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Automated Plant Phenotyping using 3D Machine Vision and Robotics

Dissertation presented to Iowa State University, Ames, Iowa, USA

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1 Introduction

Crop yield trend has been found insufficient to meet the future global demand of food, feed, fuel, and fiber in a changing climate. The bottleneck of modern crop improvement is the lack of high-throughput tools for plant phenotyping (i.e., characterization of complex plant traits). Current practice heavily relies on manual measurement, which is time-consuming, error-prone, labor-intensive, and ergonomically poor. In this dissertation, three-dimensional (3D) machine vision-based robotic systems were developed and evaluated for automated plant phenotyping applications.

2 Sorghum Architecture Phenotyping

Rationale: Sorghum is a promising biofuel feedstock and the plant architecture determines light interception and photosynthesis, thus influencing grain and biomass yield. Despite easy access to the genotypic data, a large population has to be phenotyped to dissect the genetic control of plant architecture traits (i.e., plant height, leaf angle, leaf length, etc.). Thus, an automated system is needed.

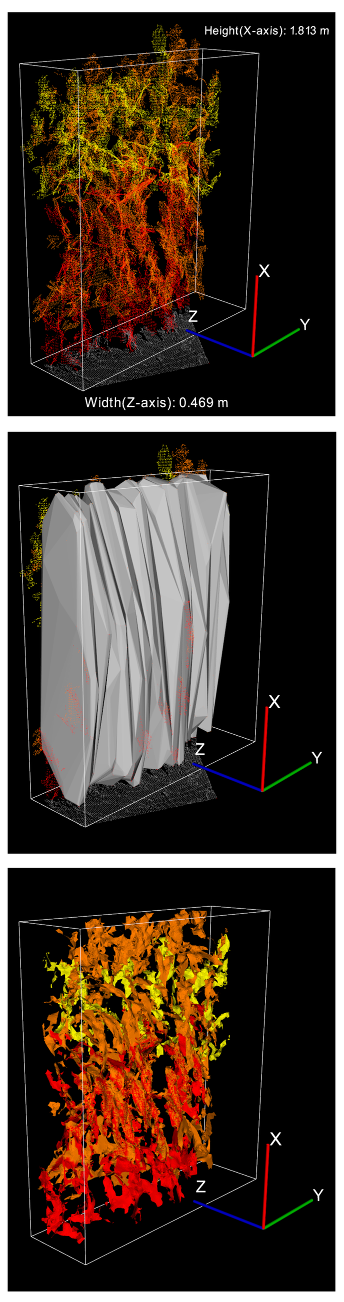
Methods: A multi-level, side-view 3D stereo imaging system was carried by a utility tractor retrofitted with an auto-guidance system. The platform navigated itself between crop rows while the cameras were triggered based on GPS locations of each plot. 3D point cloud processing algorithms were developed to extract plot-based plant architecture traits, which were evaluated using in-field manual measurements.

A multi-level, side-view stereo imaging system: PhenoBot 1.0

Results: 1) Satisfactory accuracy and precision were found between the image-derived traits and the manual measurements. 2) Manual measurements took 2.6 person-hours/plot while the robot system only took 1 min/plot.

Significance: The image-derived traits enabled plant scientists to conduct genome-wide association studies (GWAS) to identify genetic control of sorghum architecture.

Point cloud analysis



Key Results

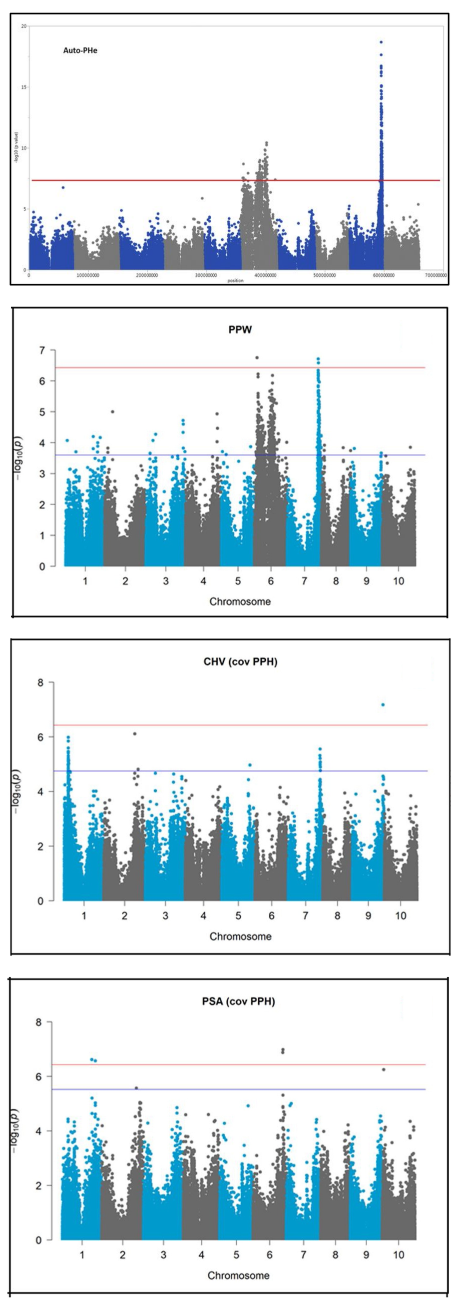
Plot-based **P**lant **H**eight → R^2 = 0.97, Coefficient of Variation (CV) = 4%

Plot-based **P**lant **W**idth → R^2 = 0.58, CV = 9%

Convex **H**ull **V**olume → R^2 = 0.69, CV = 18%

Plant **S**urface **A**rea → R^2 = 0.82, CV = 8.7%

GWAS



Association Significance → Gene location

PPH: plant height

Fernandez et al., 2017

PPW: related to leaf length and angle

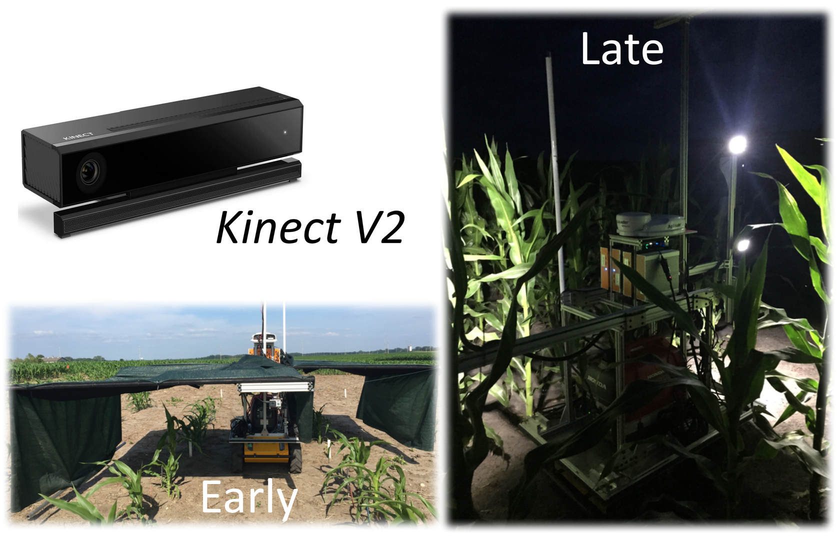
CHV: related to shoot compactness

PSA: related to leaf area

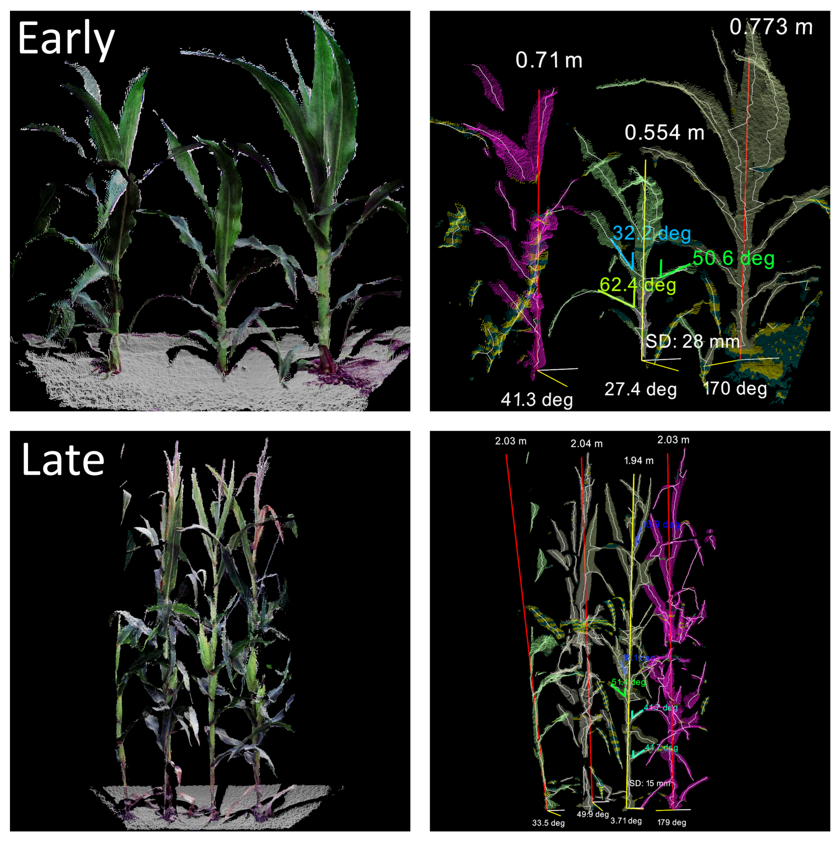
Breitzman et al., 2019

Bao et al., 2019, J. Field Robotics

3 Maize Architecture Phenotyping



PhenoBot 2.0



Individual maize architecture traits extraction using 3D point cloud skeleton analysis

Bao et al., 2019, Biosysems Eng.

Rationale: Maize is one of the most economically important cereal crops. Similar to sorghum, maize plant architecture plays a critical role in plant productivity.

Methods: A multi-level, side-view 3D imaging system was carried by an unmanned ground vehicle. Continuous RGB-D images were collected and georeferenced as the robot was remotely controlled to travel between crop rows. 3D point cloud processing algorithms were developed to extract individual plant architecture traits from individual plants.

Results: Satisfactory mean absolute error (MAE) and coefficient of determination (R^2) were achieved for plant height (before flowering: MAE 0.15 m, R^2 0.96; after flowering: MAE 0.054 m, R^2 0.83), leaf angle (MAE 2.8˚, R^2 0.83), and plant orientation (MAE 13˚).

Conclusions: The system was robust and accurate when the plants were imaged from only one side despite occlusions caused by leaves, and the method was applicable to maize plants from an early growth stage to full maturity.

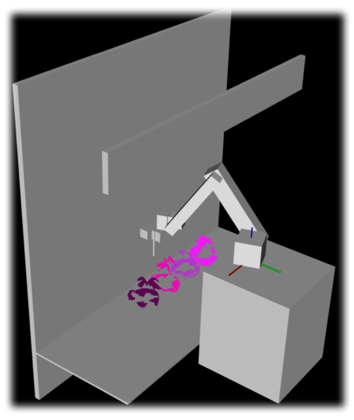
4 Robotic Leaf Probing

Operating a fluorimeter

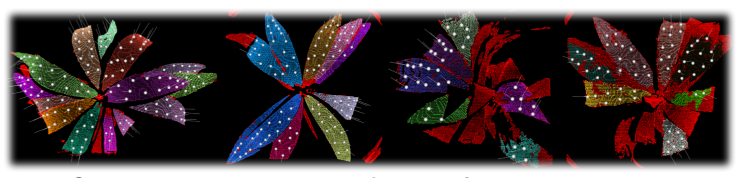
Rationale: Instrumentation devices for plant physiology study (e.g., spectrometer and fluorimeter) often require accurate positioning of their probes with respect to leaf surface. As a result, the measurement process is laborious.

System setup

Methods: A robotic arm was equipped with a Kinect V2 sensor and a laser profilometer to automate leaf probing in a growth chamber mockup. The Kinect was used to rapidly map the 3D environment, followed by K-means clustering plant segmentation. The profilometer was used to scan high-precision 3D plant models. The leaves and probing position candidates were found by 3D region-growing segmentation and super-voxel algorithms. Collision-free motion planning was adopted to maneuver the robot arm to probe leaves at user-defined distance and angle requirements.



Robot model and plant segments



Leaf segments and probing positions

Results: The system achieved an average motion planning time of 0.4 s with an average end-effector travel distance of 1 m. The average absolute probing errors of distance and angle were 1.5 mm and 0.84˚, respectively.

Bao et al., 2018, Trans. ASABE

Outcomes: Enviratron Phenomics Facility (Iowa State University)

Bao et al., 2019, Plant Methods

5 Final Remark

In this dissertation, 3D machine vision and robotics were utilized to advance high-throughput plant phenotyping in both field and controlled environments. Specifically, different 3D imaging sensors were investigated to gain insights into their utility in plant architecture characterization. Moreover, combing 3D machine vision and robotics enabled automated non-intrusive assessment and probing of 3D plant structures. The outcomes of this dissertation allowed plant scientists to conduct large-scale experiments where massive phenotypic data needs to be collected, which were previously impractical by conventional manual approaches. Finally, the highly interdisciplinary work has accelerated the understanding of complex biological systems which we rely on to feed and fuel the world.

6 Publications

1. Bao, Y., Tang, L., Salas Fernandez, M.G., Schnable, P.S. (2018). Field-based robotic phenotyping of sorghum plant architecture using stereo vision, *Journal of Field Robotics*, 36(2), 397-415.
2. Salas Fernandez, M.G., Bao, Y., Tang, L., Schnable, P.S. (2017). A high-throughput, field-based phenotyping technology for tall biomass crops. *Plant Physiology*, 174(4), 2008-2022.
3. Breitzman, M., Bao, Y., et al. (2019). Linkage disequilibrium mapping of high-throughput image-derived descriptors of plant architecture traits under field conditions. *Field Crop Research*, 244.
4. Bao, Y., Tang, L., Srinivasan, S., Schnable, P.S. (2019). Plant architectural traits characterization for maize using time-of-flight 3D imaging. *Biosystems Engineering*, 178, 86-101.
5. Bao, Y., Shah, D.S., Tang, L. (2018). 3D perception-based collision-free robotic leaf probing for automated indoor plant phenotyping, *Transactions of the ASABE*, 61(3), 859-872.
6. Bao, Y., et al. (2019). Assessing plant performance in the Enviratron. *Plant Methods*, 15(1): 117.