



Original papers

Development of a field-based high-throughput mobile phenotyping platform



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ABSTRACT

In this study, a mobile, field-based, high-throughput phenotyping platform was developed for rapid measurement of plant characteristics. The platform consisted of three sets of sensors mounted on a high-clearance vehicle. Each set contained two infrared thermometers (IRT), one ultrasonic sensor, one Crop Circle multi-spectral crop canopy sensor, and one GreenSeeker crop sensing system. Each sensor set measured canopy temperature, crop height, and canopy spectral reflectance of a plant plot. Thus, three plots were measured simultaneously in a single pass. In addition to the sensors, the platform was equipped with a laser distance sensor to measure the height of the sensor beam and an RTK-GPS system that provided precise, accurate position data for georeferencing sensor measurements. Software for collecting, georeferencing, and logging sensor data was developed using National Instruments LabVIEW on a laptop computer. The hardware and software design was modular, allowing easy addition and removal of sensors and flexible system expansion. The fast sampling rates for sensors allowed the phenotyper to operate in field at a ground speed of 3.2 km/h. Two verification tests were conducted to evaluate the phenotyping system. In the first test, data timestamps were analyzed to determine if the system could collect data at the required rates and if the time delays would cause significant position errors. Test results showed that data from all sensors were received within the desirable time frame and the largest position error was 17.9 cm when the phenotyper was moving at a speed of 3.2 km/h. The position errors can be corrected during data post processing. The second test determined whether changes in ambient light and ambient temperature had statistically significant effects on the accuracy of the sensor measurements. For the IRT sensors, a correction method using ground truth temperature measurement made during two periods within a day was recommended to correct the errors in surface temperature measured by the IRTs.

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1. Introduction

In order to meet food, feed and fiber needs of a growing world population, crop-breeding methods must be improved and new technologies must be developed. One area under focus is the decoding of the genetic basis of complex traits, such as yield and drought stress tolerance, and predicting these traits from genetic composition of lines or cultivars. In the last three decades, the genomics revolution and advances in gene technology have resulted in a wealth of genomic information (Furbank and Tester, 2011). Genotyping methods have become highly mechanized,

uniform across organisms, and relatively low in cost, with cost decreasing every year (Cobb et al., 2013). However, little improvement of methods for collecting plant trait data or phenotyping have occurred in the last 30 years, especially for collecting data for single plots or plants in field-based situations (White et al., 2012). Availability of high-quality phenotypic and corresponding environmental data has become essential to understand the genotype-to-phenotype relationship. Due to lack of phenotypic data, phenotyping is currently considered the major operational bottleneck of genetic analysis (Cobb et al., 2013; Furbank and Tester, 2011). To improve complex traits through genomic selection, phenotypic data from thousands of plant varieties grown in replications under various environmental conditions is necessary, and measurements must be repeatedly taken throughout plant development in order to observe the interaction between the

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expression of plant traits and the environment (Cabrera-Bosquet et al., 2012; Montes et al., 2007).

Current methods for collecting phenotypic data on field plots require a researcher to visit each plot and manually measure specific parameters such as canopy temperature or plant height. For smaller sized trials with hundreds of plots, manual phenotyping is feasible but, depending upon methods of data collection, may be subjective and prone to human error. With larger trials of thousands of plots, manual phenotyping would become laborious, time consuming, and costly. Consequently, many breeding programs only collect yield data at the end of the growing season, missing phenotypic information that can give insight to the in-season performance and adaptation of lines (Furbank and Tester, 2011).

Therefore, a need exists for a flexible, robust, mobile, multi-sensor platform, capable of rapidly and efficiently collecting data from hundreds to thousands of plant plots, that can be used to reliably estimate phenotypic traits. The platform should be capable of handling a variety of sensors that can collect different types of data, such as plant height, canopy temperature, and various spectral readings. Furthermore, the platform should be flexible to allow additions of new sensors as they become available. It is essential for the platform to be equipped with a high accuracy and precision positioning system, such as RTK-GPS, for georeferencing, which is necessary to correctly link data to specific plots or plants.

Various plant phenotyping platforms, including ground-based and aerial-based (manned and unmanned aerial vehicles) platforms, have been developed during recent years. Ground-based platforms were developed for indoor (laboratory and greenhouse) with controlled environment and field applications. These phenotypers also can be categorized as manually driven, vehicle carried, and robotic type, based on throughput and human involvement. Most advanced, high-throughput phenotyping systems have been those developed for transnational seed companies and large public plant research institutions, such as the Australian Plant Phenomics Facility and the European Plant Phenotyping Network (Araus and Cairns, 2014). Most of their phenotyping equipment have been for indoor facilities, such as growth chambers and greenhouses, with precise environmental control (Kumar et al., 2015). An advanced phenotyping system, the LemnaTec Scanalyzer, has been used outdoor over a field of several hundred square meters. However, it required a rail-bound crane system to move the phenotyper (Lemnatec, 2015).

Several field-based, experimental phenotyping platforms have been recently developed. These platforms varied in mechanical design, sensors, data communication, and data acquisition systems. Mechanical designs ranged from pushcarts to pulled trailers, and from self-propelled vehicles to robots. The designs also varied in sensor position adjustability, from sensors mounted to a fixed platform to sensors mounted on a height-adjustable platform. Sensor position adjustability allowed phenotyping for different crops at different growth stages. The number and types of sensors on these phenotypers varied from one or two sensors of the same type for measuring a single trait on one plot, to multiple sensors of multiple types for simultaneously measuring multiple traits on two or more plots in a single pass. Data communication and acquisition systems ranged from sensor specific data loggers with one or two ports to more general-purpose data loggers with multiple ports, and from general-purpose laptops to industrial computers running a network server equipped with a database. Compared to data loggers, computer based systems were typically more versatile due to their capability of connecting to more sensors of different interface types, whether digital or analog.

White and Conley (2013) developed a proximal sensing pushcart consisting of a rectangular frame mounted on two bicycle frames. The cart was equipped with a single set of monochrome camera, ultrasonic proximity sensor, infrared thermometer, radiometer, and a GPS receiver connected to CR1000 and CR3000

data loggers (Campbell Scientific, Inc., Logan, Utah, USA) for collecting data at 1 Hz and 5 Hz, respectively. The pushcart was more labor intensive to operate compared to motorized platforms. Crain et al. (2016) developed a hand-held phenotyper (“PhenoCorn”) with a GreenSeeker, an IRT, and a web cam. The sensors were connected to a laptop through USB ports and was controlled by a LabVIEW program (National Instruments, Austin, Texas, USA). Measurement data were geo-referenced using a GPS receiver with OmniSTAR satellite position correction (Trimble Navigation). The PhenoCorn was designed to measure only one plot of crop and it was labor intensive. Montes et al. (2011) developed a phenotyping platform to study the use of light curtains and spectral reflectance sensors to simultaneously measure height and spectral reflectance of four rows of maize during the early development stage. These measurements were then used to estimate biomass. This platform was mounted on a mini-tractor system with fixed sensor positions. The platform was able to operate at a speed of 1.0 km/h, but sensor data was not georeferenced with GPS and a 3 s break between measurement sets was required to finalize the recorded data. Busmeyer et al. (2013) developed BreedVision, a phenotyping platform for small grain cereals up to a plant height of 1.6 m. The platform consisted of a variety of sensors, including 3D time-of-flight cameras, color cameras, laser distance sensors, hyperspectral imaging systems, light curtains, and a GPS receiver, all mounted on a tractor-pulled trailer platform that was height adjustable. BreedVision was capable of phenotyping one plot in a single pass. It used an industrial PC with a MySQL database equipped network server for data storage. The interfaces between sensors and the PC system were through USB and Ethernet. Each sensor was connected to the PC through an individual microcontroller. The system developed by Andrade-Sanchez et al. (2014) contained four sets of sensors mounted on a high-clearance vehicle and was capable of measuring four plots of plants simultaneously. Each sensor set included an ultrasonic sensor, two infrared thermometers (one pointing at nadir, one pointing 30° from the vertical axis), and a Crop Circle ACS-470 multi-spectral crop canopy sensor. Three data loggers were used for data collection and storage. This system collected data at 1 Hz. Comar et al. (2012) developed a tractor mounted boom platform for high throughput phenotyping wheat cultivars in field conditions. The boom was mounted 1.5 m above the crop canopy. The system used a hyperspectral radiometer and two RGB cameras to observe the canopy from both nadir and oblique views at 57.5° zenith angle. Only one plot could be phenotyped at a time and about 100 micro-plots could be sampled per hour (Comar et al., 2012). Svensgaard et al. (2014) developed PhenoField, a box shaped phenotyping platform transported via a jib telescopic arm mounted to the back of a tractor. The PhenoField contained a 5 Mpix CCD camera mounted within the box and was illuminated by an LED panel that produced lights of nine wavelengths (from 465 to 850 nm). The unique feature of PhenoField was its complete blocking of ambient wind and ambient light during phenotyping, however this also made it slow to operate, covering only 80 m² per hour. The box structure also prevented flexible system expansion. The “Phenomobile” developed in Australia allowed various types of sensors to be used for field phenotyping. The phenotyper can be driven by three types of drive mechanisms – a pushcart type (“Phenomobile Lite”), a self-propelled high-clearance vehicle, and a robotically driven system. The wheel base and sensor height were adjustable to accommodate different plot widths and desirable fields of view. Only one plot can be measured in a single path (HRPPC, 2015).

The overall objective of this work was to advance phenomics through the development of a modular sensor platform for field-based, high-throughput phenotyping. It was envisioned that the developed platform would serve as a model and resource for future phenotyping platform designs.

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