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3D Robotic System Development for High-throughput Crop Phenotyping

Chongyuan Zhang*, Honghong Gao*,, Jianfeng Zhou*, Asaph Cousins***, Michael O. Pumphrey****, Sindhuja Sankaran***

**Department of Biological Systems Engineering, Washington State University, Pullman, WA, USA*

***Xi'an Technological University, Shaanxi, China*

****School of Biological Sciences, Washington State University, Pullman, WA, USA*

*****Department of Crop and Soil Sciences, Washington State University, Pullman, WA, USA*

Corresponding author: Sindhuja Sankaran (sindhuja.sankaran@wsu.edu)

Abstract: Plant breeding programs are working towards developing new high-yielding crop varieties to accommodate the increasing demand for food. However, high-throughput phenotyping remains to be the bottleneck that is currently limiting the complete breeding potential. In this project, a 3D robotic system was developed to conduct automated high-throughput phenotyping in cereal crops. The 3D robotic phenotyping system consisted of an aluminum framework to support a 3D sliding system (sliders and tracks), which allows a sensor mount travel in X and Y axis in a selected height (Z axis). The system was controlled with a custom designed algorithm based on LabVIEW program. A control box was used to interface the system with a computer. During preliminary evaluation, a thermal camera and a multispectral camera were installed on the sensor mount, and the integrated automated phenotyping system was continuously operated for 48 hours for autonomous data collection. The 3D robotic system had been working precisely based on the design specifications. Results showed that the 3D robotic system had time repeatability with trigger activation within 4 s and positioning error less than 0.78 mm, indicating the potential of system for automated, systematic high-throughput phenotyping.

Keywords: Automation, Crop monitoring, Data acquisition platform, Plant breeding.

1. INTRODUCTION

Plant breeding has continued to make significant contribution in the development of new high-yielding crop varieties that are tolerant to biotic and abiotic stresses, such as diseases, pests, drought, and salinity. The demand for plant breeding to come up with even better varieties is even higher than before, because of not only growing population, which is expected to grow from 7 billion in 2011 to 9.15 billion in 2050 (Alexandratos and Bruinsma, 2012), but also an increment in consumption per capita and changes in diet structure. FAO reported that in 2050, around 4.7 billion people or 52 percent of world population may consume 3,000 kcal/person/day, resulting in an increase in the consumption of agricultural products at a rate of 1.1 percent each year from 2005/2007 to 2050 or 60 percent increment of consumption of agricultural products compared with that of 2005/2007 (Alexandratos and Bruinsma, 2012). Meanwhile, climate change also threatens the agricultural production, because of the altered climate pattern and more frequent extreme weather conditions. Although genotyping makes great contribution to plant breeding due to the progress in genetic analysis technologies, such as marker-assisted selection (MAS), in recent years, progress of plant breeding is still very slow due to lack of high-throughput phenotyping techniques. Phenotyping is critical as it evaluates genotype effects and separates them from environmental effects. It is known that phenotyping is labor-intensive and time-consuming, especially for field-based trials. It is reported that a corn breeding project consisting of up to 5,000 lines and two replicates would result in 20,000 plots of 1 m by 4 m (W by L), which would take 27 h to walk through and score with a non-stopping walking speed of 3 km/h (White et al., 2012). When measurements of plant physiological or morphological traits are integrated with these measures, the processes can be almost impossible to be completed within a reasonable time span. On the other hand, some of current phenotyping technologies are destructive, for example, biomass and nitrogen estimation, which is not an option for early stage of plant breeding project due to the limited number of plants in each hybrid line. All these limitations in current phenotyping technologies raise an urgent need for non-destructive high-throughput phenotyping techniques.

With the help of sensors and robotic platforms, high-throughput phenotyping technique has the potential to replace conventional phenotyping operated by human. Researchers have reported success in applying high-throughput phenotyping techniques for the detection and monitoring of plant health, water, and nutrition status using spectral

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reflectance images. Oerke and Steiner (2010) reported that ears of winter wheat inflected by fusarium head blight shows significantly higher temperature than that of uninfected ears using infrared thermography. Similarly, Bauriegel et al. (2011) showed that fusarium infection in wheat can be detected using hyperspectral imaging in early inflection stage with a correct classification rate of 87% attributed to imaging analysis method Spectral Angle Mapper. Bravo et al. (2003) revealed through a visual spectrograph with ambient illumination conditions and a quadratic discriminating model based on the reflectance of four wavebands, it is able to successfully discriminate heathy and diseased (*Puccinia striiformis*, yellow rust) winter wheat with an accuracy rate of 96%. Besides monitoring plant health, high-throughput phenotyping can also be used to detect plant water status. Greenhouse experiment conducted by Hackl et al. (2012) detects temperature differences between stress treatments (control, drought, salt, and combined salt and drought) ranged from 1-9°C and between two Egyptian wheat cultivars (Sakha 61 and Sakha 93) ranged from 0-2°C, using infrared thermometry and thermography. Other applications of high-throughput phenotyping also include detecting early plant vigor of winter wheat (Kipp et al., 2014), vegetation, pigments, and biomass.

High-throughput phenotyping demonstrates better performance in some aspects, in terms of non-destructive measurements and high efficiency, and accomplishes what traditional phenotyping cannot do. For instance, Liebisch et al. (2015) estimated that it would take about 6 min to monitor 20,000 plots as described in White et al. (2012), if aerial remote sensing technology was utilized to accomplish the task. Similarly, challenging tasks, such as discriminating specific stressor from several stressors, can also be achieved using high-throughput phenotyping technologies. In research study performed by Bürling et al. (2011), a compact fiber-optic fluorescence spectrometer using ratio Blue/Green and Red/Far Red fluorescence is able to distinguish between Nitrogen-full, Nitrogen-deficiency, Nitrogen-full with pathogen, and N-deficiency with pathogen treatments.

To explore the high-throughput phenotyping for crop breeding, development of efficient high-throughput phenotyping systems is highly desired. Industry sector has been developing high-throughput phenotyping systems and commercial high-throughput phenotyping platforms are available in the market. These systems can operate automatically and continuously day and night, and measure a wide range of plant traits in controlled and field environments (e.g. LemnaTec, Germany; Phenospex, Netherlands). However, these commercial available platforms are high-end high-throughput phenotyping equipment that is expensive. Therefore, there is a need for development of low-cost system for automated high-throughput crop phenotyping.

Development of low-cost automated high-throughput system can provide crop screening and monitoring to both plant breeding and precision agricultural applications. Story et al. (2015) developed an autonomous computer vision-guided sensing and monitoring system that detects the health and growth status of lettuce through a series of temporal, morphological, and spectral features. Their system can potentially improve the resource use efficiency of crop production system in controlled environment. Pereyra-Irujo et al. (2012) designed a low-cost platform, equipped with both autonomous measuring and watering devices, for phenotyping of growth, water use, and drought tolerance of two soybean genotypes. van der Heijden et al. (2012) designed and developed an automated robotic system that moves along the pepper plants in the greenhouse by human power and examines the heritability and quantitative trait loci (QTL) of characteristics of 151 pepper genotypes, and they found that QTL for pepper features, including leaf area, leaf angle, leaf size and plant height, can be detected by image analysis.

The overall goal of this project was to develop a 3D robotic system integrated with multiple sensing systems for high-throughput crop phenotyping to assist breeding programs in the controlled environment. The specific objectives were to (1) develop a 3D platform and sensor control system with functions to position the sensor mount at predefined locations and trigger the sensing systems to acquire spectral images at a predetermined schedule; (2) to develop an image processing algorithm for image mosaicking and phenotype feature extraction, and (3) finally to validate the overall performance of the developed system with crops. In this presented work, we discuss the development of the 3D robotic platform and sensor control system.

2. MATERIALS AND METHOD

2.1 3D platform

A basic framework made of aluminum structure was adapted from a customized automated positioning platform (Arrick Robotics Inc., Tyler, TX, USA). The automated positioning platform consists of an aluminum structure, XY dual axis tracks, a sensor mount, two stepper motors, a stepper motor driver and a computer interface as shown in Fig. 1. The sensor mount was attached on a slider, which is driven by the step motors to move along the X and Y tracks. The motor drivers receive command from a laptop through the interface using a USB port. The frame was designed as 2.1×1.2×1.4 m (L × W × H) in dimension. Maximum payload for the automated positioning platform is 11 kg. The stepper motors have a 0.2 kg·m holding torque and travel 400 steps per revolution or 0.125 mm per step, with 2.54 mm per 300 mm accuracy.

In the 3D automated platform, X axis (indicated by b in Fig. 1) and a guiding track parallel to the X axis track, located at the other end of the frame, together provide guidance for the movement of Y axis. Perpendicular to the X axis and guiding track is the Y axis. A sensor mount is attached to the slider on the Y axis and the center of the sensor mount is the target coordinate or point of interest to be positioned using the stepper motors. As shown in the Fig. 1, the 'Home' position or origin of coordinate for 3D platform is located at the