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Simplification of leaf surfaces from scanned data: Effects of two algorithms on leaf morphology

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ABSTRACT

New technologies, such as three-dimensional (3D) laser scanning and stereo imaging, have recently been adopted for quantifying plant structure. The datasets collected using such technologies offer realistic representations of the morphological characteristics of the studied plant organs. The datasets, however, are very large and occupy excessive amount of storage space. Moreover, the computation time is also very long when these datasets are made the subject of further analysis and simulation. Some dataset simplification is essential if the balance between storage cost and computation time vs the accuracy of the plant geometry description is to be optimised. In this study, the surface morphologies of field-grown maize and tobacco leaves were measured using 3D laser scanning and were progressively simplified using two different methods – Vertex removal and Edge collapse. To evaluate the impacts of simplification on the accuracy of the leaf-surface morphological descriptions, several error metrics were developed. These metrics are able to quantify these impacts in various respects. The statistical results show that most error metrics increase only marginally, even with moderate simplifications of the leaf surfaces. The errors, however, increase quickly with over-simplification. The simulation results of light distribution in canopies indicate that over-simplification of the leaf-surface meshes results in significant deviations in the simulated leaf light-capture efficiency compared with the original leaf surfaces. Compared with the Vertex removal method, the Edge collapse method is better at retaining the original leaf-surface morphology, but loses more of the leaf-edge information. This study provides valuable information in the analysis of high-precision plant-structure data, relevant in a range of research fields including functional–structural plant modelling and high-throughput phenotyping.

1. Introduction

Plant structure plays a pivotal role in determining the light interception of a canopy (Falster and Westoby, 2003; Sarlikioti et al., 2011; Silva et al., 2014; Zheng et al., 2008), and also has important influences on other canopy properties such as rainfall and spray droplet interception (Bussière et al., 2002; Dorr et al., 2014; Oqielat et al., 2011) and lodging resistance (Pearcy et al., 2005; Zhang et al., 2014). Plant structure is also an indicator of the growth and development status of a plant (Bellasio et al., 2012; Kadioglu et al., 2012; Omasa et al., 2007) as it continuously adjusts to a dynamically changing environment. To improve yield and the adaptation abilities of crops to climate change, new plant-structure characteristics are being identified, quantified, extracted and recorded for crops grown in a range of environments. By linking this information to the vast amount of genomic data now available (Araus and Cairns, 2014; Dhondt et al., 2013; Fiorani et al., 2012; Furbank and Tester, 2011), the opportunity is created to accelerate the breeding of new cultivars for high yield and/or high stress resistance.

Several new technologies have been developed for quantifying plant structure, including stereo imaging (Biskup et al., 2009, 2007; Fiorani et al., 2012; Paproki et al., 2012; Wang et al., 2009); light detection and ranging (Eitel et al., 2010; Llorens et al., 2011; Omasa et al., 2007), laser scanning (Chambelland et al., 2008; Hanan et al., 2004; Paulus et al., 2014) and structured light (Bellasio et al., 2012; Kempthorne et al., 2014). Researchers have used the non-invasive methods to collect point clouds of plant organs, which can be used to extract their topological and geometrical traits (Paproki et al., 2012; Paulus et al., 2014; Schöler and Steinhage, 2015) or to monitor the dynamics of plant

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physiological status (Bellasio et al., 2012; Furbank and Tester, 2011). Based on the point clouds, three-dimensional (3D) plant-structure models have also been developed to simulate the spatial distribution of light (Chambelland et al., 2008) and spray droplet behaviour in the canopy (Dorr et al., 2014; Massinon et al., 2015; Oqielat et al., 2011).

The data collected using these methods can be used to present plant structures quite realistically, although the size of the datasets is usually extremely large. Paproki et al. (2012) reconstructed 3D models of cotton plants using the stereo imaging method; each plant contained 120,000–270,000 polygons. Paulus et al. (2014) used a high-precision laser scanning system to measure the structures of barley plants, and the reconstructed 3D model of each barley leaf contained up to 12,000 vertices. These data not only occupied a very large amount of storage space but also dramatically increased the calculation time when they were adopted in applications such as a simulation of plant environment interactions with mechanistic models (Dorr et al., 2014; España et al., 1999; Oqielat et al., 2011) or in high-throughput plant phenotyping.

To keep a balance between the cost of storage and of computation time vs the accuracy of the plant-geometry description, it is necessary to simplify the geometric models of organs built with high-precision data (Loch et al., 2005). Oqielat et al. (2009) developed a point-cloud fitting algorithm of the leaf surface which can control the coarseness of the underlying mesh. Based on this algorithm, they simulated the moving trajectories of water droplets on Frangipani leaf surfaces, built with different precisions. The simulation results show that changing the precision of the leaf model did not significantly affect the motion of the water droplets on leaf surface (Oqielat et al., 2011). Fournier and Pradal (2012) developed an algorithm to simplify wheat leaf-surface models, and evaluated the influence of triangular facet numbers of their leaf-surface models on the simulation of canopy light interception. Their results show that reducing the number of triangular facets by 93% decreased the canopy light interception by less than 1%. However, no systematic evaluation was carried out in these studies, to determine if significant changes in leaf surface morphology had been caused by their simplifications.

Simplification of leaf surfaces from high-precision methods inevitably results in some differences between the original and the simplified leaf surfaces. Systematic evaluation of leaf-surface simplification can be very helpful for determining the appropriate simplification method and the appropriate simplification rate in a specific application. It is also valuable for understanding the relationship between organ surface morphology and function. In this paper, leaves of field-grown maize and tobacco were scanned with a 3D laser scanner. These two crops were chosen to represent a range of leaf morphologies, with maize being a monocot having long, narrow leaves, and tobacco a dicot with much broader leaves. The leaf-surface shapes of the two crops are also both very complex, so neither can be fairly represented using a simple method (Chambelland et al., 2008; Zheng et al., 2008). Two different algorithms were used to progressively simplify the leaf surfaces, while introducing several error metrics to evaluate any changes in leaf-surface morphology induced by the simplification processes. The light interception of individual leaves in canopies, based on the original and simplified leaf surfaces, were simulated using a 3D light distribution model, and the effects of simplification on leaf light-capture efficiency were evaluated.

2. Materials and methods

2.1. Field experiments

The field experiment with maize was conducted at the Shangzhuang Experimental Station of China Agricultural University near Beijing (40.14°N, 116.18°E, Elevation 47 m). Maize seeds (*Zea mays* L. cv. ZD958) were sown with an in-row spacing of 0.2 m and a between-row spacing of 0.6 m. The plot size was 200 m^2. At the silking stage, a stand was selected containing four plants (two plants in each of two neighbouring rows), which were representative of the average growth and development status of the plants in the plot. The field experiment with tobacco was conducted at the Xundian Experimental Station in Yunnan province, China (25.51°N, 103.27°E, Elevation 1883 m). Tobacco seedlings (*Nicotiana tabacum* L. cv. Y87) were transplanted into the field with an in-row spacing of 0.5 m and a between-row spacing of 1.2 m. The plot size was 650 m^2. After topping, a stand was selected with four plants (two plants in each of two neighbouring rows).

The actual spatial positions of the selected plants were measured using a ruler for distance and a geological compass for orientation. The selected plants were then transplanted into pots after sunset and transported to the laboratory. All plants were well-watered to avoid wilting during the subsequent operations. The leaf surfaces were scanned using a FastSCAN™ Cobra™ laser scanner (Polhemus, USA, the Practical Accuracy is 0.13 mm) with a TX4 magnetic field transmitter which was set with its *x* axis point to the north and the *y* axis point to the zenith. The TX4 transmitter has a functional radius of 1.05 m, so that all leaf surfaces of one plant can be scanned using the same coordinate system by carefully adjusting the position of the transmitter before starting a measurement. The leaves were scanned from top to bottom, and removed after scanning to avoid mutual obstruction. The scanned data were visualised in real time to check for completeness and errors of the scanned leaf with the proprietary FastSCAN software (version: 4.0.7, ftp://ftp.polhemus.com/pub/FastSCAN/). During scanning, there was no interference from metallic materials and no disturbance from external light. In total, 43 maize leaves and 82 tobacco leaves were scanned.

2.2. Simplification methods and simplification rates

The proprietary FastSCAN software was used to pre-process the scanned raw leaf-surface data, including the registration of multiple scans and removing redundant points in the overlapping scans. The data for individual leaves was then exported as triangular meshes, and these served as original meshes for further simplification.

A number of triangular mesh simplification methods have been developed by computer scientists, including Vertex removal (VR, Schroeder et al., 1992), Vertex Clustering (VC, Rossignac and Borrel, 1993) and Edge collapse (EC, Garland and Heckbert, 1997). Each of these methods starts with the original model and decreases its complexity by repeatedly removing vertices, edges or faces (Erikson, 1996). In contrast to other methods, both VR and EC can maintain the topology of the original mesh and generate simplified results of relatively high quality (Garland and Heckbert, 1997). In addition, these two methods have been used widely and their working codes are readily available. So the VR and EC methods were used for mesh simplification in this study.

Different algorithms were employed by the two simplification methods. For the VR method, the error of deleting a vertex is calculated based on the distance of deleted vertex relative to an averaged plane or edge (see Schroeder et al., 1992 for details). Next, vertices with errors less than a set threshold are deleted and the holes created by the deletions are repaired by re-triangulation (Fig. 1a). Vertices are not deleted if the holes generated cannot be re-triangulated using an algorithm similar to the bisection. For the EC method, edges (or valid vertex pairs) are deleted iteratively to simplify the mesh. Quadric Matrices are used to calculate the error of each potential deletion (see Garland and Heckbert, 1997 for details). Edges (or valid vertex pairs) with minimum error are