In-situ Measurement of the Detachment Force of Individual Oranges Harvested by a Canopy Shaker Harvesting Machine

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Measuring the amount of fruit detachment force and its distribution throughout the tree canopy under real harvesting conditions can assist in improving the existing harvesting machines. The goal of this study was to evaluate the detachment force exerted on individual oranges located in different tree canopy positions during harvesting by a tractor-driven, canopy-shaking harvesting machine. Multi-node, ZigBee-based wireless sensors equipped with triple-axis accelerometer sensors were developed for this study. Sensors were placed at various locations in tree canopies in different groves. The maximum vibration and detachment forces for fruit detachment at different canopy positions were measured, and the force distribution pattern within the tree canopy was characterized. The force exerted on the fruit was dependent on the location of the fruit in the canopy. The average maximum detachment force for ‘Hamlin’ was 25.3 kg-f (force) and 23.9 kg-f for ‘Valencia’ oranges. In addition to maximum force, the duration of shaking is an important factor determining efficiency of fruit detachment.

Mechanical harvesting of citrus fruits is rapidly gaining acceptance in Florida, where many growers are using trunk- and canopy-shaking harvesting machines. Two types of canopy shakers are presently used in Florida, both manufactured by OXBO (OXBO International Corp., Byron, NY). One is a trailed-type canopy shaker (TCS; Fig. 1), which is pulled behind a tractor and shakes the canopy to detach the fruit. After falling to the ground, fruit are picked up by a hand crew or by a pick-up machine. The other shaker is a “canopy shake and catch” (CSC) harvester, which shakes the canopy, collects the fruits in a catch frame, and then delivers them to a “goat” truck through a conveyor belt. The core unit of the canopy shaker consists of a series of horizontally stacked whirls, each consisting of a set of 12 tines that are 6 to 7 ft long. The tines are connected to a central drum, and the tines reach into the tree canopy with a reciprocating motion and gently shake the fruit from its branches. The canopy shaker shakes the tree at a constant frequency and displacement amplitude that can be varied depending on the required fruit detachment force.

There are two types of variation in fruit detachment force throughout a tree canopy. One is the natural variation due to the level of maturity and position of fruit in the tree. The other variation is caused by tree variations that result in uneven distribution of the vibration force from the mechanical harvesting machine. Whitney et al. (2000) studied the reduction in fruit detachment force due to abscission chemicals during harvesting by a trunk-shaking harvesting machine. They attached accelerometers to both the shaker and the tree trunk to measure the acceleration in the x–y horizontal planes. The actual force required to detach a fruit, however, could not be measured in that study. Burns et al. (2006) demonstrated that abscission agents, combined with low trunk-shaking frequency, can achieve a high percentage of mature fruit detachment with no significant impact on return yield of the crop.

Studying the distribution of the fruit detachment force throughout the canopy will yield information for enhancing the performance of canopy-shaking mechanical harvesting machines. The goal of this study was to measure the actual force exerted on a citrus fruit for it to be detached by a canopy-shaking mechanical harvester at different locations in the tree canopy.

Materials and Methods

ZigBee sensor network. A ZigBee based wireless sensor network was developed for this study. Each sensor node consisted of a triple-axis (x, y, z) accelerometer sensor, a microprocessor, and a ZigBee module. ZigBee is a new IEEE 802.15.4 communication protocol that uses a small, low-power digital radio for data communication. This protocol allows multiple sensor nodes to communicate in a given environment without interruption through clear channel assessment (CCA) to prevent data collisions. The protocol also supports acknowledgments, error checking,
and data retries to help ensure proper data delivery. The ZigBee protocol is exceptional for applications in agriculture where a low data transmission rate with long battery life is required. The accelerometer used for this study was MMA7260Q (Freescale Semiconductor, Chandler, AZ; Fig 2). This accelerometer can measure acceleration up to 6 g. The microprocessor, an Atmel ATMega 8L, collected analog data from the accelerometer while sending the serial digital data to the ZigBee module for transmission. The microprocessor also managed the status of each node acting under control of a PC-based XBee-PRO module. The ZigBee module used in this study was an XBee-PRO module (MaxStream, Lindon, UT), which is ZigBee/IEEE 802.15.4 compliant. The module is easy to use, requires minimal power, has a very low power standby mode, and provides reliable delivery of data between sensor nodes. The data from each sensor node were collected by a receiver module that was connected to the USB port of a laptop computer. Initial testing involved a single board unit with transceiver, microcontroller, and accelerometers. After initial testing, the system was revised to have the accelerometer as a separate tethered board connected to the controller/RF unit hard-mounted in close proximity (Fig. 2).

**DATA COLLECTION.** Each sensor sends six to seven data points per second to the PC base-station where the data is captured from the USB port by an Excel macro and recorded on a spreadsheet. Data is time-tagged along with the unique ID of the sensor node for identification. To conserve battery life, sensor nodes enter a sleep mode, waking every 15 s to communicate with the base station software. The operator can wake or put to sleep each node remotely. When the nodes are awake and the operator instructs the system to begin transmission, the onboard microcontroller reads the acceleration voltage for each axis and converts the analog voltage to digital using a chip 10-bit, 5-channel analog-to-digital converter. It then sends the data wirelessly to the receiver unit.

**FIELD TEST.** Sensors were attached to fruits using a zip tie (Fig. 3) at different locations in the canopy, as shown in Fig. 4. Field tests were conducted in four different groves, two ‘Hamlin’ and two ‘Valencia’ orange groves. Trees were shaken by a tractor-drawn canopy shaker (TDCS) at a 15° tine angle and at different machine shaking frequencies (185–275 cpm). The tree location, fruit variety, and test parameters of the field tests are given in Table 1. In Test 4, the effect of an abscission chemical on fruit detachment force was also studied.

**DATA ANALYSIS.** The digital data collected from the accelerometer in the x, y, and z axes for each sensor node was converted to g-force (acceleration-force) using the equation:

\[ G = \text{Sensor reading value} \times \left( \frac{1.65}{\text{sensitivity of the accelerometer}} \right) \]

where G is the g-force (9.8 m/s²). The sensitivity value selected for this study was 0.2 Volts/g.

The force F (kg-f) that was exerted on fruit in each axis was calculated by multiplying G with the weight of each tested fruit (kg). For each fruit, the resultant force (net force) was then calculated from the force in the x, y, and z axes. Table 2 summarizes the results for each field test. The second and third columns in Table 2 show the total number of sensors which had fruit detached or not detached. For example, in Test 1, there were a total of five sensor nodes attached to the fruit. After the tree was shaken, four fruit fell off and one remained on the tree. The maximum resul-
Results and Discussion

Traditionally, fruit detachment force has been determined by measuring the amount of axial force required to remove a fruit from the stem (Burns, 2006; Whitney, 2000). The traditional method of measuring the fruit detachment force was compared with the average amount of force for fruit detachment using a mechanical harvesting machine. It was determined that the mechanical harvesting machine required twice the amount of force to remove the fruit compared to the direct axial force method. This could be due to the fact that, during shaking, there are several types of forces experienced by fruit, and fruit detachment occurs due to the combination of several stresses on the fruit. In the case of using abscission chemicals, a similar pattern was observed, although the magnitude of the detachment force was much smaller, which was expected. It was noted that not only does higher maximum force result in detachment of the fruit from the tree, but also that the duration of shaking is an important factor in fruit detachment. For each variety, the amount of detachment force decreased as the season progressed and fruit became more mature. In general, ‘Valencia’ required less detachment force than ‘Hamlin’, probably due to difference in fruit maturity on the different dates of harvest.

Conclusions

Based on the data analyzed in this report, the results from the study show that:

- The amount of fruit detachment force by the canopy shaker is about twice that of applying axial force directly on the fruit.
- The force exerted on the fruit is dependent on the location of the fruit in the canopy.
- In addition to maximum force, the duration in which the force is applied can also affect the fruit detachment.
- The force required for fruit detachment decreases as the fruit ripens.
- The fruit treated with abscission agents required half as much force to be detached as those not treated.

Literature Cited