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Introduction

Three dimensional (3D) plant reconstructions, extended to four dimensions with the use of time series and accompanied by visual modelling, is being used for a number of purposes including the estimation of biovolume and as the basis for functional structural plant modelling (FSPM). This has been successfully applied to crop species such as cotton (Paproki *et al.* 2012). Measuring the growth pattern and arrangement of a pasture sward is a difficult task but can be used as an indirect measure of other variables of interest, such as growth rate, light interception, nutritional quality, herbivore intake, *etc.* (Laca and Lemaire 2000). Digital representation of individual plants in three dimensions is one way to determine sward structure. The High Resolution Plant Phenomics Centre (HRPPC) has developed PlantScan™ which combines robotics, image analysis and computing advances, to accelerate and automate the measurement of plant growth characteristics and allow discrimination of differences between individual plants within species. Image silhouettes and LiDAR (Light Detection And Ranging) are used and combined to digitise plant architecture in three dimensions with a high level of detail. Colour information, extracted from multispectral sensors, and thermal imaging from infra-red (IR) cameras are then overlaid on these 3D plant representations, thus providing a tool to link plant structure to plant function. Successful reconstructions using data collected by PlantScan™ in controlled conditions, have been conducted for a range of grasses such as wheat (*Triticum aestivum*), rice (*Oryza sativa*), corn (*Zea mays*) and broadleaf species such as canola (*Brassica napus*), cotton (*Gossypium hirsutum*) and tobacco (*Nicotiana tabacum*). This suggests that modelling the sward structure of grass and legume pasture species should be equally achievable. This study explores the use of PlantScan™ to reconstruct 3D images of the important and common pasture legume, subterranean clover (*Trifolium subterraneum*) with a view to analysing their 3D structure in-silico.

Methods

Four cultivars (Woogenellup, Goulburn, Clare and Riverina) representing different canopy structures of subterranean clover were grown in controlled conditions (18/26°C night/daytime temperature, 50% relative humidity, and 14 hours daylight). On the 5th November 2012, 50 mg of seed was sown in a "wheat special" soil in 90 mm stormwater tube pots, to ensure a similar amount of biomass per pot. A moveable clear plastic sleeve was placed around each pot so that the growing plants were restricted from growing away from each other, to mimic the effect of intra-sward competition for light in particular. The pots were scanned twice weekly in PlantScan™ for one month, beginning 10 days after germination. In a second trial, sown on the 17th January 2013 under the same conditions as above, plants were thinned to one plant per pot, but were grown and scanned without the plastic sleeve.

PlantScan™ features

PlantScan™ is a high resolution phenotyping platform, which uses various imaging sensors (LiDAR, IR Imaging, multi-wavelength imaging) to non-invasively measure plant growth and function using in-silico approaches. Raw data is captured by placing plants on a turntable and scanning. Contextual information such as system configuration, time of acquisition, batch number and project are also saved. The data is stored in a purpose-built database as the scan is running. The various data streams are collated and used to produce full 3D representations of each plant with overlaid spectral information. The metadata collected during image acquisition are necessary inputs for the computer vision techniques which are used to create the 3D representation of the plant from which a range of metrics (volume, surface, *etc.*) can be extracted. The segmentation of the 3D meshes according to Paproki *et al.* (2012) is currently being adapted.

Image reconstruction

The processing of subterranean clover reconstruction begins with calibration of the intrinsic parameters of two RGB 3-CCD cameras on 360 degree of views simultaneously to supply the projection matrices between 2D image coordinates and 3D real world coordinates. After camera calibration, a Visual Hull algorithm is used to reconstruct the plant volume. The Visual Hull algorithm requires plant silhouettes from a separate image processing step on the 10-bit raw image data from two 3-CCD cameras. The plant volume is created at above 1k (1024^3) high resolution, then the volume is refined and converted to surface topology, and finally a smoothing algorithm is used at the end of the reconstruction.

After constructing the 3D subterranean clover model, visible light texture from the two RGB (red green blue) 3-CCD cameras and IR texture from FLIR® IR sensors are mapped to produce the results in Figure 1. The IR information is projected to the 3D mesh triangle in a different way from visible light; only IR camera views in a
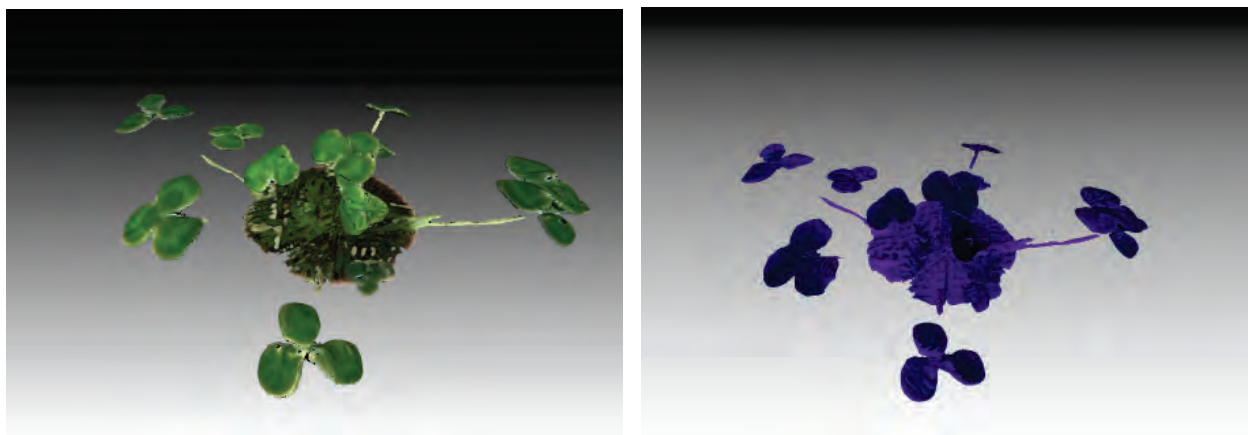
Figure 1. PlantScan™ reconstructions of subterranean clover (cv. Clare) overlaid with a visible signal (left image) and an infrared signal (right image).

30° solid angle from the surface normal are averaged in order to take into account the geometry of the acquisition system.

Results and Discussion

Preliminary scanning of subterranean clover using PlantScan™ revealed some of the challenges that applying these technologies to pasture plants may encounter. In the first trial, differentiating or segmenting between plants grown in microswards proved difficult, which was exacerbated by strong reflections caused by the plastic sleeves.

While intra-plant and intra-species competition are an essential feature of pasture growth, using single plant reconstruction as the base unit upon which to build and test more complex relationships seemed a sensible way to proceed. Figure 1 shows a successful reconstruction for the Clare cultivar at approximately five weeks, overlaid with both the visible signal and infrared signal. The lack of differentiation in the infrared image reflects the lack of a treatment to induce a thermal response.

Subterranean clover still proved quite challenging to reconstruct, because the stems are relatively weak, and may have been prone to movement as a result of the platform rotation, although this movement was imperceptible to the human eye. Reconstruction was further hindered by

indications of diatropism or helionasty in the leaves. Minimizing the amount of time that plants are removed from the growth cabinets may avoid soil drying, and ensuring plants are scanned under similar light conditions as those in which they are grown could improve successful reconstructions. The latter condition may require additional overhead lighting in PlantScan™, which currently illuminates the field of view from the side.

Conclusion

This work has described early attempts to digitise the plant architecture of subterranean clover in three dimensions. The algorithms developed here will be further refined to provide robust 3D reconstructions upon which investigations of plant function can be overlaid.

References

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