



Robotic Technologies for Automated High-throughput Plant Phenotyping

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Agenda

I. 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/>



Corn plant identification

- some of the challenges



– Intertwined Leaves



– a weed interference, damaged plants



– Double plants, plants in the background

I) 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



Color image processing for stem center identification

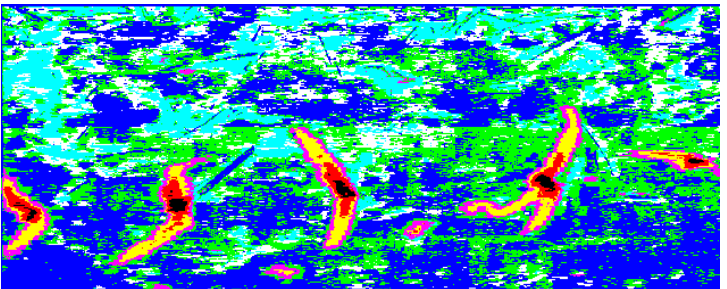


Original



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

Color Transformation

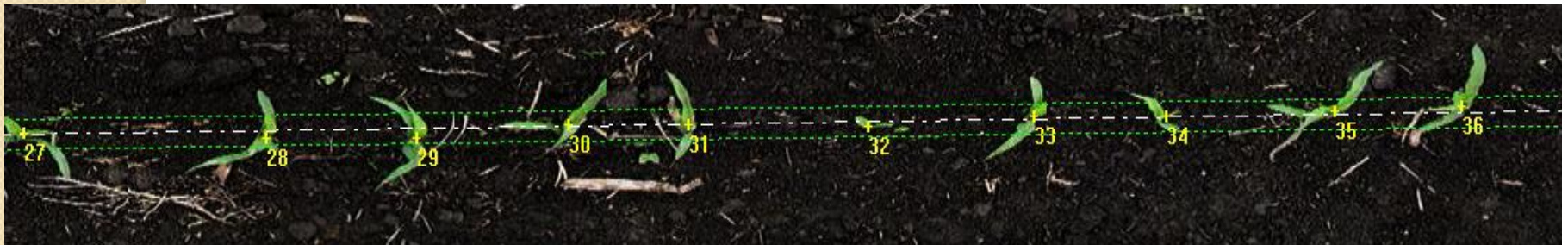
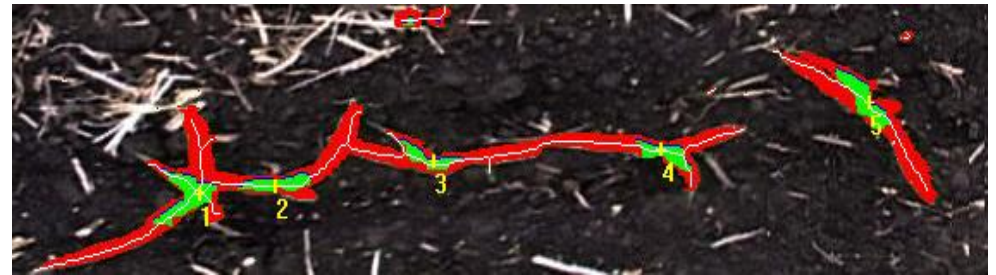


Bayes classification

K-Mean clustering

Robust crop row center-line fitting

- excluding small weed plants



Plant Identification and Spacing Measurement

Sequenced Frame Window: Sequenced-Frame Length=27800



Software Interface

Emerged Plant Sensing

File VideoSrc VideoCtrl Lut Calibration Start About

Current Frame Window (scene must move towards left direction <<----)

Spacing measurement window

Area Thresholds

Crop Type	Area Value	Mini-Factor	Max-Factor
<input checked="" type="radio"/> Corn	1400	0.20	4000.0
<input type="radio"/> Soybean	65		
<input type="radio"/> Cotton	100		

Options

View Segmentation
 Enable Manual Correction
 Enable Manual Patch

Save Spacing Data Save Current Frame Load Current Frame

Process Sequenced Frame Processing: Batch Row 1 Row 2 Total Population: 56 Guiding

Corn compactness: 0.30 Init OK Cancel

Frame Sequencing: Row 1 Row 2 Save Sequenced Frame Load Sequenced Frame

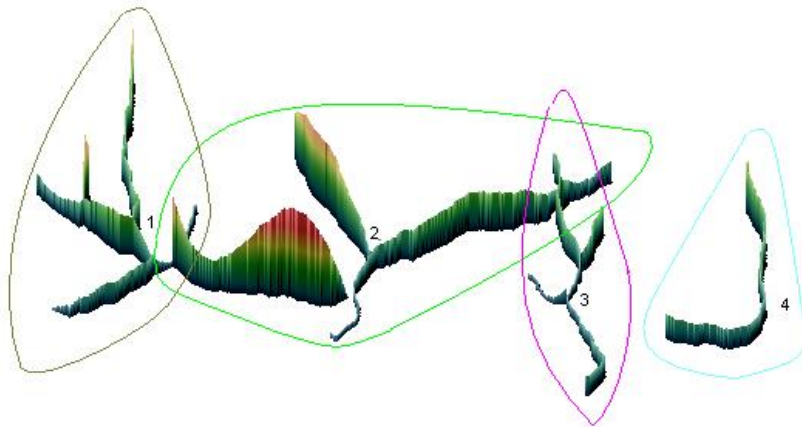
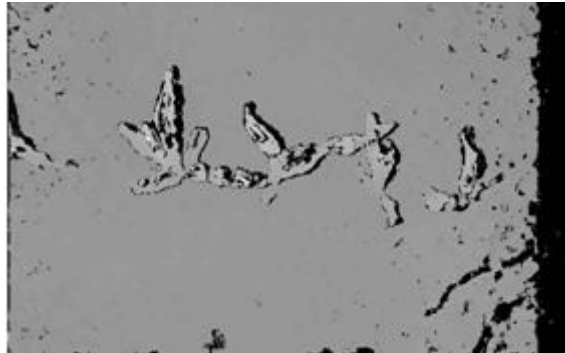
	Count	Spacing (mm)	Count	Spacing (mm)
Pop	63	56 100.54	Pop	56 3.23
Mean	81.57	57 6.47	Mean	59.01
STD	89.23	58 19.39		
CV	1.09	59 113.1E		
		60 123.0E		
		61 64.53	STD	56.10
		62 12.93		
		63 51.81	CV	0.95

Ready Ln 387, Col 18 REC | COL | OVR | READ

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 screenshot of the Videre Stereo-On-a-Chip camera's graphical user interface. The interface is divided into several sections:

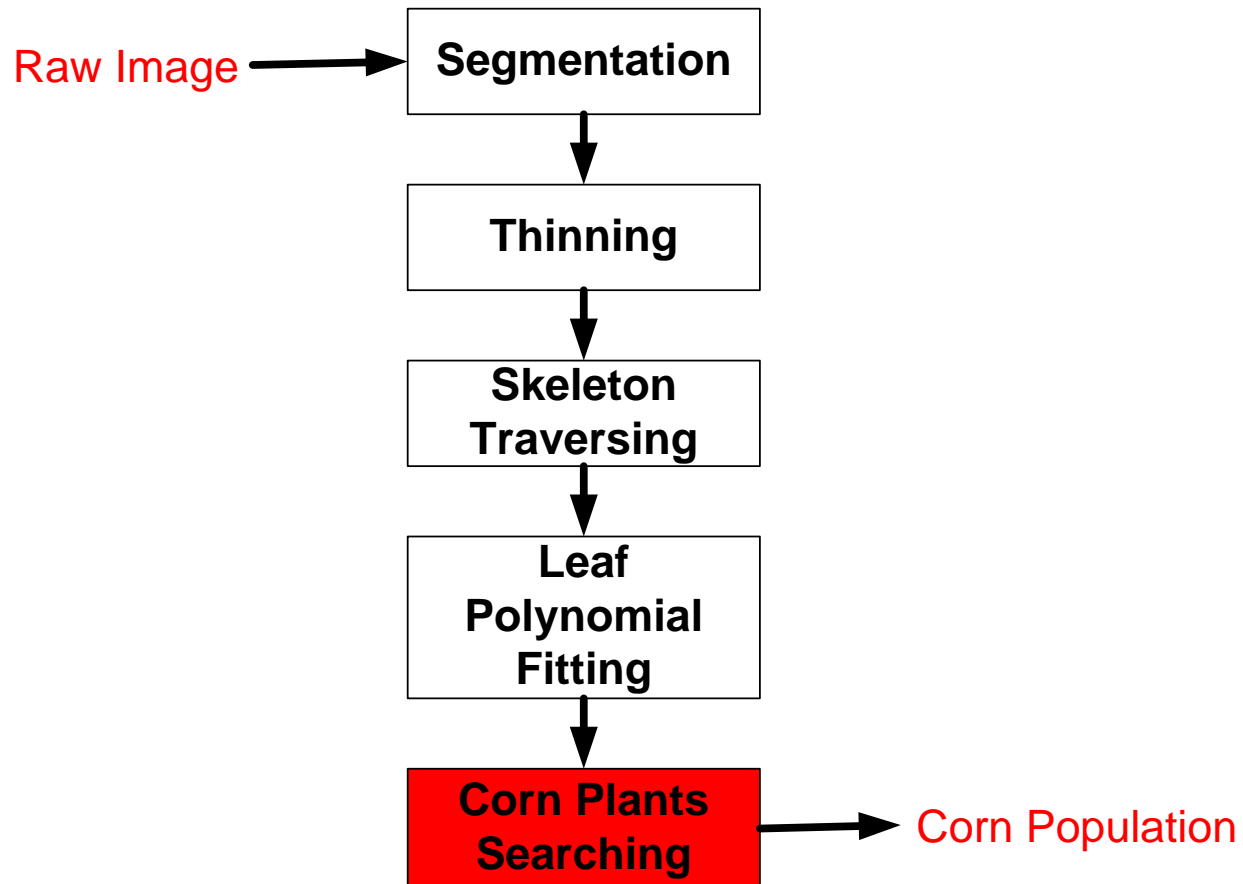
- Color Images:** Two side-by-side images. The left image is a color photograph of a green plant. Below it is a checkbox labeled "Color" which is checked. The right image is a depth map of the same plant, with colors ranging from blue (near) to red (far). Below it is a checkbox labeled "Color" which is unchecked.
- Debug Information:** A scrollable text area containing the following text:

```
SVS Version 1.1 - DES Digital Stereo Interface
Auto Exposure
Can not process on camera
MMX presence: 7
1 devices found:
VIDERE_DESIGN MDS-STH #0055050400083260
Device/Device 1: #VIDERE_DESIGN MDS-STH
#0055050400083260
Can get color image
Can process on chip
max_x_offset <= 0
Open device 0
[User] Proc mode none
[User] Proc mode disparity
```
- Function and Controls:** A dropdown menu set to "Stereo" and a "Get 3D" button. Below these are several numeric input fields:
 - Conf: 7
 - Disparity: 16
 - Unique: 14
 - Window: 12
 - Speckle: 20
 - X off: 0
- Buttons:** Three buttons labeled "Initial", "Start", and "Stop" are located at the bottom right of the control area.

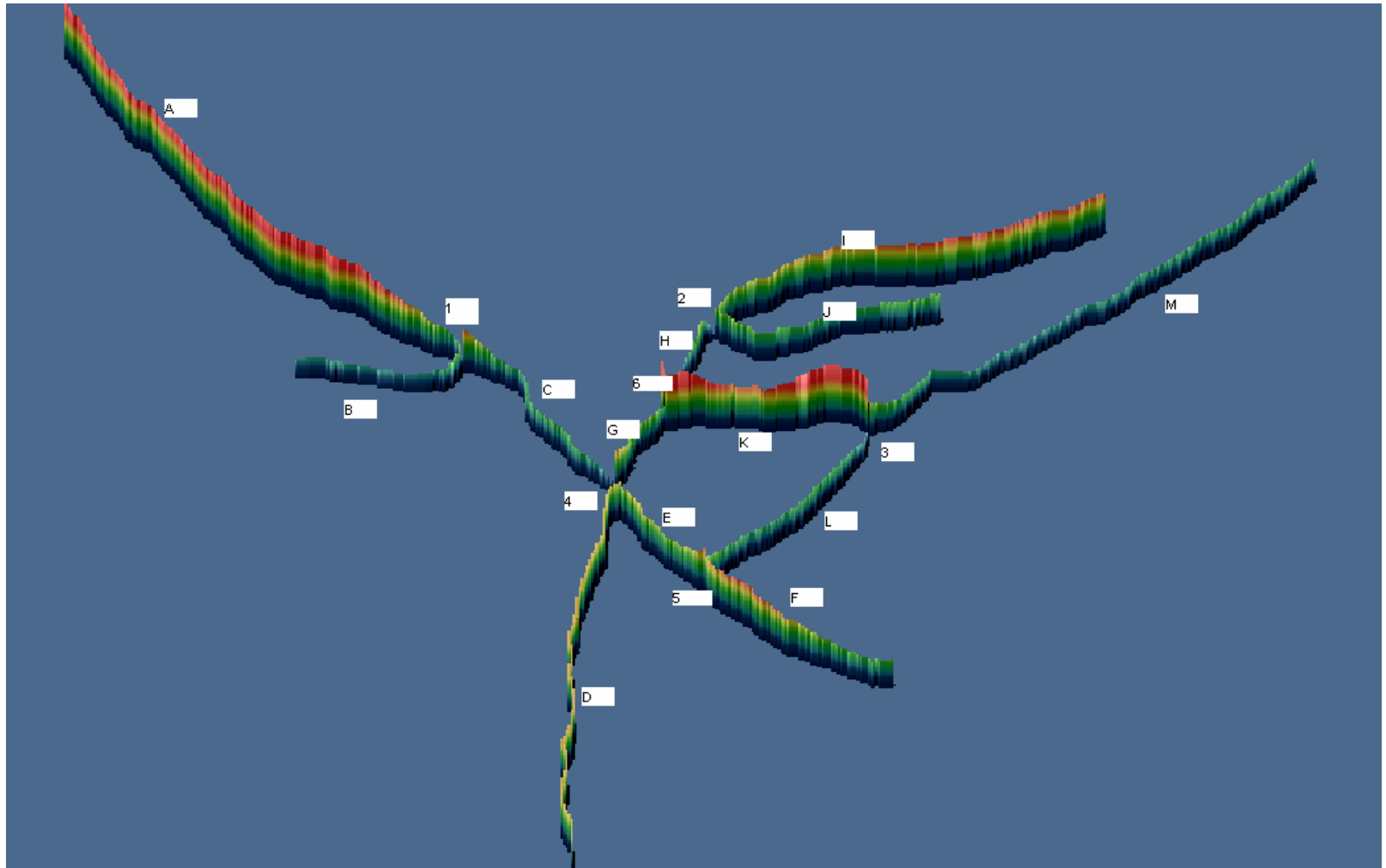
A Complicated Example



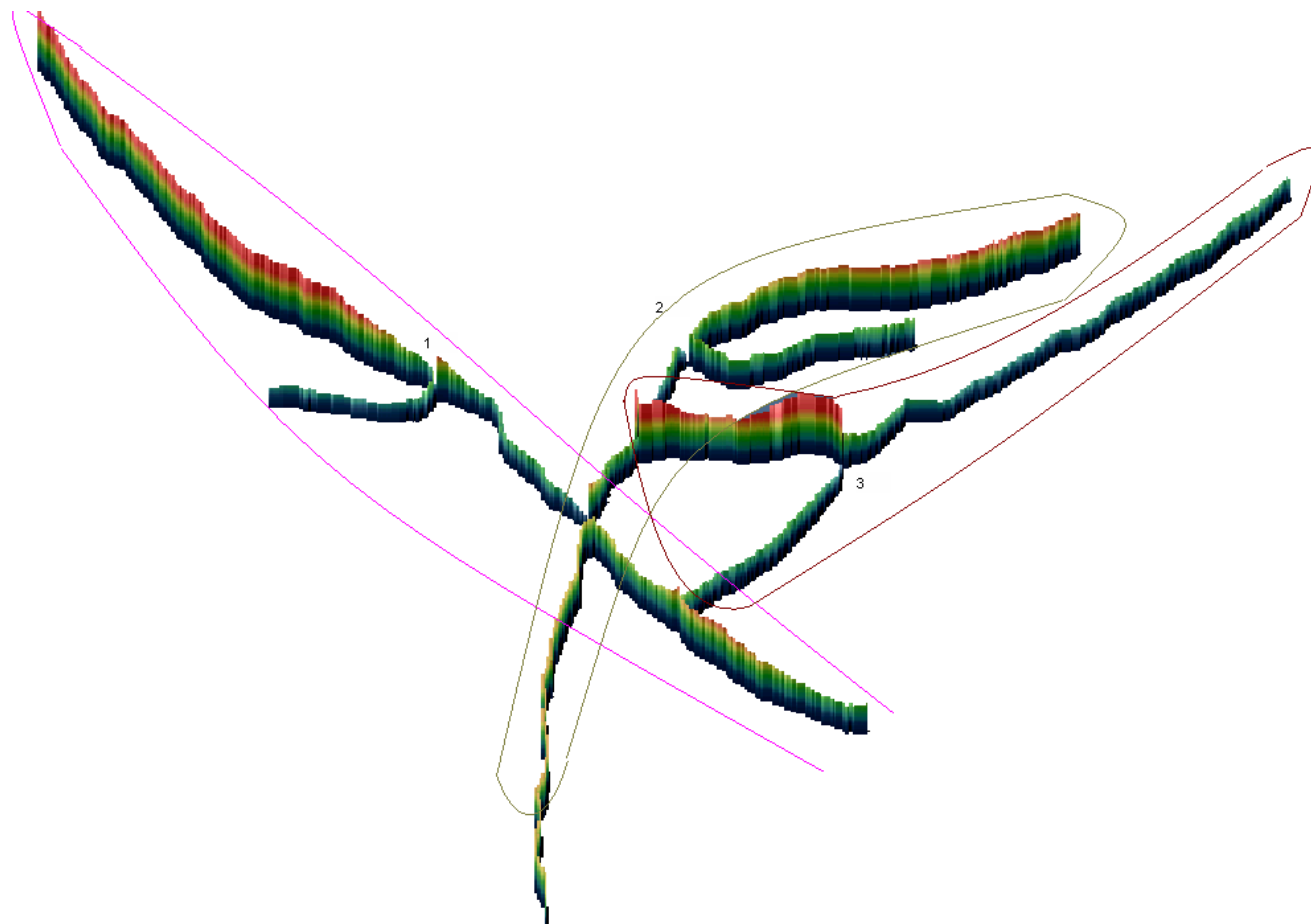
Method Overview



Skeletonization and leaf & intersection code lists

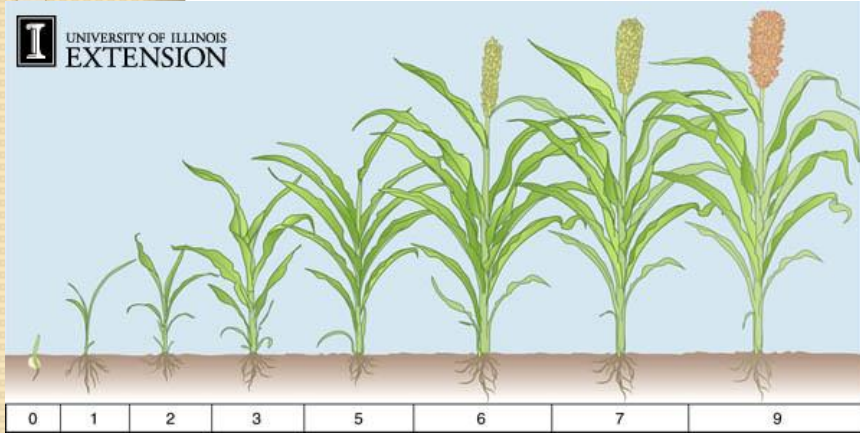


Result of identified stem centers



Robotic Phenotyping – Sorghum Biomass Traits

UNIVERSITY OF ILLINOIS
EXTENSION



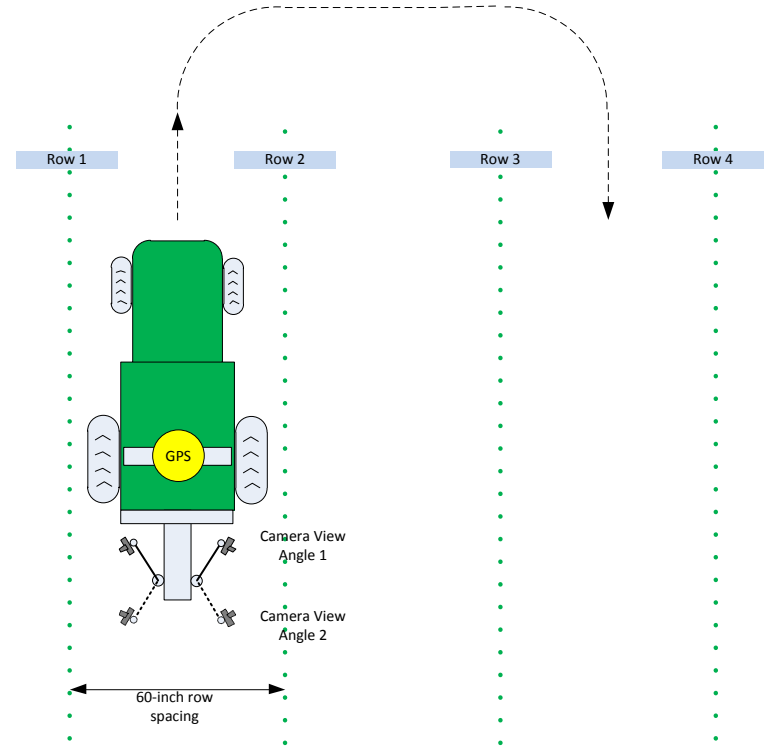
Genetic architecture of sorghum biomass yield-associated traits identified using high-throughput, field-based phenotyping technologies

PI: Patrick Schnable

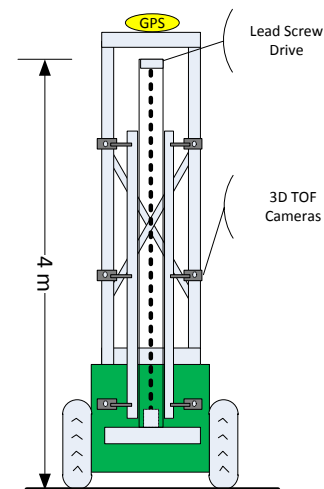
Co-PIs: Maria Salas Fernandez, Lie Tang

Sponsors: USDA, DOE

Top-View



Back-View



- Stereoscopic sensing
- Robot platform

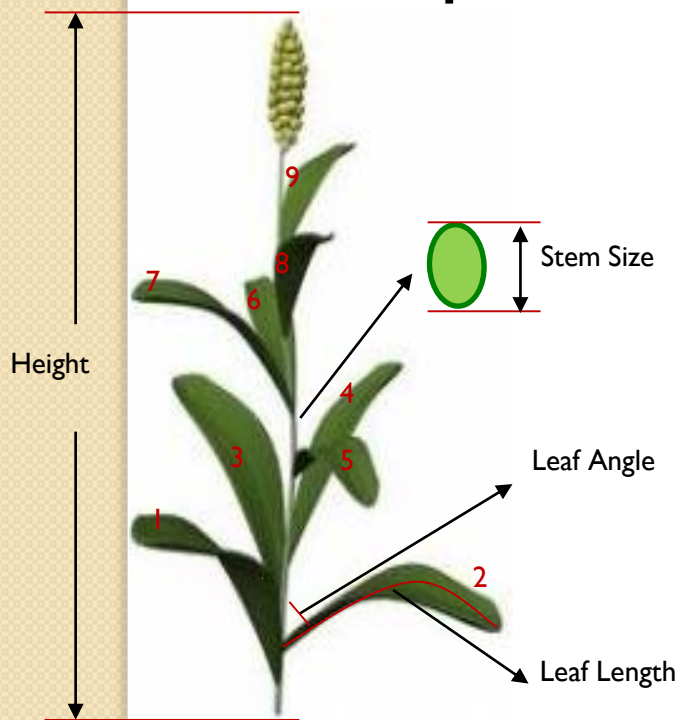
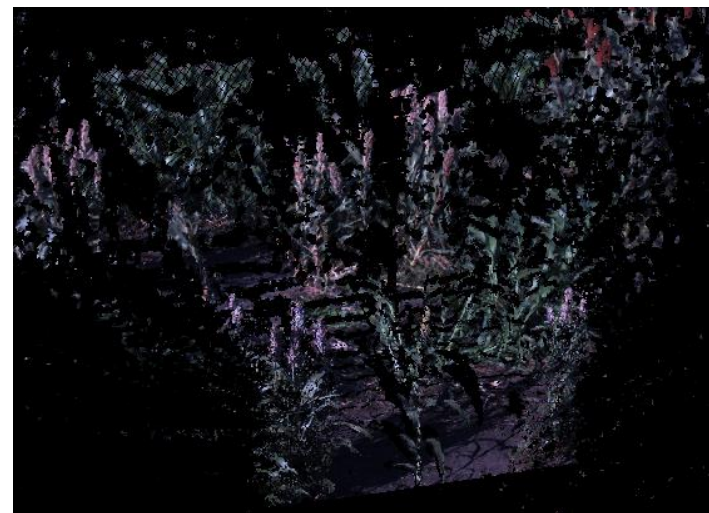
Stereo camera



Image pair

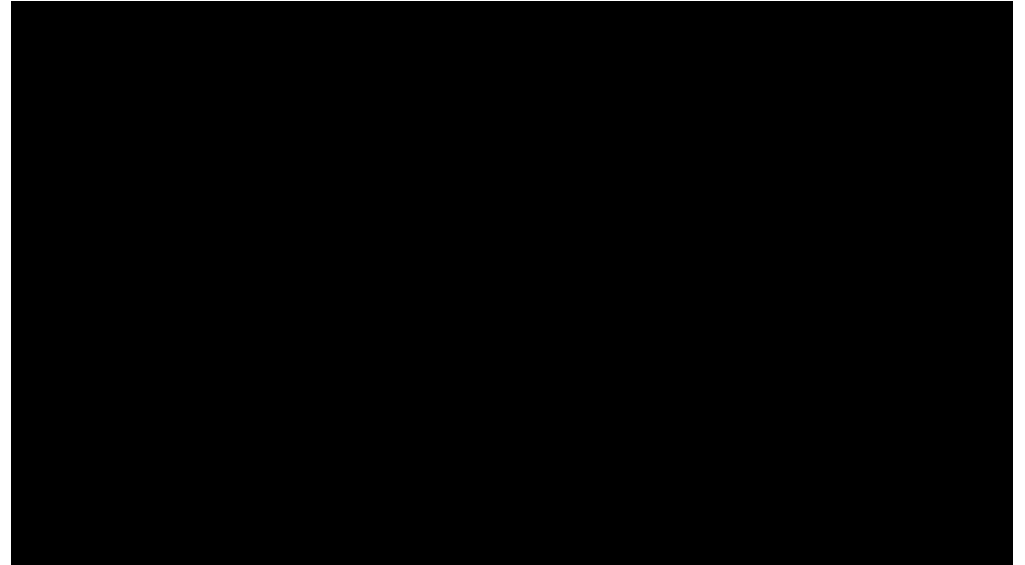


Point cloud

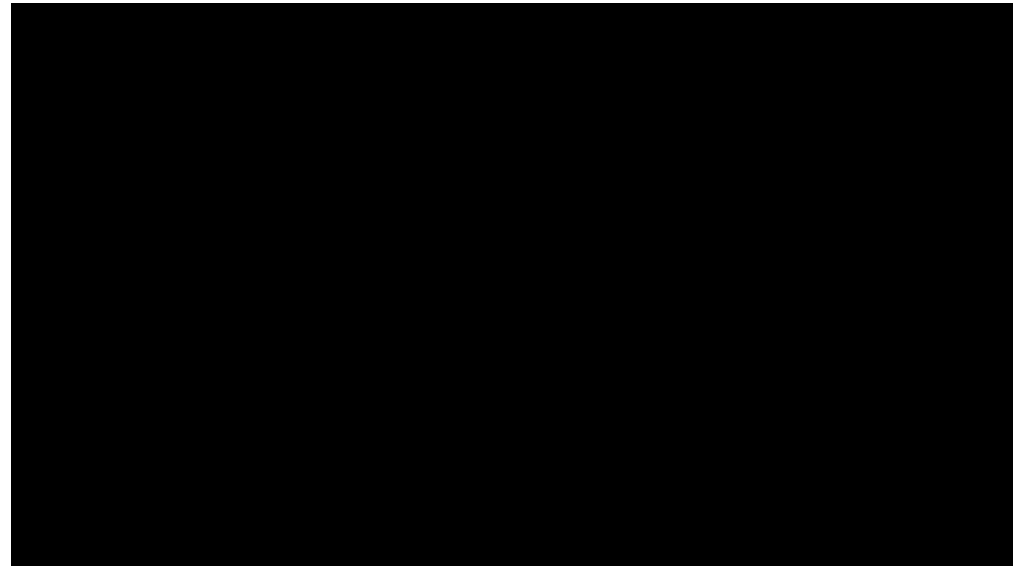


Robotic platform - PhenoBot





Video on scouting short plants



Video on scouting tall plants

Stereo camera



Camera



1. Rectification

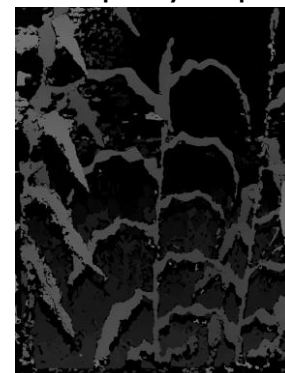


2. Equalization
3. Noise reduction



Stereo matching

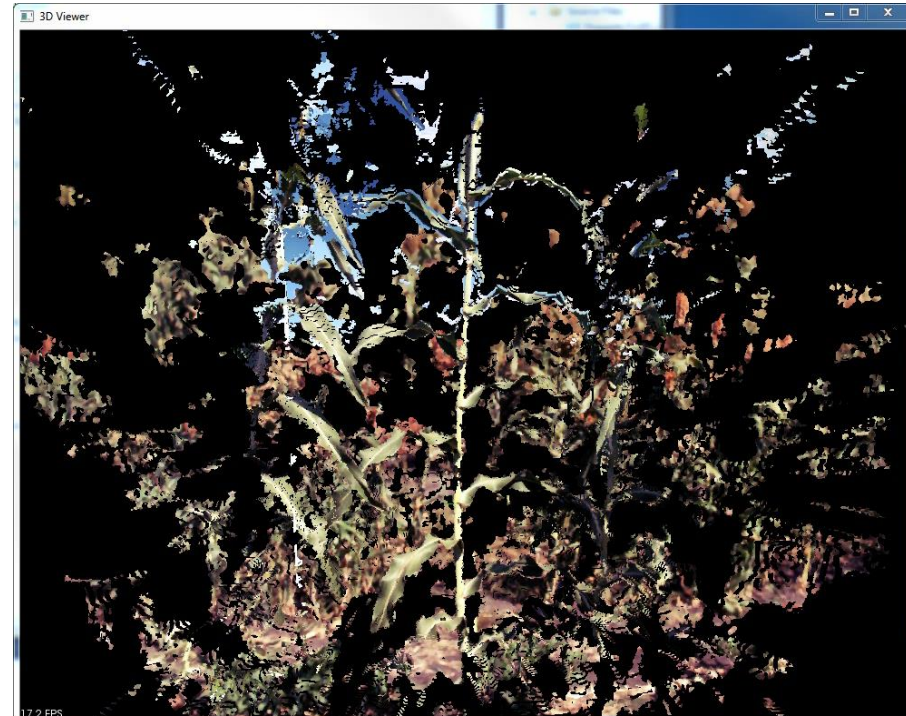
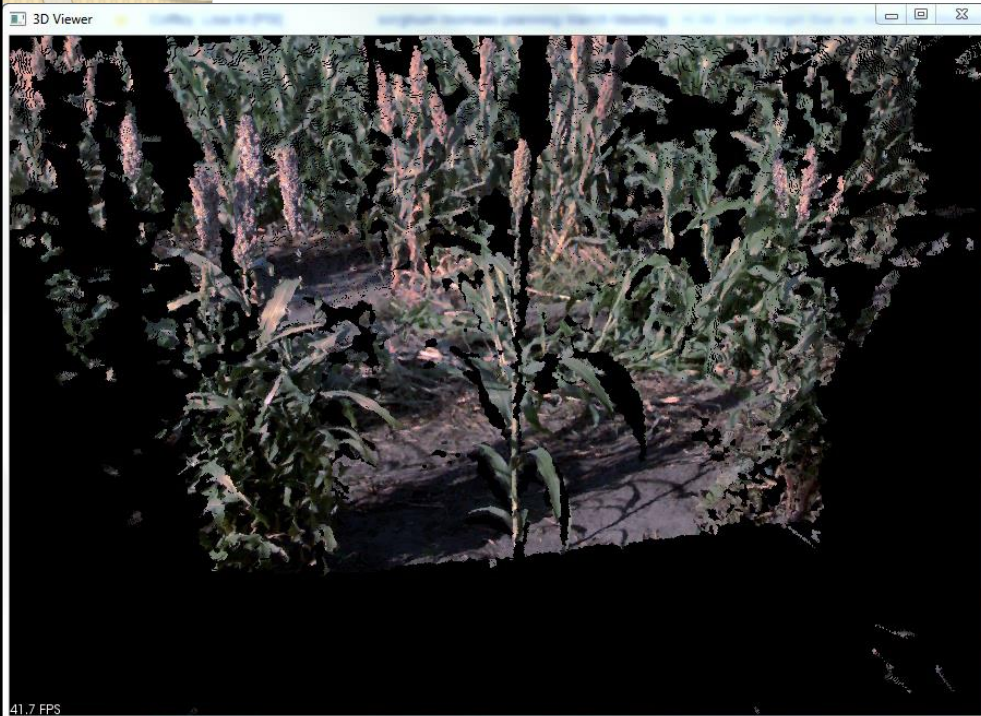
Disparity map



1. 2D to 3D
2. Remove background



3D point-cloud



3D point-cloud with higher image resolution

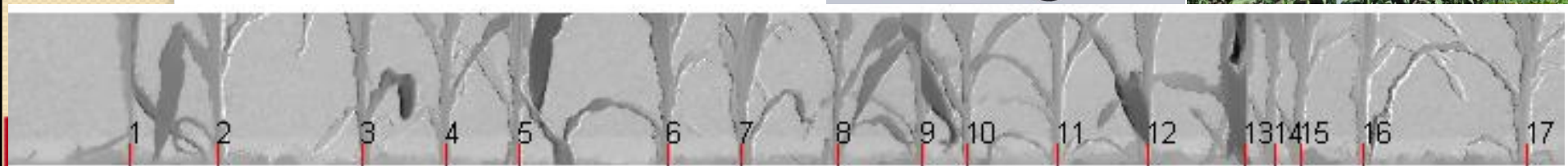
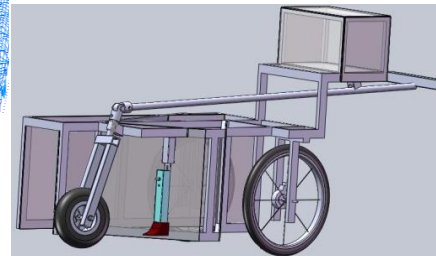
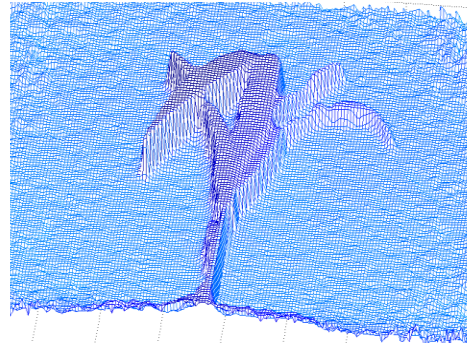
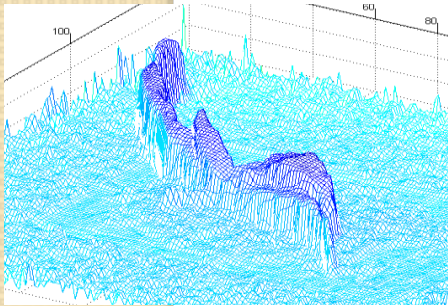
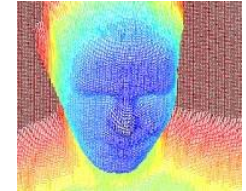
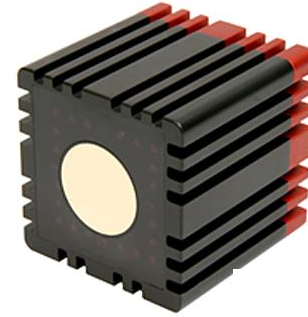
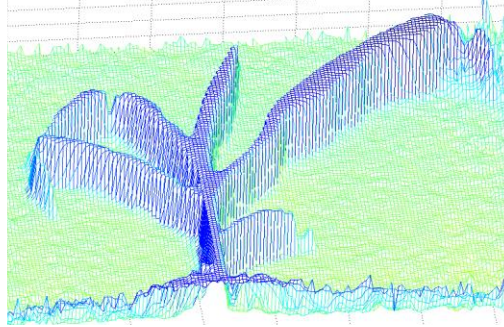


Need a clean segmentation at the first place.

Conclusions on stereo imaging

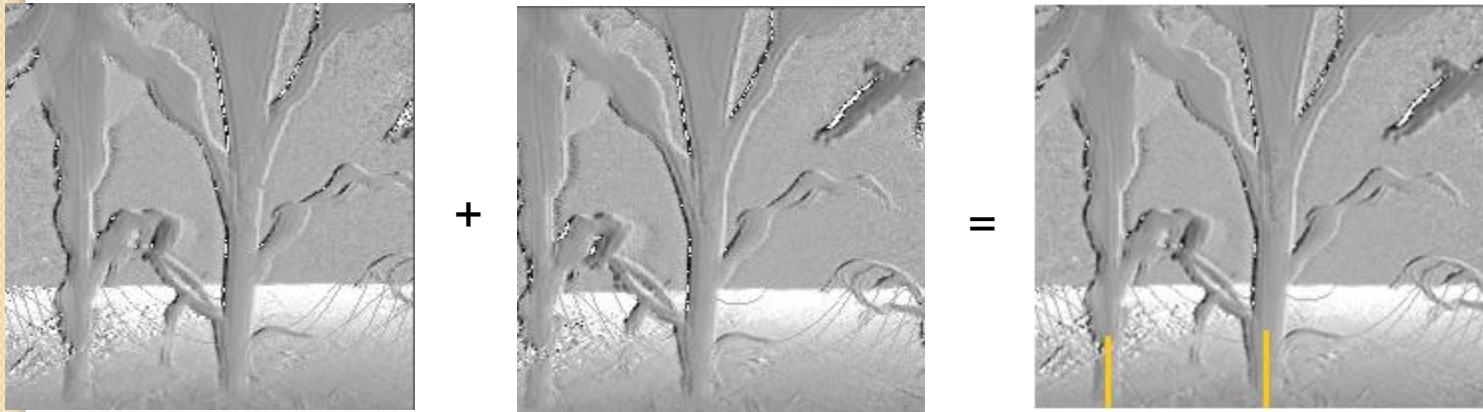
- Plus:
 - Utilization of depth information enables segmenting of individual plants.
 - High resolution and low-cost sensors are available.
- Delta:
 - The depth data generated by stereo head is often noisy and inaccurate.
 - Direct sunlight and variable lighting still impose challenges.
 - High computational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

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



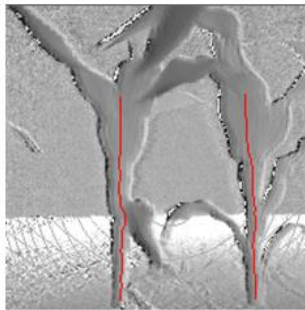
Data Processing

Stem matching & image mosaicking

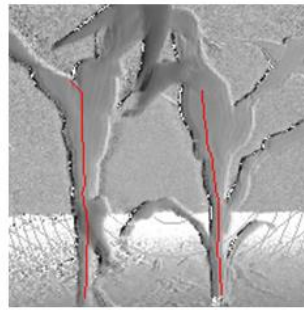


Inter-plant Spacing Sensing

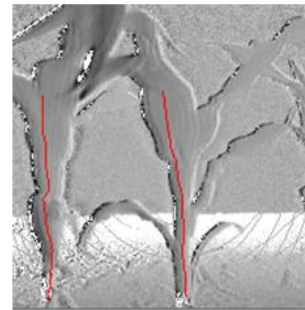
- Inter-plant distance measurement



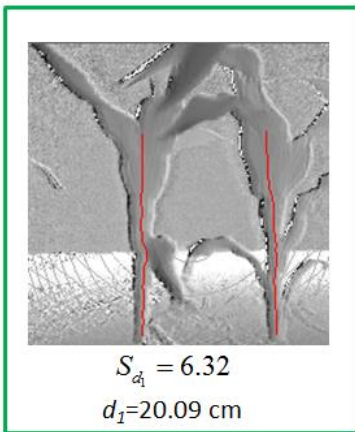
$S_{d_1} = 6.32$



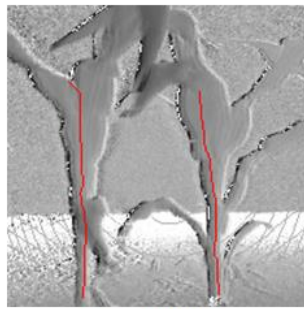
$S_{d_2} = 10.87$



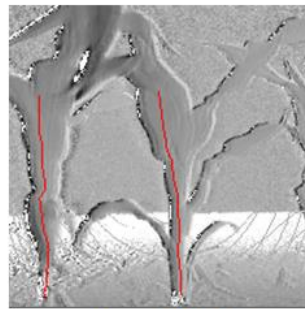
$S_{d_3} = 4070.37$



$S_{d_1} = 6.32$
 $d_1 = 20.09$ cm

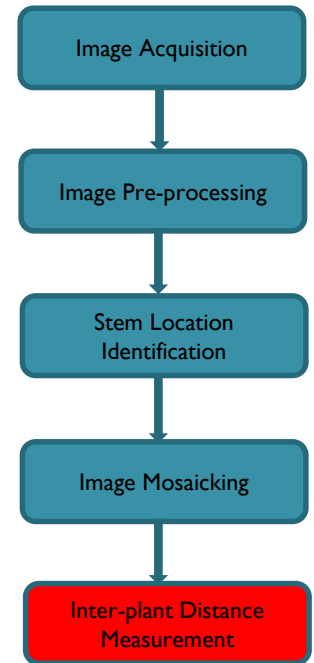


$S_{d_2} = 10.87$
 $d_2 = 20.38$ cm

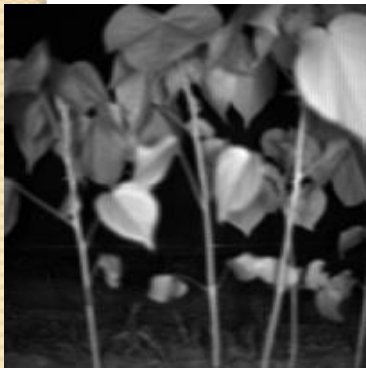
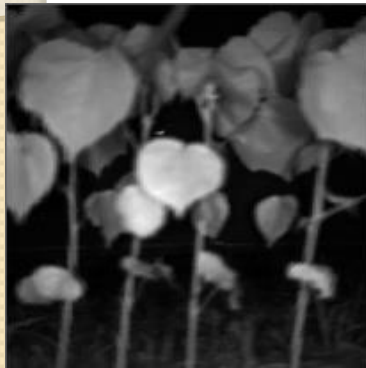


$S_{d_3} = 4070.37$
 $d_3 = 26.41$ cm

Manually measured distance was 20.21 cm.



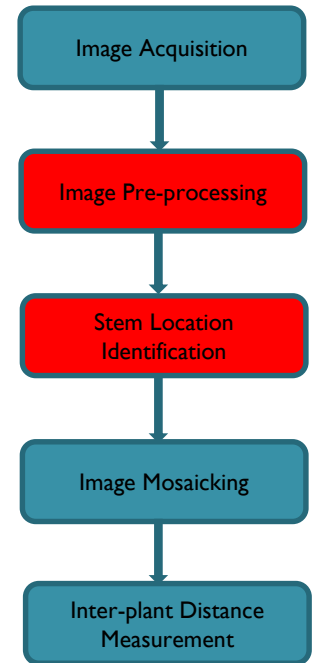
Cotton plant stem detection



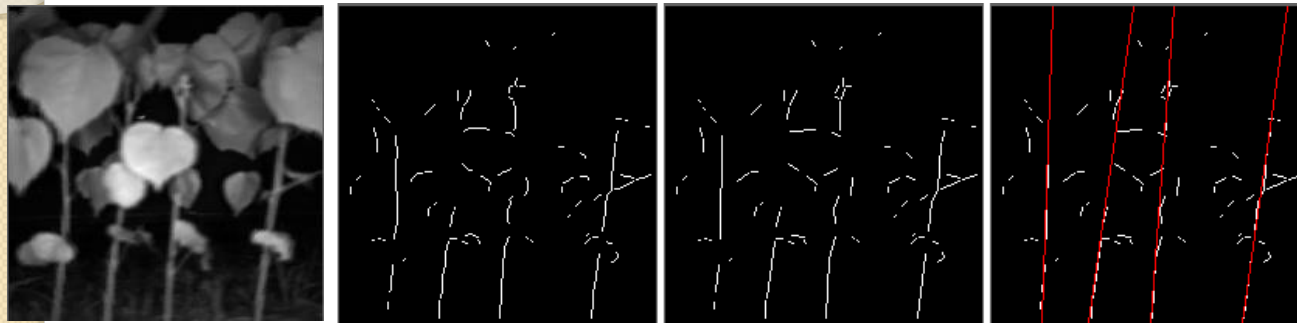
amplitude image

"vesselness" measure

"vesselness" filtered



Cotton plant stem detection

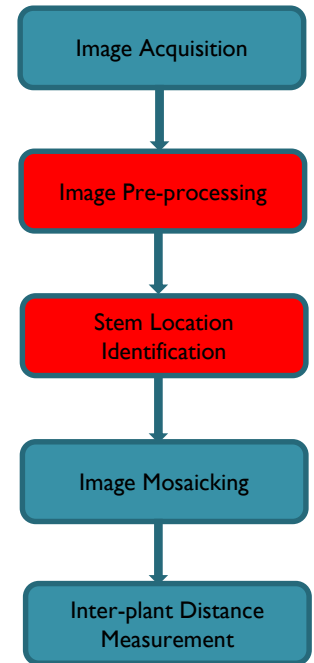


amplitude image

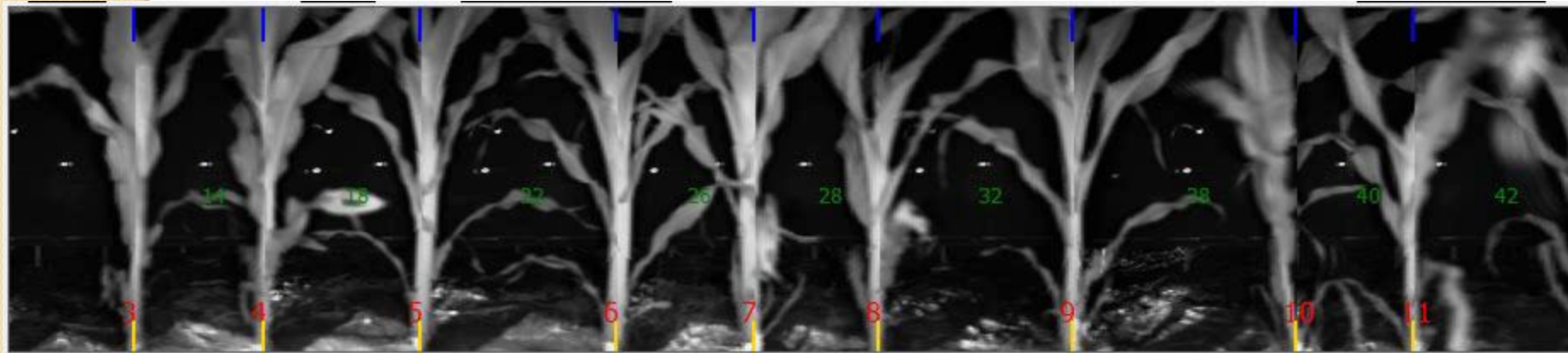
center pixels

line fitting

Hough lines



Software Demo

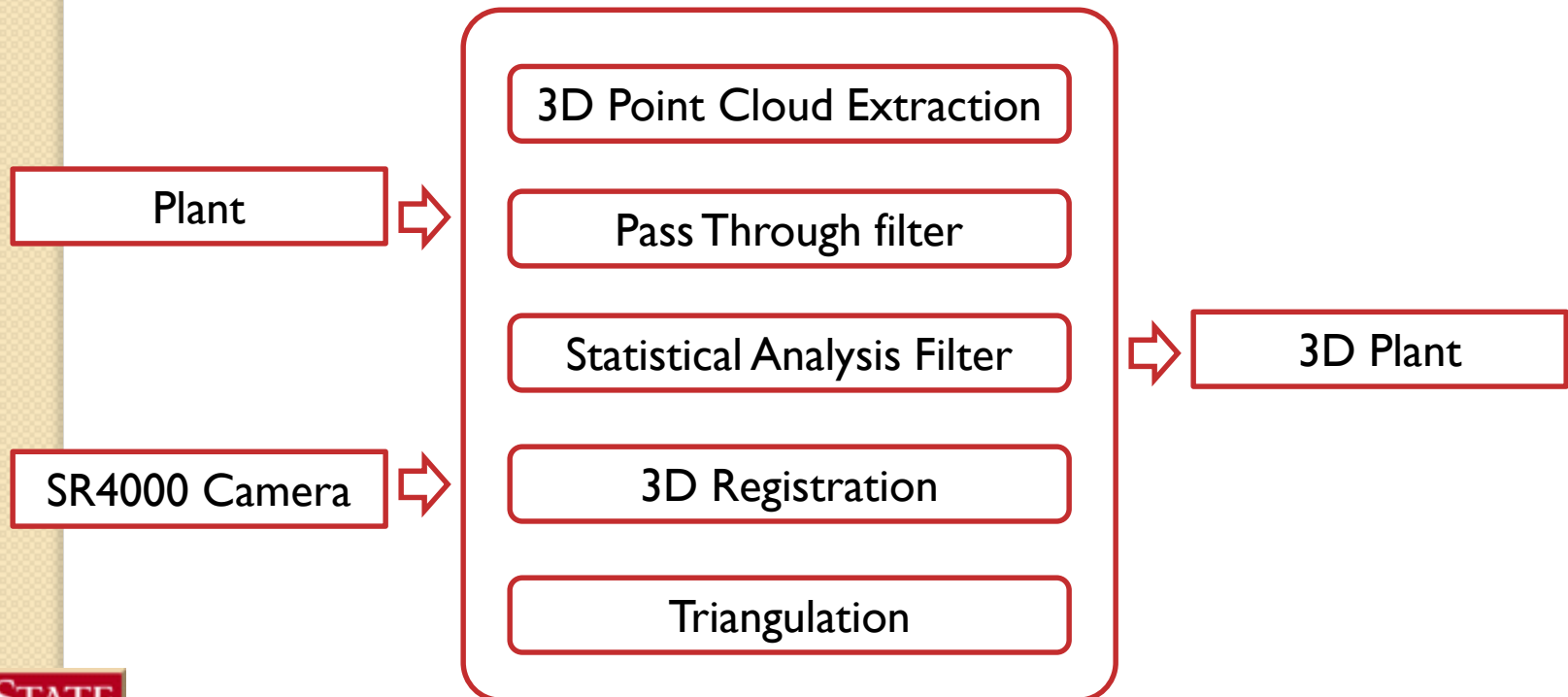


Good news: a new stand analyzer has been developed

- 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.

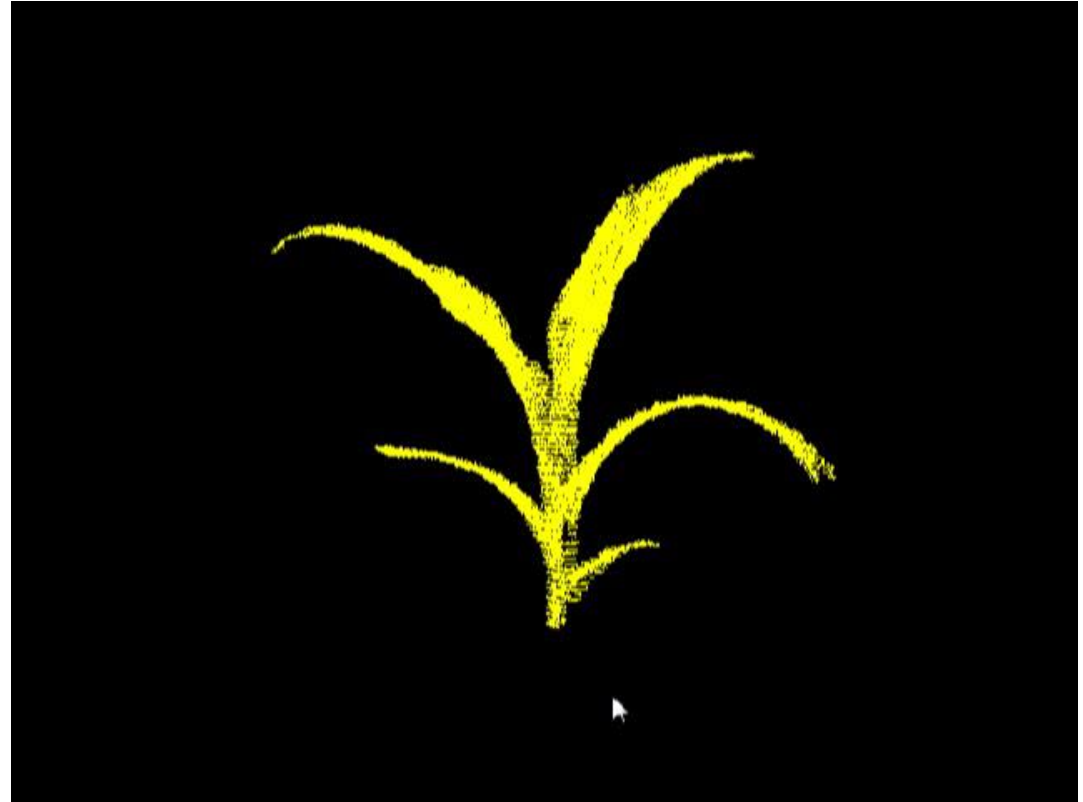
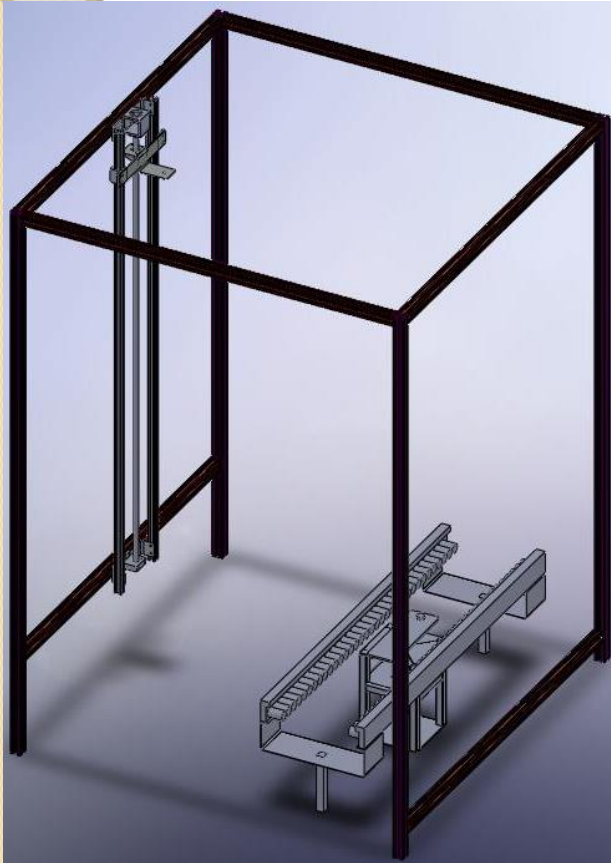
Indoor phenotyping using ToF 3D imaging

- 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

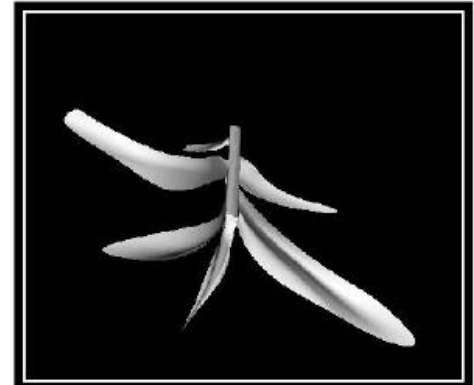
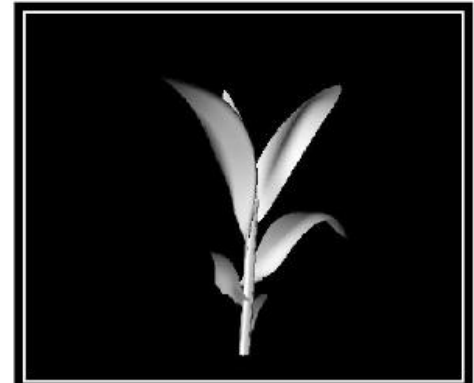
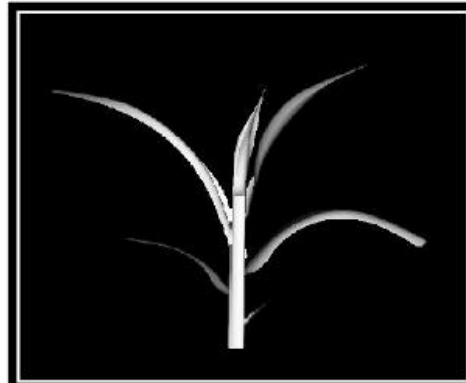
-Low image resolution necessitates multiple views



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

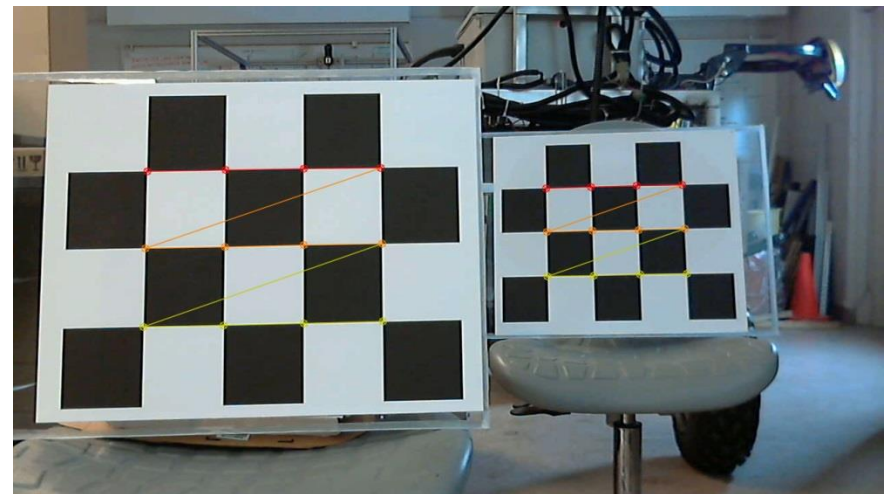
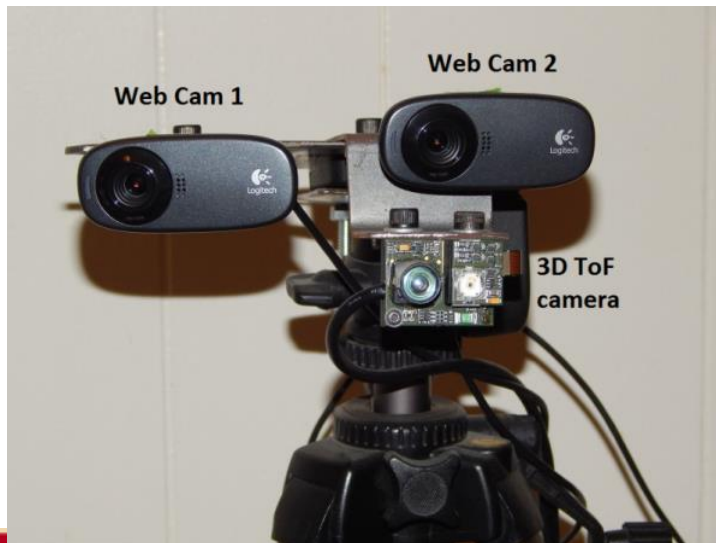
Calibration between 2D and 3D camera

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

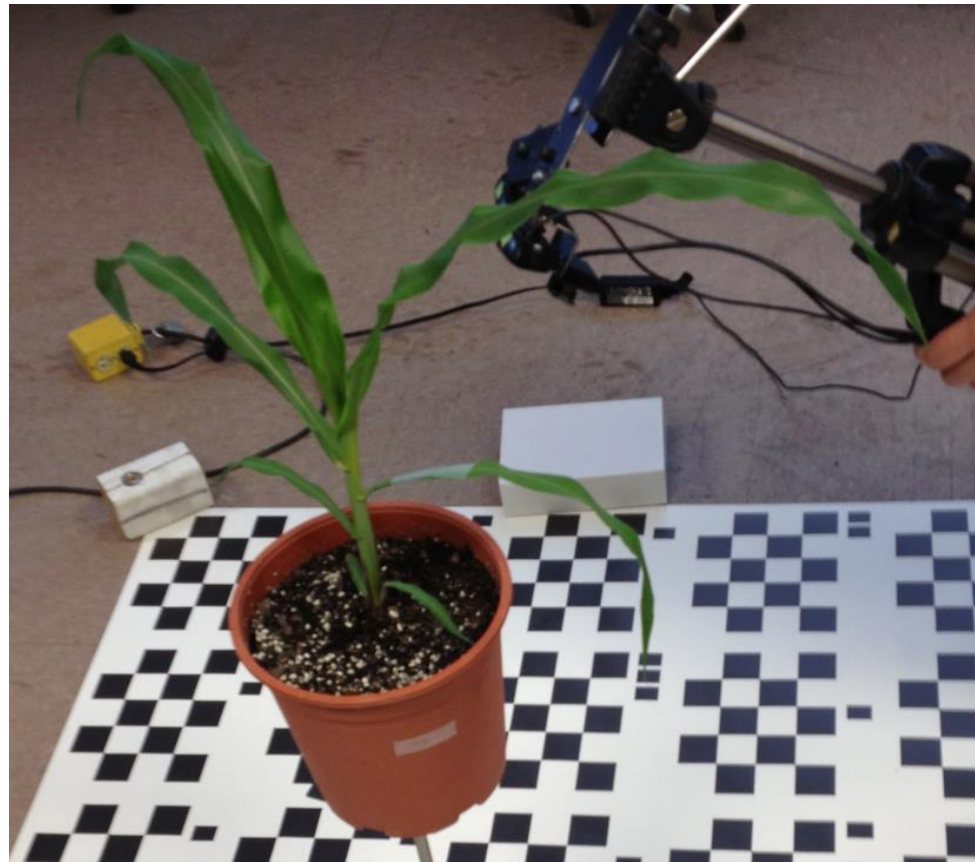
$$R_{3D22D} = R_{L22D}R_{3D2L}$$

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

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



Acquiring multiple views



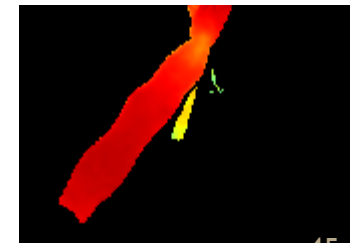
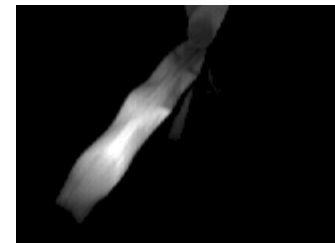
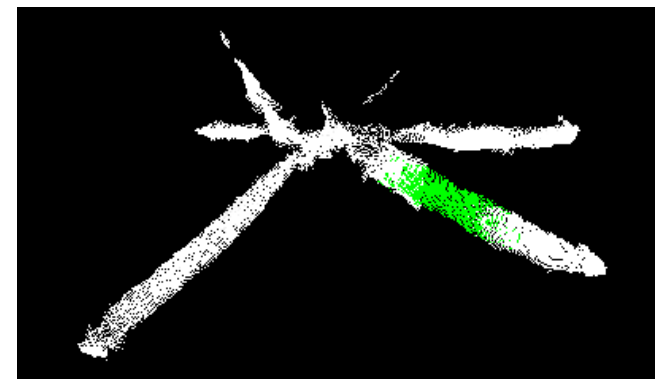
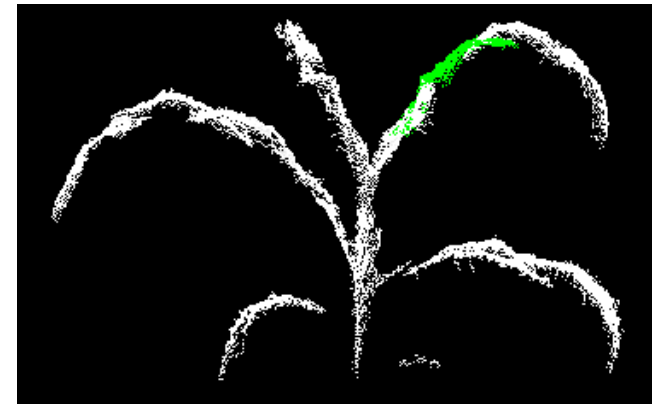
3D Registration

- 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:

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



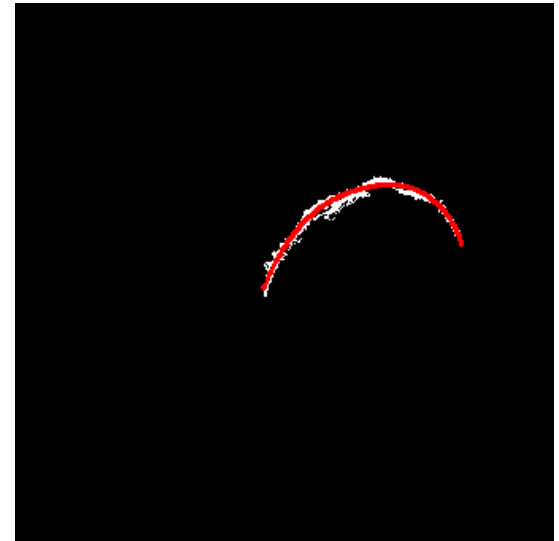
Physical parameter measurements

- 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

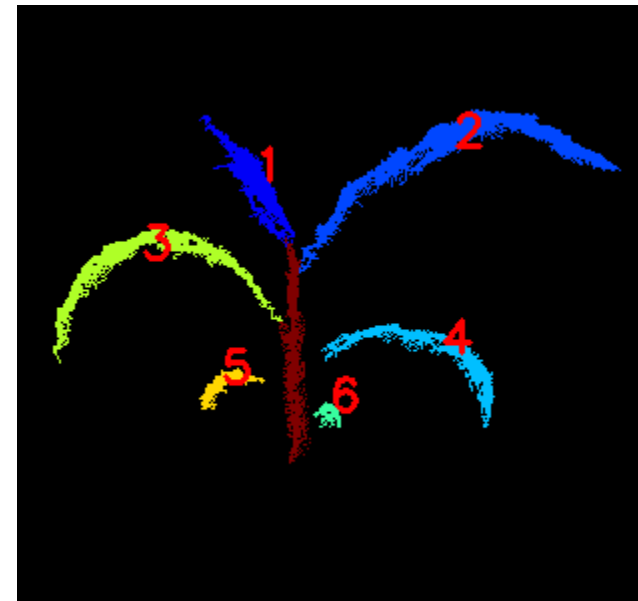
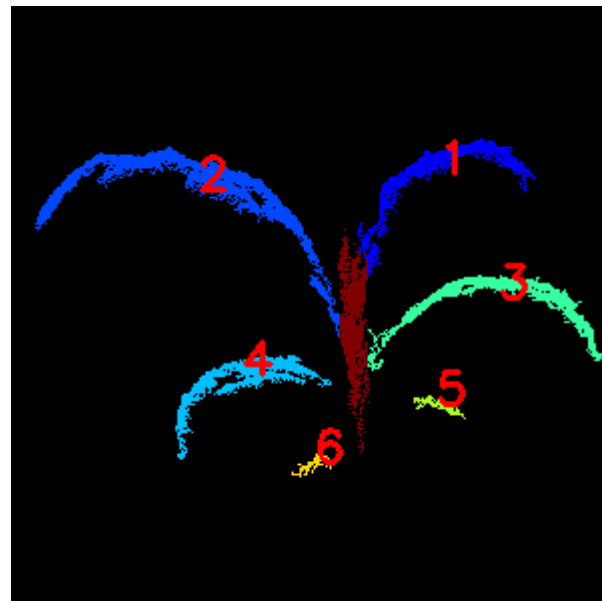
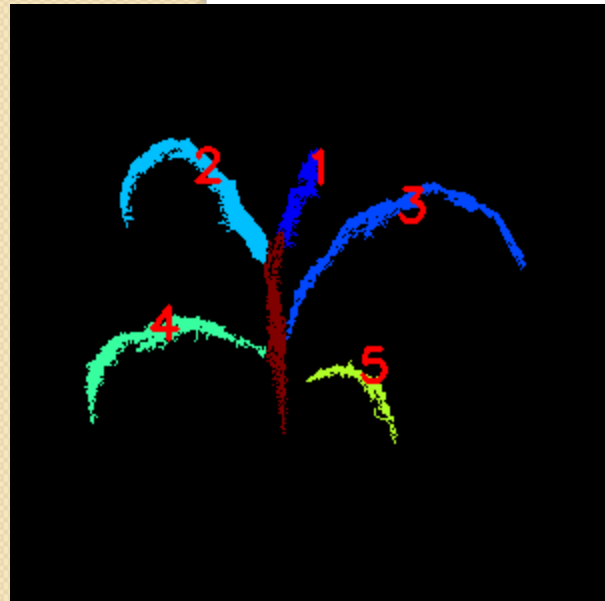


Results and Discussion

- 3D reconstruction result of plant 1

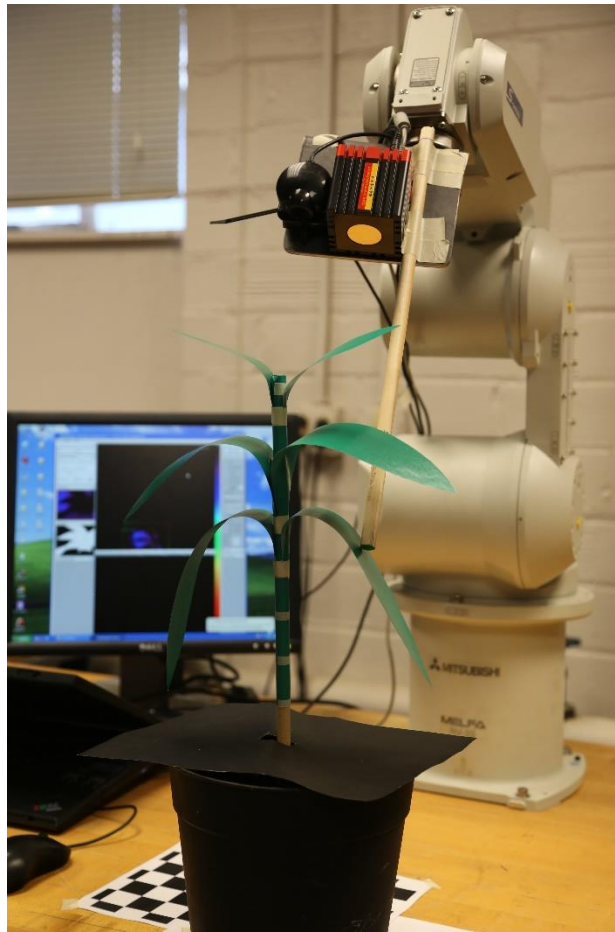


Stem and leaf recognition result



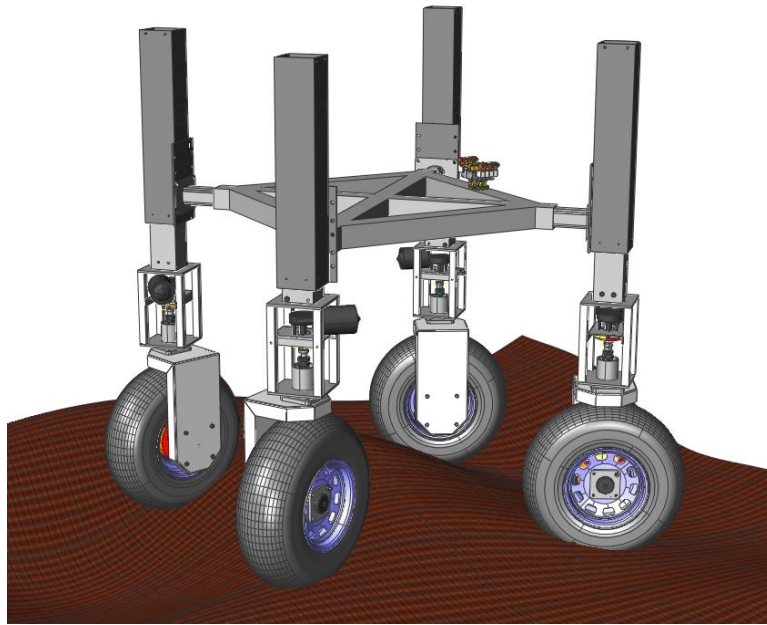
Robotic sampling and plant treatment

- sensor and hand coordination



2. Mobile Robotic Platforms

- AgRover – A Field Scouting Robotic Vehicle



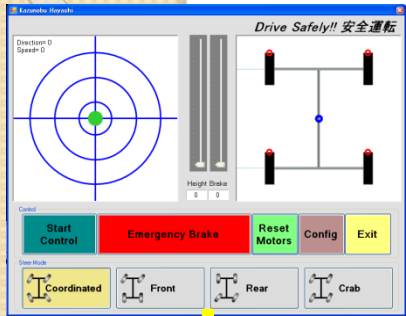
- Self-leveling on slopes
- Adjustable clearance
- 4-Wheel-Drive
- 4-Wheel-Steering
- Manual wireless Operation
- GPS-based auto-guidance

AgRover Prototype

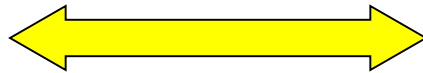


System Components

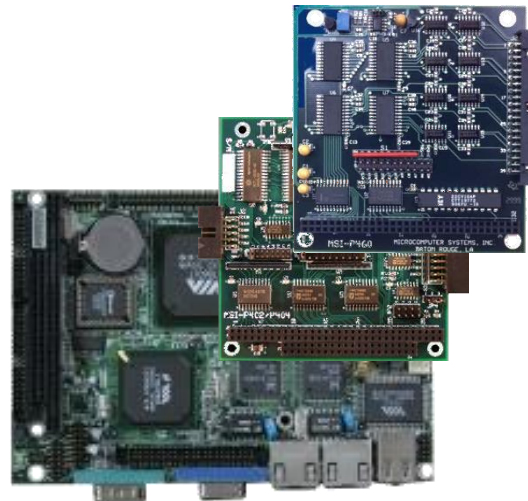
Manual and Automatic
Operation
Program



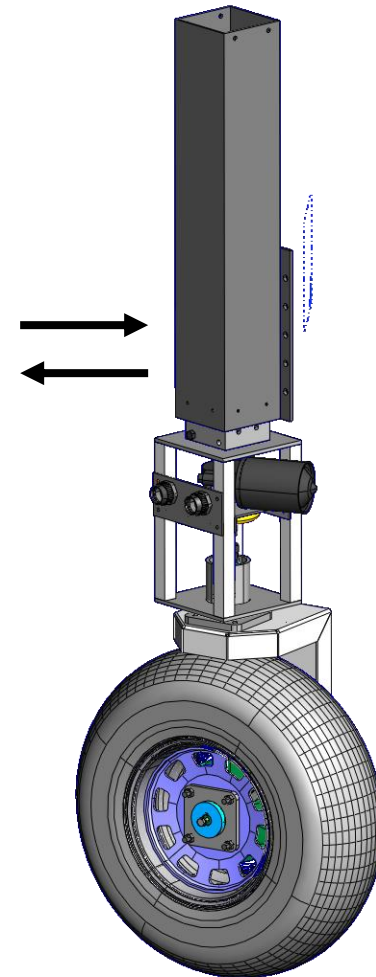
Communication
via Ethernet
by UDP Packets
(Wired or Wireless)



PCI04 I/O on
Mini PC



Motors &
Encoders



RTK-GPS



Height

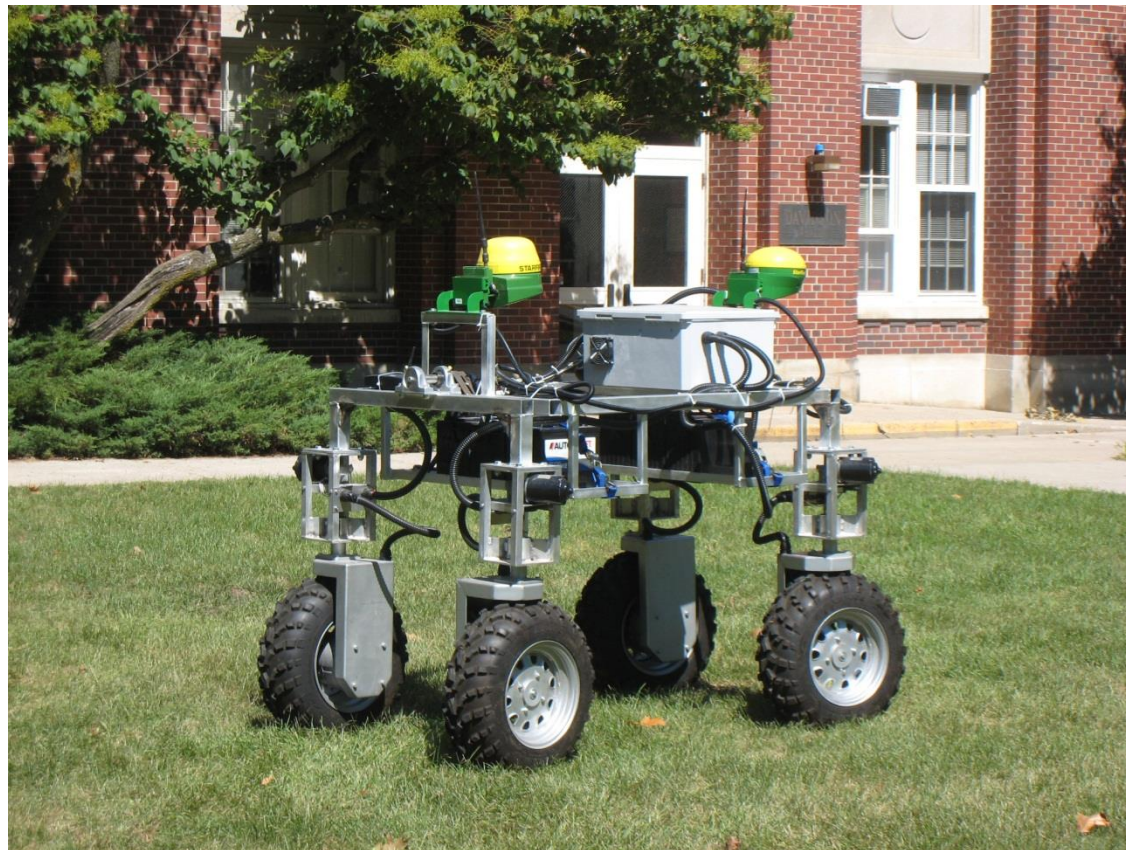


Leveling system controller

AgRover-1 Prototype



AgRover-2



AgRover-2 Scouting Robot





Thank You!