Journal of Food Engineering 232 (2018) 11–20

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Structured-illumination reflectance imaging coupled with phase analysis techniques for surface profiling of apples☆

Yuzhen Lu [a], Renfu Lu [b], *

[a] Department of Biosystems and Agricultural Engineering, Michigan State University, East Lansing, MI, 48824, USA
[b] United States Department of Agriculture Agricultural Research Service, East Lansing, MI, 48824, USA

ARTICLE INFO

Article history:
Received 2 May 2017
Received in revised form
5 February 2018
Accepted 20 March 2018
Available online 21 March 2018

Keywords:
Structured-illumination
Imaging
Demodulation
Phase analysis
Surface profiling
Fruit

ABSTRACT

Three-dimensional (3-D) geometry information is valuable for fruit quality evaluation. This study was aimed at exploring an emerging structured-illumination reflectance imaging (SIRI) system, coupled with phase analysis, for reconstructing surface profiles of fruit. Phase-shifted sinusoidal patterns, distorted by the fruit geometry, were acquired and processed through phase demodulation, phase unwrapping and other post-processing procedures to obtain phase difference maps relative to the phase of a reference plane. The phase maps were then transformed into height profiles based on phase-to-height calibrations. A reference plane-based approach, in conjunction with the curve fitting technique using polynomials of order 3 or higher, was utilized for phase-to-height calibrations, which achieved superior accuracies with the root-mean-squared errors (RMSEs) of 0.027–0.033 mm for a height measurement range of 0–91 mm. The 3rd-order polynomial curve fitting technique was further tested on two reference blocks with known heights, resulting in relative errors of 3.75% and 4.16%. Tests of the calibrated system for reconstructing the surface of apple samples showed that surface concavities (i.e., stem/calyx regions) could be readily discriminated from bruising defects from both the phase difference images and reconstructed height profiles. This study has laid a foundation for using SIRI for reconstructing the 3-D geometry, and thus expanded the capability of the technique for quality evaluation of horticultural products. Further research is needed to utilize the phase analysis techniques for detecting surface concavities of apples, and optimize the phase demodulation and unwrapping algorithms for faster and more reliable detection.

Published by Elsevier Ltd.

1. Introduction

Three-dimensional (3-D) surface profiling is to acquire surface range (height or depth) information of objects, and it is useful for non-destructive quality inspection of agricultural commodities by imaging techniques. For fruits such as apples, 3-D surface information provides a means for determination of fruit shape or size (Danckaers et al., 2015; Moreda et al., 2009), which is one of the most important quality metrics for apple sorting and grading. Currently, commercial imaging inspection systems for defect sorting are still faced with the challenge to recognize stem/calyx regions that are normal parts of fruit in the image, which, otherwise, may cause confusion with true defects. Since stem/calyx regions are located around the concave area of fruit, they can be readily recognized through the reconstructed 3-D surface of fruit (Jiang et al., 2009; Zhang et al., 2015; Zhu et al., 2007). Additionally, the 3-D geometry of an object can be used for image corrections for intensity distortions due to the fruit curvature (Gomez-Sanchis et al., 2008b), thus helping enhance the detection of fruit defect (Gomez-Sanchis et al., 2008a).

Numerous optical or imaging techniques have been developed for 3-D surface profiling or shape measurement, among which the most prevalent are time-of-flight (TOF), stereo vision and structured lighting (Chen et al., 2000; Seitz et al., 2006; Zhang, 2016). TOF uses a single camera to measure the distance between the object and the light source by detecting the time delay of modulated light pulses, which has been commercially used, with measurement errors ranging from several millimeters to centimeters (Blais, 2004; Chen et al., 2000). Stereo vision is a multi-camera based technique, which reconstructs the 3-D shape from a number of images acquired from different viewing angles based on the

---

☆ The original version of this paper was presented at the SPIE Commercial + Scientific Sensing and Imaging, Sensing for Agriculture and Food Quality and Safety IX, Anaheim, California, April 9–13 (paper 10217–15).

* Corresponding author.

E-mail addresses: luyuzhen@msu.edu (Y. Lu), renfu.lu@ars.usda.gov (R. Lu).

https://doi.org/10.1016/j.jfoodeng.2018.03.016
0260-8774/Published by Elsevier Ltd.

triangulation principle. In stereo vision, establishing correspondences between two stereo images, however, is extremely difficult, which restricts the ability of this technique to reconstruct objects with smooth surface. Structured lighting is similar to stereo vison, except that one camera is replaced with a projector, which shines structured or patterned light to an object, and it recovers the 3-D geometry by analyzing how the predefined pattern is deformed by the object. Thanks to the active light pattern projection, structured lighting technique obviates the need in stereo vision for the texture variation of an object to find corresponding points, while enabling accurate and fast 3-D reconstruction, which is closely related to its pattern coding strategies (Salvi et al., 2004, 2010). In the past two decades, structured lighting technique, benefiting from advancements in digital imaging and light projecting technologies, has become increasingly popular in 3-D shape measurement in a wide range of fields, such as manufacturing, computer science, entertainment et al. (Bell et al., 2016).

In recent years, structured lighting technique has spread rapidly into the agricultural field for 3-D imaging applications (Rosell-Polo et al., 2015; Vazquez-Arellano et al., 2016), ranging from size estimation of sweet onions (Wang and Li, 2014), to plant phenotyping (Chene et al., 2012; Jiang et al., 2016; Paulus et al., 2014) and image segmentation of plant leaves (Xia et al., 2015) and to monitoring of the body conditions of livestock (Rosell-Polo et al., 2015). In most of these applications, 3-D images were obtained by using a low-cost consumer-grade depth camera, such as Microsoft Kinect I. Kinect I is a structured lighting technique using a random pattern coding strategy, in which an infrared laser, combined with a diffractive optical element, is used to generate a unique pattern consisting of a large number of random dots (Zhang, 2012), and 3-D information is then derived from the captured patterns based on triangulation. This technique, however, has some drawbacks, such as noise sensitivity and limited spatial resolution. Among various structured lighting techniques, a digital fringe projection (DFP) technique, originated from laser interferometry, which uses computer-generated sinusoidally-modulated fringe patterns (i.e., sinusoidal or fringe patterns for brevity), has been extensively studied in optical metrology in last decade (Zhang, 2010, 2016), due to its ability to achieve accurate measurements at the pixel level. In DFP, height or depth information is computed using a phase shifting method from a phase or phase difference map, rather than intensity images that are commonly used in many other structured lighting techniques, which is typically more robust to noise (Bell et al., 2016). Since the computation is performed for each pixel, a dense 3-D reconstruction can be obtained with high measurement accuracy, if calibrations have been properly done to establish the phase-to-height relationship (Vo et al., 2012; Zhang, 2006). Despite its great potential, the DFP technique, however, has yet to be explored in agricultural applications.

Our lab has recently developed a structured-illumination reflectance imaging (SIRI) system for quality evaluation of horticultural products (Li, 2016; Lu et al., 2016; Lu and Lu, 2017). The SIRI, conceptually similar to the DFP technique, uses a digital light projector controlled by a computer to shine phase-shifted sinusoidal patterns onto a sample and then captures reflectance images from the sample. The technique has demonstrated superior performance in detecting subsurface bruising in apples through analyzing amplitude component (AC) and direct component (DC) images obtained from the demodulation of the acquired pattern images (Lu et al., 2016; Lu and Lu, 2017). Since SIRI uses sinusoidal patterns, it can be, in theory, also used for shape measurement through phase analysis.

This research was, therefore, aimed at exploring the feasibility of SIRI for 3-D surface profiling of fruit. Specific objectives of this work were two-fold: (1) to develop phase analysis techniques, including phase demodulation, phase unwrapping and system calibrations, for surface profiling; (2) to test and evaluate the techniques through the reconstruction of surface contours for reference and apple samples.

2. Phase analysis for surface profiling

2.1. Phase-height relationship

A two-dimensional (2-D) sinusoidal pattern can be mathematically described as follows:

$$I(x,y) = I_{\mathrm{DC}}(x,y) + I_{\mathrm{AC}}(x,y)\cos[\varphi(x,y) + \delta] \tag{1}$$

where (x,y) are the spatial coordinates, $I_{\mathrm{DC}}(x,y)$ and $I_{\mathrm{AC}}(x,y)$ represent the intensity distributions of DC and AC, respectively, $\varphi(x, y)$is the phase map that is usually linearly modulated as $\varphi(x,y) = 2\pi f_x x$ where f_x denotes the spatial frequency along the x-axis, and δ is the phase offset.

Now let us look at how the phase information can be utilized for height measurement in SIRI. The SIRI system, as schematically shown in Fig. 1(a), consists of a micro-mirror device (DMD) based digital light projector, a charge-coupled device (CCD) camera, a light source and a computer, and the geometry of the system is in shown in Fig. 1(b).

As shown in Fig. 1(b), the camera is vertically set up at a distance H from the horizontal reference plane, while the projector is tilted at an angle β relative to the vertical axis. Points O_1 and O_2, spaced apart at a distance d, are the optical centers of the projector and camera lenses, and the line passing through the two points intersects the horizontal axis at an angle α. Then, given a point C on the sample, its height can be readily calculated as follows:

$$h = \frac{\overline{\mathrm{AB}}}{\overline{\mathrm{AB}} + d[\sin(\alpha)\tan(\beta) + \cos(\alpha)]}H \tag{2}$$

where $\overline{\mathrm{AB}}$ denotes the length of line segment AB. Simple manipulation of Eq. (2) yields as follows:

$$\frac{1}{h} = c_1 + \frac{c_2}{\overline{\mathrm{AB}}} \tag{3}$$

where c_1 and c_2 are two constants, equal to $1/H$ and $d[\sin(\alpha)\tan(\beta) + \cos(\alpha)]/H$, respectively. Further, it is noted that $\overline{\mathrm{AB}}$ is related to the phase difference between points A and B in the reference plane. Since O_2, C and A points are on the same light ray emitting from the projector, the point A in the reference plane has the same phase values as the point C in the sample, which corresponds to the phase value of the point C′ in the image plane; the phase value of the point B in the reference plane corresponds to that of the point B′(note that C′ and B′ correspond to the same image pixel). Thus, $\overline{\mathrm{AB}}$ is actually dependent on the phase

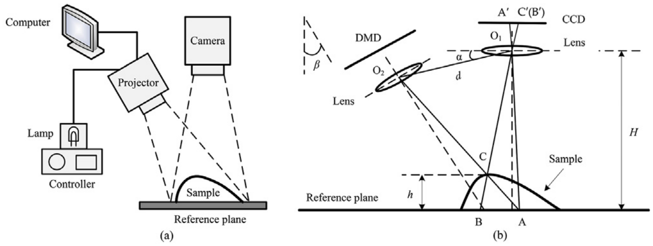

Fig. 1. Schematic (a) and geometric representation (b) of structured-illumination reflectance imaging (SIRI).