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journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Histogram-based automatic thresholding for bruise detection of apples by structured-illumination reflectance imaging

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ARTICLE INFO

Article history:
Received 30 January 2017
Received in revised form
15 May 2017
Accepted 24 May 2017

Keywords:
Automatic thresholding
Histogram
Structured illumination
Bruise
Apple

Thresholding is an important step in the segmentation of image features, and the existing methods are not all effective when the image histogram exhibits a unimodal pattern, which is common in defect detection of fruit. This study was aimed at developing a general automatic thresholding methodology for fast and effective segmentation of bruises from the images acquired by structured-illumination reflectance imaging (SIRI). SIRI images, under sinusoidal patterns of illumination at a spatial frequency of 100 cycles m^{-1}, were acquired from 120 apple samples of four varieties with artificially created bruises and from another 40 apples with naturally occurred bruises. Subsequently, three sets of images, i.e., amplitude component (AC), direct component (DC) and ratio (i.e., dividing AC by DC), were derived from the original SIRI images. A unimodal thresholding method, called UNIMODE, was first applied to DC images for background removal, and then nine automatic thresholding techniques, including one unimodal and eight bimodal, were applied to the ratio images for bruise segmentation. It was found that severe over-segmentation occurred when using the bimodal thresholding methods, and this problem was mitigated by confining threshold selection to the lower part of the histogram that contained bruise information. Three bimodal thresholding techniques, i.e., INTERMODE (histogram valley emphasized), RIDLER (iterative thresholding), OTSU (clustering based) achieved the best bruise detection results with the overall accuracies of more than 90%. The overall detection results were further improved by integrating these techniques with the unimodal thresholding, due to reductions in the false positive error. The three bimodal thresholding techniques resulted in overall detection accuracies of 77–85% for naturally occurred bruises. This study has showed that the proposed automatic thresholding methodology provides a simple and effective tool for bruise detection of apples.

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http://dx.doi.org/10.1016/j.biosystemseng.2017.05.005
1537-5110/Published by Elsevier Ltd on behalf of IAgrE.

1. Introduction

Automatic detection of defects for apples during sorting and grading has been a challenging issue (Lu & Lu, 2016). The difficulty is mainly attributed to the fact that there are a wide variety of defects, such as bruise, scar, physiological disorders, insect damage and contamination, and each of them is different in its morphological or physiological characteristics. The problem is further complicated by the fruit skin that may have great variations in colour and texture, which are dependent on variety as well as the degree of maturity or ripeness and pre- and post-harvest handling regimes. Bruise, especially fresh one, is among the most difficult defects to detect (Leemans & Destain, 2004; Leemans, Magein, & Destain, 2002; Shahin, Tollner, McClendon, & Arabnia, 2002; Unay & Gosselin, 2006), because it is often free of external symptoms or looks similar to the surrounding healthy tissue.

Numerous imaging modalities have been investigated for detection of defects on apples over the past 30 years, from visible light based monochromatic or black/white imaging to colour or RGB (i.e., red, green and blue) imaging, and from near-infrared (NIR) broadband imaging to multi- and hyperspectral imaging (Li, Huang, & Zhao, 2015; Lu & Lu, 2016). Among these techniques, NIR imaging has shown good performance in detecting such defects as bruises (Baranowski, Mazurek, & Pastuszka-Wozniak, 2013; Bennedsen & Peterson, 2005; Lu, 2003; Luo, Takahashi, Kyo, & Zhang, 2011; Xing, Saeys, & De Baerdemaeker, 2007), due to better penetration of NIR light in tissues than the visible light. However, NIR imaging has been reported to be ineffective for the detection of fresh bruises of less than one day old (Martinsen et al., 2014), because bruised tissues have not fully developed in such a short time period. Our lab recently developed a SIRI technique, which uses sinusoidally-modulated structured light in place of uniform light that is predominantly employed in the existing imaging techniques, for defect detection of apples. SIRI has the capability of enhancing image contrast and resolution and better controlling the penetration of light in the tissue by varying the spatial frequency of illumination (Li, 2016; Lu, Li, & Lu, 2016c; Lu & Lu, in press). It was found to be more effective or superior to conventional imaging under uniform illumination, in ascertaining fresh bruises within hours after impact bruising.

As in other imaging techniques, image processing, including image segmentation and classification, is critical in implementing SIRI technique for fruit defect detection. With image segmentation and classification methods, possible defect regions are first segmented by thresholding and then classified by using a detection criterion or model built upon extracted features (Li, Wang, & Gu, 2002; Throop, Aneshansley, Anger, & Peterson, 2005; Throop, Aneshansley, & Upchurch, 1995; Xing, Bravo, Jancsok, Ramon, & De Baerdemaeker, 2005; Xing et al., 2007). In defect segmentations of fruit, thresholding-based techniques are generally used to remove the background and then segment possible defect regions from normal regions; they are fast and simple to use and thus well suited for on-line applications. However, the techniques can be problematic in segmenting the images with weak contrast or uneven reflection due to the surface curvature or irregular shape of fruit. Alternatively, the two steps of image segmentation and classification can be replaced by single-step pixel-based classification models, like neural networks and support vector machines (SVM) (Ariana, Guyer, & Shrestha, 2006; Bennedsen, Peterson, & Tabb, 2007; Guyer & Yang, 2000; Unay & Gosselin, 2006). Classification-based techniques are able to address multi-class detection problems, but they are more complex and require intensive computation for model training at the pixel level, thus restricting their practical utility. In addition, the image background needs to be identified and removed prior to defect segmentation, which is traditionally done by applying a simple global threshold.

In most reported research on detection of defects on apples using thresholding techniques, the user-defined fixed threshold method, i.e., manual thresholding, is commonly used to segment the background and/or defects (Huang, Li, Wang, & Chen, 2015; Li et al., 2002; Lu, 2003; Throop et al., 2005; Zhang et al., 2015). The method requires manual involvement, and the selected threshold can be suboptimal or even erroneous if there is a bias due to limited observations from fruit samples, or when there are unexpected defect features or large fluctuations in lighting. For this reason, automatic thresholding is more desirable in determining the optimal threshold for individual fruit. Unay and Gosselin (2006) reported on the use of four automatic thresholding techniques, including three global thresholding methods, Entropy, Isodata and Otsu (corresponding to ENTROPY, RIDLER and OTSU in this study) and one local thresholding method, for segmenting defects on 'Jonagold' apples, and their results showed that Isodata and Otsu performed better than other thresholding methods for defect segmentation. In segmenting bruises on 'McIntosh' apples, ElMasry, Wang, Vigneault, Qiao, and ElSayed (2008) performed adaptive thresholding for selecting multiple thresholds based on the intensity distribution of each local neighbourhood in an image. Mizushima and Lu (2013) proposed an automatic thresholding technique for background removal in colour images based on the Otsu thresholding (Otsu, 1979) and SVM. In these applications, researchers only used bimodal thresholding techniques like the Otsu thresholding for defect segmentation, which, however, are likely to fail if the histogram is or close to unimodal (Ng, 2006; Xu, Xu, Jin, & Song, 2011). Defects on fruit are, in most cases, small in size, compared to the surface area of fruit. Hence the unimodal image histograms are expected for most fruit. Research is thus needed to evaluate the performance of different bimodal thresholding methods when they are applied to the segmentation of images with a unimodal histogram. Furthermore, improvements to the existing automatic bimodal thresholding techniques should also be considered in order to achieve more accurate and robust defect segmentation.

The main objective of this study was, therefore, to develop a general automatic thresholding methodology for effective bruise segmentation from SIRI images. Specific contributions of the study include: 1) applying a unimodal thresholding technique for automatic background removal; 2) comparing nine automatic thresholding techniques, coupled with histogram pretreatment, for bruise segmentation; and 3) integrating unimodal and bimodal thresholding techniques for improved bruise segmentation.