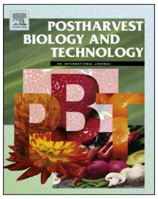
Postharvest Biology and Technology 130 (2017) 103–115

Contents lists available at ScienceDirect

Postharvest Biology and Technology

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



Glare based apple sorting and iterative algorithm for bruise region detection using shortwave infrared hyperspectral imaging

Janos C. Keresztes[a,*], Elien Diels[a], Mohammad Goodarzi[a], Nghia Nguyen-Do-Trong[a], Peter Goos[a], Bart Nicolai[a,b], Wouter Saeys[a]

[a] KU Leuven, Department of Biosystems, MeBioS, Kasteelpark Arenberg 30, 3001 Leuven, Belgium
[b] VCBT, Willem de Croylaan 42, B-3001 Heverlee, Belgium

ARTICLE INFO

Keywords:
SWIR hyperspectral imaging
Apple bruise detection
Glare
Specular reflection
Fruit sorting
Kanzi
Joly Red
Jonagold

ABSTRACT

Bruises in apples is one of the most important quality factors during postharvest, which needs to be detected early and efficiently during sorting processes. In this study, a step-wise pixel based apple bruise detection system based on line scan hyperspectral imaging (HSI) in the shortwave infrared (SWIR) is demonstrated for three apple cultivars: 'Jonagold', 'Kanzi' and 'Joly Red'. The SWIR HSI system performance was tested on apples from the different cultivars bruised at five different impact levels, and monitored from 1 to 36 h after bruising. While glare regions are commonly considered as anomalies and discarded from further analysis, their spectral signatures enabled in this work to distinguish between cultivars with a prediction accuracy up to 96%. Different partial least squares-discriminant analysis (PLS-DA) models were trained to discriminate cultivars and then to discriminate between sound, bruised, glossy and stem regions. Spectral area normalization pre-processing was found to be the most effective for pixel based bruise prediction, resulting in a prediction accuracy up to 90.1%. Post-processing of the binary images by exploiting spatial information further improved the bruise detection accuracy to 94.4%.

1. Introduction

Apples are one of the world's most popular fruit, with a global production of 80 million tons in 2014 and an annual growth rate of 2.5% (Faostat, 2016). Although the European apple production has increased yearly by 3.5% since 2010, the Belgian production decreased by 10%, due to competition with pear production which is considered more profitable (Faostat, 2016). As a response to this decreasing profitability of the main apple cultivars, such as 'Jonagold', several new cultivars have been introduced into the market such as 'Kanzi' and 'Joly Red' (Brown and Maloney, 2009; Fruitveiling, 2012). While this is an interesting attempt to regain the market, the bruise susceptibility of those new cultivars during postharvest transport and handling of apples from orchards to the supermarket is not well known, which limits their market potential (Van Zeebroeck et al., 2007).

In order to remain competitive and gain efficiency, careful handling during postharvesting is required and bruised fruits should be sorted out automatically during early fruit handling stages (Heinemann et al., 1995; Tao et al., 1995). Over the past years, visible and near infra-red (Vis–NIR) hyperspectral imaging (HSI) have been demonstrated to offer a more reliable solution than traditional machine vision techniques for apple inspection (ElMasry et al., 2008; Peirs et al., 2003; Xing et al., 2003; Lu et al., 2010). Short-wave infrared (SWIR) HSI was shown to allow detection of bruises in apples at earlier stages than Vis–NIR HSI (Kim et al., 2011; Baranowski et al., 2012; Wu and Sun, 2013). Recently, SWIR HSI has been demonstrated on a real-time sorting line for 'Jonagold' apples (Keresztes et al., 2016). However, in most studies the bruise detection performance was limited by the presence of specular reflections arising from the glossy surfaces of fruit. While a method to exclude those pixels from the region of interest using a multi-class classifier has been proposed (Keresztes et al., 2016), this approach does not allow to exploit the information contained in the spectra corresponding to the glare regions. Moreover, the use of a same pre-processing technique or wavelength selection coping simultaneously with sound, glossy and bruised regions can limit sorting efficiency. Furthermore, as gloss may differ between cultivars, the consequent variability introduced in the spectral images which can be a limiting factor preventing the usage of apple sorting systems working on multiple cultivars simultaneously. Therefore, there is a need to remove glossy regions effectively, to allow better SWIR HSI apple sorting efficiency and to cope potentially with new cultivars using existing systems. If new cultivars are introduced, it should be investigated

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* Corresponding author.
E-mail address: janos.keresztes@kuleuven.be (J.C. Keresztes).

http://dx.doi.org/10.1016/j.postharvbio.2017.04.005
Received 6 November 2016; Received in revised form 18 April 2017; Accepted 18 April 2017

whether the current sorting lines are able to handle them with limited loss. For this purpose, their bruise susceptibility should be quantified with limited destructive measurements in order to adapt the fruit sorting and transportation chain. Following the findings of Keresztes et al. (2016), it is hypothesized here that SWIR HSI could provide efficient monitoring of the bruise development in those new cultivars.

Moreover, performing an experiment such as monitoring apple browning over several days may lead to biased models if not done properly. For example, if a complete experiment lasts one month, the stored apples may change between experimental runs. Such variations should be considered during the experimental design. Therefore, the experimental design was optimized to minimize the influence of storage.

Therefore, the complete experimental procedure covered in this manuscript can be summarized in four steps:

1. **Storage:** 'Joly Red', 'Jonagold' and 'Kanzi' apples were stored under optimal conditions based on prior research conducted at VCBT.
2. **Optimal design of experiment:** Optimize the experimental design to minimize the influence of storage variation.
3. **Model building:** Use a novel semi-supervised labelling method to exclude region boundaries and human labelling errors from the model. Using PLS-DA as a classifier, predict the bruise region either:
   (a) Using a novel step-wise approach removing iteratively unwanted regions to reduce variance during the bruise region prediction, which is robust for all 3 cultivars.
   (b) Using gloss information to predict the cultivar, and further use a cultivar specific multi-class predictor to detect bruised regions.
4. **Apple bruise monitoring:** Apple bruise monitoring: monitor early stage browning evolution for 'Joly Red' and 'Kanzi' cultivars compared to 'Jonagold' from 0 until 36 h after impact damaging.

Those steps are summarized in Fig. 1. Steps 2, 3 and 4 are handled with a novel approach compared to literature. The main novelty aspects lie in how the measurements were performed and how the data was handled.

2. Materials and methods

2.1. Apple samples

Apples from the cultivars 'Jonagold', 'Joly Red' and 'Kanzi' were picked from Flemish orchards at the commercial harvesting stage in September 2014. For each cultivar fifty apples were picked. The apples were weighed and the radius of curvature was measured in the same way as described in Keresztes et al. (2016). After harvest, the apples were stored at the optimal controlled atmosphere conditions, as determined by the experimental station Flanders Centre of Postharvest Technology (Heverlee, Belgium). In the case of 'Jonagold' and 'Joly Red' apples the storage conditions were 1 °C, 1% O_2 and 3% CO_2, while 'Kanzi' was stored at 4 °C, 2% O_2 and 0.7% CO_2.

2.2. Bruising experiment

The apples were bruised using the pendulum device described in Keresztes et al. (2016) and Van Zeebroeck et al. (2007), which monitors impact force, displacement and acceleration. The impact occurred on the equator once per apple. The apples were allowed to adapt to room temperature for 24 h prior to bruising.

2.2.1. Experimental design

As it was the first time to the best of our knowledge that a bruising experiment was performed for 'Kanzi' and 'Joly Red', a designed experiment involving several damage levels was performed. The experiment was designed such that the number of controlled atmosphere (CA) storage openings would be minimized (one for 'Kanzi' or one for 'Jonagold' and 'Joly Red'), while time drifts associated to storage duration or noise of the imaging system were avoided. As 12 apples could be measured within one bruising experiment consisting of 36 h of monitoring, the experimental runs were designed such that they involved either 12 'Kanzi' apples or 6 'Jonagold' and 6 'Joly Red' apples (with permutations). In this way, only one storage container had to be opened per experimental run. To obtain different degrees of bruising, five pendulum arm angles (20°, 23°, 27°, 31° and 35°) were selected as these levels were expected to provide a wide range of bruise sizes. Testing five impact levels allowed 10 replicates per cultivar per bruise level. The selection of the number of apples, impact levels and cultivars used per run was optimized using the JMP 12 (SAS, CA, USA) software. The apples were first split in batches of 6 per cultivar. On one hand, it was desired to measure as many samples as possible in the same experiment. On the other hand, it was desirable to measure them well balanced over time, with a preference for maximizing the sample size at early stages to limit variations arising from storage. A trade-off between both design criteria was found by splitting the samples over 12 experimental runs of 12 apples and a 13th experimental run for the remaining 6 apples (2 per cultivar). The objective of the design optimization in JMP 12 was then to optimize the assignment of the 5 impact angles over the different experimental runs. After generating a design, the latter was refined manually to combine the 'Jonagold' and 'Joly Red' batches or 'Kanzi's to minimize 120 storage openings, as

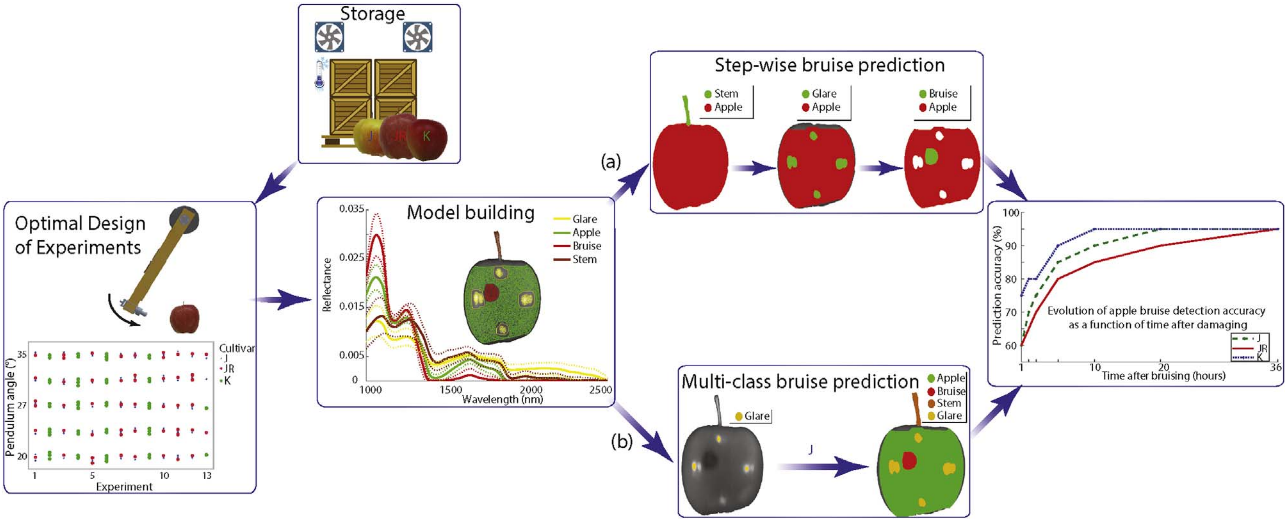

Fig. 1. Experimental procedure flowchart.