A Laser-Scanning System for Quantification of Tree-Geometric Characteristics

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Abstract. Tree-geometric characteristics such as tree canopy height, width, and volume are required for an accurate estimation of citrus yield early in the season and variable rate application of fertilizer and pesticides on each tree. A laser-based measurement system consisted of a laser scanner, a GPS, an inertial sensor, a serial-to-USB adapter, and a computer, with corresponding algorithms for measurement of the tree characteristics were developed and mounted on a utility vehicle for tree scanning. The performance of the system was tested on an orange tree in a citrus orchard.

The measurements errors of the tree canopy height, width, and volume were 0.41% with less than 1-cm difference between the laser measurement and manual measurement, 4.82% with approximately 14 cm difference, and 0.09 % with 0.01 m³ difference, respectively.

Keywords. Citrus, laser scanner, tree height, tree width, tree canopy volume.
Introduction

In Florida citrus production, measurement of tree-geometric characteristics such as tree height, width, and canopy volume are very important because the characteristics are being used to estimate citrus yield early in the season. An accurate estimation of citrus yield early in the season is highly desirable by citrus growers and will assist them with making better management and budgetary decisions. In addition, the characteristics can be used to optimize the amount of fertilizer and pesticide applied to individual trees. This can provide economic benefits for growers, also can reduce environmental pollution.

However, the current manual method is time-consuming, tedious, and inaccurate. Therefore, an accurate and fast sensing system for measurement of the tree-geometric characteristics is needed. Different types of sensors, such as ultrasonic sensors, have been used for measurement of the tree characteristics. Among them, a laser scanner noticeably has some advantages: i) fast response time, ii) high scanning resolution, and iii) high level of measurement accuracy. Several researchers showed the potential of laser scanners for measurement of the tree or plant characteristics.

A laser scanner, also called laser radar, is a non-contact optical device that measures the distance to an object in a scanning field using a pulsed laser beam. The scanner's measurement is based on the Time-of-Flight (TOF) principle. A laser source inside the scanner emits a pulsed laser beam. If this beam hits an object, part of the beam is reflected back to the scanner and hits a detector inside the scanner. The time between transmission and reception of the pulsed signal is directly proportional to the distance between the scanner and the object. The laser pulse is diverted sequentially with a specific angular interval using an internal rotating mirror. Thus, a fan-shaped two-dimensional scan is made of the surrounding area.

Ehsani and Lang (2002) built a laser-based system plant volume measurement. It was able to measure plant volume and height accurately, indicating the possibility to measure the biomass and calculate the leaf area index. Tumbo (2002) et al. compared the performance of a laser system with the performance of an ultrasonic system for tree canopy volume measurement. The laser showed better measurement accuracy especially on defoliated trees and small trees. Wei and Salyani (2004, 2005) developed a laser scanning system and corresponding algorithms for measurement of tree canopy volume. Volume measurement error over a rectangular box was 4.4%. Ehlert (2008) et al. developed a triangulation laser-based system for assessment of crop biomass density. The mean height of the laser reflection point in crop stands showed a good correlation with the crop biomass density.

Although previous research showed the potential of laser scanners for measuring canopy height and volume, the idea has never been commercialized. This is partly due to the fact the laser sensor that was used in those studies was not eye safe or it was not commercially available. Also, the system that was developed in the previous studies was not capable of correcting the measurement error due to the pitch and roll movement of the sensor while driving on an unlevel ground. In this study, a commercially available laser sensor was used; in addition, a new algorithm was designed to match the characteristics of the new sensors.

The overall goal of this study was to develop a laser-based measurement system and corresponding algorithms for tree canopy height, width, and volume measurements and test the performance of the system and algorithms.
Materials and Methods

Experimental System

A John Deere gator utility vehicle (model HPX, Deere and Company, Moline, IL) was equipped with experimental devices for test purposes (fig. 1a). A laser scanner (model LMS200, SICK Inc., Germany) was mounted on a stand that was placed in the rear of the vehicle, 1.40 m above the ground. The laser scanner was turned 90° so that it scanned trees vertically. An inertial sensor (model VG440-CA, Crossbow Technology Inc., San Jose, CA) was mounted on the top portion of an antenna tower that was mounted on the rear frame of the vehicle. The inertial sensor measured the roll and pitch angles of the test vehicle to correct the laser measurement based on the measured angles. A GPS (model GPS18-5Hz, Garmin International Inc., Olathe, KS) was mounted on the top portion of the antenna tower to measure the travel speed of the vehicle. The output rate of the GPS was 5 Hz. The laser sensor, inertial sensor, and GPS communicated with a notebook computer running at a CPU speed of 2 GHz via a serial-to-USB adapter (model 2403, Sealevel Systems Inc., Libery, SC) at baud rates of 500, 38.4, and 19.2 kbps, respectively (fig. 1 b). The interface program was written using LabVIEW (ver. 8.2, National Instruments Co., Austin, TX.) to change the settings of the sensors and collect the data.

![Image of experimental setup]

Figure 1. Experimental system: (a) test vehicle equipped experimental devices, (b) schematic of experimental devices.

Laser scanner

A laser scanner is a non-contact optical device that measures the distance to an object in a scanning field using a pulsed laser beam. The scanner's measurement is based on the Time-of-Flight (TOF) principle. A laser source inside the scanner emits a pulsed laser beam. If this beam hits an object, part of the beam is reflected back to the scanner and hits a detector inside the scanner. The time between transmission and reception of the pulsed signal is directly proportional to the distance between the scanner and the object. The laser pulse is diverted
sequentially with a specific angular interval using an internal rotating mirror. Thus, a fan-shaped two-dimensional scan is made of the surrounding area.

The light source of the LMS200 is a pulsed infrared laser 905 nm, not visible to the human eye. It operates in either mm mode or cm mode. The maximum measurement distances are 8 m with an error of ±20 mm in the mm mode and 80 m with an error of ±40 mm in the cm mode. The LMS200 has two scanning range options: i) from 40° to 140° with angular resolutions of 0.25°, 0.5°, and 1°, and ii) from 0° to 180° with angular resolutions of 0.5° and 1°. The times for scanning one cycle are 53.28 ms, 26.64 ms, and 13.32 ms at 0.25°, 0.5°, and 1° angular resolutions, respectively, in both scanning ranges. The scanner requires about 13.32 ms for one cycle rotation of an internal mirror with a 1° step. To achieve 0.25° and 0.5° angular resolutions, the 1° step is shifted to 0.25° and 0.5° at the start of the mirror wheel rotation, respectively, and four and two mirror rotations are required. For this reason, a scan with an angular resolution of 0.5° takes twice as long as a scan with an angular resolution of 1°; and a scan with an angular resolution of 0.25° takes four times as long. The horizontal resolution of the laser-scanned image is determined based on an angular resolution (i.e. time for scanning one cycle) of the laser sensor and a travel speed of the vehicle; the vertical resolution on an angular resolution of the laser sensor and the distance between the object and the laser sensor. For example, when the vehicle travels at 1 m/sec and the laser sensor scans the object with an angular resolution of 0.25° at a 2 m distance, the horizontal and vertical resolutions are 5.33 cm and 0.87 cm, respectively. The laser scanner can communicate with a computer via a serial port at a baud rate of 9.6, 19.2, 38.4, and 500 kbit/s. For the experiments, the LMS200 was operated in the mm mode and scanned target objects in the range of 40° to 140° with an angular resolution of 0.25°.

**Inertial sensor**

The core part of the VG440-CA inertial sensor is a six degrees-of-freedom (DOF) MEMS inertial sensor cluster which includes three axes of MEMS angular rate sensing and three axes of MEMS linear acceleration sensing. A DSP processor in the sensor utilizes the inertial sensor measurements to compute navigation information (attitude, heading, and linear velocity) and roll, pitch, and heading angles. In addition, the DSP processor makes use of an external magnetic sensor or GPS to help correct long term drift and estimate errors from the inertial sensors. The sensor can communicate with a computer via a serial port at the baud rates of 9.6, 19.2, 38.4, and 57.6 kbps. It outputs a roll angle between ±180°, a pitch angle between ±90°, a heading angle between ±180° with external GPS aiding, and 3-axis acceleration between ±4 g. The output data rate is programmable between 2 and 100 Hz. For the experiments, the roll and pitch angles only were collected from the inertial sensor at the highest output rate of 100 Hz.

**Tree Preparation and Manual Measurement**

For the experiments, one Hamlin orange tree planted in 1991 was selected in the Citrus Research and Education Center (CREC) orchard where the space between the tree rows was 6.10 m and the distance between the trees at each row was 4.58 m. Before the tests, the tree crown was trimmed to the shape of a spheroid, being symmetric with respect to a vertical central line on the tree trunk.

The tree height and width were measured directly using a tape measure. For the volume measurement, the circumference (Lw) of the tree canopy at a specific height was measured by bending a long PVC pipe with a small outer diameter of 1.6 cm (fig. 2). The shape made by the
pipe was close to a circle because the tree crown was trimmed to be symmetric and the pipe was a little stiff. The diameter of the circle ($D_a$) was calculated using eq. (1), and then the area ($A_a$) was obtained using eq. (2). The circumference measurement was repeated from the bottom of the crown to the top with at intervals of 20 cm (h). The volume of each slice ($V_a$) was calculated with $A_a$ and h using eq. (3). The total volume of the tree canopy ($V_{la}$) was obtained by summing up the volumes of all the slices using eq. (4). The height, width, and volume measured manually were 2.400 m, 2.970 m, and 11.286 m³.

$$D_a = \frac{L_a}{\pi}$$  \hspace{1cm} (1)

$$A_a = \frac{\pi D^2_a}{4}$$  \hspace{1cm} (2)

$$V_a = A_a \times h$$  \hspace{1cm} (3)

$$V_{la} = \sum_{a=1}^{i} V_a$$  \hspace{1cm} (4)

![Schematic of tree canopy volume measurement by the manual method.](image)

**Algorithms for Calculation of Tree Canopy Height, Width, Volume**

**Volume measurement**

Figure 3(a) shows the schematic view of the laser setup for tree scanning. During scanning the tree, the distance (TD) between the tree trunk and the laser, and the height (SH) of the laser from the ground were maintained at 2.3 m and 1.4 m, respectively. The laser sensor basically measures a distance ($d_{ik}$) to a spot ($p_{ik}$) on the tree at a scanning angle ($\theta_k$). The spot in the polar
coordinator was transformed to a point in the x-y coordinator using eqs. (5) and (6). As shown in fig. 3(b), a new point with the negative x-value and the same y-value of the point was created for volume measurement based on the assumption that the laser covers only one side of the tree and the tree canopy is symmetric with respect to the vertical centerline on the tree trunk. This procedure was applied to all the laser spots measured. The points adjacent to each other in the x-y coordinates were connected. This made a polygon. The area of the polygon was calculated using a function, “polygon”, which is provided by MATLAB (ver 7.1, The MathWorks Inc., Natick, MA). The volume of the slice (Vi) was obtained with the area of the polygon (Ai), the travel speed of the vehicle (S), and the laser scanning time per cycle (Δt, 53 msec) using eq. (7). The total volume of the tree canopy (V) was obtained by summing up the volumes of the every slices (Vi) using eq. (8).

\[
x_k = TD - d_k \cdot \sin(\theta_k)
\]

\[
y_k = SH + d_k \cdot \cos(\theta_k)
\]

\[
V_i = A_i \cdot \Delta t \cdot S
\]

\[
V = \sum_{i=1}^{n} V_i
\]

The volume obtained with the original laser measurement was compared to the volumes by the "convex hull" and "hull fit" methods. The convex hull method selects the data sets which can minimize the outline length of the polygon from the original laser measurement. The area of the polygon made with the data sets selected was calculated and then the volume was obtained using eqs. (7) and (8). For the convex hull procedure, a function of "convhull" supported by MATLAB (ver 7.1, The MathWorks Inc., Natick, MA) was used. The hull fit method returns the data sets which can minimize the polygon area by allowing only line lengths which are smaller than (P*longest line in convex hull) (Wasmeier, 2004). The P value was between 0 and 1. When the P equals 1, the data sets selected by the convex hull and hull fit methods are same. The volume of the slice was calculated with the polygon made with the hull fit data set and then the total volume by the hull fit was obtained using eq. (8).

**Width and height measurement**

As shown in fig. 4, when a vertical laser scan line hit the left-most edge of the tree canopy (i=1), a timer in the control program began to run. The timer stopped when the scan line reached the right-most edge (i=n). The width of the canopy (W) was calculated with the time measured by the timer (Tm - Ti=1) and the travel speed of the vehicle (S) using eq. (9). In each scan, the highest y-value was recorded. The maximum value of the highest y-values was selected as the height of the tree canopy (H) using eq. (10).

\[
W = (T_m - T_{i=1}) \cdot S
\]

\[
H = \max_{i=1}^{n} \left\{ \max_{k=1}^{m} (y_k) \right\}
\]
Figure 3. (a) Schematic of the laser setup, (b) laser scanning points in the x-y coordinates.

Figure 4. Schematic of the laser scanning in motion.
Experimental Method

The targeted tree was scanned vertically by the laser scanner mounted on the test vehicle in motion. To indicate the targeted tree, two wood boards with a width of 0.14 m and a height of 2.65 m were put on the left and right hand sides of the tree, respectively. The distance between the boards was 4.58 m. The ground surface condition on the travel path of the vehicle was relatively level. During tree scanning, the intended vehicle travel speed was 1.0 m/sec, and actual travel speeds were measured by the Garmin GPS at 5 Hz. The test on the same targeted tree was replicated five times.

Results and Discussion

Table 1 compares the tree canopy height, width, and volume measurements by the laser scanning system to those by the manual method. The values shown in Table 1 are the averages in five replications. The roll and pitch angles of the vehicle measured by the inertial sensor were less than 2°. Thus, the effect of the roll and pitch angles on the laser measurement was ignored.

Height Measurement

The height measurement by the laser was very close to the manual measurement. The negative sign means the laser measurement is smaller than the manual measurement, indicating the laser might miss the highest point of the tree canopy.

Width Measurement

The difference between the width measurement by the laser and that by the manual method was about 14 cm. As shown in eq. (9), the accuracy of the width measurement is based on the horizontal resolution of the laser scanning and the accuracy of the travel speed measurement. When the travel speed is constant, the horizontal resolution is determined by the angular resolution of the laser, that is, the laser scanning time per cycle. To improve the accuracy of the width measurement, it might be helpful to set up a smaller scanning time (26 or 13 ms) at a larger angular interval (0.5° or 1°), but this can lower the accuracy of the height measurement. The other factor to determine the accuracy of the width measurement is the accuracy of the travel speed measurement. The scanning frequency of the laser at a 0.25° angular resolution is 19 Hz and the sampling frequency for the travel speed measurement by the GPS is 5 Hz. Thus, the data collected from about four consecutive laser scanning cycles are recoded with only travel speed measurement. It is thought that the travel speed measurement by a GPS with a higher sampling frequency might improve the accuracy of the width measurement.

Volume Measurement

Figure 5 shows a single slice of laser scan of the tree. The red area shows a polygon formed with the original scanning points of the laser. The green line represents the boundary of a polygon made by the "convex hull method". The blue line represents the boundary of the "hull fit method" with the P value of 0.15. In Table 1, the volume measurement with original scanning data was much smaller than the manual measurement with the error of -13.99%. This was expected because the volume measurement by the laser does not include the portion of the foliage gap, but the manual measurement includes it. The convex hull method overestimated the volume with the error of 5.89%. The error of the volume measurement by the hull fit method
varied based on the P value. As the P value increased, the error also increased. The minimum error of 0.09% was found at the P value of 0.15.

As shown in eq. (5), one of the factors to cause the error of the volume measurement by the laser is the distance (TD) between the tree trunk and the laser. During scanning trees in moving in a row in a real citrus orchard, it is difficult to maintain a constant distance because the tree row is not straight and there are no markers or reference lines for the driver. The distance errors of 2, 4, 6, and 8% were made intentionally when the volume was calculated. The effect of the distance errors on the volume measurement was examined.

Figure 6 shows the relationship between the distance errors and the volume measurement errors of the original data, the convex hull method, and the hull fit method. The slopes of the trend lines were 0.89 - 1.04. This indicates that a distance error of 10 cm can cause the volume errors of 8.9% - 10.4%.

<table>
<thead>
<tr>
<th>Tree canopy characteristics</th>
<th>Data set</th>
<th>DF[a] (m, m²)</th>
<th>RE[b] (%)</th>
<th>Std. of RE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (=2.400 m by manual method)</td>
<td>Original data</td>
<td>-0.001</td>
<td>-0.413</td>
<td>0.613</td>
</tr>
<tr>
<td>Width (=2.970 m by manual method)</td>
<td>Original data</td>
<td>0.143</td>
<td>4.822</td>
<td>4.099</td>
</tr>
<tr>
<td>Volume (=11.266 m³ by manual method)</td>
<td>Original data</td>
<td>-1.579</td>
<td>-13.994</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>Data by convex hull method</td>
<td>0.665</td>
<td>5.894</td>
<td>1.062</td>
</tr>
<tr>
<td></td>
<td>Data by hull fit method P=0.15</td>
<td>0.010</td>
<td>0.090</td>
<td>0.975</td>
</tr>
<tr>
<td></td>
<td>P=0.30</td>
<td>0.409</td>
<td>3.623</td>
<td>1.209</td>
</tr>
<tr>
<td></td>
<td>P=0.60</td>
<td>0.585</td>
<td>5.180</td>
<td>1.136</td>
</tr>
</tbody>
</table>

[a] DF = measurement by the laser scanning system – measurement by the manual method, m in height and width measurements, m³ in volume measurement.

[b] RE = DF / measurement by the manual method.
Figure 5. Single slice of laser scanning of the tree.

Figure 6. Relationship between the distance error from the tree trunk to the laser and the error of volume measurement.
Conclusion

A laser-based measurement system and corresponding algorithms for tree canopy height, width, and volume measurements were developed and tested over one orange tree in a citrus grove. The following conclusions can be drawn from the test:

- The error of the height measurement was 0.41% with less than a 1-cm difference between the laser measurement and manual measurement.
- The width measurement showed a 4.82% error with a 14.32 cm difference. It is believed that the error might decrease when a GPS with an update rate higher than 5 Hz is used.
- The error of the volume measurement varied based on the techniques used to make a polygon. The minimum error of 0.09% with a 0.01 m³ difference was found when the hull fit method with the P value of 0.15 was used.
- In the volume measurement, the effect of the distance error between the tree trunk and the laser on the volume measurement was noticeable. When the distance error was 10 cm, the volume measurement error was about 9.5%.

References


