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Research Paper

Computer vision recognition of stem and calyx in apples using near-infrared linear-array structured light and 3D reconstruction

Baohua Zhang [a], *Wenqian Huang* [b,c,d,e], *Chaopeng Wang* [b,c,d,e], *Liang Gong* [a], *Chunjiang Zhao* [a,b,c,d,e,*], *Chengliang Liu* [a,**], *Danfeng Huang* [a]

[a] *State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China*
[b] *Beijing Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China*
[c] *National Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China*
[d] *Key Laboratory of Agri-informatics, Ministry of Agriculture, Beijing 100097, China*
[e] *Beijing Key Laboratory of Intelligent Equipment Technology for Agriculture, Beijing 100097, China*

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ABSTRACT

Automatic detection of common defects on apples by computer vision is still a challenge due to the similarity in appearance between true defects and stems/calyxes. Because the stem and calyx present a concave feature in apples, this paper proposes a novel stem and calyx recognition method using a computer vision system combined with near-infrared linear-array structured lighting and 3D reconstruction techniques to reveal this concavity. The 3D surface of the upper half of the inspected apples could be reconstructed by using a single multi-spectral camera and near-infrared linear-array structured light line by line on an adjustable speed conveyor belt. The height information for each pixel could be calculated by triangulation. Stems and calyxes would present a lower height than that of their neighbouring regions due to the local concave surface. In order to recognise the stems and calyxes efficiently, a standard spherical model (without stems and calyxes) is also constructed automatically, adapted to the size and boundary shape of the inspected apple. The difference between the 3D surface reconstruction and standard spherical model provides great potential for the recognition of stems and calyxes in apples. The final stem and calyx recognition algorithm was developed on the ratio images between 3D surface reconstruction images and standard spherical model construction images in gray level. The result had 97.5% overall recognition accuracy for the 100 samples (200 images), indicating that the proposed system and methods could be used for stem and calyx recognition.

* *Corresponding author*. State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China. Tel.: +86 1051503491; fax: +86 1051503705.
** Corresponding author.
E-mail addresses: zhangbaohua@sjtu.edu.cn (B. Zhang), zhaocj@nercita.org.cn (C. Zhao), chlliu@sjtu.edu.cn (C. Liu).
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1. Introduction

External quality is the most important sensory attribute of apples that can be visualised, and it can influence their market value, consumer preferences and choice (Pathare, Opara, & Al-Said, 2013; Brosnan & Sun, 2004; Blasco, Aleixos, & Moltó, 2007). Therefore, grading apples according to their external quality is necessary before marketing. External quality of apples is generally evaluated by considering their colour, size, shape and texture, as well as visual defects (Zhang et al., 2014a, 2014b; Brosnan & Sun, 2002; Xiao-bo, Jie-wen, Yan-xiao, & Holmes, 2010; Xing, Jancsók, et al., 2007; Xing, Karoui, et al., 2007; Li, Huang, & Zhao, 2015). Some external quality criteria, such as colour, size, texture and shape, have already been automated on industrial grading machines. However, automatic grading of apples according to their external defects by imaging systems is still not available, in part due to the similarity between the defects and stems/calyxes (Unay et al., 2011; Jiang, Zhu, Cheng, Luo, & Tao, 2009). Therefore, a milestone in this subject is distinguishing between defects and stem/calyx regions on apples.

The stems and calyxes are natural parts of apples, and computer vision systems are mostly confused in discriminating stems and calyxes from true defects because of their similarity in appearance (Unay & Gosselin, 2007; Zhang et al., 2015a, 2015b; Jiang et al., 2009; Zhu, Jiang, & Tao, 2007). Many attempts have been made to recognise stems and calyxes by using mechanical methods, machine learning methods and structured lighting methods. Mechanical methods locate the position of apples to ensure that the stem or calyx is at a known position or is out of the field of view of the camera, by using mechanical devices (Zhang et al., 2015a, 2015b). Campins, Throop, and Aneshansley (1997) developed two kinds of orienting devices to rotate apples of different varieties along the stem–calyx axes. However, the results showed that the varieties that were successfully oriented with one system would not orient using the other device (Li, Wang, & Gu, 2002). Bennedsen and Peterson (2005) proposed a novel approach to locate the defects and eliminate other dark areas caused by stem and calyx in the images of rotating apples. However, the mechanical methods need more time to adjust the apples, and make it impossible to use in-line or in real time (Zhang et al., 2015a). Machine learning can identify the stems and calyxes by using artificial intelligence methods. Correlation techniques have been used to match the stems and calyxes in apples by Leemans and Destain (2004). Some wounds located near the stem ends were probably confused with the stem. Unay and Gosselin (2007) proposed a novel method to recognise stem or calyx regions of 'Jonagold' apples by pattern recognition methods. Linear discriminant, nearest neighbour, fuzzy nearest neighbour, support vector machines and Adaboost were tested for stem and calyx recognition. Support vector machine was found to be the best pattern recognition method. Other machine learning methods such as relevance vector machine (Zhang et al., 2015a), back-propagation neural networks (Yang, 1996), pattern matching (Kleynen, Leemans, & Destain, 2005), and AdaBoost have also been used. The disadvantages of machine learning methods are that the recognition accuracy is highly dependent on the variable patterns and features selected and extracted, and the classifiers also need to be trained again and again before being applied in real world applications. Structured lighting methods identify the stems and calyxes according to the changing image pattern of structured light when the linear-array or speckle-array structured light is projected onto the apples. Zhang, Chen, Huang, Guo, and Wang (2012) proposed a method to identify the stems and calyxes by using speckle-array structured light. They located the stems and calyxes according to the change in the speckle-array encoding pattern caused by the concavity of stems and calyxes. An imaging system using linear-array structured lighting has been built by Yang (1993) for distinguishing the stem and calyx of apples from true blemishes. They identified the stripe patterns by using a fast and simple algorithm based on curvature analysis. However, the speckle-array and linear-array structured lighting systems are complex and the identification accuracy depends greatly on the accuracy of the structured lighting systems.

Stereo matching is a key issue in computer vision, and a core issue in 3D reconstruction with computers. Many applications of 3D reconstruction are based on binocular stereo vision. However, 3D reconstruction based on binocular stereo vision systems is time consuming and not suitable for in-line or real time inspection of fruit quality due to the complexity of stereo matching.

In order to reduce the complexity of stereo matching and improve the efficiency of the inspection task, a near-infrared linear-array structured light and a monocular camera were used for 3D reconstruction and identification of stems and calyxes in this paper.

The main objective of this paper was to develop a computer vision system to identify the stems and calyxes in apples using near-infrared linear-array structured lighting and 3D reconstruction techniques. The novelty of our research is to develop a standard spherical model without stems and calyxes, automatically adapted to the size and boundary shape of the inspected apple during the inspection task, and to realise the stem and calyx recognition on the ratio images between 3D surface reconstruction images and standard spherical model construction images in gray level.

In order to achieve the main objective, several sub-objectives have to be fulfilled: (1) extracting the centrelines of near-infrared linear-array structured light strips to represent 3D profiles of surfaces; (2) reconstructing the 3D surface of apples; (3) constructing standard spherical models without stems and calyxes automatically adaptive to the size and boundary shape of the inspected apples; (4) developing a simple algorithm for stem and calyx identification on the ratio images; (5) demonstrating the stem and calyx identification performance of the whole image processing algorithm.

2. Materials and methods

2.1. Samples used in the experiments

There are many cultivars of apples grown in China. 'Fuji' apple is one of the most popular cultivars, favoured by consumers due to its rich nutrition and healthcare benefits. Fuji apples