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Classification models of bruise and cultivar detection on the basis of hyperspectral imaging data

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ABSTRACT

The aim of this paper is to create supervised classification models of bruise detection and cultivar detection for five apple cultivars with the use of hyperspectral imaging system in the VNIR (Visible and Near-Infrared) and SWIR (short wavelength infrared) spectral regions. The Correlation-based Feature Selection (CFS) algorithm and 2nd derivative pre-treatments of the hyperspectral data were used when constructing supervised classification models of bruise and cultivar detection. The best prediction accuracy for the bruise detection models was obtained for the Support Vector Machines (SVM), Simple Logistic (SLOG) and Sequential Minimal Optimization (SMO) classifiers (more than 95% of the success rate for the training/test set and 90% for the validation set). Even higher prediction accuracies were obtained for the cultivar detection models. The percentage of correctly classified instances was very high in these models and ranged from 98.2% to 100% for the training/test set and up to 93% for the validation set. The performance of the studied models was presented as Receiver Operating Characteristics (ROC) for the bruise detection models and confusion matrices for the cultivar classification models.

1. Introduction

Apple quality and texture evaluations during harvesting and storage are really important for producers and it is a goal of some research (Zdunek et al., 2011). A great problem in apple production is to find an effective way of sorting fruits to eliminate damage of various kinds (Brosnan and Sun, 2004; Sun, 2008; Sun, 2010; Leemans and Magin, 2002). A large percentage of harvested apple fruits are wasted each year because of bruising damage that results from various static and dynamic loads occurring during picking, packing, and distribution operations. Bruise damage can be caused in apples due to impact, compression, vibration, or abrasion. Additionally, the susceptibility of apples to bruise damage depends on the mechanical properties of apple skin and flesh which are cultivar dependent and can be modified by soil cultivation, nutrition and weather conditions in the field during fruit growth (Drogoudi and Pantelidis, 2011; Ferguson et al., 1999; Grimm et al., 2012; Lleó et al., 2011; Xing et al., 2007). Therefore, the location, shape and depth of bruising vary and damage detection is difficult, especially in case of dark skin colour or a small surface area of the bruise (Sun, 2008). Although bruising is the reason for rejecting the highest number of fruits in sorting lines, the accuracy of existing automatic sorting systems is still insufficient and the manual sorting method has still to be used (Leemans and Magin, 2002; Xing et al., 2007; Qin et al., 2009). Therefore, early detection of mechanical defects in apples is really important, especially for an automatic sorting system.

In recent years, machine vision technology has been successfully used in the field of pre- and post- harvest product quality evaluation and also to detect mechanical damage to objects (Xing et al., 2007; Brosnan and Sun, 2004; Wang et al., 2011). Thermography and hyperspectral imaging deserve a special attention among other non-destructive technologies which enable quick and reliable online inspection of fruit products. Baranowski et al. (2009) used active thermography to detect early bruises in apples. It was noticed that local changes of tissue thermal properties caused by inner defects of fruit tissue could be successfully registered using pulsed-phase thermography (PPT). These authors found a linear correlation between the depth of bruising and the frequency of the thermal response. In another approach, the same authors tested a system that incorporated hyperspectral reflected radiation in the VNIR and SWIR ranges and infrared thermal imaging of emitted radiation in the MWIR range (Baranowski et al., 2012). The obtained results showed a better performance of the classification of normal versus bruised apples when a combination of the VNIR, SWIR and MWIR ranges was used, but it was found that the same combination of spectral ranges did not significantly

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affect the classification between deep and shallow bruises. Hyperspectral imaging in the VNIR and SWIR regions can also be successfully used for determining the time elapsed from the occurrence of bruising within a period of two weeks after bruising of apples (Baranowski et al., 2013).

Combining various wavelengths in differential reflectance improves detection and often identification of defects (Lee et al., 2008; Kleynen et al., 2003; Mendoza et al., 2011; Peng and Lu, 2006; Wang et al., 2011). A multispectral system was created by Mehl et al. (2002) which used a chlorophyll absorption wavelength at 685 nm and two wavelengths in the NIR band to separate defective areas in four cultivars of apples, with a high spatial resolution between 0.5 and 1 mm. X-ray imaging was also tested for early apple bruise detection (Schatzki et al., 1997). However, the line-scan X-ray imaging experiment revealed not adequate separation of one-day bruises in 'Golden' and 'Red Delicious' (Shahin et al., 2002). Considerable development was recently achieved in the efficiency of Magnetic Resonance Imaging (MRI) for detecting and monitoring the progression of internal browning in 'Fuji' apples stored under two different controlled atmosphere conditions (Gonzalez et al., 2001). Distinct regions with internal browning were observed which had lower signal intensity than normal tissue. The progression in time of browning symptoms was noticed. The system used allowed the speed of image acquisition to be improved from 5.5 min to 20 s, by reducing the spatial resolution of the images.

The aim of this study is to examine the applicability of hyperspectral imaging in the VNIR and SWIR wavelength ranges for detecting the occurrence of apple bruising in apples of five selected cultivars. The specific aims of the paper are:

- To distinguish between bruised and unaffected tissues in apples of five studied cultivars in the first two weeks after bruising by using supervised classification models based on VNIR and SWIR hyperspectral data.
- To check the effectiveness of distinguishing various cultivars based on spectral characteristics using classification models.

2. Materials and methods

2.1. Material and its preparation for measurements

The fruit material, including five apple (Malus domestica Borkh) cultivars: 'Champion', 'Gloster', 'Golden Delicious', 'Idared' and 'Topaz', was collected from an orchard of the 'STRYJNO-SAD' Fruit Producers Association (15 km from Lublin, Poland), directly after hand harvesting in autumn 2011. During the experiment, apples were stored in a climate chamber at 21 °C and at 80% relative humidity.

Four hundred and eighty apples with a diameter of 7–8 cm where divided into two groups and tested using analytical methods and hyperspectral imaging. Apples from one group were bruised, whereas apples from the other group were left non-bruised. Each apple was bruised along the equatorial line of its surface. A plastic roller with a diameter of 10 mm and a thickness of 1 mm was used for bruising. It was put on the apple surface and a cylindrical weight of 0.2 kg was dropped (the contact surface was the base of the cylinder) from a height of 400 mm.

The quality parameters of apple fruit, including firmness, soluble solids content (SSC) and bulk density, were measured for all the studied cultivars before creating the prediction models. Fruit firmness was measured using a Lloyd LRX Universal Testing Machine, produced by Lloyd Instruments Ltd., Hampshire, UK, and expressed in N. An Atago pocket refractometer, produced by Atago Co., Ltd., Tokyo, Japan, was used for the determination of soluble solids content (SSC). Bulk densities were determined by using an electronic digital Mettler XS1003S balance, Mettler Inc., Switzerland (an operating capacity of up to 1000 g with a readability of 0.001 g).

2.2. Hyperspectral imaging system

The spectral characteristics in VNIR and SWIR of apples studied were acquired using a hyperspectral imaging system which consists of spatial (2-dimensional) and spectral (1-dimensional) data. They create a 3-dimensional spectral cube (Fig. 1) in which the spectral characteristics of selected pixels can be studied as well as images obtained for various wavelengths can be analysed using available image processing methods.

A visible and near infrared (VNIR) camera with an ImSpector V10E imaging spectrograph (400–1000 nm) and a short wavelength infrared (SWIR) camera with a N25E 2/3" imaging spectrometer (1000–2500 nm), manufactured by SPECIM, Finland, were placed 40 cm above the belt conveyor. The illumination source for each camera consisted of eight halogen lamps of 20 W placed in two opposite frames positioned at an angle of 45° towards the conveyor belt surface. The measurements were performed in a dark room to prevent the influence of external illumination. The fruits examined were placed on the belt conveyor which had the speed regulated for each camera. The belt conveyor speed was adjusted individually for each camera because of the differences in spatial resolution and integration time of the cameras (Fig. 2).

The hyperspectral images obtained during the measurements were recorded using data acquisition software SpectralDAQ ver. 2.1 for SPECIM cameras. Initially, the acquired images were corrected with white and dark references.

2.3. Analysing Algorithms

Bruised and non-bruised areas were selected from the hyperspectral cube. To distinguish the bruised areas from the hyperspectral images, a script was written in ImageJ software (Rasband, 1997–2001). A modification of the procedure proposed earlier by ElMasry et al. (2009) was used for segmentation. The implementation of the Otsu thresholding algorithm was used. It divides the histogram into two classes and inter-class variance is minimized. Additionally, for images that enable regions of sizes ranging from 50 to 5000 pixels to be distinguished, particle nucleus counting was applied. This range was suitable for creating masks of bruised regions. The segmentation procedure was used as a reference to distinguish the areas with bruise for all the studied apples. It enabled to create a database of the areas within the studied fruits with and without the defects. Such a method of visual inspection of the fruit surface is not sufficient for sorting systems as was indicated earlier (Leemans and Magin, 2002; ElMasry et al., 2009; Sun, 2010). Therefore, the main interest of this study was to analyse the reflected spectrum in VNIR and SWIR ranges to create an effective classification models of apple bruise and cultivars.

The reflectance was calculated separately for all the bands and taken as an average from pixels in regions containing bruised and sound tissues.

All the classification algorithms were implemented from comprehensive software called the Waikato Environment for Knowledge Analysis, or "Weka" for short, which is available as source code on the World Wide Web at http://www.cs.waikato.ac.nz/ml/weka. The system is written in Java and is available for all major computer platforms. This software allows various methods to be provided for data pre- and post-processing and for evaluating the result of learning schemes. Pre-processing of the hyperspectral data consisted in choosing, from the whole spectral range registered by the two cameras, the range in which the spectral characteristics of the signal were sufficiently strong. Due to low