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A 3D contour based geometrical model generator for complex-shaped horticultural products

Seppe Rogge [a], Thijs Defraeye [a,b,c], Els Herremans [a], Pieter Verboven [a], Bart M. Nicolaï [a,d,*]

[a] MeBioS, Department of Biosystems, University of Leuven, Willem de Croylaan 42, 3001 Heverlee, Belgium
[b] Laboratory for Building Science and Technology, Swiss Federal Laboratories for Materials Testing and Research (Empa), Überlandstrasse 129, 8600 Dübendorf, Switzerland
[c] Chair of Building Physics, Swiss Federal Institute of Technology Zurich (ETHZ), Wolfgang-Pauli-Strasse 15, 8093 Zürich, Switzerland
[d] VCBT, Flanders Centre of Postharvest Technology, Willem de Croylaan 42, 3001 Heverlee, Belgium

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ABSTRACT

A novel geometric model generator for horticultural products is presented, which generates 3D models of fruits using shape description techniques based on shapes obtained experimentally from a measured dataset of fruits by non-destructive X-ray CT imaging. For this purpose, the 3D contour of each fruit in the scanned dataset was represented with a 2D shape signature, obtained after applying the spherical coordinate transformation. After normalisation, these signatures were described with 2D Fourier descriptors. Statistical analysis of these descriptors for all scanned fruits allowed automatic generation of new geometric fruit models, representative of the measured dataset. The accuracy of the generator was validated by means of the distributions of volumes and surface area to volume ratios of fruit scans and the newly generated shapes. This 3D shape description and generation method allows to process the entire 3D contour of the observed objects and can be applied to all star-shaped objects (shapes that do not curve back on themselves with respect to the centre of mass). This way, more accurate geometrical models can be produced compared to similar model generators based on shape description using 2D cross-sections. This generator enables fast generation of geometrical models to be used in numerical simulations of heat or mass transport phenomena within horticultural products or their exchange processes with the surrounding environment.

1. Introduction

The shape of horticultural products is one of the most important factors that affect heat and mass transport within plant organs or the exchange with the surrounding environment. Therefore, accurate geometrical models are required when applying numerical models to analyse physiological processes such as cooling of produce (Dehghannya et al., 2010), convective drying of food (Kaya et al., 2006), long-term storage of horticultural products (Delele et al., 2010), individual quick freezing (Peralta et al., 2010) and mechanical vibrations occurring during harvesting and handling (Jancsók et al., 2001). Though techniques exist for both modelling (Mebatsion et al., 2009) and virtual generation (Abera et al., 2014) of the microstructure of pome fruit tissue, and software is already available to generate models of some kinds of plants and plant organs (Pradal et al., 2009; Prusinkiewicz and Runions, 2012), this is not yet available to generate macroscale models of common types of fruit or vegetables. This often makes that researchers reduce the complex shape of these products to basic geometries such as spheres, certainly when multiple geometrical entities are required, because the other available techniques are much slower (Ambaw et al., 2012; Delele et al., 2009, 2008). With this method, many important shape features are lost. Further, because the shape of fruit and vegetables is highly variable (even between cultivars), this is not sufficiently accurate for numerical simulations.

Alternatively, shape description methods are often applied to quantify the shape variability (Costa et al., 2011). Many different techniques for describing 2D shapes exist, of which the use of Fourier descriptors (FDs) is one of the most popular techniques (Moreda et al., 2012; Zhang and Lu, 2004). Basically, the contour of a 2D shape is represented with a 1D function or shape signature. An example of a shape signature is the centroid distance function, which expresses the distance to the centre of the image (centroid) as a function of an angle. This periodic function is then approximated with a Fourier series expansion. The coefficients in the expansion are the Fourier descriptors (FDs). FDs have been used, amongst

* Corresponding author. Tel.: +32 16 322 375.
E-mail address: bart.nicolai@biw.kuleuven.be (B.M. Nicolaï).

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others, to describe the shape of various kinds of fruit such as apple (Paulus and Schrevens, 1999; Currie et al., 2000), starfruit (Abdullah et al., 2006) and citrus unshiu (Blasco et al., 2009); to discriminate split and unsplit shells of pistachio nuts (Ghazanfari et al., 1997); and to detect shape changes in drying fruit slices (Fernández et al., 2005). So far, shape description of horticultural products with FDs has always been done on 2D contours, with 1D FDs. For quasi-axisymmetric 3D shapes, such as those of apples, realistic models can be made by capturing the cross-sectional contour of the object, and subsequently revolving half the contour around the rotational axis (e.g., Dintwa et al., 2008). Shape description, e.g., with FDs, can then be used to describe and reconstruct the cross-sectional contour. Besides the certainty that the resulting surface is smooth, the main advantage is that FDs are easy to handle, so that interpolation between two sets of FDs (and so, two half contours) can easily be performed. This way, asymmetric geometrical models can be made. Additionally, perturbations can be added to the geometry -when generating the 3D model by rotating the 2D contour- to make the geometrical model appear more realistic (Mebatsion et al., 2011).

The most realistic geometric 3D models are obtained using reverse engineering techniques, directly constructing models from data obtained with 2D or 3D imaging techniques, such as photographs of slices (Goñi et al., 2007), photographs at different angles (Moustakides et al., 2000), X-ray CT (Defraeye et al., 2012; Ho et al., 2011) or MRI (Goñi et al., 2008). Because these techniques are time consuming, they are used when only one or a few geometric models are required. However, when a whole set of objects is scanned, statistical methods can be used to analyse biological variability (Bernat et al., 2014). Furthermore, the statistical analysis can be used as basis for a fast algorithm for generating random, accurate geometric models. As a result, an unlimited amount of geometric models can be created, featuring the same biological variability as the original set of shapes. This method has been explored in the past (Jancsók et al., 1997) and recently been refined (Rogge et al., 2014). Because this method is based on the rotation and interpolation of the two halves of one 2D contour, the resulting models will be 'near-symmetric'.

In order to generalise this method to less-symmetric objects, shape description of the whole 3D surface of the plant organ instead of only a single contour is required, which implies the use of 2D Fourier descriptors. Indeed, 2D Fourier series may be used directly on the 2D shape signature representing the 3D contour instead. 2D Fourier series are used, for example, to describe and match fingerprints (Wang et al., 2007) or for image compression to the JPEG file format (Wallace, 1992), but have not been used before to describe plant organ shapes. Here, we present a new geometrical model generator for constructing 3D geometric models of plant organs with complex shapes such as concave and/or asymmetric shapes. This generator aims to swiftly generate an unlimited number of realistic 3D models, all individually different, by random generation based on an a priori acquired dataset of 3D shapes. This dataset is obtained by non-destructive imaging using X-ray CT after which the visualised 3D contours are described with a 2D Fourier series. Statistical analysis of the obtained descriptors enabled generation of new descriptors, representative for the original distributions of descriptors. This way, new random 3D geometrical models with the same biological variability as the original dataset were successfully created. By applying shape description on the entire 3D contour, much more detail of the original shapes is included in the newly generated shapes. The resulting geometrical models are, therefore, significantly more accurate than those based on 2D shape description. Apart from this more accurate shape description technique, this model generator also allows generating a large quantity of geometrical models of a plant organ in a short time.

2. Materials and methods

2.1. Fruit

Two datasets of CT scans were used to test the geometrical model generator: 94 scans of apple (cv. 'Braeburn') and 66 scans of pear (cv. 'Conference'). Both the apples and pears were grown on a field of the Centre of Fruit Growing (pcfruit, Sint-Truiden, Belgium) in 2009 and in 2011. All harvesting dates were within the optimal commercial picking window for each cultivar, as determined by the Flanders Centre of Postharvest Technology (VCBT, Belgium).

2.2. Image acquisition

X-ray CT was used to acquire the images required for the development of the statistical geometrical model generator. X-ray CT is an imaging method with which 3D images of an object can be obtained by reconstruction of 2D radiographic images taken under different view angles using an X-ray source and detector. The radiographs are made by rotating the object in discrete steps over an angle of 180°. The difference between two view angles is the angular increment. Cross-sectional slices, in the resulting 3D image stack represent the X-ray attenuation properties of the fruit. In this study, the X-ray CT scans were made on a microfocus X-ray CT (AEA Tomohawk, Philips, The Netherlands) using a Philips HOMX 161 X-ray source. The most important scanning parameters (voltage, current and angular increment) are listed in Table 1. The size of the voxels in the resulting reconstructed 3D images ranged from 81 to 96 μm for the apples and from 110 to 138 μm for the pears.

2.3. Geometrical model generator

The geometrical model generation described below was entirely coded in Matlab (The MathWorks Inc., Natick, MA). The algorithm was optimised to reduce the amount of necessary manual user intervention to a minimum to make the procedure fast and user friendly. All computations were performed on a computer with an Intel Core2 Quad Q9650 @ 3.00 GHz processor with 8 GB RAM. A schematic overview of the followed procedure is given in Fig. 1.

2.3.1. Shape description

For each scanned fruit, the 3D contour (which is a point surface) was extracted with Matlab's edge detection routines. The first step in obtaining 2D Fourier descriptors for this 3D contour is finding a suitable 2D shape signature. We used spherical coordinate transformation for this purpose, because it exploits the available symmetry. The centre of mass was determined with Matlab procedures, and the three original coordinates (x, y, z) were subsequently transformed into a 2D function of the distance to this centre (r), depending on the two angles θ (azimuth) and ϕ (elevation), as shown in Fig. 2. The resulting shape signature r is a projection of the apple shape on a rectangle, similar to a projection of the shape of the Earth to a map. In this coordinate frame, the object is rotated,

Table 1
scanning parameters.

Apple	Scan date	V (kV)	I (mA)	$\Delta\Omega$ (°)	Pear	Scan date	V (V)	I (mA)	$\Delta\Omega$ (°)
	17-11-09	85	0.41	0.5		26-11-09	85	0.41	0.5
	26-11-09	85	0.41	0.5		10-11	75	0.463	0.3
	02-12	75	0.463	0.3		11-11	75	0.463	0.3
	03-12	75	0.463	0.3					