An Active Thermography Method for Immature Citrus Fruit Detection

H. Gan[1], W.S. Lee[1], V. Alchanatis[2], A. Abd-Elrahman[3]

[1] Department of Agricultural and Biological Engineering, University of Florida, Gainesville, Florida

[2] Depart of Sensing, Information and Mechanization Engineering, Institute of Agricultural Engineering, ARO – The Volcani Center, Bet Dagan, Israel

[3] Gulf Coast Research and Education Center, University of Florida, Plant City, Florida

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Abstract. *Fast and accurate methods of immature citrus fruit detection are critical to building early yield mapping systems. Previously, machine vision methods based on color images were used in many studies for citrus fruit detection. Despite the high resolutions of most color images, problems such as the color similarity between fruit and leaves, and various illumination conditions prevented those studies from achieving high accuracies. This project explored a novel method for immature citrus fruit detection by using videos from a thermal camera, which can capture the surface temperatures of citrus canopies. Fruit and leaves in citrus canopies have different thermal characteristics, which can present different temperatures during a heating or a cooling process. An active thermography system was developed which created a thermal excitation signal on the surface of citrus canopies to change their temperatures and then take thermal images. Because of the high temperatures in Florida during the growth period of citrus fruit, a cooling method was selected by spraying water. The system was implemented using a golf cart, on which a water spray system and a thermal imaging system were mounted. The water spray system installed in the front of the golf cart sprayed water on the surface of citrus canopies. Then the thermal imaging system, which was mounted at the end of the golf cart, acquired videos of the citrus canopies. Novel fruit detection and tracking algorithms were developed for counting the number of fruit from the videos. An average precision of 87.2% was achieved using thermal video frames for immature citrus fruit detection.*

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1. Introduction

With the development of artificial intelligence and big data, more and more industries are going smart. In agriculture, the smart farm is beyond a concept. Modern farms with increased automation, improved sensing and monitoring systems are emerging all over the world. However, there still are many challenges remained in this area. One of the primary challenges is to develop proper sensors and sensing methods for collecting field data rapidly, conveniently and accurately.

Yield data, as an important indication of crop health and a direct measure of profits, is perhaps the most important information for farmers. Therefore, sensing and monitoring yield data has been attempted. In general, autonomous yield monitoring has been well-developed for agronomy crops, by measuring the weight or volume of crops while harvesting (Schueller & Bae, 1987; Searcy et al., 1989; Lee et al., 2005). However, for tree crops, autonomous yield monitoring remains a difficult problem partially because of lacking mechanical harvesting solutions. One early attempt was done by Schueller et al. (1999). In the study, a system was developed to record the locations of containers of harvested citrus fruit and generate yield maps for the citrus grove. Later, more attempts were made using machine vision methods. Chinchuluun & Lee (2006) used two CCD color cameras to acquire images of citrus canopies from a ground vehicle and identified ripe fruit from those images. Instead of using a ground vehicle, a mini helicopter was used by MacArthur et al. (2006). The study calculated the areas of orange pixels to estimate the yield directly. An important advantage provided by the machine vision methods is that yield can be estimated before harvest. Thus, studies have been conducted to identify immature fruit by cameras to create an early yield map.

The main challenges for identifying immature green fruit are the color similarities between fruit and leaves and various illumination conditions. Taking citrus fruit as an example, multiple methods and algorithms have been created. Kurtulmus et al. (2011) created a novel feature named ‘eigenfruit’ from color images of green citrus canopies. A correct identification rate of 75.3% was obtained. Also using color images, Sengupta & Lee (2014) and Zhao et al. (2016) developed different methods that combined feature and color information to separate green fruit and leaves. Correctly identified fruit rates of 80.4% and 83.4% were obtained by the two studies, respectively. Instead of using color images, Kane & Lee (2007) used multispectral imaging method and Okamoto & Lee (2009) tested hyperspectral imaging method for this task. All these methods were limited by illumination conditions. Canopies hit directly by strong sunlight or hidden in the shades were major troubles for these methods. In worse situations, illumination changes with a single image which may cause very poor detection results.

To solve the problems of color similarity and various illuminations, better techniques should be utilized. Among possible solutions, thermal imaging shows a great potential. Bulanon et al. (2008) studied the temporal variation of temperature in citrus canopy under natural environment. Thermal images of citrus canopies were acquired for 24 hours. Due to the differences in thermal properties, fruit presented different temperatures from leaves. The relatively large temperature difference was found in the afternoon, around 16:00. They also did a preliminary test on fruit detection using the thermal images, which demonstrated the potential of thermal imaging with a limited time range. A similar multimodal system was also built by Wachs et al. (2009) for apple detection. The study achieved a recognition accuracy of 74%. Although demonstrated the potential, these studies couldn’t achieve high accuracies using thermal imaging. More effective methods should be developed to transform the potential into actual applications.

The imaging system developed in this study utilized an active thermography method that an external stimulus was applied to the surfaces of tree canopies to induce temperature contrast between fruit and leaves. The goal was to create novel thermal imaging system that could eliminate some of the limitations when color and traditional thermal imaging methods were used. Specific objectives include: 1. Develop an active thermal imaging system for fruit detection; 2. Create algorithms to achieve high fruit detection speed and accuracy.

2. Materials and Methods

This section describes (1) the design of the active thermal imaging system; and (2) the development of the fruit detection and counting algorithms.

2.1. The imaging system

The imaging system consisted of a mobile platform, a water spray system and a video acquisition system. A standard-sized golf cart was modified as the mobile platform that carried the water spray system and the video acquisition system. Metal bars were mounted in the front of the golf cart to allow the installation of three nozzles vertically. At the back of the golf cart, a water tank and a pump system were mounted and connected to the three nozzles using rubber hose. Next to the water tank, two 12-volt car batteries were anchored as a power supply to the spray system. An adjustable metal bar structure, which was used for installing the image acquisition devices, was mounted behind the water tank and extended outside of the golf cart. Fig. 1 shows the nozzles and the entire imaging system.

Fig. 1. The imaging system. Left: the metal bars and three nozzles mounted vertically on the bar. Right: A view from the back of the entire imaging system

2.1.1. Design of the spray system

The spray system was the most critical component as it determined how much difference in temperature between fruit and leaves can be reached. It must create uniform temperature changes on both fruit and leaves' surfaces while maximizing the temperature difference between these two substances quickly. In addition, the spray should cover the entire field of view of the camera and be able to penetrate the tree canopies.

To meet the requirements, two sets of nozzles and different distances between the nozzles and the canopies were tested. Experiments were also conducted at different time periods of a day. The two sets of nozzles tested were TeeJet XR80015VS and XR11001VS. Two distances, 0.5 m and 0.8 m, were selected between the nozzles and the tree canopies. Based on how uniform the canopies were sprayed and the temperature differences between the fruit and leaves' surface, the TeeJet XR80015VS and the 0.5 m were selected. In addition, the pressure of the system was set to 276 kpa. The selected parameters showed the most consistency and visually the most obvious temperature differences. Fig. 2 shows example video frames of citrus canopies before and after water spray.

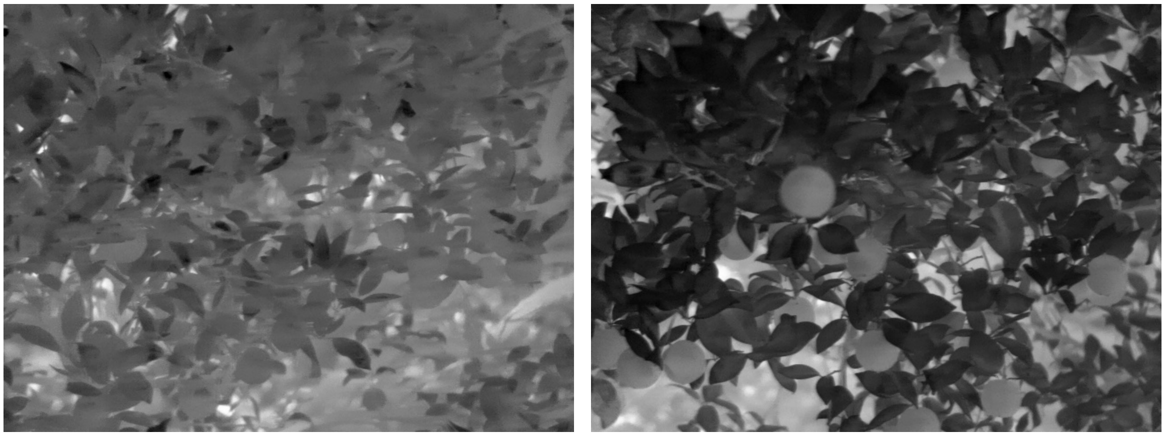


Fig. 2. Thermal images of citrus canopies. Left: the thermal image of a citrus canopy before being sprayed by water; Right: the thermal image of a citrus canopy after been strayed by water

2.1.2. Video acquisition

The image acquisition system consisted of a thermal camera (FLIR A655sc, FLIR, Wilsonville, OR, USA) and a laptop (Precision M4700, Dell Inc, Round Rock, TX, USA) with FLIR's ResearchIR software installed. The system enabled the highest acquisition speed of 30 fps with each frame having a size of 640 × 480 pixels. Acquisition of thermal videos was triggered to start at the beginning of each row and to stop at the end. During the acquisition, the camera was set about 2 m away from the closest surface of canopies and captured a field of view of approximately 1 × 0.7 m^2. The speed of the golf cart was manually controlled at approximately 1 m/s. Therefore, two consecutive frames of the video had more than 95% overlaps. Videos were acquired for both sides of tree canopies to include both bright and dark illumination conditions.

2.2. Fruit detection and counting algorithms

Fruit detection and counting algorithms were developed using Python programming language. It combined the Faster R-CNN algorithm and the optical flow tracking method. Faster R-CNN is a state-of-the-art object detection network. It combines an object classification network, such as VGG16, ResNet, with a region proposal network (RPN) for quick detections. In this study, VGG16 was selected as the classification net of the Faster R-CNN. Optical flow is an algorithm that detects intensity changes in consecutive frames of a video to estimate the motions of objects. It was used to track locations of detected fruit from videos to avoid multiple-count problems. A total of 289 thermal images, which included around 2000 fruit, were trained using the Faster R-CNN. The trained model was integrated with the optical flow algorithm for detecting fruit from videos.

3. Results and Discussions

The goal of spraying water was to create a uniform and visible temperature changes on the surfaces of fruit and leaves. Thus, the quality of the spray system was evaluated based on the standard deviations of the surface temperatures of fruit and leaves and the average difference between the two. Ten fruit and ten leaves' surfaces of canopies before and after spray were randomly sampled. Therefore, there were 40 sample areas in total. For each sample area, the standard deviations and mean values were calculated. Table 1 shows the measurements and the comparison between values before and after the spray. The average temperature difference between fruit and leaves before spray was 0.1 °C, and it increased to 3.1 °C after spray. The standard deviations of fruit and leaves' temperatures were 0.25 °C and 0.15 °C before spray, respectively. After spray, the standard deviations of fruit and leaves' temperatures were 0.16 °C and 0.24 °C, respectively. The average values of the two standard deviations were both 0.20 °C before and after spray. Therefore, it indicated that the surface of fruit and leaves were cooled down by water spray uniformly.

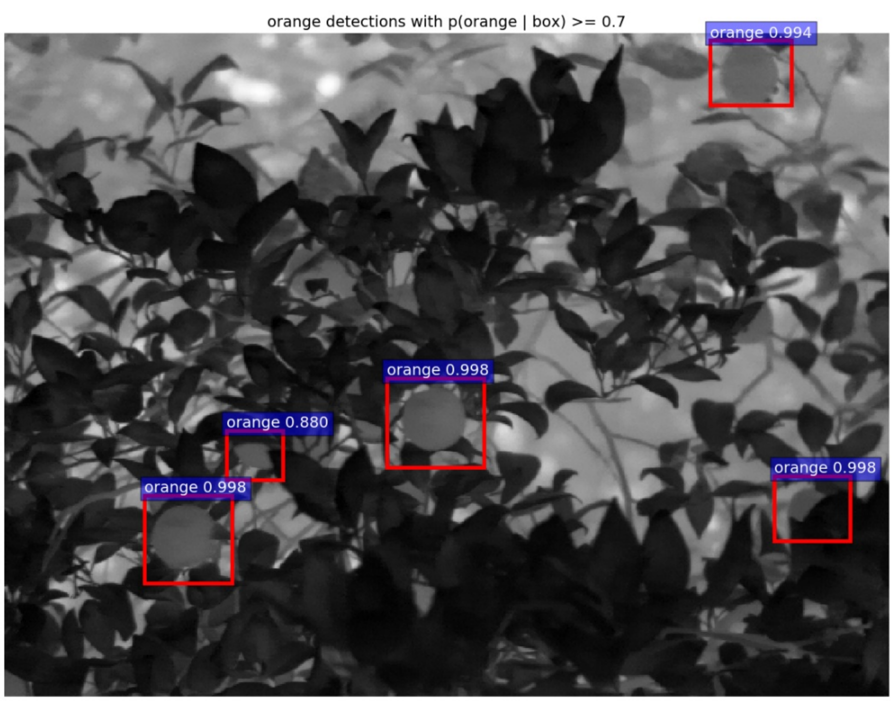
Table. 1. Standard deviations (Std.) and mean temperature values of randomly selected fruit and leaf areas, before and

after spray (unit: °C)

	Fruit–before spray		Leaf–before spray		Fruit-after spray		Leaf-after spray	
Area #	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean
1	0.4	31.2	0.1	30.9	0.2	30.0	0.2	26.5
2	0.1	32.0	0.1	32.3	0.1	29.8	0.2	26.5
3	0.1	32.3	0.2	32.2	0.1	29.9	0.2	26.4
4	0.5	30.7	0.2	31.8	0.1	30.3	0.2	27.5
5	0.3	31.5	0.2	32.0	0.1	30.1	0.3	26.9
6	0.4	31.8	0.1	31.8	0.2	29.5	0.3	26.7
7	0.1	31.6	0.1	31.4	0.2	29.5	0.3	27.1
8	0.3	31.5	0.2	30.9	0.3	29.7	0.2	26.8
9	0.1	32.0	0.2	30.6	0.1	29.5	0.2	26.6
10	0.2	31.9	0.1	31.5	0.2	30.8	0.3	27.3
Average	0.25	31.6	0.15	31.5	0.16	29.9	0.24	26.8

The accuracy of fruit detection was evaluated based on its average precision when detecting fruit on individual images and compared with fruit detection using color images. The counting algorithm was applied to count number of fruit from two thermal videos.

The trained Faster R-CNN model was tested on 58 randomly selected thermal video frames of citrus canopies after spray, and an 87.2% average precision was achieved. This is approximately 10% higher than using color images with the Faster R-CNN, which was 77% (Gan et al., 2017). Fig. 4 shows example images of detected fruit in citrus canopies.



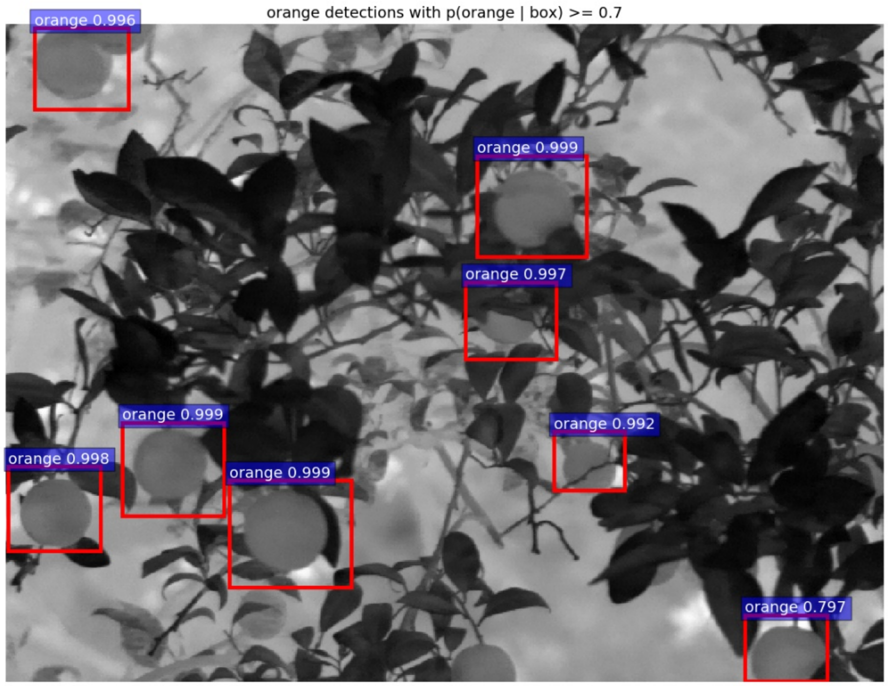


Fig. 4. Example thermal images of citrus canopies after spray. The detected fruit was labeled with red rectangles and confidence values

The combined detection and counting algorithm was tested on two videos, which were acquired from two rows of citrus trees from the beginning to the end. The algorithm could successfully detect fruit in each frame and track their locations for counting purpose. The accuracy of the algorithm will be evaluated by comparing manual count numbers as a next step.

4. Conclusion

An active thermography imaging system was developed for creating temperature differences between fruit and leaves, and a detection and tracking algorithm was created to count the total number of fruit in each row of citrus trees. The system could successfully change fruit and leaves' surface temperature uniformly and achieved an average temperature difference of 3.1 °C. The detection algorithm utilized the Faster R-CNN and achieved an average precision of 87.2% on fruit detection from video frames.

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