PlantScan™: a three-dimensional phenotyping platform for capturing the structural dynamic of plant development and growth

Xavier Sirault[1], Jurgen Fripp[2], Anthony Paproki[2],Peter Kuffner[1], Chuong Nguyen[3], Rongxin Li[4], Helen Daily[1], Jianming Guo[1], Robert Furbank[1]

[1]*High Resolution Plant Phenomics Centre, CSIRO Plant Industry, Cnr Clunies Ross St and Barry dr, Canberra ACT 2601, Australia,* [2]*Australian e-Health Research Centre, CSIRO ICT Centre, Brisbane, Australia,* [3]*CSIRO CMIS, ANU,* [4]*CSIRO ICT Centre, Sydney*

*correspondence: xavier.sirault@csiro.au

Highlights: PlantScan™ is an integrated analysis pipeline, seamlessly integrating hardware and software tools, to provide automated, non-invasive analyses of plant structure (topology, surface orientation, number of leaves, internode length...), morphology (leaf size, shape, area, volume...) and function (conductance,…). By utilising cutting edge information technology to automatically digitise plants in three-dimensions, it enables plant scientists to better understand the complex interactions involved in plant growth, i.e., the plant's genetic make-up, its physical characteristics and the environment in which it grows, thus, providing essential information to populate functional structural plant models.

Keywords: Plant architecture, transformational technology, automated feature extraction, quantification

INTRODUCTION

Plant architecture is of major importance for agricultural production. It is a major determining factor for yield potential as evidenced by the first green revolution, which resulted in a doubling of global cereal production worldwide. This was achieved by the breeding of high yielding cultivars with reduced plant stature (Hedden, 2003). Because plant architecture also determines the physical, chemical and biotic factors to which a plant is exposed (Wilson and Chakraborty, 1998), plant breeders and geneticists have been actively selecting for plant architecture and have been exploiting natural genetic variation in canopy architecture for centuries.

Nevertheless, the genetic control of plant architectural characteristics still remains today largely unknown due to the complexity and challenges in accurately and rapidly quantifying plant structure and geometry. This difficulty of measuring plant structure is compounded when studying plant architecture dynamically and its impact on physiological traits (conductance, light interception…) across a large number of genotypes. Indeed, not only does it require determination of plant topology and quantification of shape and size of each organ in high throughput but it also requires capturing and tracking organ expansion and growth over time under various environmental conditions. Despite the technological challenge, exploiting the dynamic nature of plant architecture and its influence on physiological traits within breeding programs represents a window of opportunities for improving yield potential in response to changing climatic conditions.

Analysis of digital representation of individual plants in three dimensions, in combination with proxy-sensing technologies (hyperspectral, infrared, visible imaging) is one way to determine plant topology, quantify plant geometry and assess simultaneously their impact on plant function. In this manuscript, we introduce an advanced automated phenotyping platform, PlantScan™, which combines the advantages of stereo-optical cameras and laser ranging sensors for faithfully digitising plants in three dimensions. Combining these two technologies is particularly valuable for digitising thin structures such as leaves and stems (Li *et al*, *in prep.*). To provide a link between plant structure and function, colour and thermal infrared images are projected onto these 3D structural representations. These digital objects are then fed to a generalised analysis processing pipeline that automatically derives structural (e.g. topology, surface orientation, number of leaves…), morphological (e.g. leaf size, shape, area, volume…) and functional information (conductance, photosynthesis...) at the whole organ or plant level (Paproki *et al*, 2012). Although the platform has been tested on a range of plant species (rice, wheat, canola, eucalyptus, tobacco, millet and tomato), we illustrate our results using mainly corn and cotton; nonetheless we will discuss the inherent difficulties at applying these *in-silico* methods to complex cereals such as rice or wheat.

THE DIGITISATION PLATFORM

PlantScan™ is a custom-built imaging chamber integrating multi-wavelength, optical-imaging sensors and Light Detection and Ranging (LiDAR) systems, which are arranged in a multi stereo configuration (Fig 1). Two microbolometer sensors (model A645, FLIR systems Inc, MA, USA) collect thermal information with temperature resolution of 0.045°K in the waveband 7.5 to 14 μm, while three JAI 3-CCD optical sensors (model AT-200GE) and one JAI 4-CCD RGB/NIR optical line scanner (model LQ-200 CL), equipped with Fujinon zoom lenses (model C22x17R2D-ZP1) collect information in the visible and near infrared spectra. In addition, two synchronised light detection and ranging (LiDAR) sensors (SICK LMS400) operating at a wavelength of 650nm with a 70° sweep collect time of flight data and reflectance data at a rate of 270Hz.
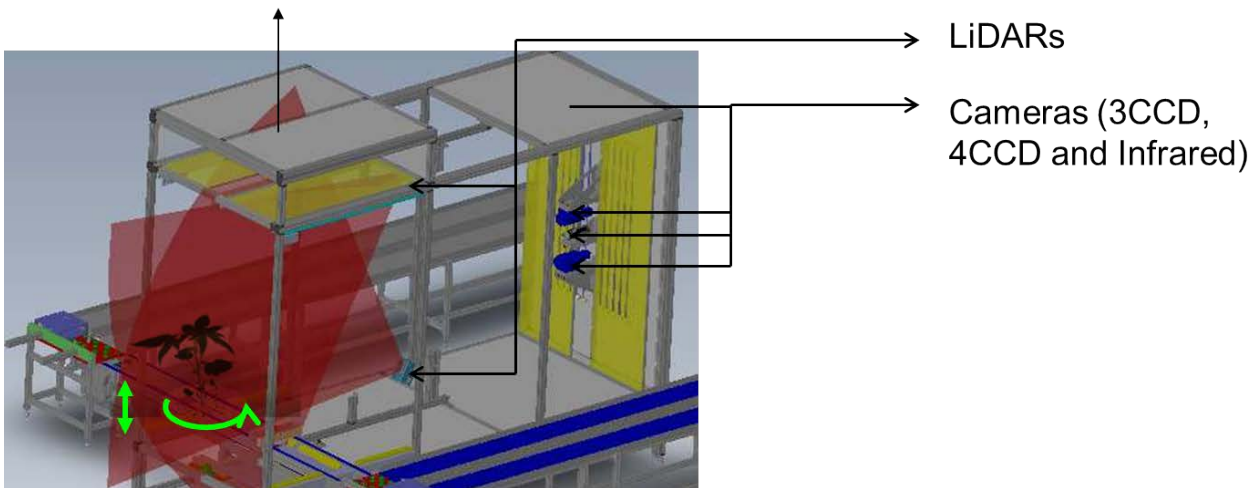
Cameras (3CCD, and Infrared)

LiDARs

Cameras (3CCD, 4CCD and Infrared)

Fig. 1.The PlantScan™ phenotyping platform

The light spectrum in the chamber is generated by fluorescent light run on a 75 kHz electrical signal to avoid noise in the acquired images. The light is diffused to approximate Lambertian conditions using Y20 Miniprism diffuser panels within the imaging chamber (York precision panels, Sydney, Australia).

The platform is composed of a double conveyor belt, manually loaded, with plants held in position on pot carriers. Individual plants are identified by 2D bar codes. A first transfer station diverts the plant to a split conveyor belt which accurately positions the plant for imaging using laser proximity sensors. A rotating turntable, fitted with an incremental encoder with up to 2.5 million counts per revolution and mounted on a scissor-lift platform (10μm linear accuracy), ensures the plant is scanned from every angle in a 360° rotation. After imaging, the plant is conveyed to a second transfer station before being ejected by an actuator onto a double gravity belt. Plants are then manually unloaded and transported back to their growing environments.

All motion control and image acquisition was realised utilising the graphical programming environment LabVIEW (National Instrument).

The platform is able to scan very small seedlings or plants from a few centimetres to a couple of metres in height and up to a metre thick. Image and LiDAR data are captured simultaneously in 50 seconds (one image every 3° from all cameras, while LiDAR is continuously acquiring) with their contextual information and collated into one multi-layer data file before being stored in a purpose-built database.

THE SOFTWARE PIPELINE

To obtain 3D architectural representations of crops, trees and/or model species, overlayed with spectral information, a number of computer vision techniques have been simultaneously integrated in a reconstruction scheme running on a computer cluster, thus combining the respective advantage of each technique:

- Stereo-techniques using silhouette-based (Visual hull) and Embedded Voxel Colouring (Leung *et al*, 2012) (Fig 2A) and textural methods (Patch based Multi-view Stereo - PMVS) (Furukawa and Ponce, 2010)(Fig 2B);

- Fusion of LiDAR Point cloud to mesh results using Random sampling and Consensus (RANSAC) approaches associated with iterative closest point (ICP) algorithms (Fig 2C);
- Fusion of spectral signals onto 3D structural representations: only colour and thermal infrared images close to the surface normal (within 30°) of each mesh polygon are averaged and projected, thus taking into account the influence of plant geometry on data collected by proxi-sensing technologies (Guo *et al*, *in prep*) (Fig 2D).

To achieve higher reconstruction accuracy, we designed a new calibration algorithm, which estimates camera parameters (including geometric distortion) from all camera positions at once around a rotating axis (Chuong *et al*, *in prep.*). The results are high-resolution 3D plant meshes with sub-millimetre resolutions, which are then automatically segmented in order to semantically identify the different parts of the plants as detailed in Paproki *et al*. 2012. Figure 2E shows a maize mesh automatically segmented and Fig 2F shows the fitting of spline function to the midrib of two leaves from the corn plants in Fig 1E. A longitudinal 3D matching pipeline for plant mesh parts can also be used to evaluate temporal changes at the whole plant and/or organ level.
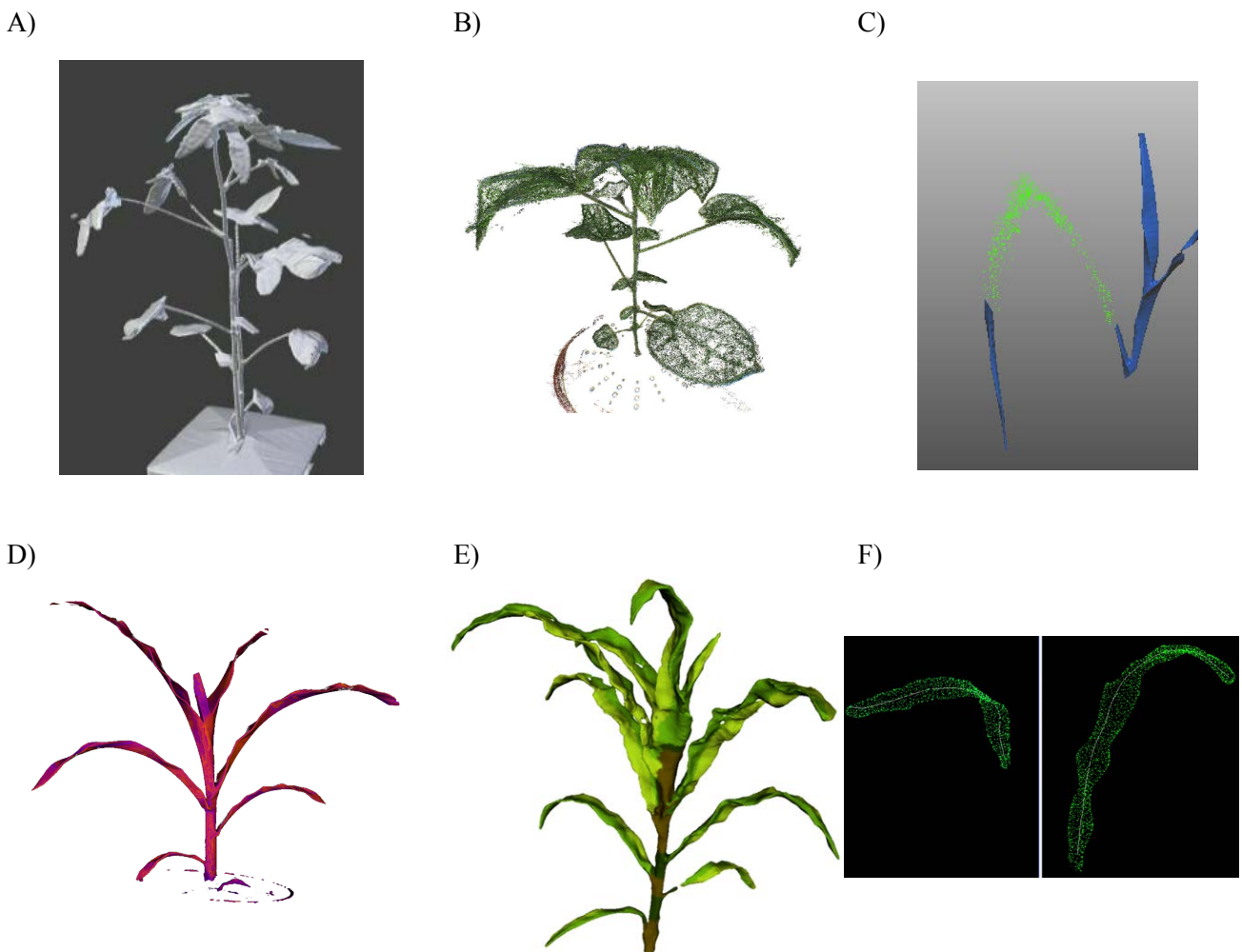
RESULTS AND DISCUSSION

A)

B)

C)

D)

E)

F)

Fig. 2. Automated reconstruction of Gossypium species by A) Visual hull methods, and B) Patch-based Multi-view stereo. C) fusion of LiDAR and mesh information for wheat species (the mesh has been deleted to show the co-registration of LiDAR information), and D) 3D data fusion of Infrared information for Zea mays (false colour imaging of leaf temperature). E) False colour imaging of mesh segmentation for Zea mays: green identifying each leaf and brown identifying the stem, F) automated margin extraction and spline fitting of the midrib for two of the maize leaves in E)

Currently, there are a few limits to our methods, in particular when trying to reconstruct complex cereals like wheat or rice as our algorithms do not cope well with overlapping structures and concave surfaces when using visual hull-based methods alone. To address this issue, we are looking at integrating prior-knowledge of geometric structures by using x-ray geometric datasets, parametric models and statistical shape models as well as prior-knowledge of plant development in our reconstruction scheme. For PMVS methods, the accuracy relies on texture quality. Plants are known to lack surface texture. Improving results from PMVS can be addressed by using higher resolution images. Today, our system can resolve structures as small as 0.5mm. This is suitable for monitoring organ development or overall plant growth but not enough to resolve leaf thickness. Another area of improvement is on the calibration of our optical system. Currently our calibration algorithm does not work at sub-pixel resolution, thus limiting our ability to achieve higher accuracy.

By providing an integrated multi-sensing platform relying on a range of imaging sensors, PlantScan increases scientists' capacity to precisely and accurately quantify the biological processes involved in the development and functioning of plants and this with greater detail, frequency and objectivity than traditional methods. We point to the prospect that outputs from such a platform, which was developed for phenomics applications, i.e. measurement of correlated phenotypes in high-throughput, could provide a suite of new tools for populating functional structural plant models (FSPM) assuming that these outputs can be transformed into model parameters (Vos *et al*, 2010). These 3D models of plants with metadata will be made available via an on-line data repositories in self-contained collections (e.g. Data Access Portal - https://data.csiro.au/dap/), along with the means to handle, test, measure and interrogate them, allowing empirical research on these virtual models of crop plants. We are hoping that the information deposited on this repository will provide the necessary data for developing a predictive framework for enabling *in-silico* physiological breeding in the future.

LITERATURE CITED

Furukawa Y and Ponce J 2010 Accurate, dense and robust multiview stereopsis. IEEE Transaction on Pattern Analysis and Machine Intelligence, **32**(8): 1362-1376**.**

Hedden, P. 2003 The genes of the Green Revolution. Trends Genet. **19**: 5–9

Leung Carlos, Ben Appleton, Mitchell Buckley and Changming Sun 2012 Embedded Voxel Colouring with Adaptive Threshold Selection Using Globally Minimal Surfaces. International Journal of Computer Vision **99**(2): 215-231 (2012)

Paproki Anthony. Xavier Sirault, Scott Berry Robert Furbank and Jurgen Fripp 2012. A novel mesh processing based technique for 3D plant analysis.. *BMC Plant Biology* **12**(1): 63.

Peng SB, Laza R, Visperas RM, Khush GS, Virk PS, Zhu DF 2004. Rice: progress in breaking the yield ceiling. In "proceedings of the 4th international cro science congress" (eds T Fisher, N Turner, J Angus, L McIntyre, M Robertson, A Borrell, D Lloyd) (The regional institute Ltd: Brisbane).

Vos J, J. B. Evers, G. H. Buck-Sorlin, B. Andrieu, M. Chelle, and P. H. B. de Visser 2010 Functional–structural plant modelling: a new versatile tool in crop science J. Exp. Bot. **61**(8): 2101-2115

Wilson P and Chakraborty S 1998. The virtual plant: a new tool for the study and management of plant diseases. Crop Protection. **17**: 231–239.

Zheng Bangyou, Shi Lijuan, Ma Yuntao, Deng Qiyun, Li Baoguo and Guo Yan 2008. Comparison of architecture among different cultivars of hybrid rice using a spatial light model based on 3D digitising. Functional Plant Biology **35**: 900-910