Computers and Electronics in Agriculture 152 (2018) 117–125

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

Original papers

Immature green citrus fruit detection using color and thermal images

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ARTICLE INFO

Keywords:
Immature citrus
Information fusion
Registration
Thermal
Yield mapping

ABSTRACT

Citrus fruit detection is one of the most important and challenging steps in citrus yield mapping. The distinct color differences between the ripe fruit and leaves allowed previously-described imaging-based methods to achieve good results. However, immature green citrus fruit detection, which aims to provide valuable information for citrus yield mapping at earlier stages is much more difficult because the fruit and leaf colors are very similar. This study combines color and thermal images for immature green fruit detections. Experiments identified optimal conditions for thermal imaging. A multimodal imaging platform was built to integrate color and thermal cameras. A novel image registration method was developed for combining color and thermal images and matching fruit in both images which achieved pixel-level accuracy. A new Color-Thermal Combined Probability (CTCP) algorithm was created to effectively fuse information from the color and thermal images to classify potential image regions into fruit and non-fruit classes. Algorithms were also developed to integrate image registration, information fusion and fruit classification and detection into a single step for real-time processing. An increase in recall rate from 78.1% when using only color images to 90.4% after fusing the color and thermal images was obtained at similar precision rates, and an increase in precision rate from 86.6% to 95.5% was obtained at similar recall rates. The fusion of the color and thermal images effectively improved immature green citrus fruit detection.

1. Introduction

Yield mapping is considered as one of the most important steps in implementing precision agriculture technologies. Yield mapping systems have been well studied and widely used for agronomic crops, such as wheat, sorghum, soybean and silage (Schueller and Bae, 1987; Searcy et al., 1989; Lee et al., 2005). However, it remains a challenging task to automatically create yield maps for tree crops. Citrus is the most important tree crop in Florida. Many studies have been conducted to estimate citrus yield. One of the early studies was done by Schueller et al. (1999), where they developed a strategy and system to generate yield maps for hand-harvested citrus. Although the method was simple and reliable, it did not map the yield of individual trees. Systems based on machine vision can estimate the yield of individual trees and generate yield maps before harvest. Chinchuluun and Lee (2006) developed a citrus yield mapping system in which two Charge-Coupled Device (CCD) color cameras and a differential GPS receiver were used to segment and count fruit based upon color differences between fruit and citrus canopies. MacArthur et al. (2006) mounted a color camera on a mini helicopter for taking photos from the top of citrus canopies. Pixels classified as fruit were counted for estimating the yield. In order to estimate yields earlier in the season to aid management and marketing, studies of citrus yield mapping have been focusing on creating early yield maps at the immature green stage.

Creating accurate early yield maps has been a much more difficult task, due to the color similarities between fruit and leaves and relatively smaller sizes of fruit at the immature green stage. Since fruit detection is the most crucial step in citrus yield mapping, most studies have been conducted to increase fruit detection accuracies. With high spatial resolutions of color cameras, detection using color images was still one of the primary choices for most researchers. Among various types of immature green fruit, apple and citrus were studied the most. Linker et al. (2012) developed an algorithm for green apples detection in natural environment. The algorithm detected potential apple areas using color and feature information and performed segmentation using contour analysis. The algorithm achieved correctly identification rates of 85% under non-directly sunlight conditions and 95% under diffusive lighting conditions. However, the algorithm suffers from strong direct sunlight

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https://doi.org/10.1016/j.compag.2018.07.011
Received 18 March 2018; Received in revised form 3 July 2018; Accepted 6 July 2018
0168-1699/

conditions. Another study by Linker and Kelman (2015) developed an approach to detect green apples in nighttime images by analyzing spatial distribution of the light around bright spots. Relationships between the number of detected fruits and the number of manually counted fruits were established. The estimated numbers had errors within 10%. Besides apples, research on green citrus detections were mainly conducted in Florida, USA. Kurtulmus et al. (2011) extracted a novel 'eigenfruit' feature from color images of green citrus and combined with color and circular Gabor texture features to detect green fruit under outdoor conditions. Fruit was detected using three different features separately and determined by majority voting with a precision of 72.7% and a recall of 75.3%. Sengupta and Lee (2014) integrated shape analysis and texture classification for identifying and determining the number of immature green citrus fruit from color images with a precision of 74.7% and a recall of 80.4%. Zhao et al. (2016) developed a new algorithm based on color feature and sum of absolute transformed difference (SATD) using color images. This study improved the detection precision to 88.6% and recall to 83.4%. Other imaging methods, such as multispectral imaging and hyperspectral imaging were also tested in green citrus detection (Kane and Lee, 2007; Okamoto and Lee, 2009). Although these imaging methods using wavelengths outside of the visible spectrum range provided richer information, the qualities of the images were limited by the imaging hardware, including lower spatial resolution of the cameras and more distortions in the images. Thus, these methods are not superior to using color images.

Combining multiple imaging techniques has the potential to improve performance. Although multi-modal imaging methods have not been used for immature citrus fruit detection, they have been tested on mature citrus fruit and some other types of fruits. Bulanon et al. (2009) built a multi-modal system using a thermal camera and a color camera to detect matured citrus fruit. They demonstrated that image fusion of the two types of images improved fruit detection compared to using a thermal image alone. Wachs et al. (2010) mounted a thermal camera and a color camera together as a multimodal imaging system to detect green apples. The system used maximum mutual information (MI) method for image registration and tested two approaches for apple detection based on low and high-level visual features. The low-level feature-based method achieved a 74% recognition accuracy compared to 53.16% achieved by the high-level feature based method. Although these two studies couldn't achieve high accuracies, they showed that combining thermal images with color images could potentially improve fruit detections.

Therefore, a multimodal imaging system based on color (RGB) and thermal cameras for immature green citrus fruit detection was created in this study. Specific objectives included: 1. Build a system that color and thermal images can be accurately registered; 2. Develop algorithms to combine registration, information fusion and detection into one step and achieve real-time processing; 3. Obtain high accuracy on immature citrus fruit detection by fusing the two imaging sources.

2. Materials and methods

Color and thermal images were studied separately at first to analyze and identify valuable information. Then, image registration and information fusion methods were developed for achieving improved detection results.

2.1. Related thermal characteristics of citrus canopies

Thermal characteristics of immature citrus canopies were analyzed using a thermal camera (FLIR A655sc, Wilsonville, OR, USA). The camera had a spatial resolution of 640 × 480 pixels, with an operational temperature range from −40 °C to 150 °C and accuracy of ± 2% of readings. It was placed in a citrus grove, facing the western side of a randomly selected citrus tree in north-south direction rows. Therefore,

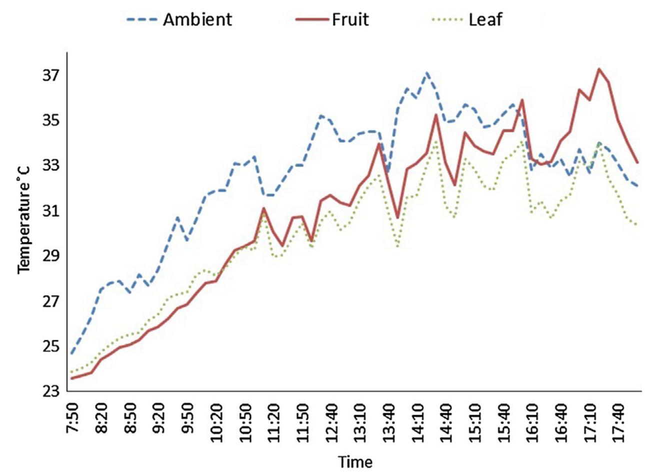

Fig. 1. Temperature changes of ambient atmosphere (blue dashed line), citrus fruit surfaces (magenta line) and citrus leaf surfaces (green dashed line) in the daytime on August 7th, 2015 (a typical day in the summer). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

it was the dark side of the tree in the morning and bright side in the afternoon. On August 7th, 2015 which was a typical summer day in Florida, thermal images of the canopy were taken from 7:50 AM till 18:00 with an interval of 10 min. Atmospheric temperatures were recorded using a hand-held weather station (Kestrel 3000 Pocket Wind Meter, Nielsen-Kellerman Co. PA, USA). The ResearchIR software (FLIR, Wilsonville, OR, USA) was subsequently used to extract temperatures of multiple fruit surfaces and leaves and the average temperatures for fruit and leaves were computed. Fig. 1 plots three lines, showing the changes of the mean temperatures of the ambient atmosphere fruit surfaces and leaf surfaces. In the early morning of the day the temperatures of the leaves were always higher than that of the fruit surfaces and in the late afternoon the fruit surfaces had higher temperatures than that of the leaves. Fig. 2 shows a series of thermal images acquired during the day. Darker areas represented lower temperatures and brighter areas corresponded to higher temperatures. The images showed a consistent result with the temperature plots.

Based on the temperature plots and thermal images, early mornings and later afternoons were identified as potential time periods for thermal imaging. The average temperature differences between fruit and leaf surfaces in the morning and the late afternoon were approximately 0.5 °C and 2.0 °C, respectively. However, further analysis showed that in the morning the citrus canopies were heated more uniformly, because they were primarily heated by the atmosphere. While in the afternoon, both the sunlight and atmosphere had major impacts on the temperature of fruit and leaves, which caused non-uniform heating pattern. Fruit and leaves exposed to the sunlight had higher temperatures and those hidden inside the canopies had lower temperatures. Although the average temperature difference between fruit and leaf surfaces in the afternoon was larger, some fruit hidden behind leaves did not have noticeably higher temperatures. Eventually, early mornings, between half an hour (about 7:30 AM EDT in Florida during August) and two and a half hours after sunrise, were selected as the optimum time periods for thermal imaging.

2.2. Imaging system

An imaging system consisting two color cameras (USB 3.0, The Imaging Source, Charlotte, NC, USA) and a thermal camera (A655sc, FLIR, Wilsonville, OR, USA) was mounted on a 3D printed frame as shown in Fig. 3. The lens (FUJINON HF9HA-1B, FUJIFILM Corporation, Tokyo, Japan) used with the color cameras had a focal length of 9 mm and apertures from f1.4 to f1.6. Images from all three cameras had the