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A multimodal machine vision system for quality inspection of onions

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ABSTRACT

A multimodal machine vision system was developed to evaluate quality factors of onions holistically and nondestructively. The system integrated hyperspectral, 3D, and X-ray imaging sensors. A LabVIEW program was developed to acquire color images, spectral images, depth images, X-ray images of onions, and measure the weight of onions. With the multimodal data collected, algorithms were developed to calculate the maximum diameter, volume, density, and detect latent defects of onions. Three groups of sweet onions (regular, inoculated with *Burkholderia cepacia*, and inoculated with *Pseudomonas viridiflava*) were tested. Results showed that the system accurately measured the weight (RMSE = 3.6 g), diameter (RMSE = 1.7 mm), volume (RMSE = 16.5 cm^3), and density (RMSE = 0.03 g/cm^3) of onions, and correctly classified 88.9% healthy and defective onions. This work demonstrated a promising approach to evaluate both external and internal quality parameters of onions, which is applicable to onion packinghouses. The proposed system and methods are also potentially applicable to quality inspection of other agricultural products.

1. Introduction

The standards for onion grades in the United States (U.S. Department of Agriculture, 1995) enforce a comprehensive regulation on the quality of commercial onions (*Allium cepa* L.). All fresh onions sold in the U.S. fresh market have to meet certain requirements, such as: diameter greater than 1.5 in., mature, no soft or spongy spot, free from decay/scallians/wet sunscald, free from serious damage or defects, to name a few. In addition to complying laws and regulations, U.S. onion growers tend to maintain a stringent quality inspection standard since a large portion of their produces are stored in cold rooms and controlled atmosphere rooms for a fairly long period (1–6 months). Pathogens in defective onions brought into the storage room can be devastating and sometimes could ruin an entire room of healthy onions. Diseased onions not only cause significant economic losses, but also can affect consumers' health and damage the brand owners' reputation.

In a typical U.S. onion packing house, onions are cleaned in automated sorting lines and then delivered to inspection stations by conveyor belts to be checked by trained inspectors. The labor-intensive human visual inspection (HVI) method, however, has many limitations and drawbacks. First, human are prone to making subjective and inconsistent decisions due to fatigue and distractions. Second, labor shortage in many U.S. onion production states and the rising labor cost inevitably increases the onion post-processing cost while decreases the accuracy of quality inspection. Particularly, onions are susceptible to many postharvest diseases such as sour skin (*Burkholderia cepacia*) and neck rot (*Botrytis allii*) (Schwartz and Mohan, 2008). Disease infections can occur in outer scales first and symptoms on onion surface could be latent in early stages (Mark et al., 2002). Since onions are a multilayered vegetable with thick outer skins, it is difficult to evaluate the internal condition of onions by HVI. In summary, it is highly necessary to develop an automated nondestructive approach to inspect and sort onions effectively and efficiently based on both external and internal traits.

Considerable nondestructive machine vision and sensing techniques have been reported for the quality inspection of agricultural and food products, such as color and grayscale imaging methods (Blasco et al., 2009), VIS/NIR spectroscopy (Nicolaï et al., 2007), spectral imaging (Lu, 2008; Qin et al., 2013), magnetic resonance imaging (Marcone et al., 2013), and electronic nose (Li and Heinemann, 2007). In addition, X-ray imaging has been increasingly investigated as an online inspection tool for internal quality assessment of food and agricultural products (Haff and Toyofuku, 2008; Mathanker et al., 2013). Particularly, line scan X-ray imaging has been proven to be a promising non-contact inspection technique to detect internal defects of several agricultural products such as apples (Mendoza et al., 2010; Shahin et al., 1999). Tollner et al. (2005) demonstrated that X-ray imaging is a promising

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method to detect defects in sweet onions, such as voids and foreign inclusions.

Many of these techniques have potentials for online quality inspection of onions, and a series of studies have been conducted to develop nondestructive sensing methods to evaluate various quality factors of onions in the past six years. Li et al. (2009) applied gas sensor array and support vector machine to detect sour skin in onion storage room. A multispectral imaging approach (Ruiz-Altisent et al., 2010; Wang et al., 2012a,c) was proposed to distinguish sour skin-infected onions from healthy onions using images at two selected near-infrared wavelengths. Wang et al. (2013) used hyperspectral imaging in 400–1000 nm to quantitatively predict the soluble solids content and dry matter content of onions. Wang and Li (2014) proposed a RGB-D method to measure the size traits of onions based on their point cloud images. Each of these studies evaluated certain quality traits of onions. The quality of an onion bulb, however, is determined by a combination of all important quality factors including size, shape, and defect level. Therefore, to meet the classification demand of onion postharvest handling, a comprehensive and automated evaluation of onion quality is needed.

Multisensor data fusion exploits the synergy in information acquired from multiple sources to make better decisions than using any of the information sources individually (Hall and Llinas, 1997). This technique has gained increasing attentions in nondestructive quality evaluation for fruits and vegetables. Steinmetz et al. (1999) discussed the general strategies for applying multiple sensors to assess the quality of fruits using different levels of data fusion process models. Henningsson et al. (2006) proposed a multiple sensor system to monitor the turbidity of milk with an integration of conductivity meter, density meter, and an optical instrument. Bulanon et al. (2009) applied image registration technique to combine color and thermal images of canopy of orange trees to detect oranges in an orchard. Fricke and Wachendorf (2013) combined the height measured by an ultrasonic instrument with the vegetation indices measured by spectral devices to assess the biomass of legume-grass swards. In many other reported applications (Li et al., 2007; Mendoza et al., 2012; Olafsdottir et al., 2004; Ruiz-Altisent et al., 2006), data fusion techniques were also applied to integrate manually operated measurements together with partially automatic nondestructive measurements.

This work was aimed to design and implement a multimodal system and develop multisensor data fusion algorithms to inspect key external and internal quality properties of onions. The main goal was to investigate a potential online approach to evaluate the quality of onions nondestructively and holistically. Specific objectives of the study were to: (1) select appropriate nondestructive sensing technologies for onion quality inspection and integrate a multimodal machine vision system; (2) design a software program for data acquisition; (3) develop algorithms to measure key onion quality parameters based on the collected multimodal data; and (4) evaluate the performance of the proposed system by a laboratory validation test.

2. Multimodal inspection system

2.1. System design

Aimed at providing a potential online sorting solution, various nondestructive sensing techniques were considered and evaluated in the course of the system design. The sensing capability, cost, and scanning speed of techniques were key factors considered in the system design. The proposed design (Fig. 1) consisted of several machine vision techniques with complementary sensing capabilities: color imaging, RGB-depth (RGB-D) imaging, spectral imaging, and X-ray imaging. The rationales for selecting these image techniques were: color imaging provides spatial and color information of onions; spectral imaging can be used to examine surface blemish and rot of onions; RGB-D sensor can measure size and geometry information of onions based on the topological data it collects; X-ray imaging can be used to detect internal defects and disease infections in onions. The potential of selected technologies on onion quality evaluation have been proven by previous studies (Tollner et al., 2005; Wang and Li, 2014; Wang et al., 2012a). This work focused on the integration of these techniques to make a comprehensive evaluation of the quality of onions.

In the proposed design, an onion sample moves from left to right and is scanned at three sequential stages (Fig. 1(B)). First, onion passes the color camera and RGB-D sensor to acquire color and depth images. Second, a liquid crystal tunable filter (LCTF)-based NIR hyperspectral imager was employed to acquire spectral images of the onion. At last, the sample is scanned by an X-ray line-scanner. For all stages, the onion sample is held by a

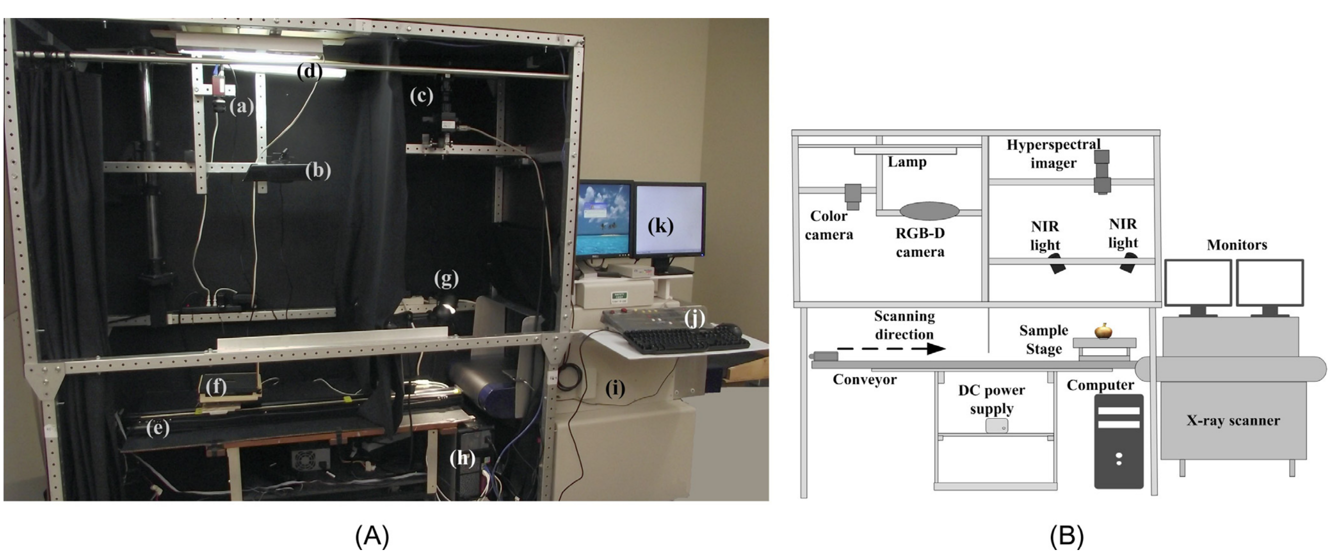

Fig. 1. (A) Components and layout of the system: (a) color camera, (b) RGB-depth sensor, (c) hyperspectral imager, (d) fluorescent lamps, (e) motorized linear slider, (f) onion holder, (g) halogen lamps, (h) computer, (i) X-ray scanner, (j) keyboards, and (k) monitors. (B) Schematic of the multimodal machine vision system for onion quality inspection.