Computers and Electronics in Agriculture 73 (2010) 118–125

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

Identification of insect-damaged wheat kernels using short-wave near-infrared hyperspectral and digital colour imaging

Chandra B. Singh[a], Digvir S. Jayas[a,*], Jitendra Paliwal[a], Noel D.G. White[b]

[a] Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, Canada R3T 5V6
[b] Agriculture and Agri-Food Canada, Cereal Research Centre, Winnipeg, MB, Canada R3T 2M9

ARTICLE INFO

Article history:
Received 5 September 2009
Received in revised form 26 April 2010
Accepted 1 June 2010

Keywords:
Grain quality
NIR
Hyperspectral imaging
Machine vision

ABSTRACT

Healthy wheat kernels and wheat kernels damaged by the feeding of the insects: rice weevil (*Sitophilus oryzae*), lesser grain borer (*Rhyzopertha dominica*), rusty grain beetle (*Cryptolestes ferrugineus*), and red flour beetle (*Tribolium castaneum*) were scanned using a near-infrared (NIR) hyperspecrtal imaging system (700–1100 nm wavelength range) and a colour imaging system. Dimensionality of hyperspectral data was reduced and statistical and histogram features were extracted from NIR images of significant wavelengths and given as input to three statistical discriminant classifiers (linear, quadratic, and Mahalanobis) and a back propagation neural network (BPNN) classifier. A total of 230 features (colour, textural, and morphological) were extracted from the colour images and the most contributing features were selected and used as input to the statistical and BPNN classifiers. The quadratic discriminant analysis (QDA) classifier gave the highest accuracy and correctly identified 96.4% healthy and 91.0–100.0% insect-damaged wheat kernels using the top 10 features from 230 colour image features combined with hyperspectral image features.

1. Introduction

Canada produces approximately 5.27×10^{10} kg (52.7 Mt (million tonnes)) of grains annually (FAOSTAT, 2009), of which 60–70% are exported. Wheat is one of the major crops grown in Canada with 2.53×10^{10} kg (25.3 Mt) average annual production and 1.85×10^{10} kg (18.5 Mt) annual export (FAO, 2006). Canada is the sixth largest wheat producing country, ranking among the largest exporters in the world, and has a reputation of exporting high quality grain. Wheat grain quality is defined by several parameters, of which damage caused by insect infestation is considered one of the important degrading factors. Canada loses a significant amount of grain due to stored-product insects and associated spoilage and remedial actions (White, 1995). Stored grain can have losses in both quantity and quality during storage as a result of insect or mite infestation, fungal infection or any combination of these. Deterioration and contamination result in downgrading of grain due to the presence of insect parts and odor, grain weight loss, increase in free fatty acids, heat damage, toxicity due to fungal activity, and poor milling and baking quality. Insect infestation adversely affects the baking quality of wheat flour produced from the damaged grain such as decreased loaf volume, compact and inelastic crumb, bitter taste, and off-flavors (Sanchez-Marinez et al., 1997).

Insect damage to grains results in loss of nutrients and germination ability and also increases susceptibility to fungal contamination. Insects produce heat and moisture due to their metabolic activity and sometimes develop insect-induced localized hotspots in grain bins, which can produce black burnt (heat-damaged) grains and create favorable moisture and temperature condition for the growth of fungi. There is an increasing demand among grain buyers and consumers towards zero-tolerance to contamination in grain and processed grain products. Detection of internal infestation by insects such as weevils and borers in the whole grain is complicated by the presence of hidden immature stages of insects (eggs, larvae, and pupae) inside grain kernels. Sometimes samples of grain may appear to be insect-free due to the absence of adults; however, they might be infested by hidden immature stages.

Presently, the Berlese funnel method is used by the Canadian Grain Commission as a standard method to detect live insects in grain samples (CGC, 2009). Methods such as visual inspection, sieving, insect traps, insect fragment inspection, and floatation are the common methods traditionally used for the detection of insects in grain. Most of these methods have one or several drawbacks such as being subjective, destructive, inaccurate, time consuming, and most of them are unable to detect internal insect infestation. Several methods cited by Singh et al. (2009) namely enzyme-linked immunosorbent assays (Brader et al., 2002), carbon dioxide and uric acid measurement (Karunakaran et al., 2004), electronic nose (Zhang and Wang, 2007), acid hydrol-

* Corresponding author. Tel.: +1 204 474 9404; fax: +1 204 474 7568.
E-mail address: Digvir_Jayas@Umanitoba.ca (D.S. Jayas).

0168-1699/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.compag.2010.06.001

ysis (Brader et al., 2002), electrical conductance (Pearson and Brabec, 2007), magnetic resonance imaging (MRI) (Chambers et al., 1984), computed tomography (Toews et al., 2006), acoustic impact emissions (Pearson et al., 2007), and thermal imaging (Manickavasagan et al., 2008) have also been investigated for insect detection in grains. Many of these methods are unable to detect low-level internal infestations and have not shown the potential for automated inspection. For real-time detection of insect-damaged grain at grain elevators (grain handling facilities), an objective, non-destructive, rapid, and accurate method is required.

Near-infrared (NIR) spectroscopy has been used for detection of insect and insect parts in whole grain and ground samples (Dowell et al., 1998; Baker et al., 1999; Dowell et al., 1999; Maghirang et al., 2003). However, commercial NIR spectroscopic instruments are point based, scanning instruments as they record only one average spectrum from each sample. Ridgeway and Chambers (1998) used differences of NIR images at manually selected wavelengths (1202 and 1300 nm) to visually detect insect-damaged wheat kernels without developing any supervised classification algorithm for future prediction. In another study, Ridgway et al. (1999) used the NIR spectra of healthy and insect-damaged wheat kernels to select the most important wavelengths to acquire NIR images for detection of insect damage using image differences. Hyperspectral imaging systems with optically tunable filters can record the NIR images at hundreds of contiguous wavelengths (narrow spectral resolution) in the form of a hypercube (three-dimensional hyperspectral data). These hypercubes can be directly analyzed for wavelength selection using multivariate image analysis without using spectroscopic data to overcome system variations between these two instruments. Colour images have been used in grain quality analysis to identify different grain types, varieties, classes, and impurities (Majumdar and Jayas, 2000a–d; Paliwal et al., 2003; Choudhary et al., 2008) using external surface features of the object under investigation. Zayas and Flinn (1998) used features of digital colour images in supervised classification to detect adult insects and their body parts in wheat and achieved above 90.0% accuracy. However, colour-based machine vision systems might not be able to detect internal insect infestations as these mostly rely on surface features.

Hyperspectral imaging provides the spectral information in a spatially resolved manner; therefore, spectral information from each pixel of the sample image can be obtained. This spectral information arising from the reflectance or absorbance of the insect-infested wheat kernels would potentially carry the information about internal infestation that would be used for discrimination of healthy kernels from insect-damaged kernels. In a recent work (Singh et al., 2009), the authors used long-wave NIR hyperpsectral imaging (1000–1700 nm wavelength) to discriminate insect-damaged wheat kernels from healthy kernels and achieved very high accuracy. However, the cost of the detectors (e.g., InGaAs detectors) working in the long-wave NIR region is very high. The investigation by Ridgway et al. (1999) has shown the potential of hyperspecrtal imaging for detection of insect-damaged wheat kernels using the short-wave NIR region (700–1100 nm). The charge-coupled device (CCD) detectors used in the hyperspectral imaging systems working in the short-wave NIR region are relatively inexpensive and colour imaging systems are the least expensive among these three systems. The aim of the development of any quality monitoring device would be to achieve a higher level of performance at lower system cost without compromising the performance. Therefore, the objective of this research was to assess the potential of short-wave NIR hyperspectral imaging for insect damage detection in wheat and to compare the performance with colour imaging.

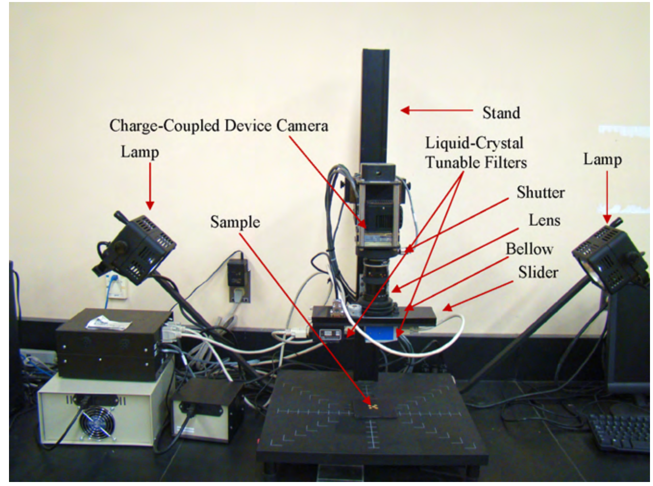

Fig. 1. Short-wave near-infrared hyperspectral imaging system.

2. Materials and methods

2.1. Sample preparation

Canada Western Red Spring wheat (cv. AC Barrie) samples at approximately 15.0% moisture content (wet basis) were used in this study. Moisture content was determined using a standard oven method by drying about 10 g samples in triplicate at 130 °C for 19 h (ASAE, 2003). Healthy wheat samples and wheat samples damaged by the insects: rice weevil (*Sitophilus oryzae*, (L.)), lesser grain borer (*Rhyzopertha dominica*, (F.)), rusty grain beetle (*Cryptolestes ferrugineus*, (Stephens)), and red flour beetle (*Tribolium castaneum*, (Herbst)) were prepared at the Cereal Research Centre, Agriculture and Agri-Food Canada, Winnipeg, Canada. Adult insects of each species were mixed with 50 g whole wheat and kept for 4 weeks at 30 °C temperature and 70% relative humidity. Damaged kernels were visually selected and stored at the same temperature and relative humidity conditions prior to imaging. A total of 300 healthy kernels and 300 kernels damaged by each insect species were selected for imaging.

2.2. Near-infrared hyperspectral imaging

2.2.1. Hyperspectral imaging system

The imaging system consisted of a 532 × 256 pixel size FFT-CCD area scan image sensor (Model no. C7042, Hamamatsu Photonics, Hamamatsu, Japan) working in the visible (VIS) (400–700 nm) and NIR regions (400–1100 nm) with two stage thermoelectric cooling and two electronically tunable liquid crystal tunable filter (LCTF) devices (Model no. MIR06, Cambridge Research and Instrumentation Inc., Woburn, MA, USA) for rapid wavelength selection (Fig. 1). The camera was attached to a shutter and a lens was attached to the other end of the shutter. A slider was screwed below the lens in such a way that it moved the selected filter into the exact optical path of the lens. The user had the option to select VIS, NIR, or a hard filter through the user interface. The lens and filter slider moved independently and the lens could be used to adjust the focus. The whole unit was mounted on a copy stand with flexibility of vertical movement to adjust the focus and alignment. Two dimmer-controlled 300 W halogen–tungsten lamps mounted at 45° angles and 0.5 m away from the imaging area were used as illumination sources. Image data were acquired by a data acquisition board (Model no. NI PCI-1422, National Instruments Corp., Austin, TX, USA) operating at 333 K samples/s at 16-bits. System controls developed in LabVIEW (Version 7.1, National Instruments, Austin,