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Research Paper

Integration of simultaneous tactile sensing and visible and near-infrared reflectance spectroscopy in a robot gripper for mango quality assessment

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Development of non-destructive tools for determining mango ripeness would improve the quality of industrial production of the postharvest processes. This study addresses the creation of a new sensor that combines the capability of obtaining mechanical and optical properties of the fruit simultaneously. It has been integrated into a robot gripper that can handle the fruit obtaining non-destructive measurements of firmness, incorporating two spectrometer probes to simultaneously obtain reflectance properties in the visible and near-infrared, and two accelerometers attached to the rear side of two fingers. Partial least square regression was applied to different combinations of the spectral data obtained from the different sensors to determine the combination that provides the best results. Best prediction of ripening index was achieved using both spectral measurements and two finger accelerometer signals, with $R_P^2 = 0.832$ and RMSEP of 0.520. These results demonstrate that simultaneous measurement and analysis of the data fusion set improve the robot gripper features, allowing assessment of the quality of the mangoes during pick and place operations.

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1. Introduction

Mango (*Mangifera indica* L.) is a tropical fruit marketed throughout the world with a very high economic importance (Calatrava, 2014, chap. 2; Luke, 2013) and is generally harvested a little before the fully mature stage to avoid the onset of climacteric respiration during transportation to distant markets (Jha, Chopra, & Kingsly, 2007). Therefore, mango requires a ripening period before it achieves the taste and texture desired at the time of consumption (Cortés et al., 2016). The ripening process, and hence the organoleptic quality, is regulated by genetic and biochemical events that result in biochemical changes such as the biosynthesis of carotenoids (Mercadante & Rodriguez-Amaya, 1998), loss of ascorbic acid (Hernández, Lobo, & González, 2006), increase in total soluble solids (Padda, do Amarante, Garcia, Slaughter, & Mitcham, 2011), physical changes in mass, size, shape, firmness and colour etc. (Kienzle et al., 2011; Ornelas-Paz, Yahia, & Gardea-Bejar, 2008), and changes in aroma, nutritional content and flavour of the fruit (Giovannoni, 2004). The evaluation of these changes plays an important role for determining the ripening level at harvest, which will decide the market (i.e. domestic, export) and/or price of the product. Traditional determination of these changes has required a destructive methodology using specialised equipment, procedures and trained personnel, which results in high analysis costs (Torres, Montes, Perez, & Andrade, 2013). In addition, destructive methods allow only a small set of samples to be analysed to represent the variability of the whole production, though the ideal situation could be only achieved if all fruits are inspected in automated lines (Kondo, 2010). Traditionally, electronic sorters based on computer vision, used in postharvest to inspect the quality of the fruit, work at a very high speed, analysing the surface of the fruits but not providing any internal inspection. The most advanced and innovative sorters can incorporate NIR technology for testing the internal properties of produce, e.g. Vélez-Rivera, Gómez-Sanchis, et al. (2014) and Vélez-Rivera, Blasco, et al. (2014) developed computer vision techniques to determine damages and ripeness of mango 'Manila' through colour measurements. However light is projected on to the fruit from a fixed distance and the reflected or transmitted light is also measured at a certain fixed distance from the fruit. As the fruits have different sizes and shapes, the measurements can be strongly influenced by these features.

Robots have enormous potential to automate production in the food sector (Blasco, Aleixos, & Moltó, 2003; Wilson, 2010). Their main current function is to transport and manipulate objects but they have clear difficulties when handling soft and variable products (Bogue, 2009). Advances in new robot grippers are allowing their introduction in industrial and manufacturing systems for monitoring and controlling production (Tai, El-Sayed, Shahriari, Biglarbegian, & Mahmud, 2016). Automation with robots, in primary packaging operations, makes it possible to incorporate different sensors that can be used to assess fruit quality. Tactile sensors added to gripper fingers provide the capability to evaluate a product through physical contact (Lee & Nicholls, 1999) and have been used for classifying aubergine (Blanes, Ortiz, Mellado, & Beltrán, 2015) and to assess the firmness of mangoes cv. 'Osteen' (Blanes, Cortés, Ortiz, Mellado, & Talens, 2015) with a good prediction performance of the PLS model ($R_P^2 = 0.760$ and RMSEP $= 17.989$).

Visible and near-infrared spectroscopy combined with multivariate analysis has been widely used for quantitative determination of several internal properties or compounds, to determine ripeness and to measure quality indices in fruits in general and in mango in particular (Cortés et al., 2016; Jha et al., 2013; Schmilovitch, Mizrach, Hoffman, Egozi, & Fuchs, 2000; Theanjumpol, Self, Rittiron, Pankasemsu, & Sardsud, 2013). Cortés et al. (2016) predicted, in a laboratory study, the internal quality index for cv. 'Osteen' mangoes using visible and near-infrared spectrometry (VIS–NIR), obtaining good results with the full spectral range and some selected wavelengths ($R_P^2 = 0.833$ and $R_P^2 = 0.815$, respectively). Thus, incorporating the capability of performing spectral measurements into gripper fingers in combination with other sensors would multiply the possibilities of measuring internal fruit quality when the fruit is handled. However, this would require development of sensor fusion techniques to obtain the maximum value from the combined information of all the sensors, and avoid redundancy (Cimander, Carlsson, & Mandenius, 2002).

Furthermore, sensor fusion enables rapid and economical in-line implementation for fruit quality assessment (Ignat, Alchanatis, & Schmilovitch, 2015). Multiple sensors have been widely used in a variety of fields. Steinmetz, Roger, Moltó, & Blasco (1999) developed a robotic quality inspection system for apples that included a colour camera and NIR spectroscopy to predict sugar content using sensor fusion techniques. Since then, significant advances in the field of sensor fusion for food products have been developed, for example in computer vision and near-infrared spectroscopy to assess fish freshness (Huang et al., 2016), fusion of impedance e-tongue and optical spectroscopy to determine the botanical origin of honey (Ulloa et al., 2013), sensor fusion of electronic nose and acoustic sensor to improve mango ripeness classification (Zakaria et al., 2012) and fusion of electronic nose, near-infrared spectrometer and standard bioreactor probes to monitor yoghurt fermentation (Cimander et al., 2002). Hitherto, examples of combination of visible and near-infrared spectroscopy spectral data and tactile sensors in a robot gripper are non-existent. Therefore, getting a sensor fusion system integrating tactile and spectral properties of the fruit would be a key advance for the post-harvest industry.

Thus, the aim of this study is to develop a novel robotic gripper that incorporates accelerometers and fibre-optic probes coupled to a spectrometer to analyse mango ripening state by simultaneously measuring firmness and visible and near-infrared reflectance when the fruit is handled in the packing house during postharvest operations.

2. Materials and methods

2.1. *Experimental procedure*

A batch of 275 unripe mangoes (*M. indica* L., cv 'Tommy Atkins') were selected with similar size and colour and free of