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Research Paper

Integration of visible branch sections and cherry clusters for detecting cherry tree branches in dense foliage canopies

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To minimise the demand for seasonal workers in sweet cherry production, there is a need to develop automated harvesting systems. The first step in automating a shake-and-catch type harvesting system is to develop a machine vision system for detecting tree branches and localising shaking points in those branches. In this study, an image processing algorithm was developed to detect branches of cherry trees using segmentation of branch and cherry pixels. Firstly, partially visible branch segments within the tree canopies were connected using morphological features of the segments to form whole branches. Then, the positions of cherry clusters in the canopy were used as an indication to detect branch sections that were occluded by cherries and leaves. Different cherry clusters were grouped together based on their spatial location and distance between them. Branch equations were then defined through those cherry clusters using minimum residual criteria. Overall, 93.8% branches were detected in a Y-trellis fruiting wall cherry orchard, with 55.0% of branches detected using only branch pixels and 38.8% additional branches detected using cherry clusters. The method resulted in a total of 12.4% of false positive detection. The results showed that branch detection accuracy can be substantially improved by integrating cherry location information with the location of segments of partially visible branches. This study has shown the potential of machine vision systems to detect cherry tree branches in full foliage season, which is highly promising for the development of automated sweet cherry harvesting systems.

1. Introduction

Sweet cherry harvesting is a highly labour intensive operation which constitutes more than 50% of total production costs (Seavert, Freeborn, & Long, 2008). Currently sweet cherry harvesting is carried out manually by semi-skilled seasonal labour. Thousands of cherries growing in random spatial locations on individual tree canopies make commercial hand-picking highly inefficient and costly (Li, Lee, & Hsu, 2011). With

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Nomenclature

UFO	upright fruiting offshoots
USDA	United States Department of Agriculture
RDA	rapid displacement actuator
LED	light emitting diode
HFOV	horizontal field of view
x	feature vector
w_i	class definition
$P(w_i)$	prior probability of class w_i
$p(x\|w_i)$	class conditional distribution of x given that it belongs to class w_i
$p(w_i\|x)$	posterior probability of w_i given the evidence x
$p(x)$	probability of x
$di(x)$	decision function to decide class given the value of x
C_i	covariance matrix
m_i	mean vector
$\|C_i\|$	determinant of covariance matrix
Y	pixel position in rows
X	pixel position in columns
m	slope
C	intercept

the decreasing availability of agricultural workers and increasing labour costs, developing automated solutions for cherry harvesting has been one of the most critical needs of the sweet cherry industry around the world.

There are several factors that hinder the development of automated harvesting solutions including technological, economical and horticultural factors. Tree architecture is one of the important factors affecting the harvesting efficiency (Ampatzidis & Whiting, 2013). In recent years, growers of Washington State and other parts of the USA have been adopting more mechanisation-friendly plant architectures (Long, 2010; Peterson & Wolford, 2001). The upright fruiting offshoots (UFO) canopy architecture is one of the examples of a modern, planar training system that consists of trees with a permanent horizontal limb from which multiple vertical limbs are grown (Whiting, 2009). The UFO system may be trained to a vertical or Y-trellised architecture and provides a compact fruiting wall canopies. Investigations on mechanical harvesting have shown the potential to improve harvest efficiency by adopting the UFO training system (Chen et al., 2012; Du, Chen, Zhang, Scharf, & Whiting, 2011). This architecture is also amenable to automated harvesting aided by a machine vision system for fruit and branch detection.

Mechanisation of harvesting operation for various type of tree fruit and nuts has been widely investigated in the past with commercial success for various crops including nuts and fruit destined for processing market. One of the most widespread tree fruit harvesting techniques investigated and commercialised in the past is mechanical shaking (He et al., 2012), which has been investigated for several kinds of tree fruit crops including pistachio (Polat et al., 2006), apricot (Erdoğan, Güner, Dursun, & Gezer, 2003), olive (Blanco-Roldán, Gil-Ribes, Kouraba, & Castro-García, 2009), apple (Peterson, Bennedsen, Anger, & Wolford, 1999) and mango (Parameswarakumar & Gupta, 1991). A mechanical harvester developed and comprehensively evaluated by United States Department of Agriculture (USDA) in early 2000's (Peterson & Wolford, 2001) was based on engaging a rapid displacement actuator (RDA) on a limb using a manual controller. Evaluations of the efficiency of this prototype mechanical harvester revealed the difficulty for the operators to position the actuator due to the limited viewing angle from the operator's fixed seated position (Peterson, Whiting, & Wolford, 2003). A subsequent study of the harvester reported a significant effect of orchard characteristics and operator performance on the harvesting speed (Larbi & Karkee, 2014). In addition, multi-layer catching surfaces located very close to the canopy may be essential to improve collection rate and reduce fruit damage rate during mechanical harvesting (observation based on ongoing work at Washington State University). However, this type of collection mechanism will critically limit the visibility and ability of an operator to localise branches for shaking. To address this issue, there is a need to develop an automated harvester using a machine-vision-based system for detecting branches, identifying shaking points and positioning the end-effector.

Various investigations have been conducted in the past to detect and reconstruct branches and trunks of fruit trees (Karkee & Adhikari, in press; Karkee, Adhikari, Amatya, & Zhang, 2014; Tabb, 2009; Wang & Zhang, 2013). However, most of these studies have focused on detecting branches in dormant season with potential application in pruning and crop-load management. Machine vision has also been widely investigated in the past for automating tree fruit harvesting operation. Some examples include the machine vision systems studied for harvesting apples (Baeten, Donne, Boedrij, Beckers, & Claesen, 2008), oranges (Slaughter & Harrell, 1989), peaches (Kurtulmus, Lee, & Vardar, 2014), and cherries (Amatya, Karkee, Gongal, Zhang, & Whiting, 2016; Tanigaki, Fujiura, Akase, & Imagawa, 2008). Tanigaki et al. (2008) developed a 3D machine vision system for picking cherries form tree canopies in greenhouse environment. Most of these studies are focused on identifying individual fruit for selective harvesting. However, only limited studies have been reported in investigating machine vision system for fruit harvesting using bulk harvesting techniques such as branch shaking.

Amatya et al. (2016) developed a method for detecting branches to automate cherry harvesting using branch shaking. They used partially visible branch sections in a full foliage canopy to reconstruct cherry tree branches and reported an accuracy of 89.2% in a vertical architecture with relatively lighter canopy density (Fig. 1a). With higher density of foliage and cherry clusters, the branch visibility may decrease drastically (Fig. 1b), limiting the accuracy of branch detection method using visible branch segments. However, as cherries grow along the branches, location of cherry clusters can be useful in estimating location of branches that are hidden by cherries and leaves. The specific objective of this study is to integrate the sections of partially visible branches and location of clusters of cherries to detect cherry tree branches in the presence of dense foliage during harvest season. The result can be used to guide the actuating mechanism of a harvester to tree branches for automated cherry harvesting.