FEDER UNACOMA
Italian Agricultural Machinery Manufacturers Federation

CLUB OF BOLOGNA
strategies for the development of agricultural mechanisation

Accademia dei Georgofili

Giuseppe Pellizzi Prize 2020

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Automated plant phenotyping using 3D machine vision and robotics

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Extended Abstract

Chapter 1. General introduction

To feed the global population, crop production needs to be doubled by 2050; yield trend, however, has been found insufficient to meet this requirement, let alone the rising demand for feed, fuel, and fiber. This growing agricultural crisis must be tackled in many different aspects to boost crop yield in a sustainable way. One of the most effective ways to increase crop yield potential is through plant breeding programs. The basic principle of plant breeding is to make crosses between different varieties under different environments, and select the best progeny based on the plant phenotypes. The rapid advancements in high-throughput genotyping technologies have greatly improved the efficiency and lowered the cost of molecular breeding in the last few decades. In contrast, little efforts have been dedicated to improving the efficiency of plant phenotyping to match the genotyping advances. Nowadays, the common practice of acquiring plant phenotypic data still resorts to in-field manual measurements and scouting, which is labor-intensive, time-consuming, and prone to human errors. Consequently, phenotypic data collection has been lacking spatial and temporal resolutions as well as precision; and the massive genomic information acquired with high-throughput DNA sequencing technologies has not been fully utilized for crop improvement. Therefore, there is a strong need for high-throughput plant phenotyping (HTPP).

Chapter 2. Field-based robotic phenotyping of sorghum plant architecture using stereo vision

Sorghum (*Sorghum bicolor*) is known as a major feedstock for biofuel production. To improve its biomass yield through genetic research, manually measuring yield component traits (e.g. plant height, stem diameter, leaf angle, leaf area, leaf number, and panicle size) in the field is the current best practice. However, such laborious and time-consuming tasks have become a bottleneck limiting experiment scale and data acquisition frequency. This paper presents a high-throughput field-based robotic phenotyping system which performed side-view stereo imaging for dense sorghum plants with a wide range of plant heights throughout the growing season. Our study demonstrated the suitability of stereo vision for field-based three-dimensional plant phenotyping when recent advances in stereo matching algorithms were incorporated. A robust data processing pipeline was developed to quantify the variations or morphological traits in plant architecture, which included plot-based plant height, plot-based plant width, convex hull volume, plant surface area, and stem diameter (semi-automated). These image-derived measurements were highly repeatable and showed high correlations with the in-field manual measurements. Meanwhile, manually collecting the same traits required a large amount of manpower and time compared to the robotic system. The results demonstrated that the proposed system could be a promising tool for large-scale field-based high-throughput plant phenotyping of bioenergy crops.

Chapter 3. Field-based architectural traits characterization of maize plant using time-of-flight 3D imaging

Maize (*Zea mays L.*) is one of the most economically important cereal crops. Though time- consuming and labor-intensive, manually measuring phenotypic traits in the field has been the common practice for maize breeding programs. This study presents a system for automated characterisation of several important plant architectural traits of maize plants under field conditions. An algorithm was developed to extract 3D plant skeletons from point cloud data acquired by side-viewing Time-of-Flight cameras. Plants were detected as 3D lines by Hough transform of the skeleton nodes. By analyzing the graph structure of the skeletons with respect to the 3D lines, the point cloud was partitioned into plant instances with the stems and the leaves separated. Furthermore, plant height, plant orientation, leaf angle, and stem diameter were extracted for each plant. The image-derived estimates of traits were compared to manual measurements at multiple growth stages. Satisfactory accuracies in terms of 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˚), except for stem diameter due to the limitations of the depth sensor. The results showed that 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.

Chapter 4. 3D perception-based collision-free robotic leaf probing for automated indoor plant phenotyping

Various instrumentation devices for plant physiology study such as spectrometer, chlorophyll fluorimeter, and Raman spectroscopy sensor require accurate placement of their sensor probes toward the leaf surface to meet specific requirements of probe-to-target distance and orientation. In this work, a Kinect V2 sensor, a high-precision 2D laser profilometer, and a six-axis robotic manipulator were used to automate the leaf probing task. The relatively wide field of view and high resolution of Kinect V2 allowed rapid capture of the full 3D environment in front of the robot. The location and size of each plant were estimated by k-means clustering where "k" was the user-defined number of plants. A real-time collision-free motion planning framework based on Probabilistic Roadmaps was adapted to maneuver the robotic manipulator without colliding with the plants. Each plant was scanned from the top with the short-range profilometer to obtain high-precision 3D point cloud data. Potential leaf clusters were extracted by a 3D region growing segmentation scheme. Each leaf segment was further partitioned into small patches by a Voxel Cloud Connectivity Segmentation method. Only the patches with low root mean square errors of plane fitting were used to compute leaf probing poses of the robot. Experiments conducted inside a growth chamber mock-up showed that the developed robotic leaf probing system achieved an average motion planning time of 0.4 seconds with an average end-effector travel distance of 1.0 meter. To examine the probing accuracy, a square surface was scanned at different angles, and its centroid was probed perpendicularly. The average absolute probing errors of distance and angle were 1.5 mm and 0.84˚, respectively. These results demonstrate the utility of the proposed robotic leaf probing system for automated non-contact deployment of spectroscopic sensor probes for indoor plant phenotyping under controlled environmental conditions.

Chapter 5. General conclusions

In this dissertation, 3D machine vision and robotics were utilized to advance the research area of high-throughput plant phenotyping (HTPP) in both field environments and controlled environments. First, two field-based (robotic) plant architecture phenotyping systems using 3D imaging were developed and evaluated for maize and sorghum plants, respectively. Second, 3D perception-based collision-free robotic leaf probing was realized for indoor plant phenotyping. Through the three projects reported in Chapter 2, 3 and 4, three types of 3D sensors (i.e., stereo camera, time-of-flight camera and laser profilometer) were investigated to gain insights into their utility in different HTPP applications. Moreover, combing 3D machine vision and robotics enabled automated non-intrusive assessment and probing of 3D plant structures. Future research will focus on developing a robotic platform that can self-navigate in standard crop row spacing and a stereo camera module with active strobe lighting to overcome the challenging field lighting conditions. In addition, deep convolutional neural networks will be investigated for 2D and 3D instance segmentation of plant organs (i.e., stems, leaves, panicles and ears).

Final remarks concerning the competition benchmarks and strength points

The outcomes of the dissertation are helping plant scientists accelerate crop improvement in a changing climate. The system-derived phenotypic data in Chapter 1 were successfully utilized in a genome-wide association study to locate significant genes for bioenergy sorghum plant architecture breeding. The system reported in Chapter 3 is the foundation of the Enviratron plant phenomics facility at Iowa State University, where plant gene-environment interaction research is being conducted.