Giuseppe Pellizzi Prize 2024 - V Edition

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High-throughput robotic plant phenotyping using 3D machine vision and deep neural networks

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Extended Abstract

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Automation is crucial for improving the efficiency of plant breeding and crop production to meet the increasing food and energy demands of over nine billion people by 2050. Plant phenotyping, which refers to the assessment of plant phenotypic features related to growth, tolerance, architecture, and yield, can potentially aid in identifying high-yielding and stress-tolerant crop species. Robust crop species could be developed more rapidly than is currently possible by analyzing the relationship between genotypes and phenotypes under various growing environments. Boosted by technological developments such as high-throughput DNA sequencing, the efficiency of genotyping has greatly improved. However, phenotyping capability remains a bottleneck for dissecting the genetics of quantitative traits such as plant height, leaf angle, leaf area, and stem diameter. Conventional phenotyping practices are time-consuming, labor-intensive, and prone to human errors, with most phenotypes obtained destructively or through manual observations. Thus, it is vitally important to develop automation techniques for collecting phenotypic data with higher accuracy and efficiency.

The dissertation investigates and develops automated computer-vision-based robotic systems for plant phenotyping under controlled environments and field conditions. In particular, a novel stereo module was developed and utilized to acquire high-quality image data for in-field plant phenotyping. The system showed superior performance for agricultural applications, outperformed off-the-shelf 3D cameras, and has high market potential. With high-fidelity reconstructed 3D models and robust image processing algorithms, a series of plant-level and organ-level phenotypic traits of sorghum and maize plants were accurately extracted. The results demonstrated that, with proper customization, stereo vision can be a highly desirable sensing method for field-based plant phenotyping using high-fidelity 3D models reconstructed from stereoscopic images. The proposed approaches in this dissertation provide efficient alternatives to traditional phenotyping that could potentially accelerate breeding programs for improved plant architecture and significantly improve production efficiency in agricultural systems.

1. AUTOMATED MORPHOLOGICAL TRAITS EXTRACTION FOR SORGHUM PLANTS VIA 3D POINT CLOUD DATA ANALYSIS

Sorghum is an important grain crop and a promising feedstock for biofuel production due to its excellent drought tolerance and water use efficiency. If phenotypes such as plant height, stem diameter, and leaf area can be deduced from the 3D plant architecture without destroying the sorghum plant, then detailed evaluations of these parameters through time can help study the genetic basis of complex traits over a variety of genotypes, and hence improve the efficiency of breeding programs. However, in reality, phenotyping sorghum plants via imaging remains a particularly challenging task due to the occlusions caused by overlapping leaves and tillers, often leading to the requirement of user interaction to facilitate the image analysis.

An automated, low-cost machine vision system based on a commodity depth camera was developed to vertically acquire sequential side-view images of sorghum plants grown under controlled conditions at multiple developmental timepoints. The system aimed to: 1) reconstruct 3D surface models of plants, 2) develop a robust data processing pipeline to characterize plant architecture, 3) extract phenotypic data such as plant height, stem diameter, leaf angle, and leaf area, and 4) explore the use of extracted traits for plant biomass estimation. A novel 3D skeletonization algorithm was implemented to detect individual leaves and distinguish tillers by analyzing the 3D point cloud with a graph-based approach. The algorithm first identified the stem in the merged point cloud data and then the associated leaves. By slicing the point cloud vertically and linking connected Euclidean clusters between layers, overlapping tillers were separated using heuristic rules. Multiple parameters, including plant height, stem diameter, leaf angle, and leaf surface area, were obtained from the skeleton and reconstructed point cloud.

The study demonstrates that the use of automated machine vision and 3D modeling in agricultural automation and electronics shows great potential to advance plant phenotyping, reduce labor costs, and enhance the efficiency of plant breeding. The system demonstrated high correlations between manual measurements and estimated values, validating its accuracy. Statistical analyses revealed that stem volume was a promising predictor of shoot fresh weight and dry weight, and total leaf area was strongly correlated with shoot biomass at early stages. This indicates that the system can facilitate genomic studies and plant breeding programs by providing accurate and efficient phenotypic data. Future work will focus on improving algorithms to better address leaf occlusions and adapting this approach to different growth environments.

2. MEASURING STEM DIAMETER OF SORGHUM PLANTS IN THE FIELD USING A HIGH-THROUGHPUT STEREO VISION SYSTEM

The second phase studied the feasibility of stereo imaging for automatically measuring plant architectural traits in the field. Automating a process that can accurately measure organ-level traits of sorghum plants in the field has been challenging. A robust 3D imaging system is of great importance for agricultural automation under field conditions. In recent years, stereo vision has offered a viable three-dimensional (3D) solution due to its high spatial resolution and wide selection of camera modules. However, the performance of in-field stereo imaging for plant phenotyping has been adversely affected by textureless regions, occlusions, variable outdoor lighting, and wind conditions. In this research, a novel stereo imaging module, named PhenoStereo, was developed for high-throughput field-based plant phenotyping. PhenoStereo featured a self-contained embedded design, capable of capturing images at 14 stereoscopic frames per second. Additionally, a set of customized strobe lights was integrated to overcome lighting variations and enable the use of high shutter speeds to overcome motion blur.

To test its potential in agricultural automation applications, the developed 3D imaging system was utilized for phenotyping sorghum plants in the field. Stem diameter is an important trait for evaluating stalk strength and biomass potential but has been challenging to automate due to the complexity of the imaging object and environment. PhenoStereo was used to acquire images of sorghum plants, and an automated point cloud data processing pipeline was developed to extract the stems and quantify their diameters via an optimized 3D modeling process. The pipeline employed a Mask Region Convolutional Neural Network for detecting stalk contours and a Semi-Global Block Matching stereo matching algorithm for generating disparity maps. The correlation coefficient between the image-derived stem diameters and the ground truth was 0.97, with a root mean square error of 1.39 mm, outperforming previously reported sensing approaches. These results demonstrated that with proper customization, stereo vision can be a highly desirable sensing method for field-based plant phenotyping using high-fidelity 3D models reconstructed from stereoscopic images. With the promising results from sorghum plant stem diameter sensing, this stereo sensing approach can likely be extended to characterize a broad spectrum of plant phenotypes, such as leaf angle and tassel shape in maize plants, and seed pods and stem nodes in soybean plants.

3. FIELD-BASED ROBOTIC LEAF ANGLE DETECTION AND CHARACTERIZATION OF MAIZE PLANTS USING STEREO VISION AND DEEP CONVOLUTIONAL NEURAL NETWORKS

This study aims to develop an automated system for measuring the plant architecture of agronomically grown plants in the field. Maize is one of the three major cereal crops in the world. Leaf angle is an important architectural trait of crops due to its substantial role in light interception by the canopy and hence photosynthetic efficiency. Traditionally, leaf angle has been measured using a protractor, a process that is both slow and laborious. Efficiently measuring leaf angle under field conditions via imaging is challenging due to leaf density in the canopy and the resulting occlusions. However, advances in imaging technologies and machine learning have provided new tools for image acquisition and analysis that could be used to characterize leaf angle using three-dimensional (3D) models of field-grown plants.

Developing field-based automated high-throughput phenotyping systems for agronomically grown maize plants remains difficult due to the following field and crop conditions: (1) Narrow row spacing: Agronomically spaced maize crop rows are typically 0.76 m apart in the US, requiring the robotic vehicle to have a narrow body to traverse between crop rows; (2) Extreme plant height: Some maize plants can grow over 10 ft tall, necessitating multiple tiers of imaging sensors to cover the whole plant within the narrow agronomic row spacing; (3) Uneven ground surface: Running a narrow vehicle to image tall maize plants in close proximity on uneven field surfaces demands real-time balancing of the sensor mast; (4) Occlusion of plant canopies: There are serious occlusions of the plant organs (e.g., leaves, stalks) toward the imaging sensors; (5) Environmental variations: Variable lighting and wind conditions in the field can complicate the acquisition of images.

In this study, PhenoBot 3.0, a robotic vehicle designed to traverse between pairs of agronomically spaced rows of crops, was equipped with multiple tiers of PhenoStereo cameras to capture side-view images of maize plants in the field. A novel automated image processing pipeline (AngleNet) was developed to measure leaf angles of nonoccluded leaves. This pipeline detects each leaf angle as a triplet of keypoints in two-dimensional images and extracts quantitative data from reconstructed 3D models. AngleNet-derived leaf angles and their associated internode heights were highly correlated with manually collected ground truth measurements. Additionally, the framework was successfully implemented to explore the variation of leaf angle in the shoot architecture of two maize inbred lines, B73 and Mo17. The results of quantitative analysis were consistent with the actual leaf angle distributions along plant height in these lines. Our study demonstrates the feasibility of using stereo vision to investigate the distribution of leaf angles in maize plants under field conditions. The proposed system is an efficient alternative to traditional leaf angle phenotyping that could accelerate breeding for improved plant architecture.

4. Impact on Automation and Electronics in Agricultural Mechanization

Automation enabled by robotic systems and advanced sensor designs reduces labor costs and increases the efficiency and accuracy of phenotyping and other processes. The integration of electronics and AI, particularly through the use of high-speed, high-resolution imaging and novel processing algorithms, enhances the capability of these systems to operate under diverse field conditions, overcoming challenges such as variable lighting and occlusions. The impact of these technologies extends to accelerating breeding programs by providing high-quality and vital phenotypic data in an automated way. Furthermore, the ability to perform non-destructive, high-throughput phenotyping facilitates large-scale studies and the rapid development of more resilient and productive agricultural crops. In conclusion, the studies not only enhance the efficiency and accuracy of agricultural mechanization but also pave the way for future innovations in precision agriculture, contributing to the sustainability and productivity of global food systems.

Final remarks concerning benchmarks and strength points of the the Pellizzi Prize 2024

Dr. Xiang's dissertation merits the prize for these reasons:

- **Addressing Key Topics:** It addresses critical topics in "automation and electronics" within "Agricultural Machines and Mechanization," and presents innovative automation solutions through robotics and AI integration to tackle technical and labor challenges in agriculture.
- **Innovation and Originality:** It highlights a transformative approach by developing novel robotics and sensors for crop sensing and other agricultural applications.
- **Commercial Potential:** The research has high market transfer potential in its sensors and algorithms. The PhenoStereo system outperforms off-the-shelf 3D cameras for agricultural in-field applications, such as plant phenotyping, harvesting, field scouting, and precision weed control.
- **Impact on Agriculture:** The work significantly impacts agriculture by reducing labor costs for farmers, accelerating breeding programs, increasing production efficiency, and ultimately helping to feed more people.