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Development of a multispectral imaging system for online detection of bruises on apples

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ABSTRACT

Detection of bruises on apples is important but difficult for an automatic apple sorting system. The objective of this study was to develop a prototype multispectral imaging system for online detection of bruises on apples. A hyperspectral imaging system with the wavelength range of 325–1100 nm was built to select the effective wavelengths for detecting bruises on 'Fuji' apples. Segmented principal component analysis (PCA) was conducted on the 450–1000 nm, 450–780 nm and 780–1000 nm hyperspectral images respectively and the resultant principal component (PC) images were compared. Three effective wavelengths 780, 850 and 960 nm were determined by the weighing coefficients of the best PC images. The performance of the selected effective wavelengths was evaluated by 183 apples. The detection accuracies of apples with bruises created by dropping a steel ball from a 500 mm height in 1, 12 and 24 h were 90.4%, 92.3% and 92.3%, respectively. The detection accuracies of apples with bruises created by dropping a steel ball from 200, 300, 400 and 500 mm heights in an hour were 92.4%, 96.2%, 96.2% and 94.7%, respectively. Then a multispectral imaging system with two dichroic beamsplitters, two band-pass filters and three prism-based 2CCD multispectral progressive area scan cameras was developed. The online image acquisition speed was about 3 apples per second. The performance of the developed system was evaluated by static and online tests using 59 independent apples. The classification accuracies of bruised apples in static and online tests were 91.5% and 74.6%, respectively. Results showed that the developed multispectral imaging system based on the selected effective wavelengths using a hyperspectral imaging system and segmented PCA could be used for online detection of bruises on apples.
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1. Introduction

Bruise is one of the main defects of apple, which could be caused by impact or mechanical damage during harvesting or handling stages (García-Ramos et al., 2003; Van Zeebroeck et al., 2007). Detection of bruises on apples is very important because the presence of bruise will affect consumer's satisfaction and lead to spoilage and loss of nutritional value as well as substantial economy losses (Opara and Pathare, 2014). Although machine vision technology has been widely used in the apple industry for automated online sorting and grading of apples (Tao et al., 2006; Heinemann et al., 1995; Cubero et al., 2011), the detection of surface defects especially bruises on apples still faces some difficulties (Kondo, 2010; Li et al., 2011).

Because bruises are particularly difficult to detect using conventional RGB imaging technology, researchers have to find a new effective imaging system. A hyperspectral imaging system as a powerful analysis tool for simultaneous acquisition of spatial and spectral information of objects has attracted much attention of researchers for detecting the internal and external quality of a variety of agricultural products (Gowen et al., 2007; Lorente et al., 2012). This system has been successfully applied to detect bruises on pickling cucumbers (Ariana et al., 2006), pork marbling (Qiao et al., 2007), contaminant detection on poultry carcasses and cantaloupes (Lawrence et al., 2006; Vargas et al., 2005a,b), pits in tart cherries (Qin and Lu, 2005), nematodes in cod fillets (Heia et al., 2007), cracks in shell eggs (Lawrence et al., 2008), and so on. Recently, hyperspectral imaging systems have been widely used to detect bruises on apples. Lu (2003) developed a 900–1700 nm hyperspectral imaging system and a computer algorithm to detect both new and old bruises on apples. Results showed that the spectral region between 1000 and 1340 nm was most appropriate for bruise detection. However, no effective wavelengths were determined. Xing and Baerdemaeker (2005) used a 400–1000 nm hyperspectral imaging system to detect bruises on 160 'Jonagold' apples and principal component analysis (PCA) was used to aid in visualizing the hyperspectral images and six efficient wavebands 571,

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608, 671, 709, 798 and 867 nm were selected. Results showed that the correct classification rate for sound apples was 77.5% for the 1-day-old bruises based on the images of six efficient wavebands. Zhao et al. (2008) analyzed the apples' hyperspectral images between 500 and 900 nm using PCA and an asymmetric second difference method, and found that 540 nm images could be used to detect bruises on apples. Results showed that the detection accuracy is 88.57%. ElMasry et al. (2008) reported that the early bruises on 'McIntosh' apples could be detected using a 400–1000 nm hyperspectral imaging system combined with partial least squares and stepwise discrimination analysis methods, and three effective wavelengths 750, 820 and 960 nm were determined for bruises detection. Results showed that the proposed multispectral algorithm could be used to detect bruises after an hour of bruising. Baranowski et al. (2012) studied the early detection of bruises on apples based on two hyperspectral imaging systems in visible–near infrared (VIS–NIR) 400–1000 nm and short wavelength infrared 1000–2500 nm, and a thermal imaging camera in mid-wavelength infrared 3500–5000 nm. The PCA and minimum noise fraction analysis of the hyperspectral images were used to detect the bruises. A detection accuracy about 86–97% was obtained for different degrees bruises on apples. However, no effective wavelengths were determined. In our previous study, we combined the 820 and 970 nm images selected from 400 to 1000 nm hyperspectral images with PCA to detect the early bruises on apples with 96% bruise classification accuracy (Huang et al., 2013a). At the same time, our study also found that three effective wavelengths 1060, 1329 and 1949 nm images selected from 1000 to 2500 nm hyperspectral images using PCA could be used for early detection of bruises on apples (Huang et al., 2013b).

Due to the long acquisition time and high cost, it is not feasible for a hyperspectral imaging system to be applied for online detection of bruises on apples (Lorente et al., 2012; Kim et al., 2008). Thus, development of a multispectral imaging system which would be faster and cost-effective based on the selected effective wavelengths is necessary for online detection of bruises on apples (Qin et al., 2012). Many scholars have tried to develop a multispectral imaging system for detection of surface defects, including bruises on apples. Wen and Tao (1998) tested and compared twelve dual-filter combinations using four filters with wavelengths centered at 650, 700, 750 and 800 nm under different sorting requirements and a 700 and 800 nm vision system was determined as the best solution for online detection of defective apples. Kleynen et al. (2005) and Unay and Gosselin (2006) developed a multispectral image acquisition system based on four band-pass filters centered at four most effective wavebands 450, 500, 750 and 800 nm respectively resulting from their previous study (Kleynen et al., 2003). They reported that a good contrast between bruise and sound tissue could be offered by 750 and 800 nm bands images while 450 nm images were most suitable for detection of slight defects like russet. An overall 84.6% classification rate of four defect categories was achieved in their studies. Later, the overall accuracy was improved to 93.5% in a new study carried out by Unay et al. (2011) using the same four-band imaging system and a two-category grading solution. Meanwhile, in other studies a 740 and 950 nm two-band imaging system was developed by Bennedsen et al. (2005), Bennedsen and Peterson (2005) and Throop et al. (2005) and 950 nm was proved to be the optimal wavelength for detecting bruises, punctures, and scalds on apples. Our preliminary study also showed that it could be effective for static detection of bruises on apples using a multispectral imaging system (Huang et al., 2013c).

In the above-mentioned studies, the effective wavelengths for detection of bruises on apples are almost different such as 540, 571, 608, 671, 709, 750, 798, 820, 867, 950, 960, 970, 1060, 1329 and 1949 nm due to the different equipment configurations and experimental conditions. Although researchers have developed many multispectral imaging systems for the detection of apple's surface defects, these systems were mainly designed for common defects inspection and there was seldom a system specially developed for detection of bruises on apples. Considering about the high variability of most surface defects on apples, the detection of each kind of defect should be carefully studied. The wavelengths in the existing multispectral imaging systems for bruise identification may not be optimal. Furthermore, the effective wavelengths selected from the reduction of the dimensionality of hyperspectral data should also be validated by developing a multispectral imaging system based on these wavelengths. PCA was widely used for the determination of effective wavelengths from the hyperspectral images (Lu, 2003; Xing and Baerdemaeker, 2005; ElMasry et al., 2008; Baranowski et al., 2012; Qin et al., 2008). However, the full set of hyperspectral data were usually used to perform the PCA operation. Therefore, the selected effective wavelengths may not be optimal as the performance of PCA was degraded for the low correlations between spectral bands at different wavelength regions (Jia and Richards, 1999).

The objective of the present study was to develop a multispectral imaging system based on the selected effective wavelengths for detection of bruises on apples and evaluate its performance. Specific aims of this study are: (1) to select the effective wavelengths for detection of bruises on apples using a 325–1100 nm hyperspectral imaging system and a segmented PCA method; (2) to evaluate the performance of the selected wavelengths by detecting bruises with different degrees and different time of occurrence; (3) to develop a multispectral imaging system based on the selected effective wavelengths and an image processing algorithm to identify bruise from normal surface; (4) to evaluate the performance of the developed multispectral imaging system by static and online tests.

2. Materials and methods

2.1. Apple samples

250 'Fuji' apples were purchased from a local supermarket in Beijing. The 'Fuji' apple is a darker colored variety usually having a red peel which bruises are difficult to identify (Bennedsen and Peterson, 2005; ElMasry et al., 2008). These samples were washed in order to eliminate the effect of surface contamination, and they were numbered before imaging. The 250 samples were separated into two groups. The hyperspectral images of all samples were acquired before bruises were made on these samples. The first group of 190 samples was used for the selection of wavelengths using a hyperspectral imaging system and evaluation of the effectiveness of the selected wavelengths, and they were separated into 55 and 135 samples for two subsets. In the first subset, 3 samples with obvious defects were discarded and bruises on the other 52 samples were manually made using a steel ball weighing 33 g with a 20 mm diameter fall from a fixed height about 500 mm and hit the apples at the equatorial area. In the second subset, 4 samples with obvious defects were discarded and bruises on the other 131 samples were manually made using the same ball dropped from fixed heights about 200, 300, 400 and 500 mm respectively and hit different positions at the equatorial area. The second group of 60 independent samples was used for the evaluation of the developed multispectral imaging system through static and online tests. In this group, 1 sample with obvious defects was discarded and multispectral images were obtained before and after bruises on the other 59 samples were manually made at the equatorial area using the same ball dropped from a 500 mm height.

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