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Volumetric mass flow sensor for citrus mechanical harvesting machines

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ABSTRACT

A volume-based mass flow sensor system was developed to estimate the total mass of fruit travelling on the inclined and horizontal conveyors of two citrus mechanical harvesting systems. A LIDAR (light detection and ranging) sensor was used to scan the conveyor cross-sectional area and use the distance related-information to estimate the bulk volume and total mass of fruit on the conveyor by integrating the data over time. A custom algorithm was developed to analyze the data and calculate the fruit volume. Fruit volume was used to estimate the total fruit mass.

Sensor system was tested in the laboratory on two different conveyor systems: an inclined conveyor used in a mechanical harvester (conveyor flap height = 8 cm), and a horizontal conveyor used in a debris removal system (conveyor flap height ⩽3 cm). The tested conveyor speeds ranged from 0.59 m/s to 1.71 m/s. The system performance for the tested speed ranges was an average error of 7% (standard deviation [SD] ± 7%) and 7% (SD ± 5%) for the inclined and horizontal conveyors, respectively. The average total fruit mass estimation error during mechanical harvesting was 10% (SD ± 6%) for 11 field trails that involved scanning 512–1356 kg of the fruit on a horizontal conveyor of a debris removal system. Overall, the developed sensor system can be used for volumetric yield monitoring of citrus. The sensor system performance will likely be improved using instant conveyor speed during the estimation of total fruit mass.

1. Introduction

Yield monitoring is one of the important components of precision agriculture. A yield monitoring system quantifies yield variation and provides direct feedback to the growers about the yield variability within the field or orchard, and is the first step of site-specific crop management (Pelletier and Upadhyaya, 1999). Yield monitoring is also essential for the creation of accurate yield maps (Persson et al., 2004). The growers can use such maps to make better management decisions which could lead towards increased profitability.

Yield monitoring and mapping systems for different crops have been widely researched and studied. Schueller and Bae (1987), Searcy et al. (1989), and others have studied yield mapping systems for grain harvesters since the 1980s. Examples of yield mapping and monitoring for other crops include cotton (Roades et al., 2000; Wilkerson et al., 2001), sugarcane (Benjamin, 2002; Magalhães and Cerri, 2007; Price et al., 2011), potatoes (Campbell et al., 1994), citrus (Whitney et al., 1998; Schueller et al., 1999; Annamalai, 2004; Ehsani et al., 2009), blueberries (Chang et al., 2012), tomatoes (Pelletier and Upadhyaya, 1999), peanut (Thomasson et al., 2006), silage (Lee et al., 2005), and tubers (Persson et al., 2004). The non-contact approaches involved the use of emitter-photo-detector arrays, (fiber) optical mass flow sensors (Wilkerson et al., 2001; Thomasson et al., 2006; Grift et al., 2006), and color imaging (Annamalai, 2004; Chang et al., 2012), whereas the contact approaches involve the use of load cells (Pelletier and Upadhyaya, 1999; Magalhães and Cerri, 2007; Maja and Ehsani, 2010). Variation in the environmental light and fruit shadowing were some of the major concerns in applying color imaging for yield monitoring (Annamalai, 2004; Chang et al., 2012). In addition to the sensor instrument failures in field conditions and occasional saturation of sensors at maximum measurable flow rate, sensor damage due to mud, dust, and wetting critically affected the yield estimation by optical mass flow sensing techniques (Thomasson et al., 2006; Price et al., 2011). Overall, to have better optical sensor performance, a common suggestion was to recalibrate the sensor(s) for each variety and for changes in field conditions. Similarly, the load cell based contact-type yield monitoring systems were shown to have larger systematic errors when measuring loads at the upper-end of the sensor ranges (Pelletier and Upadhyaya, 1999) and malfunction due to dirt and moisture ingress.

The majority of citrus harvest in Florida consists of oranges processed into juice. Most of the crop (about 0.5 million acres [0.2 million ha]) is harvested manually. Canopy shake harvesting machines

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are being used recently by some growers to harvest about 7% of the total acreage (Roka, 2012). There is no commercial mass flow yield monitoring system available for these machines. Yield monitoring systems for such mechanical harvesting machines could provide the information of the mass loaded into the hauling trucks, fruit yield of the harvested area, and approximate yield of a tree.

Maja and Ehsani (2010) successfully developed and tested an experimental yield monitoring system for citrus mechanical harvesting machines using an impact plate system. The system performed well in laboratory and field tests, but had durability issues due to the impact created by the fruit striking the plate. There were also issues with non-fruit debris such as broken branches and limbs that could damage the impact sensor or block the fruit flow on the conveyor belt. A non-contact mass flow sensor for yield monitoring systems of harvested crops could aid the performance of existing mass flow sensors or eventually replace them. This is because the non-contact sensor will not be damaged by fruit and debris impact.

Canopy shake and catch harvesters have a conveyor mechanism that carries the harvested fruit and transports it to the hauling truck. It would therefore be useful to develop a sensor which can be implemented on the citrus carrying conveyors to monitor the citrus fruit volume passing along the conveyor. Citrus fruit firmness, volume, juice content and weight parameters are governed by fruit maturity (Ladanyia, 2007). Since the mature fruit in commercial citrus orchards has a relatively constant fruit density, sensed fruit volume can be converted into an estimate of fruit mass. This assumption is based on the fact that the fruit density will change only due to varying maturity levels or due to the frost damage to the fruits (Miller, 1990; Ladanyia, 2007). Therefore, the goal of this study was to develop and evaluate a non-contact mass flow sensor system to be used on either horizontal or inclined conveyor systems of citrus mechanical harvesters.

2. Materials and methods

2.1. Volumetric mass flow sensor system

A SICK® LMS 200 laser scanner (SICK, Düsseldorf, Germany), hereafter referred as the LIDAR sensor, was used for measuring the citrus fruit volume. The scanner generates the surface from which the fruit volume is obtained by systematically sweeping the measurement area with the laser. The laser beam of the LIDAR sensor can cover a large area while its head rotates horizontally and a mirror flips vertically. It scans a two-dimensional space and produces real-time data in a polar coordinate system. In this study, an angular resolution of 1° and a scanning angle of 180° were used. The LIDAR sensor has a standard RS-422 serial port for data transfer. Custom algorithms were developed in LabVIEW® 8.6 (National Instruments Corporation, Austin, TX, USA) and MATLAB® 7.8 (The Mathworks Inc., Natick, MA, USA) for data acquisition and data processing, respectively.

2.2. Data collection

The mass flow sensor system performance was first evaluated on an inclined conveyor system similar to the conveyors used on continuous canopy shake and catch systems (CCSC). CCSC's (Model: 3220, OXBO International Corporation, Clear Lake, WI, USA) are the only mass harvesters widely used in Florida citrus. The CCSC shakes the citrus canopy causing fruit to fall from the tree onto a catch frame. This fruit is then carried by the conveyor system of the mechanical harvester and dropped into the hauling truck. The conveyor is oriented in such a way that it makes a 50° angle with respect to the horizontal. The location of the conveyor system on the CCSC is shown in Fig. 1a. A conveyor section from the CCSC harvester shown in Fig. 1a was removed from the harvester and driven by a small hydraulic motor for laboratory testing of the yield monitoring system (Fig. 1b).

The LIDAR sensor was installed above the fruit carrying conveyor, perpendicular to the conveyor surface, at a distance of 30–50 cm (Fig. 1b). The sensor system was tested for conveyor speeds of 0.59, 0.79, and 1.06 m/s, minimum, intermediate and maximum operating speeds of the harvester conveyor. At each speed, a known mass of Valencia oranges was sensed by the LIDAR sensor system. Acquired data was then processed using the fruit volume estimation algorithms (Sections 2.3 and 2.4). In the calibration stage, three repetitions were performed for each of the total fruit mass at each of the conveyor speeds. For each conveyor speed, estimated volume and actual total fruit mass data was regressed to establish mass–volume relationships. The developed relationships at respective speeds were then used during the test stage. Testing involved conveying a known amount of total fruit mass, estimating the total fruit volume, and then using the mass–volume relationship developed in calibration stage to estimate the total mass. For a given conveyor speed, the sensor system was tested at five different total mass values.

The mass flow sensor was also tested on a horizontal conveyor of a debris removal system developed by our research group (Precision Agriculture Laboratory, Citrus Research and Education Center, Lake Alfred, FL, USA) (Fig. 2). The debris removal system was built specifically to remove branches, stems, leaves, and small green fruits from the mechanically harvested citrus fruit loads. This system can also be used as a platform to mount and test citrus fruit yield and quality monitoring sensor systems.

To establish the relationship between the volume scanned by the sensor and the mass conveyed underneath it at different conveyor speeds, the sensor system was tested at speeds of 1.03, 1.34, and 1.71 m/s, respectively. Three replicate runs at each of the speed settings were performed such that known amount of fruit mass (<50 kg) travelled underneath the LIDAR sensor on conveyor. Methods similar to that of inclined conveyor testing were followed to establish and test the fruit mass–volume relationships. The calibration relationships between the actual total mass and corrected fruit volume were used to estimate the total fruit mass in test runs. The percent error (Eq. (1)) between the estimated and actual total mass was used to quantify the performance of the developed yield monitoring system.

$$\text{Error }(\%) = \frac{|\text{estimated total mass} - \text{actual total mass}|}{\text{actual total mass}} \tag{1}$$

Sensor system performance was also evaluated in the field during the 2012 harvesting season involving large fruit loads (512–1356 kg). Due to modifications in the conveyor of the debris removal system, the relationship between the total fruit mass and estimated volume was reestablished for the field datasets. Field testing involved collecting fruit volume data for a total of 15 experimental trials. The first four trials (data collected on 01-May-2012) were used to establish the mass–volume relationship. During the field trials, the conveyor belt speed was approximately 0.62 m/s and the distance between sensor and conveyor surface was 44 cm.

2.3. Volumetric yield calculation algorithm

The volumetric yield estimation algorithm uses discrete point data captured by the LIDAR sensor mounted above the conveyors. As discussed above, the sensor scans the space in the polar coordinate system, and captures the distance-related information. After converting the data to the Cartesian coordinate system, it represents the cross-sectional information along the conveyor width. Information along the conveyor length was attained by acquiring