiple rows (2 – 8) simultaneously.
5) GPS-ready for individual crop stand georeferencing and mapping.
6) High corn plant stand counting accuracy (>97%) has achieved in preliminary field test.

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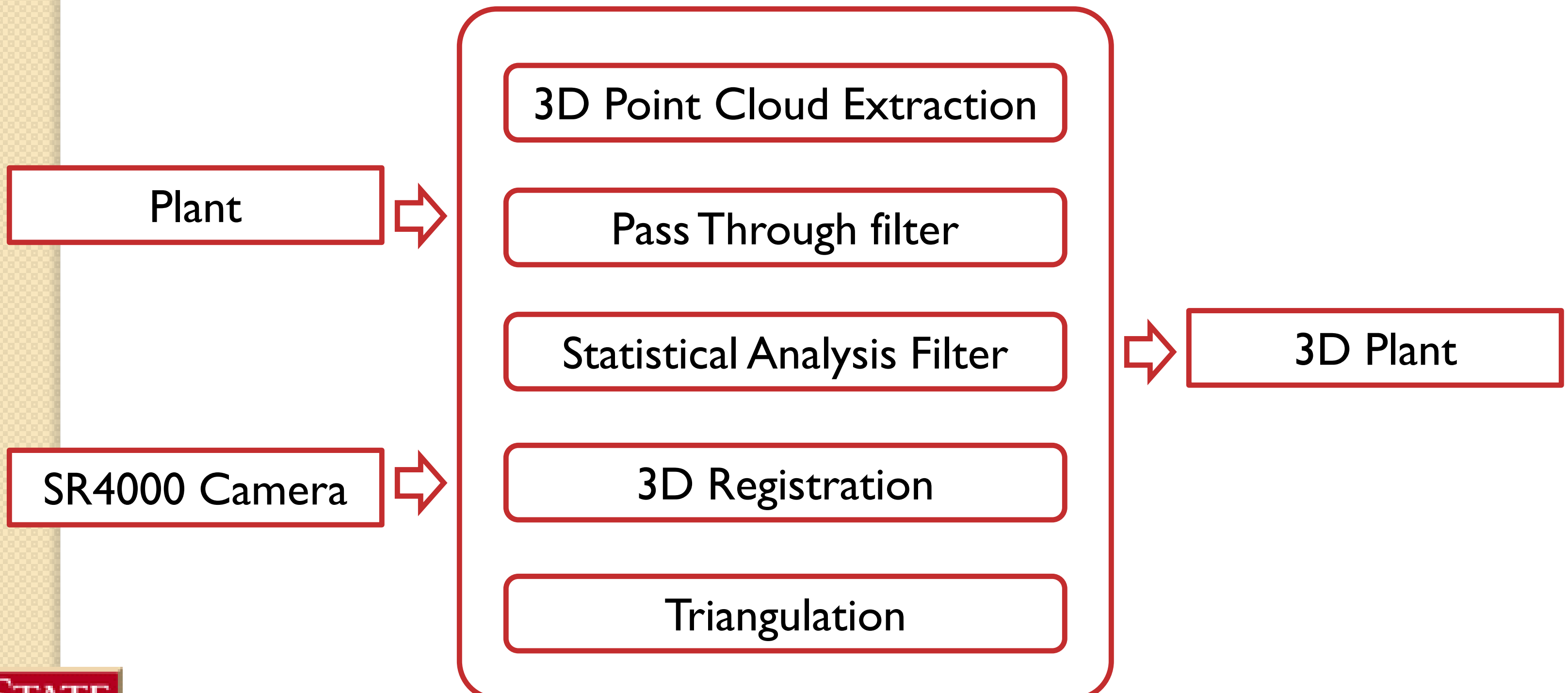
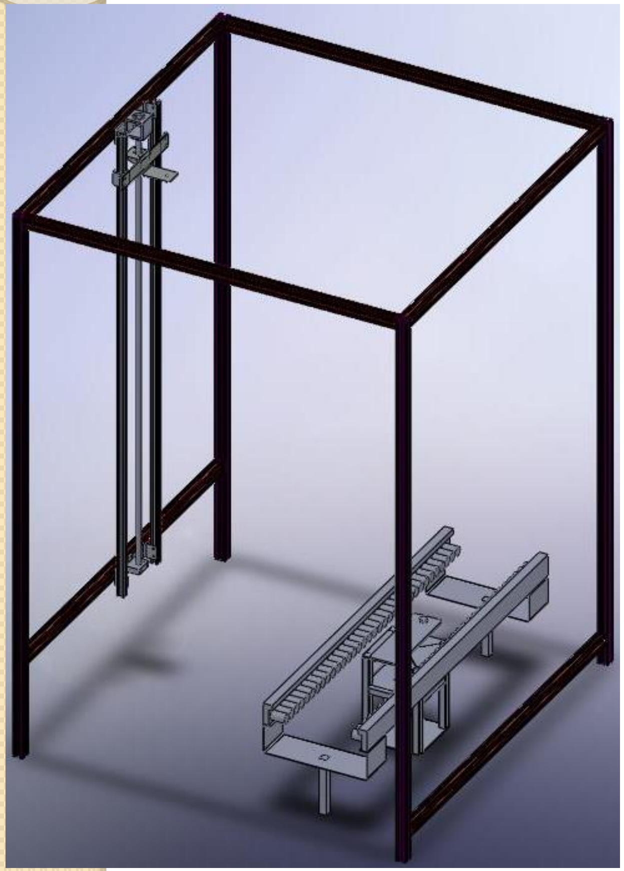
Indoor phenotyping using ToF 3D imaging

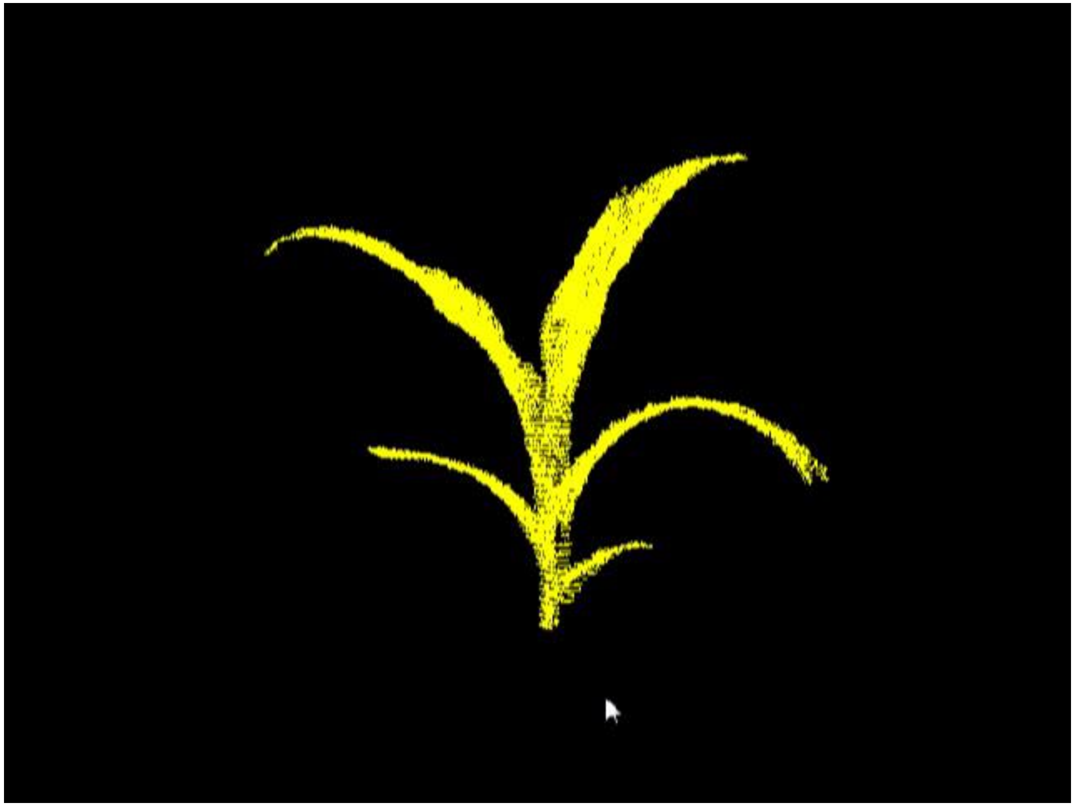
- Objective: 3D vision algorithm for the phenometrics related to plant structure and growth such as the number of leaves, leaf length, leaf locations, plant volume, and plant height



3D holographic reconstruction

-Low image resolution necessitates multiple views

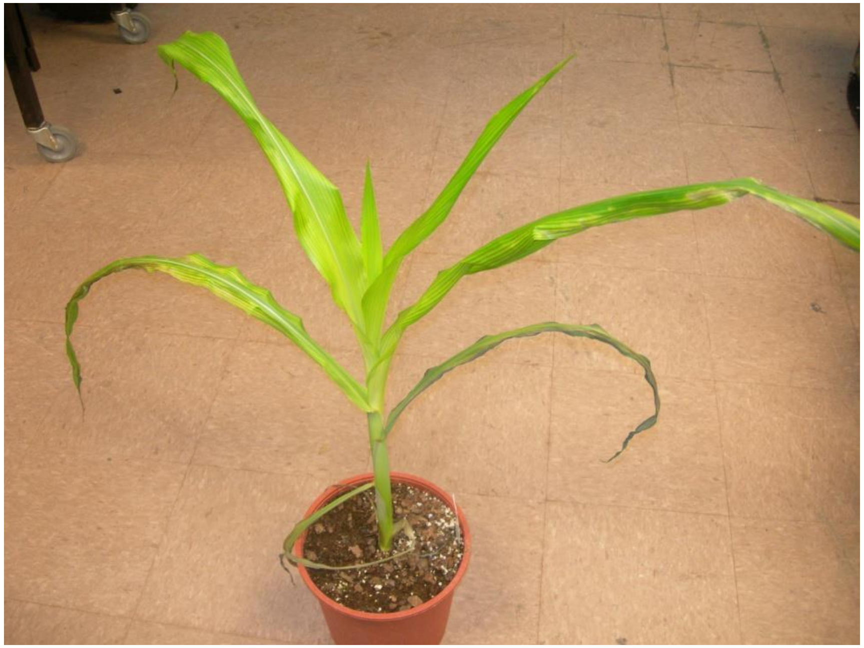




3D holographic reconstruction and characterization

Real plant

3D plant



Color image of corn plant

Amplitude image from
PMD Nano camera

Distance image from
PMD Nano camera

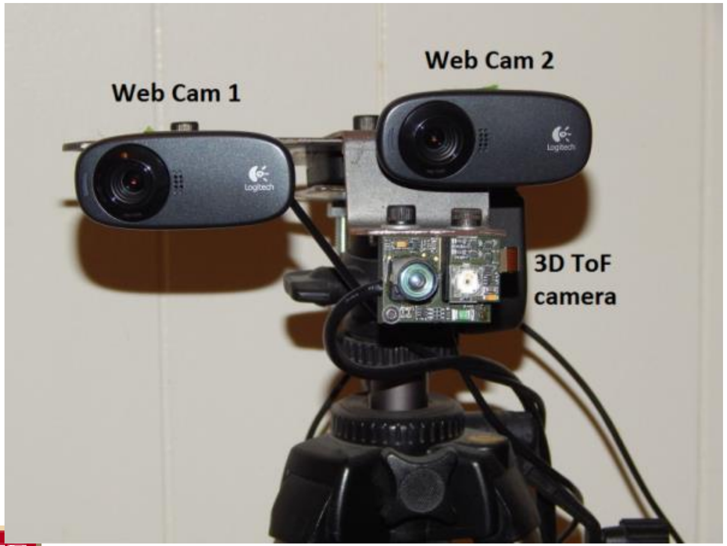
Calibration between 2D and 3D camera

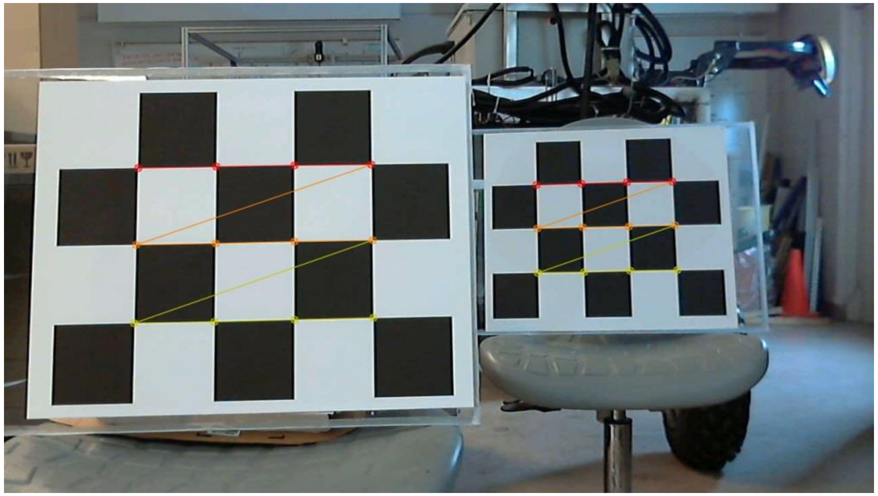
- The Rotation matrix and translation between 2D and 3D camera:

$$R_{3D22D} = R_{L22D} R_{3D2L}$$

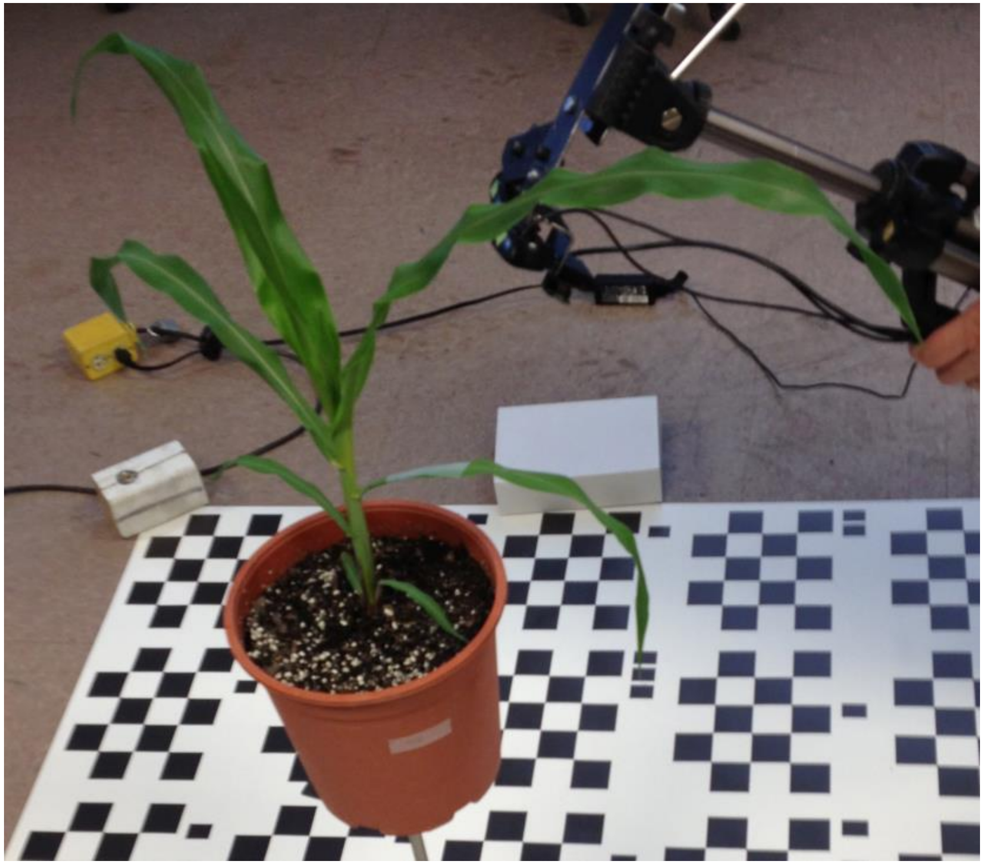
$$t_{3D22D} = R_{L22D} t_{3D2L} + t_{L22D}$$

$$Q_{2D} = R_{3D22D} Q_{3D} + t_{3D22D}$$





Acquiring multiple views



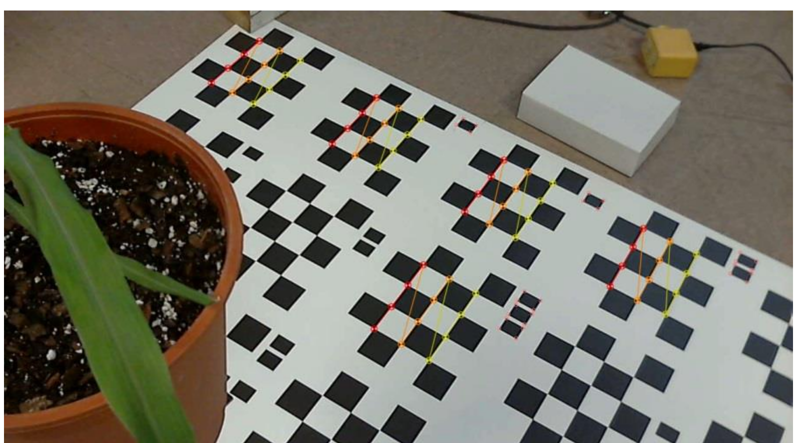
3D Registration

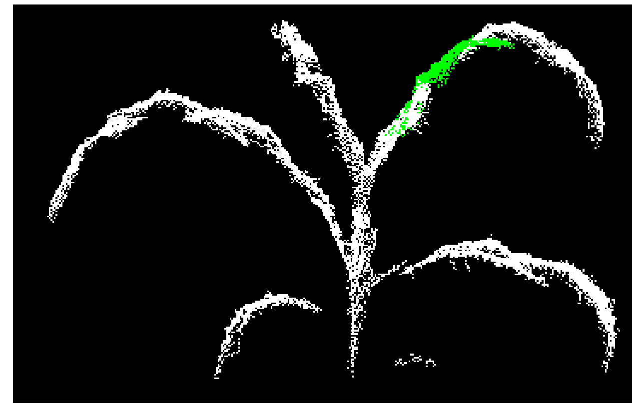
- The relationship between 2D camera and target array is achieved

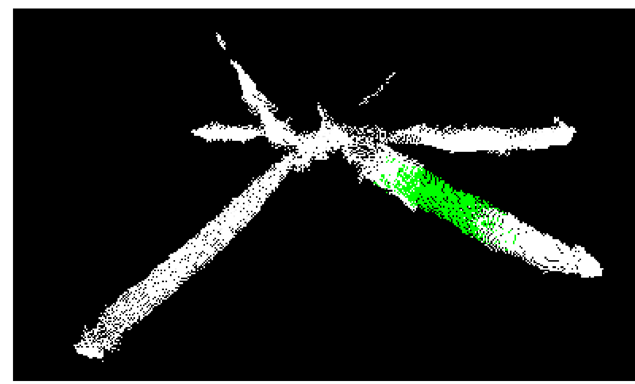
$$Q_{2D} = R_{2D} Q_w + t_{2D}$$

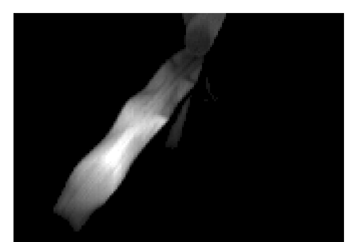
- Convert different 3D point cloud data view to consistent world coordinate system defined by the target array:

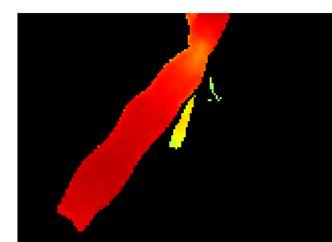
$$Q_w = R_{2D}^{-1}(R_{3D22D} Q_{3D} + t_{3D22D} - t_{2D})$$











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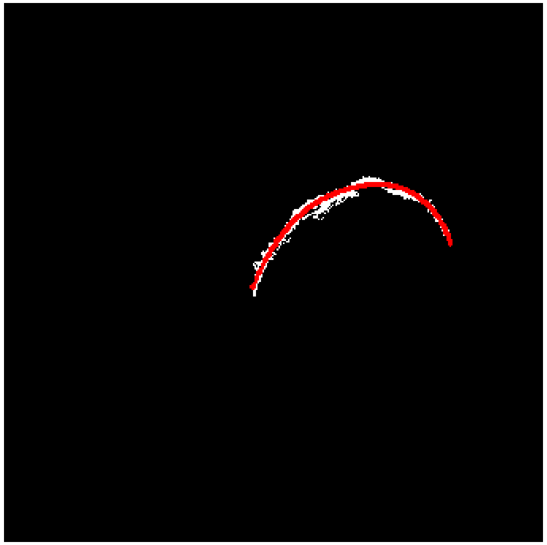
Physical parameter measurements

- Leaf skeleton estimation
  - Singular Value Decomposition (SVD) regression method

$$\tilde{y} = x\sin(\varphi) + y\cos(\varphi)$$

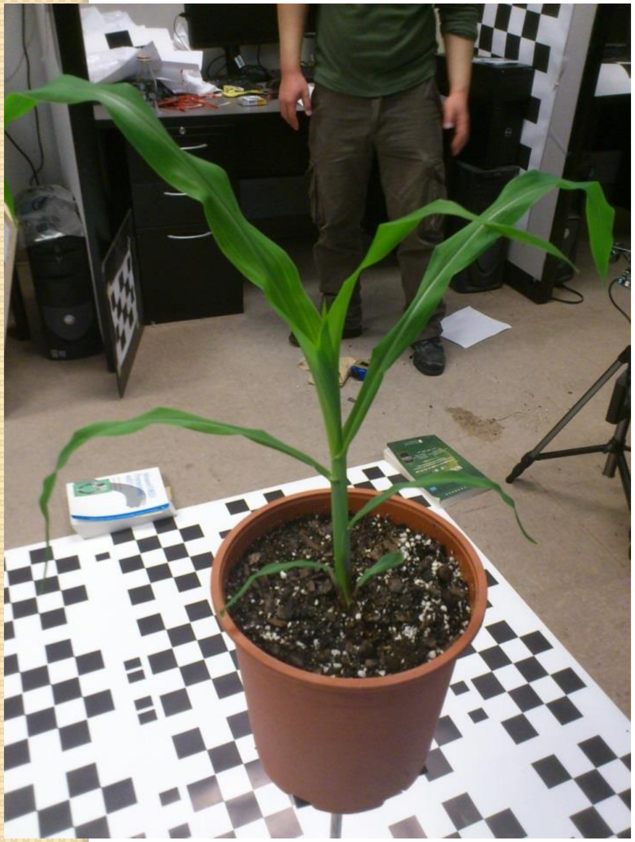
$$z = a\tilde{y}^4 + b\tilde{y}^3 + c\tilde{y}^2 + d\tilde{y} + e$$

- Leaf length
- Leaf width
- Leaf area
- Leaf collar height

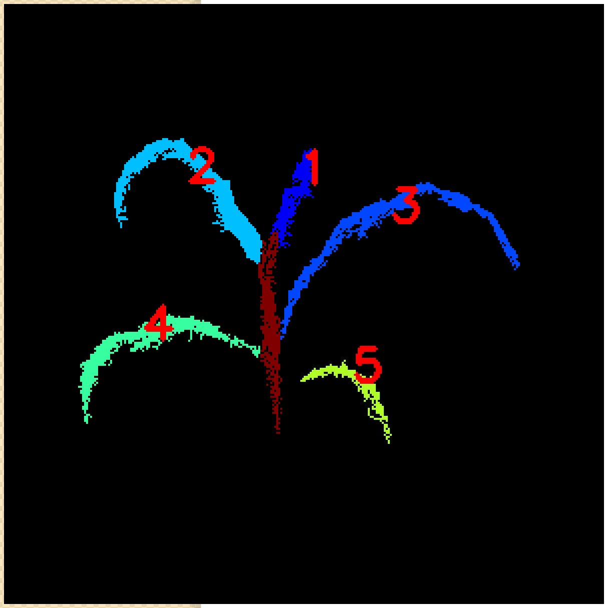


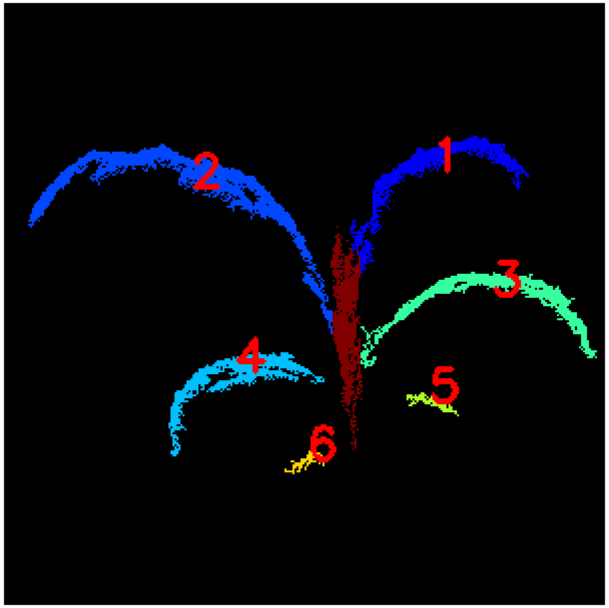
Results and Discussion

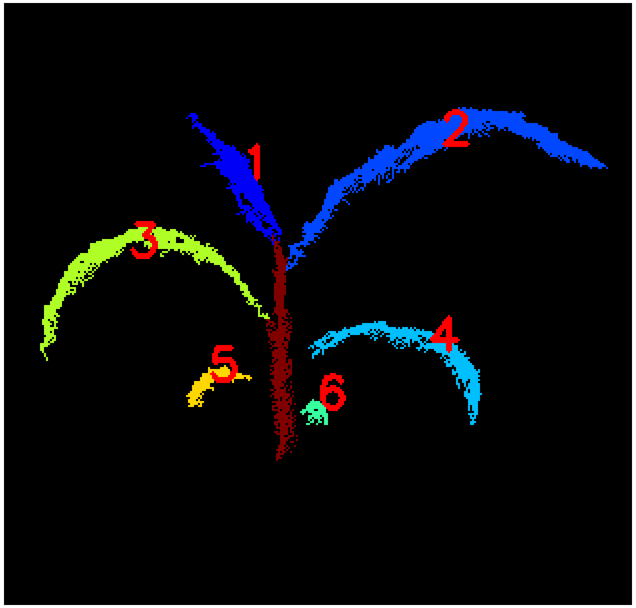
- 3D reconstruction result of plant 1



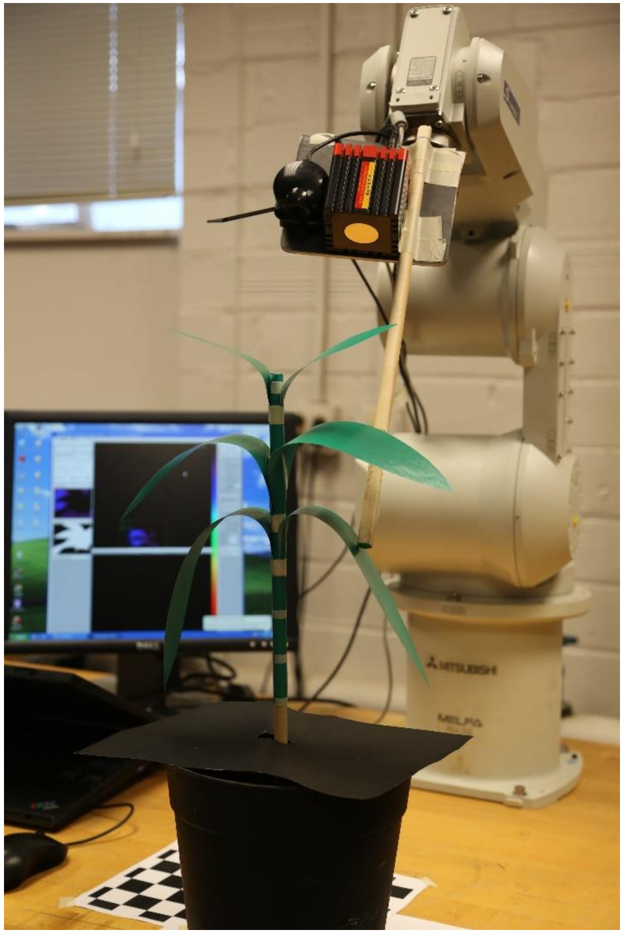
Stem and leaf recognition result

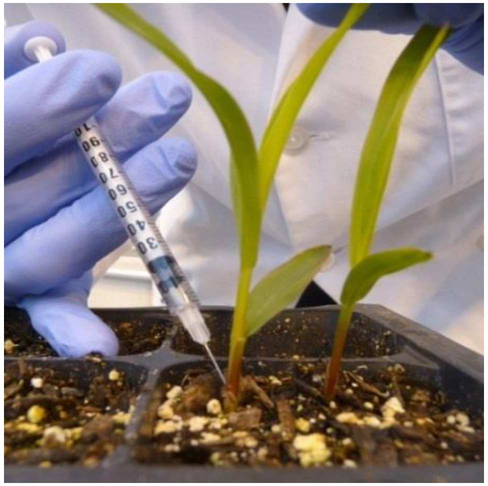






Robotic sampling and plant treatment
- sensor and hand coordination





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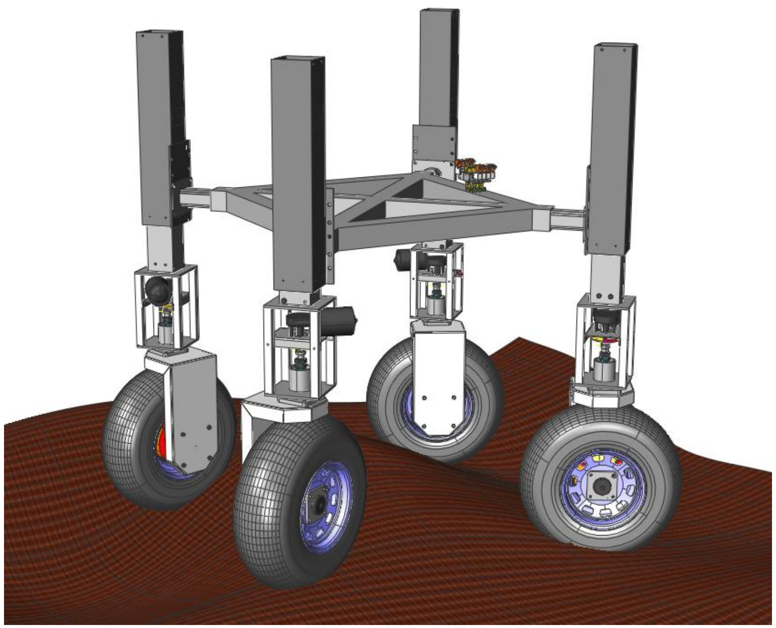
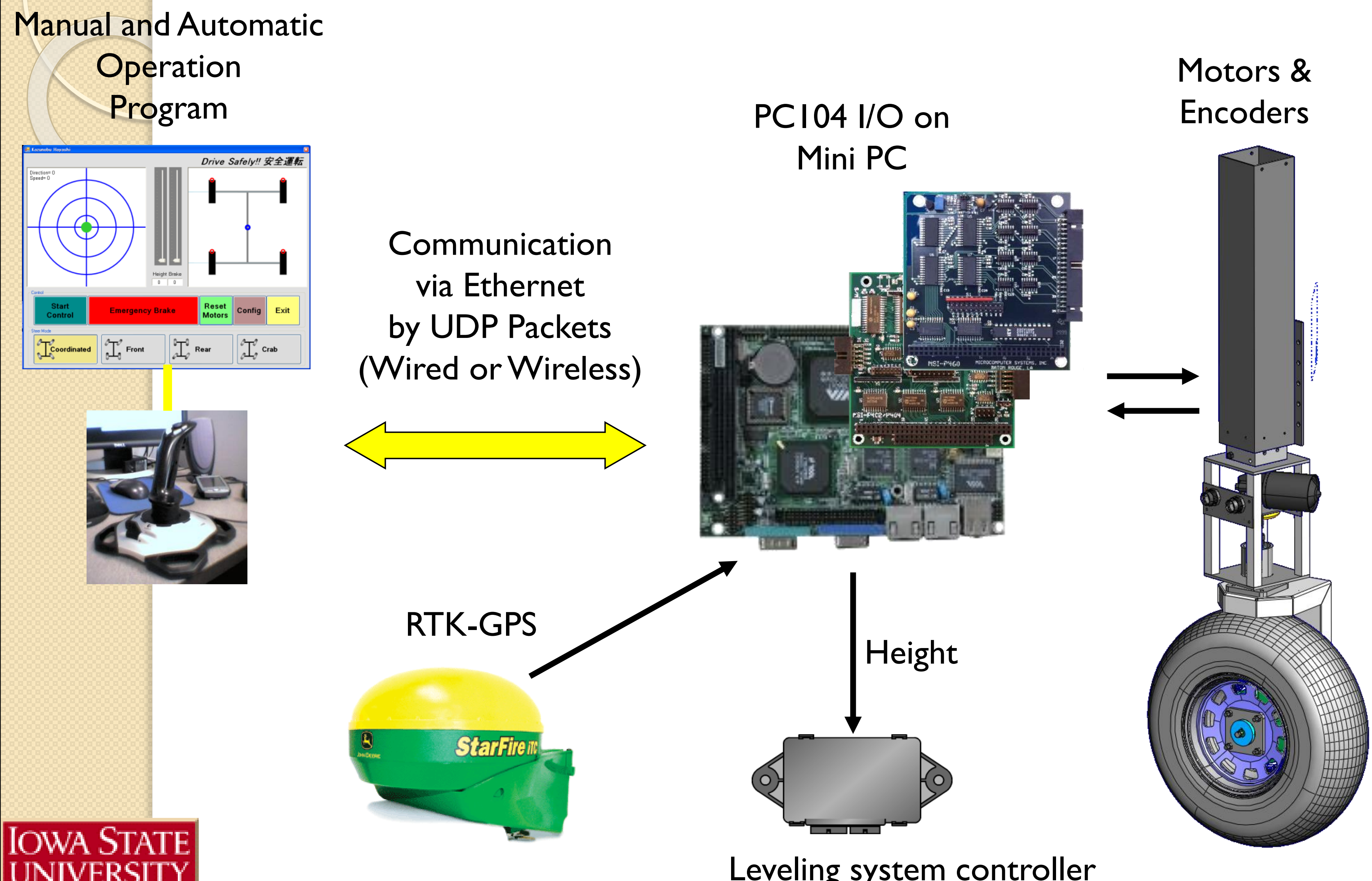
2. Mobile Robotic Platforms
- AgRover – A Field Scouting Robotic Vehicle



- Self-leveling on slopes
- Adjustable clearance
- 4-Wheel-Drive
- 4-Wheel-Steering
- Manual wireless Operation
- GPS-based auto-guidance

AgRover Prototype

System Components



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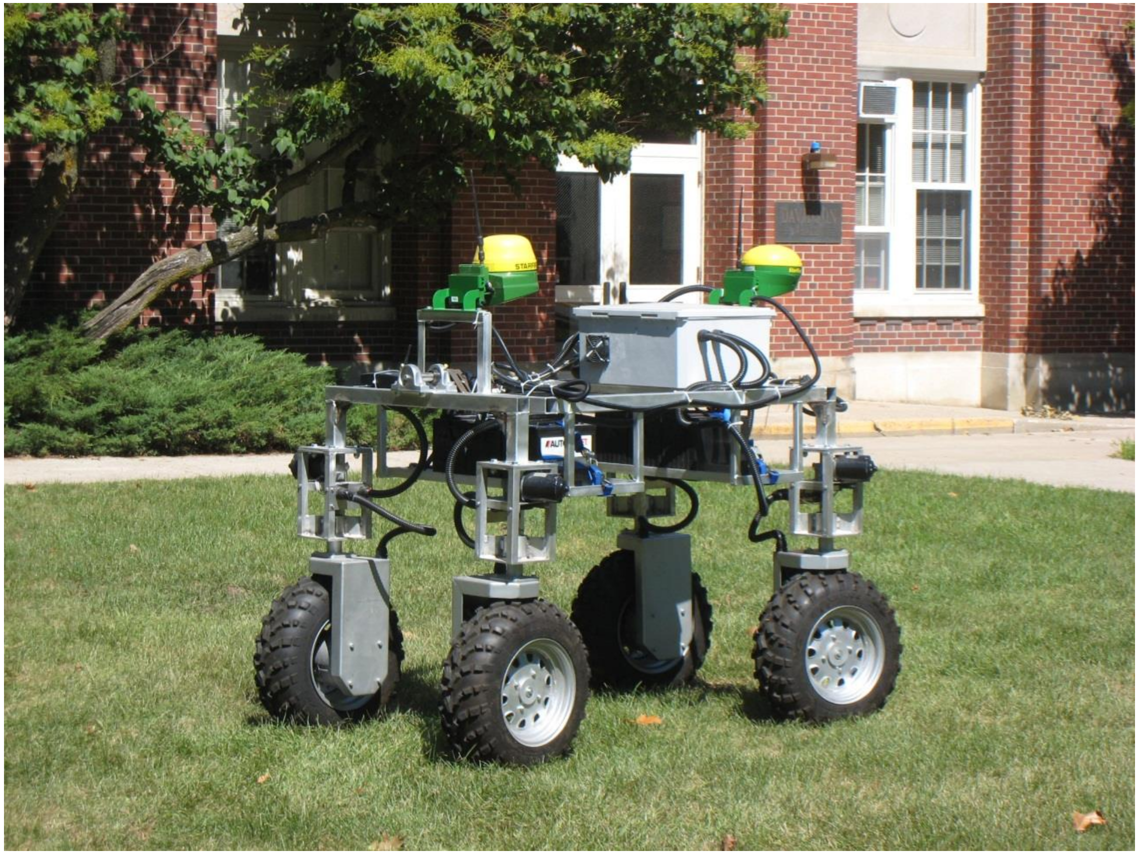
AgRover-1 Prototype

AgRover-2



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AgRover-2 Scouting Robot

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Thank You!

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