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A geometrical model generator for quasi-axisymmetric fruit

Seppe Rogge*, Shiferaw Beyene, Els Herremans, Thijs Defraeye, Pieter Verboven, Bart Nicolai
Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, University of Leuven, Willem de Croylaan 42, B-3001, Leuven, Belgium
**correspondence:* seppe.rogge@biw.kuleuven.be

Highlights: A geometrical model generator for fruit is presented. The generator uses X-ray tomography images of quasi-axisymmetric fruit as input, describes the shape of the fruit with elliptical Fourier descriptors, and uses statistical analysis to randomly generate new representative fruit shapes from this dataset, which can be directly used as CAD models for CFD or FEM analysis.

Keywords: elliptic Fourier descriptors, shape description, shape generation, biological variability

INTRODUCTION

Structure, shape and size are significant features of plant organs for gas and water exchange in relation to physiological processes such as growth (Abera et al., 2012), respiration (Ho et al., 2011) and photosynthesis (Ho et al., 2012), as well as to postharvest quality of plant products such as fruit (Jancsók et al., 2001; Nguyen et al., 2006; Veraverbeke et al., 2006; Delele et al., 2008, 2009; Ambaw et al., 2012). However, realistic descriptors and models of the geometry of biological products are not always available, and complex shapes are often replaced by basic geometries, like ellipsoids (Rashidi & Gholami, 2008) or spheres (Delele et al., 2008, 2009; Ambaw et al., 2012).

2D shape description and representation of complex shapes has recently been achieved (Costa et al., 2011; Moreda et al., 2012). A popular way to describe the contour of a 2D image are Fourier descriptors (FD). FD have some advantages compared with other methods: the descriptors are simple to compute, they have a physical meaning, and they capture both global and local features (Zhang & Lu, 2004). Mebatsion et al. (2011) described the contour of sections of plant organs with these descriptors, and interpolated different contours to construct 3D models of the plant organs. The more complex the shape, the higher the number of contours used for one image. A drawback of this method is its destructive nature. New techniques, such as MRI (magnetic resonance imaging) and X-ray tomography reveal the inner and outer structure of biological material in a non-destructive way (Lammertyn et al., 2003; Herremans et al., 2013). Furthermore, shape description analysis on a set of products opens perspectives to automatic generation of random shapes, based on statistical analysis of the dataset, but has not been explored yet. The resulting database of biological products could introduce biological shape variability, as present in reality, into numerical simulations.

Here, we present a geometrical model generator for apple fruit based on X-ray tomography of whole apples; once a limited number of fruit shapes is analysed by means of FD, an unlimited amount of new shapes, representing the variability of a certain species or even cultivar, can be generated. The procedure was entirely coded in Matlab (The MathWorks Inc., Natick, MA), and the amount of necessary manual intervention was reduced to a minimum.

METHODOLOGY

The geometrical model generator consists of two parts: in the first part, shapes are analysed by means of FD, and in the second part, new models are generated based on the FD statistics. The input dataset consists of X-ray computed tomography (CT) scans of 73 Braeburn apples. For each apple, a cross section image was constructed. This section was chosen manually in such a way that it always contains the centre of the apple, and that the stem appears as little as possible in the image. Large stems cannot appear in the image, because they are curved and disrupt the (quasi-)symmetry of the apple that results in 3D shape artefacts, when generating a new fruit shape. The contour of the section was extracted by Matlab's built-in edge detection and boundary tracing routines.

Fourier descriptors were calculated from the contours. In this study, elliptic Fourier descriptors (EFD) introduced by Kuhl and Giardina (1982), were applied. The important advantage of this type of FD is that they can deal with outlines that curve back on themselves. The number of computed EFD is a multiple of four: a sine and a cosine term both in the r and z-direction (cylindrical coordinates). From sensitivity analysis, 25x4 descriptors were found to be sufficient; higher order descriptors represented unnecessary details in the contour. In the resulting 3D model, fluctuations in the r and z-direction should not be too prominent compared with those in the θ-direction. From the 73 sets of FD, a new set of FD with the average value of each descriptor, and the covariance matrix of all descriptors, was calculated.

With the covariance decomposition method described in Alabert (1987), new 2D geometrical contours were generated, using the descriptor averages and the covariance matrix. The first step towards making a 3D model of the new set of descriptors was calculating the EFD of its mirror image along the axis of (quasi)symmetry. Subsequently, a number of new FD sets was generated by interpolating between these two sets of descriptors. Each set is then converted to a contour (see Figure 1). Next, the contours are rotated around the axis of symmetry at an angle between 0 and π. An example with only 20 (for clarity) half-contours can be seen in Figure 2a. This way, a smooth 3D shape is created by interpolation. The final step was creating a NURBS surface, that fits to the set of datapoints, and exporting this surface as an IGES file, a file format which can be directly used as a CAD input in numerical software for modelling transport and physiological processes.

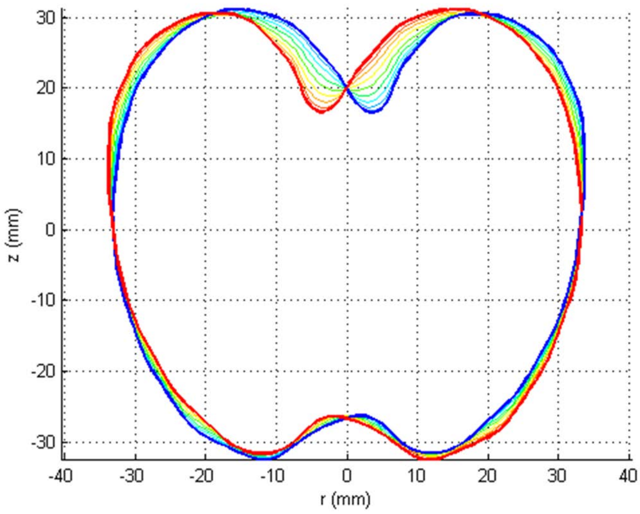

Fig. 1. A newly generated contour (thick blue line), the mirror image of this contour (thick red line), and contours created by interpolating between the two sets of EFD of these contours (small lines). Only 10 contours are shown for clarity.

RESULTS AND DISCUSSION

A resulting apple shape can be seen in Figure 2b. The quality of the generated shapes was tested by comparing the volumes of the original 73 Braeburn apples with the volumes of the generated shapes. For this purpose, 1000 new shapes were generated. They had an average volume of 208 cm^3, with a standard deviation of 36 cm^3, while the original apples had an average volume of 208 cm^3, with a standard deviation of 31 cm^3.

The perfect agreement of the average volume of the generated shapes with that of the real fruit indicates that the shape generator is a stable algorithm. The slightly higher spread in volumes, on the other hand, can be explained by the fact that only one section is used to generate a new shape. In real apples, cross-sections with a small or large surface will be somewhat averaged out by the other cross-sections.

It should be noted that some of the generated shapes do not represent realistic apple shapes with smooth axisymmetric features. These shapes originate particularly when asymmetric contours are revolved. Nevertheless, the majority of the shapes (roughly 80%) are good-quality (both shape and size) apple-like shapes; bad shapes can easily be excluded by the user.

In conclusion, a geometrical model generator for quasi-axisymmetric shapes is presented. The method is found to be fast and requires little human intervention. The resulting output are generally realistic apple shapes, which are exported in the form of CAD models, that can easily be used for numerical simulations.

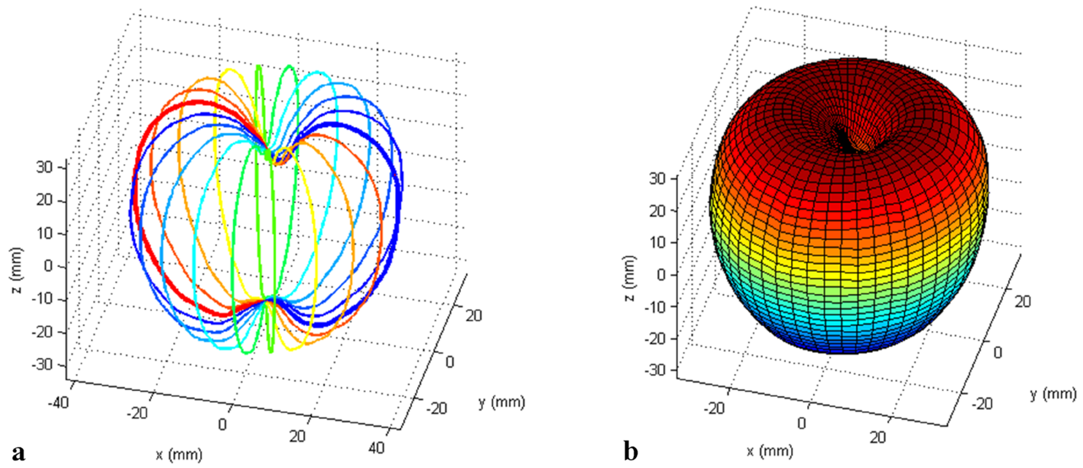

Fig. 2. New 3D generated shape of an apple. a) Contours revolved around the rotation axis. The thick blue line at the right and the thick red line at the left describe the original contour. Only 20 half-contours are shown for clarity. b) NURBS surface fitted to the revolved contours.

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