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Fast detection and visualization of early decay in citrus using Vis-NIR hyperspectral imaging

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ABSTRACT

Early detection of fungal infection in citrus fruit is one of the major problems in the postharvest phase. The automation of this task is still a challenge for the citrus industry. In this study, the potential application of hyperspectral imaging, which combines conventional imaging and spectroscopy to simultaneously acquire both spatial and spectral information from an object, was evaluated for automatic detection of the early symptoms of decay caused by *Penicillium digitatum* fungus in citrus fruit. Hyperspectral images of sound and decayed navel oranges were acquired in the wavelength range of 325–1100 nm. Principal component analysis (PCA) was applied to a dataset comparing of average spectra from decayed and sound tissue to reduce the dimensionality of data and to observe the ability of visible-near infrared (Vis-NIR) hyper-spectra to discriminate data from two classes. And, a mean normalization step is applied prior to PCA to reduce the effect of sample curvature on spectral profiles. In this case it was observed that sound and decayed spectra were separable along the resultant first principal component (PC1) axis, then, four wavelength images centered at 575, 698, 810 and 969 nm were selected as the characteristic wavelength images by analyzing the weight coefficients of PC1 in order to develop a fast classification method for establishing an on-line multispectral imaging system. Subsequently, a combination image, which obtained by multiplying the characteristic weight coefficients by corresponding to mean-normalized characteristic wavelength images of each orange sample, was calculated for determination of decayed fruits. Based on the obtained multispectral combination image, the technique of intensity slicing as one of the pseudo-color image processing methods is used to transform the combination image into a 2-D visual classification image that would enhance the contrast between sound and decayed classes. Finally, an image segmentation algorithm for detection of decayed fruit was developed based on the pseudo-color image coupled with a simple thresholding method. For the investigated 210 naval orange samples including 80 sound fruits and 130 infected fruits, the total success rate is 100% for training set and 98.6% for test set with no false negatives, respectively, indicating that the proposed multispectral algorithm here is capable of detecting decay caused by *penicillium digitatum* in naval orange fruit using only four key wavelength images. The results from this study could be used for development of a non-destructive monitoring system for rapid detection of decayed citrus on the processing line. The idea behind the proposed algorithm can be extended to detect the non-visible damages of other fruit, such as slight bruise and chilling injury in apples.

1. Introduction

Globally citrus is an important horticultural product, and in China its annual production is over thirty million tons. Decay caused by *Penicillium* spp. fungi is among the main problems affecting postharvest and marketing processes of citrus fruit (Eckert and Eaks, 1989; Palou et al., 2011). Infected fruit can be neither stored for a long time nor long-term transported during exportation since a small number of decayed fruit can infect a whole consignment. Thus, fungal infections generate great economic losses to the citrus industry if damaged fruit are not early detected. However, detection of decayed fruit is very difficult. Damage caused by fungi is not visible in the early stages because the appearance of the damage is very similar to sound skin. At

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present, the visual inspection of decayed citrus fruits (i.e. in "black light" rooms) is commonly performed by workers through the fluorescence induced by ultraviolet (UV) light in citrus packinghouses because the infected region can emit visible yellow fluorescence under UV illumination (Momin et al., 2013). However, this process entails a number of problems because exposing people to this kind of lighting is potentially hazardous for human health, and it is therefore very necessary to develop a technology without the use of UV light. One possible solution arises from the use of automatic machine vision system.

Machine vision system based on color cameras has become widely used to automate the inspection of skin damage of fruit and vegetables (Brosnan and Sun, 2004; Cubero et al., 2011). Currently, its application to the external defect inspection of citrus fruit is also under research (Kim et al., 2009; López-García et al., 2010; Li et al., 2013). Nevertheless, some defects, such as decay at very early stages, are virtually identical to the sound skin, and they are therefore very difficult to be detected by standard RGB vision systems, which are limited to the visible region of the electromagnetic spectrum (Blasco et al., 2007b). Thus, a UV-induced fluorescence imaging technology has also been developed for automatically detecting decay in citrus fruit imitating the fluorescence technology used in the industry by humans. Blasco et al. (2007b) developed a fluorescence image acquisition system for detecting the decay caused by *penicillium digitatum*. Blanc et al. (2010) patented an automatic machine for decay detection using UV illumination, and Kurita et al. (2009) developed an inspection system based on visible and UV illumination systems using light-emitting diodes. However, the use of UV light has some limitations because not all decay lesions and not all the citrus cultivars present the same level of sensitivity to the fluorescence phenomena (Kurita et al., 2009; Momin et al., 2012), and on the contrary, other defects like chilling injury, peel cut or peel wound also can result in some fluorescence (Slaughter et al., 2008; Obenland et al., 2010), thus reducing the performance of these systems.

Besides machine vision technique, until recently, one of the most commonly used ways is spectroscopy, mainly because it is a low-cost, non-destructive, accurate and reliable method, which generally requires minimal or no sample preparation prior to analysis (Nicolaï et al., 2014; Wang et al., 2015). Decay process in citrus fruit implies changes in enzymatic activity, resulting in an enhanced water-soluble pectin fraction, and consequently, weakening of the cell wall (Barmore and Brown, 1979) and subsequent changes of properties of fruit tissue can be detected by spectroscopy (Blasco et al., 2000; Lorente et al., 2015). Unfortunately, the distribution of the chemical composition or tissue properties of a sample cannot be achieved via this technique because conventional spectroscopy system only can provide one spectrum of a small area of the target sample without giving any spatial information. In reality, there are some cases, such as our present study on identification of decayed citrus fruit, where spatial distribution of classification information is needed.

Thus, hyperspectral imaging has been introduced to integrate both spectroscopic and imaging techniques in one system for providing both spectral and spatial information simultaneously. Hyperspectral imaging technique provides the spatial distribution of a chemical entity in a substance besides providing the spectral information for each pixel in the image in hundreds of contiguous discrete spectral bands. As a result, each hyperspectral image contains a large amount of information in a three-dimensional (3D) form called "hypercube" which can be analyzed to characterize the object more reliably than the traditional machine vision or spectroscopy techniques (Liu et al., 2015). Now, hyperspectral imaging technology has been used successfully as a new alternative to detect non-visible damages such as slight bruise on apples (Lee et al., 2014) and chilling injury in apples (ElMasry et al., 2009). In terms of citrus fruit, some works have been carried out to detect decay caused by fungi (Gómez-Sanchis et al., 2008, 2014; Lorente et al., 2013). These studies showed that hyperspectral imaging technology is a powerful tool to identify the decayed citrus fruit. The used hyperspectral imaging systems in these studies were based on Liquid Crystal Tunable Filters (LCTFs). This imaging system involves keeping the image field of view fixed, and obtaining images one wavelength after another, therefore it is conceptually called the wavelength-scanning method. The wavelength-scanning image acquisition based on LCTFs is suitable for many applications where a moving tested sample is not required (Sun, 2010). So it is not effective for either a moving target or for real-time task. Furthermore, this system needs more time to be tuned in the actual applications (Gómez-Sanchis et al., 2014). Compared with hyperspectral imaging system based on Liquid Crystal Tunable Filters (LCTFs), image spectrophotometer, which offers a more high spectral resolution, is characterized by the fact that they acquire spectral data about a scene line by line using the relative movement of that scene with respect to the instrument. This method is particularly well suited to conveyor belt systems, and may therefore be more practicable than the former one for food industry applications (Sun, 2010). However, the number of bands to be used should be reduced because a large number of bands would produce a reduction in system performance due to the high acquisition time needed for each band, which would make real-time work impossible (Elmasry et al., 2013; Liu et al., 2013). Although many algorithms have been developed for selecting the optimal wavebands/features (Burger and Gowen, 2011; Liu et al., 2014), no method exists for the systematic identification of the optimal number and location of wavebands based on hyperspectral image data. Recently, principal component analysis (PCA) was used to reduce the spectral dimensionality of hyperspectral reflectance images, and to determine several dominant wavebands that could be used for multispectral detection.

In addition, some latest studies proved that hyperspectral imaging technique can be utilized for visualizing chemical composition or classification information of a sample. Examples include detection of water, fat and protein contents in lamb meat (Kamruzzaman et al., 2012), determination of water-holding capacity in fresh beef (ElMasry et al., 2011), grading and classification of pork (Barbin et al., 2012), determination of total viable count (TVC) in chicken breast fillets (Feng and Sun, 2013), distribution measurement of texture profile analysis (TPA) parameters in salmon fillet (Wu et al., 2014), etc. These studies provided the inspiration for our work. Although this visual technology has not yet been used in fruit process and quality assessment, it is a promising method to be used to classify those decayed citrus fruit in our current study.

The aim of this study is to propose a simple, effective and fast visual classification algorithm to identify decay caused by *P. digitatum* to the skin of citrus using a laboratory-based line-scan hyperspectral reflectance imaging technique. The hyperspectral imaging system was set to acquire the emission spectrum for each image pixel in the Vis-NIR wavelength range (325–1100 nm). The specific objectives of the current study were (1) to investigate the feasibility of Vis-NIR hyper-spectra to discriminate data from two classes containing sound and decayed citrus tissue by PCA and to identify the feature wavelength images for detection of decayed citrus fruit; (2) to correct the adverse effects produced by the reflection of light on the spherical geometry of the citrus fruit; (3) to develop image processing algorithms (based on feature multispectral images) used to generate a 2-D visual classification image, which showed maximal contrast between normal and decayed tissue, for visualization the tested different tissue information and (4) to identify decayed fruit from sound fruit on basis of 2-D visual classification image and to assess the performance of algorithm.