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# Multisensor X-ray inspection of internal defects in horticultural products

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ABSTRACT

A combination of 3-D vision and X-ray radiography is proposed to enable low-cost, generally applicable online inspection of internal quality of horticultural and potentially other products. The underlying concept assumes that the shape of the product is known beforehand through a deformable shape model. A 3-D vision system is used in combination with the shape model to accurately determine the complete outer surface shape of the sample. This shape is voxelized to generate a reference product from which a X-ray radiograph is simulated to be compared with a measured radiograph, hence revealing the presence of any defects or disorders. Advantages of this method are that small deviations in internal density are detected easily since the cumulative information of the bulk object shape is removed. Furthermore, no specific detection algorithms have to be developed for different types of defects, since the method will directly identify deviations from the ideal. Validation on two datasets and comparison with two reference detections methods (classical image processing and a human operator) shows that the proposed method reliably (accuracy >99%) detect defects larger than 3.5 mm radius with densities differences between sample and defects as small as 10%. Voids are reliably (accuracy >99%) detected down to a radius of 1.5 mm, corresponding to a volume of less than 0.02 $cm^3$.

## 1. Introduction

Horticultural products often develop internal defects, cracks or cavities that reduce their commercial value. Currently the most widespread method to detect these is destructive evaluation where a number of samples is randomly selected from each batch and cut open for inspection (Shewfelt et al., 2012). This has some inherent disadvantages like financial losses because of destroying a number of samples and the fact that only a small subset of all products is checked.

Recent research shows that a number of internal defects can be detected using non-destructive technologies such as visible/near-infrared (NIR) spectroscopy (Bobelyn et al., 2010; Magwaza et al., 2012; Nicolaï et al., 2007), nuclear magnetic resonance (MRI, Nicolaï et al., 2014; Zhang and McCarthy, 2013), hyperspectral imaging (Haff et al., 2013; López-Maestresalas et al., 2016), and magnetic resonance imaging (MRI, Clark et al., 1999; Herremans et al., 2014; Lammertyn et al., 2003a, 2003b). X-ray based methods, however, have as advantage their sensitivity to spatial density differences inside an object and the excellent penetration properties of X-rays in horticultural products (Kotwaliwale et al., 2014).

X-rays populate the electromagnetic spectrum between 10 and 0.01 nm. When passing through an object, these X-rays physically interact with the object material and are partly absorbed and scattered (Barrie Smith and Webb, 2010). The remaining X-rays are recorded on a detector, resulting in an X-ray radiograph, an image containing superimposed information or a projection of the 3-D object in a 2D plane. X-ray radiography is a fast and cheap 2D imaging technique and is already used in industry for detection of foreign bodies with distinct density (e.g. metals, stones) such that they appear with high contrast in the resulting image for easy segmentation and detection. Internal defects usually cause smaller attenuation differences in the object. Furthermore, radiographs render the cumulative attenuation along the X-ray path from source to detector and therefore are affected by the size and shape of the scanned object. Contrast gradients in the image are thus not only due to density variations due to defects and other local features, but are also caused by object shape and size. Although radiographs have proven to be useful in detecting certain types of

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internal defects in horticultural products (Haff et al., 2006; Hansen et al., 2005; van Dael et al., 2016a), variations in their shape, size, position and density reduce the classification accuracy of the method, especially when defects are small. Shape variation can be considerable for agricultural and horticultural products (Rogge et al., 2015).

In X-ray computed tomography (CT) multiple radiographs of the same object, taken from different angles, are combined to produce a 3-dimensional image using a mathematical algorithm (Magwaza and Opara, 2014; Nicolaï et al., 2014). The resolution varies from 1 mm in medical scanners down to the nanometer level on dedicated micro-CT scanners (Verboven et al., 2008). X-ray CT has been used successfully to detect internal disorders in pear (Lammertyn et al., 2003a), apple (Herremans et al., 2014; Nicolaï et al., 2014; Schatzki et al., 1996) and pineapple (Haff et al., 2006). However, the equipment is expensive and the 3-dimensional reconstruction comes at a high computational cost making it difficult to apply into existing sorting lines.

The aim of this paper is to improve the detection accuracy of internal defects of horticultural products by means of inline X-ray radiography. To achieve this objective, the method patented in (van Dael et al., 2016b) is applied to internal quality inspection of horticultural products, explicitly taking into account the shape, size and orientation of the object by means of a 3-D vision system and a deformable shape model. This normalizes the measured radiograph for the bulk shape and size of the inspected sample by simulating a reference radiograph from the shape model that is fitted to the point cloud produced by the 3D-vision system. A range of product shapes and defects are considered. The principle of the method is demonstrated by comparing it to radiography detection algorithms which use a conventional method of imaging and detection.

## 2. Materials and methods

### 2.1. Products

The shape of the majority of horticultural products can be approximated with curvilinear shapes. In this work, we have first considered a family of curvilinear shaped model objects (tori) with artificially induced defects of different sizes and contrast and subsequently a real horticultural product, namely ‘Conference’ pears with a defect known as core breakdown (Franck et al., 2007; Lammertyn et al., 2003a,b). All simulations and calculations were performed on a on a desktop pc with a quad-core 3.4 GHz processor, 16 GB of RAM memory and an nVidia Quadro K600 1GB graphics card.

#### 2.1.1. Torus shapes

A set of random tori ($1\,\text{mm} < r < 25\,\text{mm}$, $1\,\text{mm} < R < 25\,\text{mm}$, $N = 2240$, with $r$ and $R$ the minor and major radius respectively and N the number of samples) was voxelized according to Patil and Ravi (2005) to a binary 3-dimensional matrix. These dimensions were chosen arbitrarily to not exceed a maximum diameter of 100 mm, approximating the size range of many horticultural products. Spherical defects ($0.5\,\text{mm} < \text{r} < 7\,\text{mm}$) were added at random locations with voxel values (representing fractional density of the defect to the object material) ranging from 0 (voids) to 1 (no defect present) in 0.1 increments. Fig. 1 shows 3 tori with added defect shapes in the top row, together with a radiograph simulated from a random orientation in the bottom row.

#### 2.1.2. X-ray CT imaging of ‘Conference’ pears

The realistic dataset consisted of a set of X-ray CT scans of *Pyrus communis* cv. ‘Conference’ pears harvested from orchards in the province of Limburg, Belgium between September 17–23, 2013. The pears were stored at −1 °C and environmental gas conditions until January 7, 2014 when the X-ray CT scans were performed.

Samples were randomly selected (N = 30) and scanned in a Philips AEA Tomohawk X-ray CT system equipped with a Nikon metrology 160 Xi Gun set and a Thomson TH 9428HX – Adimec MX12P image intensifier – CCD camera pair. Source parameters were 65 kV at 500 μA, 380 projections were captured with a rotation step of 0.5° and reconstructed resulting in an effective voxel size of 131 μm (Lammertyn et al., 2003a,b). A subset of the dataset is shown in Fig. 2. Radiographs from 15 random orientations were simulated from each pear ($N = 450$) as described in Step 2. X-ray simulation. Defects were manually segmented from CT scans and photographs were taken to serve as a ground truth. Since the segmented defects are elongated in shape along the core, they were approximated with ellipsoids using a normalized second central approach (Mukundan and Ramakrishnan, 1998). A histogram of the ellipsoid axis lengths is shown in Fig. 3 to quantify the size of the defects.

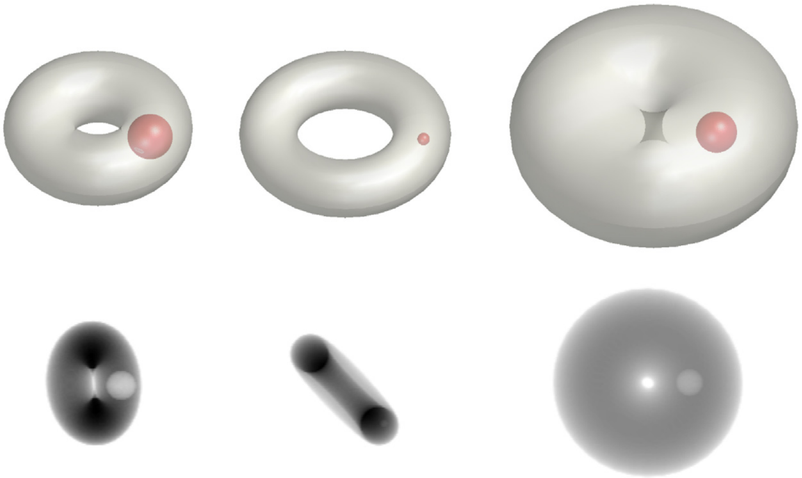

**Fig. 1.** Top row: three tori with added defects rendered in red. Bottom row: radiographs simulated from the randomly oriented tori with a detector pixel size of 0.5 mm using the ASTRA toolbox. Defect densities in these examples are 0% of sample densities i.e. voids.