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Identification and determination of the number of immature green citrus fruit in a canopy under different ambient light conditions☆

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Yield mapping for tree crops by mechanical harvesting requires automatic detection and counting of fruits in tree canopy. However, partial occlusion, shape irregularity, varying illumination, multiple sizes and similarity with the background make fruit identification a very difficult task to achieve. Therefore, immature green citrus-fruit detection within a green canopy is a challenging task due to all the above-mentioned problems. A novel algorithmic technique was used to detect immature green citrus fruit in tree canopy under natural outdoor conditions. Shape analysis and texture classification were two integral parts of the algorithm. Shape analysis was conducted to detect as many fruits as possible. Texture classification by a support vector machine (SVM), Canny edge detection combined with a graph-based connected component algorithm and Hough line detection, were used to remove false positives. Next, keypoints were detected using a scale invariant feature transform (SIFT) algorithm and to further remove false positives. A majority voting scheme was implemented to make the algorithm more robust. The algorithm was able to accurately detect and count 80.4% of citrus fruit in a validation set of images acquired from a citrus grove under natural outdoor conditions. The algorithm could be further improved to provide growers early yield estimation so that growers can manage grove more efficiently on a site-specific basis to increase yield and profit.

1. Introduction

Computer vision is very applicable for fruit identification and localisation. Efficient detection and estimation of fruit numbers in their natural environment is one of the main applications of computer vision in agriculture. Automated computer vision techniques undoubtedly offer great benefits for more efficient crop management.

Florida is the leading state in the United States for the production of citrus, which plays a crucial part in Florida's overall economy. In 2009–2010, Florida accounted for 65.2% of the total citrus production in the USA (USDA-

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Nomenclature

Symbols

b	bias
D	result of convolving an image with a difference-of-Gaussian function
G	variable scale Gaussian matrix
I	two dimensional image matrix
L	Gaussian-filtered image matrix
l	label
R	radius
$\boldsymbol{w}$	weight vector
$\boldsymbol{x}$	feature vector
Y	response of SVM (−1 or +1)
θ	angle
φ	feature-space transformation
σ	standard deviation

Abbreviations

CHT	circular Hough transform
DoG	difference-of-Gaussian
ECHO	extraction and classification of homogeneous objects
NIR	near infrared
PCA	principal component analysis
RT	real-time
SIFT	scale invariant feature transform
SVM	support vector machine

NASS, 2010), whilst the percentage was approximately 71% in 2008.

The focus of this study was to develop an early yield mapping system for immature green citrus fruit so that growers can manage grove more efficiently well before harvesting to increase yield and profit. Due to large in-field spatial variabilities in soil type, soil fertility, tree size and other cropping conditions, citrus yields vary greatly in the field. Therefore, in order to increase yield, it would be very helpful for citrus growers if they could predict yield well in advance of harvest so they could as quickly as possible use more soil nutrients or fertilisers to increase yield at the different locations.

One of the major challenges in detecting immature green citrus fruit lies in the similarity of the colour of the fruit and the leaves. As any vision algorithm has to work under natural outdoor conditions, non-uniform illumination is another challenging problem. Also, partial occlusion of the fruit by leaves, branches and by other fruit can cause further challenges in detecting green citrus using computer vision.

Many researchers have investigated using computer vision and other image processing techniques (Sonka, Hlavac, & Boyle, 1999) for the detection of citrus and other fruits. A thorough review regarding fruit recognition systems can be found in Jiménez, Ceres, and Pons (2000). One of the earliest studies in the field of automatic detection of fruits was by Schertz and Brown (1968). In their study, both individual fruit and mass harvests were considered with long and short range selection of citrus fruit among leaves and branches. According to their measurements, the light reflected from an orange was ten times greater than that reflected from a leaf. For short range selection, Gamma-ray backscatter also had discriminative characteristics. Among shape analysis and texture based methods, Whittaker, Miles, Mitchell, and Gaultney (1987) designed an automatic system to detect tomatoes based on the shape in natural environment. They used a modified Hough transform for circular objects, which helped them identify fruits even when they were partially occluded by other fruits or leaves. Pla, Juste, and Ferri (1993) studied the characterisation of spherical objects in grey-scale images and applied their techniques for detecting mature citrus on the trees. Under artificial illumination conditions, their system yielded a 75% success rate and an 8% false detection rate. Fernandez-Maloigne, Laugier, and Boscolo (1993) proposed a technique based on texture of an image to find green apples. They assumed that apples would have bright spot in the image, and that apple region would be homogeneous and circular. Those assumptions might not hold for any uncontrolled natural outdoor environment. Real-time (RT) video sequences were also used to study the fruit detection problem. Tabb, Peterson, and Park (2006) developed a method using RT video sequences to locate mature apples on trees. Their algorithm, global mixture of Gaussian, was based on the mixture of Gaussian distributions to model the background in colour images. The detection rate was relatively higher – approximately 85–96%. Recently, Rakuna, Stajnkoa, and Zazulab (2010) designed a computer vision based model for object detection that can work as an initial step in fruit identification. They were able to estimate the number of apple fruit and their diameters using three distinctive features – colour, texture and 3D shape.

Most of these studies were aimed at detecting mature fruits; however researchers started investigating immature fruit detection earlier in this century. Annamalai and Lee (2004) developed a spectral based system to identify immature green citrus in images. They measured diffuse reflectance of green citrus fruit and leaf samples using a spectrophotometer and identified two significant wavelengths (815 nm and 1190 nm) to distinguish green citrus from green canopies. They reported that using a threshold on the average reflectance ratio at these wavelengths, immature green citrus fruit could be identified by spectral measurement. Thermal imaging system was also used to detect and estimate the number of fruits on trees. Stajnko, Lakota, and Hocevar (2004) used images captured by a thermal camera to estimate the number of apples and measured their diameter. Thermography (sensing the heat radiation on an object) and several image processing algorithms were employed in their approach. Safren, Alchanatis, Ostrovsky, and Levi (2007) implemented a green apple yield mapping system using hyperspectral images in the visible and near infrared (NIR) ranges. Principal component analysis (PCA), extraction and classification of homogeneous objects (ECHO), morphological operations, watershed, and blob analysis were the major components of their multistage algorithm. Their correct detection and overall error rates were 88.1% and 14.1%, respectively. Recently Wachs, Stern, Burks, and Alchanatis (2010) presented two approaches to detect green apples in tree canopies under