International Conference of Agricultural Engineering
AgEng 2014 Zurich 6–10 July
Ref: C0200

Optical measurement techniques for the ripeness determination of Braeburn apples

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Abstract

The manual picking of fruits is a labour intensive operation and hence one of the major costs in fruit production. As a solution, the mechanical harvest of fruits has recently been investigated extensively. Optical methods are promising in several fruit and food applications. Therefore, in this study, three optical techniques have been evaluated with respect to their potential for the non-destructive evaluation of apple ripeness in the orchard. The experiments were conducted on the bicolored *Braeburn* apple variety picked weekly until commercial harvest.

The first technique investigated is **VIS/NIR spectroscopy** in which light with wavelengths ranging from 380 nm to 1690 nm is sent onto the apple sample. After interaction with the apple, the light is dispersed in its different wavelengths (post-dispersive) and captured on the diode array spectrophotometer to give a spectrum per measurement. The second method is the **Multiplex®** apparatus which uses light-emitting diodes (LEDs) with different excitations (UV, blue, green and red) and silicon photodiodes to capture the fluorescent light after interaction with the apple. From these fluorescence measurements it calculates several physiology-related parameters like flavonol content, anthocyanin content, chlorophyll content, blue-green fluorescence and other fluorescence ratios. The last method is **Hyperspectral Laser Scatter Imaging (HLSI)** which is a contactless technique that projects a small beam of monochrome light in the 550-1000 nm range onto the apple to generate a glow spot caused by diffuse reflectance. A CCD camera is used to capture an image of this spot per wavelength (pre-dispersive).

Destructive measurements were performed on the apples as a reference for ripeness. The apple firmness, soluble solids content and starch degradation were combined in the Streif Index parameter. Using partial least squares (PLS) analysis, the different output parameters of the optical measurement techniques were correlated with the Streif index to give an indication of fruit ripeness. All techniques show good correlations in this cultivar with R^2 ranging from 0.72 to 0.98. The potential of the different techniques to be used in a robotic harvesting system mainly relies on the cost, system dimensions and measurement speed.

Keywords: Fluorescence, Spectroscopy, Scatter-Imaging, Ripeness, Harvesting

1. Introduction

The manual picking of fruits is a labor intensive operation and hence one of the major costs in fruit production (Sarig, 1993). In this context, the mechanical harvest of fruits has recently been investigated extensively (Baeten, Donn, & Boedrij, 2008; De-An, Jidong, Wei, Ying, & Yu, 2011; Peterson, 2005). However, mechanical harvesting brings forward several challenges such as automatic fruit ripeness detection. Moreover, the variability in individual fruit maturity often limits the potential to perform a mechanical harvest (Peterson, 2005). So far, apple harvest has relied on the subjective ripeness decision of the picker, which can lead to postharvest disorders or highly heterogeneous products along with increases in the cost of hand picking over the years (Sarig, 1993). An automated mechanical harvester has to be able to solve an important part of this problem by assessing apple ripeness in a fast, reliable and non-destructive way. In this sense, optical methods are promising in several fruit and food applications (Nicolaï et al., 2007).

Studies have shown the potential to use Vis/NIR spectroscopy for the prediction of the optimal picking date in apples (Peirs, Lammertyn, Ooms, & Nicolaï, 2001). However, to use such optical techniques in field conditions, a contactless, fast and robust way of measuring would be preferable. In this sense, quality attributes of fruits have been evaluated using hyperspectral imaging (Baiano, Terracone, Peri, & Romaniello, 2012), spatially resolved spectroscopy (Lu & Peng, 2006), laser scattering techniques (Romano, Nagle, Argyropoulos, & Müller, 2011) and fluorescence measurements (Kolb et al., 2006). Nonetheless, most of the above mentioned techniques lack the possibility to be used in field conditions, lack discrimination power or do not provide enough info from inside the sample. In addition, none of these studies have been directed to compare the performance of different techniques over a single apple variety.

Therefore, in this study, three optical techniques have been evaluated with respect to their potential for a non-destructive evaluation of ripeness in *Braeburn* apples. *Braeburn* is an important cultivar in Belgium, being a candidate to incorporate mechanical-automated harvest in the near future. This work is performed in order to incorporate the most promising technique in further orchard applications. The potential of these techniques to be used in a mechanical harvesting environment will be discussed.

2. Materials and methods

2.1 Hyperspectral Laser Scatter Imaging (HLSI)

The setup used to make hyperspectral laser scatter images consisted of two parts. The first part used a supercontinuum laser (SC450-4, Fianium Ltd., Southampton, UK) as a light source, with 4W total output and a spectral broadening over the range 450-2400 nm. The generated white light was focused into a high-precision Czerny-Turner monochromator (Oriel Cornerstone 260 ¼ m, Newport, Irvine, USA), which resulted in a beam of monochrome light with a tunable wavelength. For this a 0.1 mm output slit width was used. The stability of the outcoming light was monitored by a Silica detector (PDA100A, Thorlabs Inc., New Jersey, USA). This first part of the setup is described in detail by Aernouts *et al.* (2013). The light from the monochromator was further focused into an optical fiber (multimode, NA 0.22, 200 µm core diameter) and guided towards the second part of the setup. The light from the optical fiber was then focused (COL-UV/VIS, Avantes BV, Apeldoorn, The Netherlands) onto the sample in a 20° angle. The diffuse reflectance caused by the incoming light was captured by a CCD camera (TXG14-NIR, Baumer GmbH, Germany) located above the sample (Van Beers, Aernouts, De Baerdemaeker, & Saeys, 2013).

The bicolored apple samples were measured on the sun exposed side (reddish side) between 550 nm and 1000 nm with a 5 nm resolution, resulting in 91 images per measurement. The intensities on each raw image were radially averaged at equal distances from the center of illumination. Per wavelength, a raw data profile with CCD intensity in function of the distance from the illumination center was obtained. These raw profiles were first dark corrected and thereafter converted into relative reflectance profiles by a white reference measurement using a 50 mm diameter integrating sphere (AvaSphere-50-REFL, Avantes BV, Apeldoorn, The Netherlands). From this spatial profile, a reflectance at a fixed distance (1.40 mm) from the illumination spot edge was taken per wavelength. The result per apple sample was a wavelength dependent reflectance profile.

A total of 300 apples of the cultivar *Braeburn* were harvested at the research station for fruit growing (pcfruit vzw) in Sint-Truiden (Belgium) in the 2013 season. Each week, starting 7 weeks before and 2 weeks after commercial harvest (CH), 30 apples were harvested of which 20 apples were measured on the HLSI setup and 10 apples were used to determine a mean starch value (*S*) by means of the lugol test. After the HLSI measurement, the remaining 20 apples were destructively measured at the Flanders Centre of Postharvest Technology (VCBT). The firmness (*F* - kg/cm^2) was determined using a universal testing machine (LRX, LLOYD Instruments Ltd., Hampshire, UK), which uses an 11 mm diameter plunger to puncture the fruit. The soluble solids content (*R* - °Brix) was derived using a digital refractometer (PR-101α, Atago, Tokyo, Japan). These destructive measurements were performed on two opposite equatorial positions on the fruit surface and averaged to have one value per fruit. The obtained values were combined in one ripeness parameter called the Streif index according to (Streif, 1996):

$$Streif\ index = \frac{F}{R * S} \qquad (1)$$

From the different days measured, the two first days (60 apples) were not included. These measurement days show a high variability in the Streif index caused by the inaccurate starch measurement on unripe apples, causing a large effect on the calculated Streif index.

2.2 Vis/NIR spectroscopy and Multiplex

For the measurements using Vis/NIR and Multiplex, *Braeburn* apples were harvested during the 2011 season from orchards located at the research station of fruit growing (pcfruit vzw) in Sint-Truiden and at the ‘Fruitteeltcentrum’ in Rillaar (both in Belgium). On these locations, 20 apples were picked during CH including 20 additional fruits picked 1 week before CH both in Rillaar and Sint-Truiden and 20 fruits three weeks before harvest in Sint-Truiden. The Vis/NIR setup described by (Peirs et al., 2001) was also used here. It consists of a Vis/NIR spectrophotometer measuring in the spectral range from 380 to 1680 nm with a 2 nm resolution and a diffuse reflectance accessory. For the Multiplex measurements, a portable unit (Model 3, Force A, France) was used for sensing fluorescence signals (Ben Ghozlen, Cerovic, Germain, Toutain, & Latouche, 2010) and calculating anthocyanin, chlorophyll and flavonol associated indexes for the scanned fruits.
All the fruits were collected and immediately transported to the VCBT and scanned with the Vis/NIR and Multiplex unit under artificial light conditions. With both instruments each individual fruit was measured one time on the sun-exposed side at the equator. Afterwards, the apples were measured destructively as described in paragraph 2.1. The Streif Index was calculated according to equation (1).

All data processing algorithms were implemented in Matlab (version 7.10, The Mathworks Inc., Massachusetts, USA) and the PLS toolbox from Eigenvector (Eigenvector Research Inc., Wenatchee, USA) was used to perform Partial Least Squares (PLS) modelling.

3. Results and discussions

The correlation between the obtained optical signal and the Streif index gives an indication of the potential to distinguish between ripe and unripe apples in the field. This will be of importance for further implementation in a mechanical harvesting environment.

For the HLSI measurements the data were preprocessed using a baseline correction, an External Parameter Orthogonalization (EPO) filter and mean centering. Also a logarithmic transformation (10 base) was performed on the Streif reference values (Peirs, Schenk, & Nicolaï, 2005). With an internal cross validation using Venetian Blinds (5 fold) an overall PLS model with an R^2 in cross validation (CV) of 0.97 was established using 8 latent variables (Figure 1 a). For an eventual ripeness classification however, the ripeness classes around the harvesting period are most important. For this reason models were made with this restricted ripeness range, shown in Figure 1 b. This figure also shows the ripeness boundaries for the optimal harvest of *Braeburn* apples as dashed lines. *Braeburn* apples are considered good for harvest when the Streif index lies between 0.14 and 0.20.

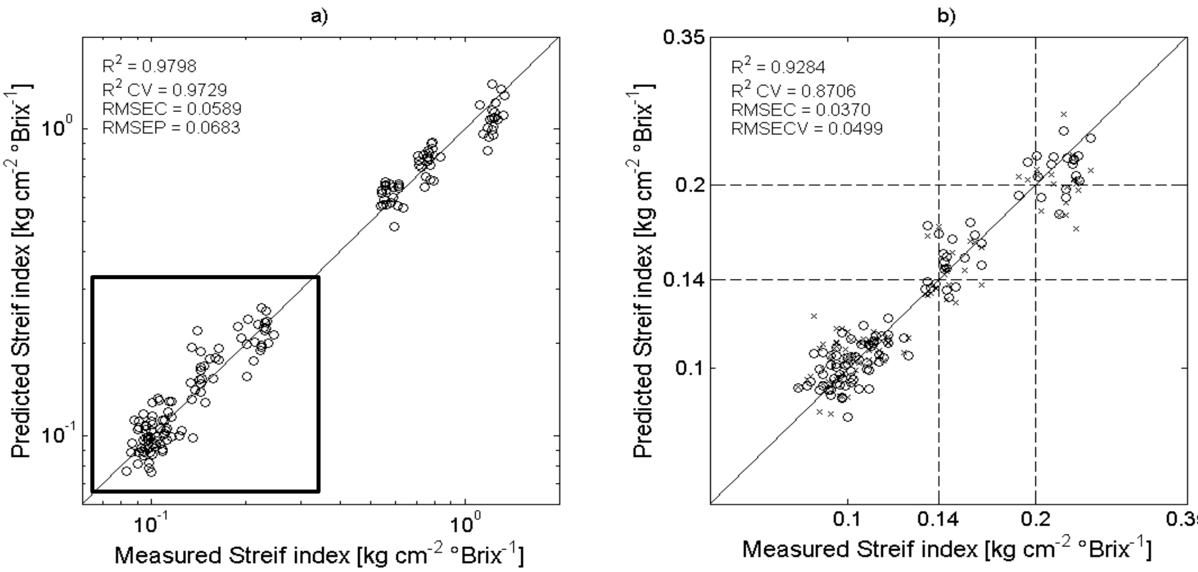

Figure 1: (a) PLS model showing predicted Streif Index by using the HLSI measurement technique on all measured data (b) PLS model on the smaller range of apple data (black box on the on the left). The dashed lines indicate the ripeness boundaries for Braeburn apples. Under 0.14 is considered overripe, above 0.20 is considered unripe. The circles indicate the calibration result while the crosses indicate the prediction result of cross-validation.

Based on Figure 1 a classification into three ripeness classes (overripe, ripe and unripe) seems possible. Looking at the ripeness classes, 11.5% of the apples were misclassified. An advantage of the HLSI technique is that both information on absorption (chemical characteristics) and scattering (physical characteristics) can be derived from the signal. Here the technique is used in a similar way as point spectroscopy, only with a larger distance between source and detector. The usage of the entire spatial signal will further improve the above correlations and give more information on the physical properties of the apple.

Using Vis/NIR spectroscopy, the classification also seems possible for a model built with the data closest to the CH. However, in contrast to the results of the spectra derived from the HLSI technique, more exhaustive preprocessing was needed to reach comparable results. By using the complete dataset considering all dates for all orchards, an EPO plus Mean Center transformation of the spectra resulted in a misclassification of 14% (PLS with R^2=0.8 and RMSECV=0.0927). However, by restricting the data to the last two measurement dates, selecting the considered wavelengths by iPLS and additionally, including preprocessing techniques, a much better regression and classification can be obtained, with only 6 out of 160 apples misclassified (3.75%), R^2=0.83 and RMSECV=0.0438 (Figure 2 a).

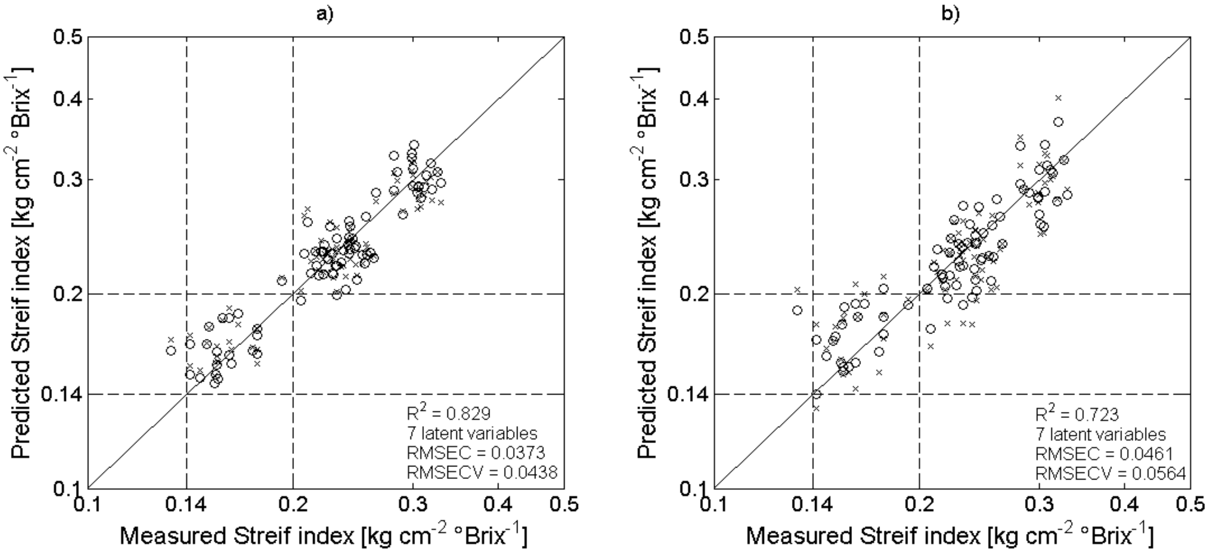

Figure 2: PLS regression results on apple maturity assessment by using (a) Vis/NIR and (b) Multiplex techniques. The dashed lines indicate the ripeness boundaries for Braeburn apples. The circles indicate the calibration result while the crosses indicate the prediction result of cross-validation.

Such additional preprocessing techniques included Smoothing (order 2, window: 15 points), Multiplicative Scatter Correction (mean, with intercept) and a first derivative (order 2, window: 15 points). In the case of the Multiplex, classification is also possible, but with a lower performance than the Vis/NIR technique. The error of classification is 10.6% (R^2=0.72; RMSECV=0.0564) (Figure 2 b).

The above results are in agreement with these described for Vis/NIR spectroscopy by Nicolaï et al. (2007). For Multiplex -to our knowledge- there are no previous reports of its performance on apple maturity assessment. The comparative evaluation in this study gives an advantage of Vis/NIR over Multiplex which could be explained by a higher amount of information from the fruit being captured by Vis/NIR sensors. This measurement is performed in contact with the fruit surface and the spectrum is influenced by both the peel and internal tissue of the fruit, with a penetration of light up to 1 cm into the apple flesh (Lammertyn, Peirs, Baerdemaeker, & Nicolaı, 2000). With the Multiplex, the captured information is more related to the anthocyanin content in the peel (Ben Ghozlen et al., 2010), but could miss important information on internal properties of flesh tissue like firmness or starch content. Comparing the Vis/NIR technique and HLSI, the latter shows a better R^2 but similar RMSE values. The advantage of HLSI over Vis/NIR is its contactless way of measuring. Also the HLSI technique is in an early stage of development, giving room for improvement. For example, incorporating more spatial information can give a better understanding of the physical properties, leading to better correlations with parameters like firmness. Additionally, the amount of information contained in spectra gives the possibility of finding the most relevant variables to consider in future regression models (~variable selection).

To use these techniques in a robotic harvesting environment, different elements have to be considered. System dimensions are of great importance for the system performance, whereby the Multiplex apparatus will be difficult to implement under the current state of development. For now, Vis/NIR spectroscopy seems a compact, fast and cheap way of measuring. Though, its main disadvantage is the contact with the fruit. HLSI can be a good alternative for solving this problem. When going from a lab setup to a field setup by selecting appropriate wavelengths by variable selection, the use of inexpensive laser diodes can lead to a cheap, non-contact and compact measuring unit.

4. Conclusions

The possibility to determine ripeness of *Braeburn* apples was evaluated using three optical measuring techniques. Vis/NIR spectroscopy showed a better performance than the Multiplex apparatus with an R^2 of 0.83 and a low error of classification. Therefore, at the moment, Vis/NIR spectroscopy is a good option to be evaluated in a robotic harvesting environment. However, the good performance of the HLSI technique gives a promising perspective towards future applications (R^2 of 0.93). A non-contact way of measuring and a laser diode based compact sensor can be advantageous on a harvesting robot.
In future research, the 3 techniques should be evaluated in parallel on the same apples and their potential should be evaluated on different apple varieties.

5. Acknowledgements

The research leading to these results has received funding from the European Commission's Seventh Framework Programme (FP7/2007-2013) under the grant agreement CROPS, project n° 246252. Robbe Van Beers is a PhD student funded by the Agency for Innovation by Science and Technology in Flanders (IWT).
The authors gratefully acknowledge the support of the Flanders Centre of Postharvest Technology (VCBT). Likewise, the experimental station in Sint-Truiden (pcfruit vzw) and the 'Fruitteeltcentrum' in Rillaar (both in Belgium) are acknowledged for providing the apples.

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