A Laser Scanner Based Measurement System for Quantification of Citrus Tree Geometric Characteristics

K. H. Lee, R. Ehsani

Abstract. *The overall goal of this study was to develop a laser scanner based measurement system and associated algorithms to measure tree geometric characteristics such as tree canopy, height, width, surface area, and volume. A measurement system, which consisted of a laser scanner, an inertial sensor, a GPS, a serial-to-USB converter, a LabVIEW interface program, and a computer, was developed and mounted on a test vehicle. The laser scanner mounted on the test vehicle vertically scanned a target tree, which was trimmed to be symmetric with respect to a vertical line on the tree trunk, using two angular resolutions of 0.25° and 0.5°. The test vehicle moved along the tree-row direction at three average travel speeds of 0.63, 1.00, and 2.21 m/s. The tree geometric characteristics were estimated by three datasets: an original laser data set, a data set processed by the convex hull method, and a data set processed by the Savitzky-Golay filter. Under the experimental condition of a 0.63-m/s travel speed and a 0.25° angular resolution, the relative errors between the laser measurements and the manual measurements for tree canopy height, width, surface area, and volume were -0.37%, 0.01%, -1.99%, and 5.96%, respectively. Estimations of the tree geometric characteristics by the convex hull method were close to the manual measurements in general. Although the estimations by the original laser data set and the Savitzky-Golay filter data set deviated further from the manual measurements, the data sets could describe the profile of the tree in detail with a higher spatial resolution than that obtained by the convex hull method. It is expected that the data sets may provide more useful information in predicting tree growth and productivity. The distance error of 10 cm between the laser travel line and the tree row line caused errors of 4.0% and 9.2% in surface area and volume measurements, respectively. The laser scanner based measurement system developed in this study demonstrated that it can measure the tree geometric characteristics with a relatively good accuracy. However, measurement errors may increase for asymmetrically shaped trees.*

Keywords. *Laser scanner, Tree height, Tree canopy width, Tree canopy surface area, Tree canopy volume, Citrus.*

Tree leaves absorb solar radiation and the energy absorbed drives such biological processes as photosynthesis and transpiration (Giuliani et al., 2000). The quantity and pattern of solar radiation interception by foliage depends on tree canopy geometric characteristics such as tree canopy height, width, surface area, volume, and leaf area index (Maddonni and Otegui, 1996; Wünsche et al., 1997; Castro and Fetcher, 1998; Broadhead et al., 2003). Therefore, tree canopy geometric characteristics are directly related to tree growth and productivity, and hence can be indicators for tree biomass estimation, growth estimation, yield prediction, water consumption estimation, health monitoring, and long-term productivity monitoring (Adlard, 1995; Li et al., 2002; Pereira et al., 2006; Villalobos et al., 2006; Zaman et al., 2006). Canopy characteristics supply valuable information for tree-specific management by way of controlling pesticide and fertilizer inputs based on the tree conditions. The tree-specific management reduces production costs and public concerns about environmental pollution.

Several sensing techniques are capable of estimating tree canopy geometric characteristics. A plant canopy analyzer (LAI-2000, Li-Cor Inc., Lincoln, Nebr.) estimates leaf area index (LAI). The analyzer measures diffuse radiation with a hemispherical (fisheye) lens sensor at five zenith angles. The light level is measured above the tree and below the canopy. The ratio of the two values gives an estimate of the amount of light interception by the foliage. LAI is estimated by inversion and numerical integration of the light interception data (Li-Cor, 2002). Macfarlane et al. (2000) reported the LAI-2000 underestimated LAI by 16% to 30% due to greater foliage clumping. The measurement by the LAI-200 has been applied to predict tree water use, biomass, crown volume, and yield. (Nagler et al., 2004; Mõttus et al., 2006; Villalobos et al., 2006).

Hemispherical canopy photography is a technique to acquire images through a hemispherical lens from beneath the canopy or above the tree looking downward. Canopy variables can be estimated by processing the acquired images based on light attenuation and contrast between the features in the image. Hemispherical photographs provide a wide angle of view, generally of 180° (Jonckheere et al., 2004). This technique has been used widely to measure leaf area

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The authors are **Kyeong-Hwan Lee, ASABE Member,** Postdoctoral Fellow, and **Reza Ehsani, ASABE Member Engineer,** Assistant Professor; Agricultural and Biological Engineering Department, University of Florida, IFAS, Citrus Research and Education Center, Lake Alfred, Florida. **Corresponding author:** Reza Ehsani, Agricultural and Biological Engineering Department, University of Florida, IFAS, Citrus Research and Education Center, 700 Experiment Station Road, Lake Alfred, FL 33850; phone: 863-956-1151 ext. 1228; fax: 863-956-4631; e-mail: ehsani@ufl.edu.

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index and gap fraction (Macfarlane et al., 2000; Frazer et al., 2001; Wagner, 2001; Zhang et al., 2005; Wagner and Hagemeier, 2006). The drawback of this technique is that the quality of the image captured is highly dependent on sunlight distribution inside the canopy as well as photographic exposure. Zhang et al. (2005) reported that hemispherical photographs taken with automatic exposure under different sky brightness conditions showed underestimations of the leaf area index by 16-71% and overestimations of the corresponding gap fraction by 18-72%.

Ultrasonic sensors transmit high frequency sound waves towards an object and sense the reflected echo. Sensors measure the distance to the object by calculating the time difference between the transmission and reception of the waves. The distance measurement by multiple sensors positioned vertically at different heights was used to estimate canopy characteristics (Giles et al., 1988; Tumbo et al., 2002; Zaman and Salyani, 2004; Schumann and Zaman, 2005; Zaman et al., 2006). However, since the divergence angle of an ultrasonic wave is relatively wide, the spatial resolution for tree scanning and the accuracy for the measurements of the canopy characteristics can be limited (Wei and Salyani, 2004).

Similar to ultrasonic sensors, laser scanners measure the distance to an object using a pulsed laser signal. The time between the transmission and reception of the pulsed signal is proportional to the distance between the sensor and the object. The laser pulse is diverted sequentially with a specific angular interval using a rotating mirror. Thus, a fan-shaped, two-dimensional scan is made of the surrounding area. Unlike the sound waves of ultrasonic sensors, a laser beam has a very small divergence angle and a high energy density, and hence can travel a long distance in a straight line while maintaining a narrow beam. Thus, laser scanners are more widely employed for measuring tree geometric characteristics and describing the structural characteristics of trees. Tumbo et al. (2002) compared the performance of ultrasonic and laser sensors for the measurement of tree canopy volume. The laser sensor was more accurate than the ultrasonic sensor because of the higher spatial resolution. Wei and Salyani (2004) developed a laser scanning system and an algorithm for the measurement of tree volume. Volume measurement of a rectangular box gave a relative error of 4.4%. Watt and Donoghue (2005) used ground-based laser scanners to measure tree diameter, height, and density in densely stocked plantation forests. They demonstrated that the laser could be a useful device to measure the tree variables accurately, with potential applications in tree volume, growth, and biomass measurements. Zande et al. (2006) used a commercially available laser scanner for the quantitative description of tree structure. The laser scanner could depict the structural characteristics of a tree with complex geometry. The study showed that laser technology had the potential to describe tree structural characteristics in three dimensions, irrespective of all weather conditions. Ehlert et al. (2008) measured crop biomass using a laser-based scanning system under field conditions. The height of the laser reflection point in crop stands showed a good correlation with crop biomass. Lee and Ehsani (2008) compared two commercially available laser scanners for measurement drifts over time, effect of target material on measurement accuracy, and the ability to map different surface patterns. They reported that the laser scanners needed some settling time for the measurements to be stabilized; the measurement accuracy varied based on the characteristics of target material, and the ability to reconstruct objects with different surface patterns depended on the angular resolution of the laser scanner.

Previous research showed the potential of laser scanners for measuring tree geometric characteristics; however, the measurement accuracy of laser scanners on a real tree in an orchard and the factors directly affecting the measurement accuracy have not been studied thoroughly.

Objectives

The overall goal of this study was to develop a laser scanner based measurement system and associated algorithms to quantify tree geometric characteristics such as tree canopy height, width, surface area, and volume. The specific objectives were: (i) to test the performance of the measurement system and algorithms developed on a tree in an orchard and (ii) to examine the effect of the travel speed and angular resolution of the laser, different data processing methods, and the distance variation between the laser sensor travel line and the tree row line on the measurement accuracy.

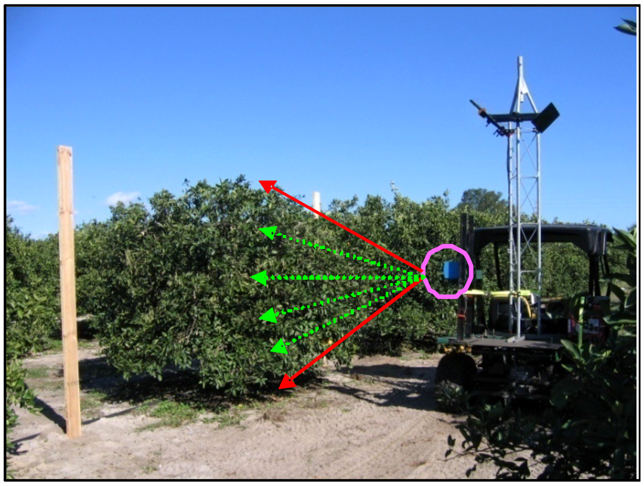
Materials and Methods

Experimental System

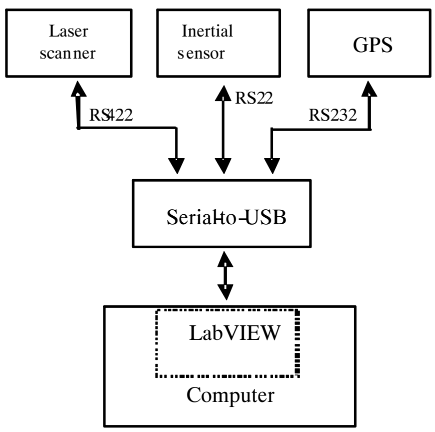
A John Deere Gator utility vehicle was equipped with experimental devices for test purposes (fig. 1a). A laser scanner (LMS200, SICK Inc., Germany) was mounted on a stand that was fixed in the rear of the vehicle at 1.40 m above the ground. The laser scanner was positioned with a vertical setup so that it scanned the tree vertically. The scanner measured the distance to a tree canopy at sequential measurement angle steps. The laser beam, at a measurement angle of 90°, was parallel to the ground. An inertial sensor (VG440-CA, Crossbow Technology Inc., San Jose, Calif.) was placed by the laser on the stand. It measured the roll and pitch angles of the test vehicle (i.e., the roll and pitch angles of the laser sensor) in order to correct the laser measurements based on the angles. A GPS (GPS18-5Hz, Garmin International Inc., Olathe, Kans.) was attached to the top portion of an antenna tower that was mounted on the rear frame of the vehicle to measure the forward travel speed of the vehicle (i.e., the forward travel speed of the laser sensor). The output rate of the GPS was 5 Hz. The laser sensor, inertial sensor, and GPS interfaced with a notebook computer running at a CPU speed of 2 GHz via a serial-to-USB adapter (2403, Sealevel Systems Inc., Libery, S.C.) at the baud rates of 500, 38.4, and 19.2 kbps, respectively (fig. 1b). An interface program was written using LabVIEW (ver. 8.2, National Instruments Co., Austin, Tex.) to set the configurations of the sensors and collect the data from the sensors. The laser measurements at each vertical slice were recorded along with the roll and pitch angles of the vehicle from the inertial sensor, the travel speed of the vehicle from the GPS, and the elapsed travel time.

Laser Scanner

The LMS200 laser scanner is equipped with a pulsed infrared laser of wavelength 905 nm, which is not visible to the human eye. Its maximum measurement distance is 8 m with an error of ±20 mm in the mm mode or 80 m with an



(a)



(b)

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

error of ±40 mm in the cm mode. The LMS200 has two selectable scanning ranges (40° to 140° and 0° to 180°) and three selectable angular resolutions (0.25°, 0.5°, and 1°). The time intervals between two consecutive scans at 0.25°, 0.5°, and 1° angular resolutions are 53.28, 26.64, and 13.32 ms, respectively. The scanner requires about 13.32 ms for one rotation of the 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.

When the laser sensor scans a target tree vertically, the horizontal scanning resolution of the tree is determined by the time interval between consecutive scans (i.e., angular resolution) and the travel speed of the laser sensor; the vertical scanning resolution is determined by an angular resolution, and the distance between the laser sensor and the tree. As shown in table 1, the horizontal resolution becomes larger as the travel speed increases and smaller as the angular resolution increases; the vertical resolution becomes larger at a greater angular resolution without the effect of the travel

Table 1. Horizontal and vertical scanning resolutions of the laser sensor at different forward travel speeds and angular resolutions.[a]

Travel Speed (m/s)	Orientation	Angular Resolution (°)		
		0.25	0.50	1.00
0.5	Horizontal	2.65	1.30	0.65
	Vertical	0.87	1.75	3.49
1.0	Horizontal	5.30	2.60	1.30
	Vertical	0.87	1.75	3.49
2.0	Horizontal	10.60	5.20	2.60
	Vertical	0.87	1.75	3.49

[a] The vertical resolutions are calculated under the assumption that the distance between the laser sensor and a target is 2 m. Scanning resolutions in cm.

speed. 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 kbps. For the experiments, the LMS200 was operated in the mm mode and scanned the target tree in the range of 40° to 140° with angular resolutions of 0.25° and 0.5°.

Inertial Sensor

The acceleration of a rotated object is different based on the orientation of the object within three dimensional (xyz) space. Therefore, the accelerometer measurements can be processed to determine the orientation angles of the object. However, the accelerometer measurements are often affected by the sensor noise or drift. This leads to the inaccuracy in the angle determination (Kao and Chen, 2008). A new approach was introduced in which a xyz-axis accelerometer and a xyz-axis angular rate gyroscope were integrated by a sensor fusion technique to improve the accuracy of the angle estimation.

The VG440-CA inertial sensor used in this study adopts the new integrated approach. The VG440-CA consists of three main components: (i) a MEMS xyz-axis angular rate sensing unit, (ii) a MEMS xyz-axis acceleration sensing unit, and (iii) a digital signal processor (DSP). Each sensing unit measures angular rates and accelerations in xyz directions (fig. 2). By integrating the outputs of the sensing units, the DSP can compute roll and pitch angles, and a heading angle with input from an external GPS. The VG440-CA inertial sensor can communicate with an external device via a serial port at baud rates of up to 57.6 kbps. It outputs a roll angle of ±180°, a pitch angle of ±90°, a heading angle of ±180° with input from an external GPS, three-axis angular rate of ±200°/s, and three-axis acceleration of ±4 g. The output data rate is programmable between 2 and 100 Hz. In the experiments, only the roll and pitch angles were collected from the inertial sensor at the highest output rate of 100 Hz.

Experimental Method

The experiments were designed to compare the tree canopy height, width, surface area, and volume measured by the laser scanning system with the manual measurements under different experimental conditions. For the experiments, one 16-year-old Hamlin sweet orange tree was selected in an orchard of the Citrus Research and Education Center (CREC), University of Florida (Lake Alfred, Fla.). The space between the tree rows was 6.10 m and the distance between the trees in each row was 4.58 m. There was approximately 1.50 m of free space between the canopy of

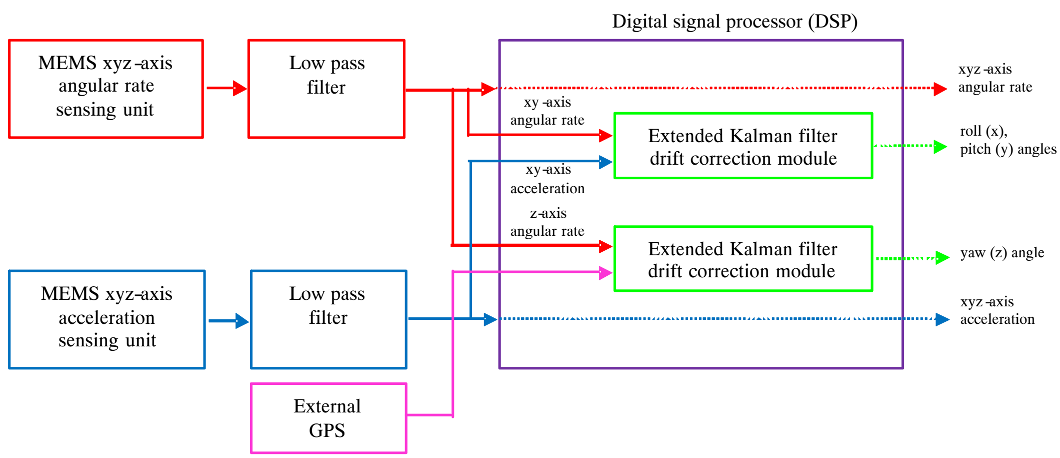


Figure 2. Simplified functional block diagram of the VG440-CA inertial sensor.

the selected tree and adjacent trees. In order to improve the accuracy of the manual measurements, the tree crown was trimmed to the shape of a spheroid, being symmetric with respect to a vertical line on the tree trunk. To indicate the target tree, two wooden boards with a width of 0.14 m and a height of 2.65 m were erected on the left and right hand sides of the tree on the tree row line. The inner distance between the boards was 4.30 m.

The laser sensor mounted on the test vehicle scanned the target tree vertically, moving along the tree-row direction (west-east). A straight line was made with a plastic rope (20 m length) on the ground at a distance of 2.3 m from the tree trunk to guide the vehicle driver in a straight path. The scanning was repeated at the three different forward travel speeds of the vehicle. The intended forward travel speeds were 0.5, 1.0, and 2.0 m/s. The actual forward travel speeds were obtained by measuring the travel time of the known distance between the boards with a timer in the interface program and by directly measuring the speeds using the GPS at 5 Hz. The ground surface for the travel path of the vehicle was relatively level. The tests were conducted in the CREC orchard on a sunny day with an average temperature of about 25°C and wind of less than 1 m/s. Scanning of the target tree was replicated five times at the three travel speeds each at two laser angular resolutions of 0.25° and 0.5°.

Manual Measurements

Albrigo et al. (1975) and Wheaton et al. (1995) developed manual methods for estimating a tree canopy volume. They computed a tree canopy volume using two canopy diameters, which were parallel and perpendicular to the tree row near the ground, and a maximum canopy height. It was predicted that their methods might be inaccurate as a reference method for evaluating laser measurements because the tree canopy volume in their method was calculated using only two canopy diameters and a maximum canopy height based on the assumption that the shape of the tree was ellipsoid. Therefore, a new manual method for measuring tree canopy geometric characteristics accurately was used in this study.

The tree height and width were measured directly using a measurement tape. For the volume measurement, the circumference (L_k, m) of the tree canopy at a specific height was measured by encircling the tree with a calibrated PVC tubing (1.6 cm I.D.) (fig. 3). The shape made by the tubing was close to a circle because the tree crown was trimmed to be symmetric with respect to a vertical line on the tree trunk. The diameter of the circle (D_k, m) was calculated using equation 1, and then the area (A_k, m^2) was obtained using equation 2. The circumference measurement was repeated from the bottom (k = 1) of the crown to the top (k = t) with an interval (h) of 20 cm. The volume of each horizontal slice was calculated by a product of A_k and h. The total volume of the tree canopy (V_m, m^3) was obtained by adding up the volumes of all the slices using equation 3. The total surface area of the tree canopy (S_m, m^2) was obtained by adding up the surface areas of the individual slices that were calculated by a product of L_k and h (eq. 4). The height, width, surface area, and volume measured manually were 2.40 m, 2.97 m, 16.54 m^2, and 11.29 m^3, respectively.

$$D_k = \frac{L_k}{\pi} \tag{1}$$

$$A_k = \frac{\pi D_k^2}{4} \tag{2}$$

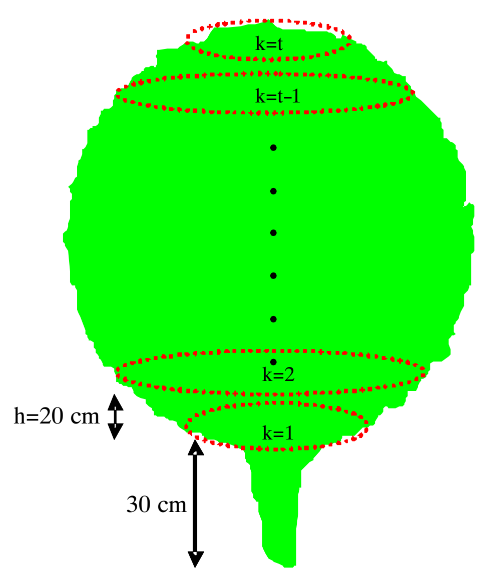


Figure 3. Schematic view for tree canopy surface area and volume measurements by the manual method.

$$V_m = \sum_{k=1}^{t} A_k \times h \quad (3)$$

$$S_m = \sum_{k=1}^{t} L_k \times h \quad (4)$$

Algorithms for Estimation of Tree Geometric Characteristics

Volume and Surface Area Estimations. Figures 4a and b show the schematic view of laser scanning on-the-go and scanning illustration of the scan of a single slice, respectively. In the figures, the x, y, z axis present the tree row line, the horizontal path of the laser beam towards the tree, and the vertical line on the tree row line, respectively. The i and j indices show a scanned slice of the tree on the x axis and the laser scanning spot on the z axis at each slice, which is directly related to the consecutive measurement angle of the laser sensor, respectively. While scanning the tree, the distance (TD) between the laser sensor travel line and the tree row line, and the height (SH) of the laser above the ground were maintained at 2.3 and 1.4 m, respectively. The laser sensor measured a distance (d_{ij}, m) to a spot (P_{ij}) on the tree canopy at a scanning angle (θ_{ij}, degree). The spot in the polar coordinate system was transformed to a point in the Cartesian coordinate system using equations 5 and 6.

$$y_{ij} = TD - d_{ij} \cdot \sin(\theta_{ij}) \quad (5)$$

$$z_{ij} = SH - d_{ij} \cdot \cos(\theta_{ij}) \quad (6)$$

Only the points that satisfied the following conditions were projected on the Cartesian coordinate plane (fig. 4c):

$$0 < y_{ij} < TD \quad (7)$$

$$z_{ij} > \alpha \quad (8)$$

where α is an approximate clearance between the tree skirt and the ground. Because of this value, the ground could be removed from the scanned image. In this study, the clearance was set to 20 cm. As shown in figure 4c, a new virtual point with the negative y-value and the same z-value of an original point was created based on the assumption that the laser covers only one side of the tree and that the tree canopy was symmetric with respect to the vertical line on the tree trunk. This procedure was applied to all the laser spots. The points adjacent to each other in the Cartesian coordinate plane were connected. This made a polygon very close in shape to a circle. The area of the polygon was calculated using a function, "polygon," which is provided by MATLAB (ver 7.1, The MathWorks Inc., Natick, Mass.). The volume of the slice was obtained from the area of the polygon (A_i, m^2), the travel speed of the vehicle (TS, m/s), and the time interval between two consecutive vertical scans (Δt, s). The total volume of the tree canopy (V_L, m^3) was obtained by adding up the volumes of the individual slices using equation 9.

$$V_L = \sum_{i=1}^{m} A_i \cdot TS \cdot \Delta t \quad (9)$$

The perimeter of the polygon (P_i, m) was calculated by adding up the distances between adjacent points in the Cartesian coordinate plane as shown in equation 10. The total surface area (S_L, m^2) of the tree canopy was obtained by adding up the surface areas of the individual slices calculated with P_i, TS, and Δt (eq. 11).

$$P_i = \sum_{j=1}^{2n} \sqrt{\left(y_{ij+1} - y_{ij}\right)^2 + \left(z_{ij+1} - z_{ij}\right)^2} \quad (10)$$

$$S_L = \sum_{i=1}^{m} P_i \cdot TS \cdot \Delta t \quad (11)$$

The volume and surface area estimated with the original laser data were compared with those estimated with the data sets that were processed by the convex hull method and the Savitzky-Golay filter. The convex hull method selects the points in the Cartesian coordinate plane that would minimize the perimeter of the polygon. The Savitzky-Golay filter is a smoothing technique that uses the polynomial regression fitting in a moving window to improve the smoothing outcome. The filter has two parameters, a polynomial degree and a window size. The Savitzky-Golay filter and the convex hull method were applied to the data of the individual slices. The area and perimeter of the polygon made with the data sets processed by the convex hull method and the Savitzky-Golay filter were calculated and then, the volume and surface area were obtained using equations 9 and 11. For the convex hull method and the Savitzky-Golay filter procedures, the MATLAB functions of "convhull" and "sgolayfilt" were used, respectively.

Width and Height Estimations. As shown in fig. 4a, when a vertical laser scan line hit the left-most edge of the tree canopy (i = 1), a timer in the interface program began to run. The timer stopped when the scan line reached the right-most edge (i = m). The width of the canopy (W_L, m) was calculated with the travel time measured by the timer ($T_{i=m} - T_{i=1}$) and the travel speed of the vehicle (TS) using equation 12. At each vertical scan line, the highest z value was recorded. The maximum value among the highest z values was selected as the height of the tree (H_L, m) as depicted in equation 13.

$$W_L = (T_{i=m} - T_{i=1}) \cdot TS \quad (12)$$

$$H_L = \underset{i=1}{\overset{m}{Max}}\,\underset{j=1}{\overset{n}{Max}}\left(z_{ij}\right) \quad (13)$$

The whole procedure for offline estimations of the height, width, surface area, and volume was developed using MATLAB.

Results and Discussion

Measurements at a Single Laser Angular Resolution and a Constant Travel Speed

Tree canopy height, width, surface area, and volume were estimated by the laser method with travel speeds measured by either the GPS at 5 Hz or by the travel time between two poles at the left and right sides of the tree (the "two-pole method") (table 2). The angular resolution of the laser scanner was set to 0.25°. The average forward travel speed of the test vehicle (i.e. the forward travel speed of the laser scanner) was 0.63 m/s. The tree canopy surface area and volume were determined by three different data sets: an original data set of the laser measurements, a data set processed by the convex hull method, and a data set processed by the Savitzky-Golay filter. The differences (DF) and the relative errors (RE) between the laser estimations and the manual measurements are the averages of five replications. The roll and pitch angles of the vehicle measured by the inertial sensor during the scanning of the tree were less than 2°. The effect of the roll and pitch angles on the laser data was ignored when the tree geometric characteristics were estimated. The relative errors between the two speed measurement methods were similar, but the errors were quite different based on the tree geometric characteristics and the data processing methods. The standard deviations of the relative errors of the five replications were less than 4% except for those of the surface area measurements by the original data set.

Height and Width Measurements

The height estimations at both the travel speed measurement methods were the same as expected because height measurement was not affected by travel speed information as shown in equation 13. The difference between the laser estimation and the manual measurement (DF) was -0.01 m. This negative value meant that the laser estimation was smaller than the manual measurement, indicating the laser might have missed the highest point of the tree. The mean relative error (RE) of five replications was -0.37% with the standard deviation of 0.38%. The width estimation by the two-pole method was closer to the manual measurement than that by the GPS method. The DF with the two-pole method was less than 0.5 cm and the RE was 0.01%.

Surface Area and Volume Measurements

In the tree canopy surface area and volume estimations, the relative errors with the two-pole method were similar to those with the GPS method in general. The surface area and volume estimations by the original laser scanner data set were quite different with the manual measurements. As shown in fig. 5, the original laser scanner data points fluctuated due to tree foliage gaps. For surface area estimation, the total distance between adjacent data points in

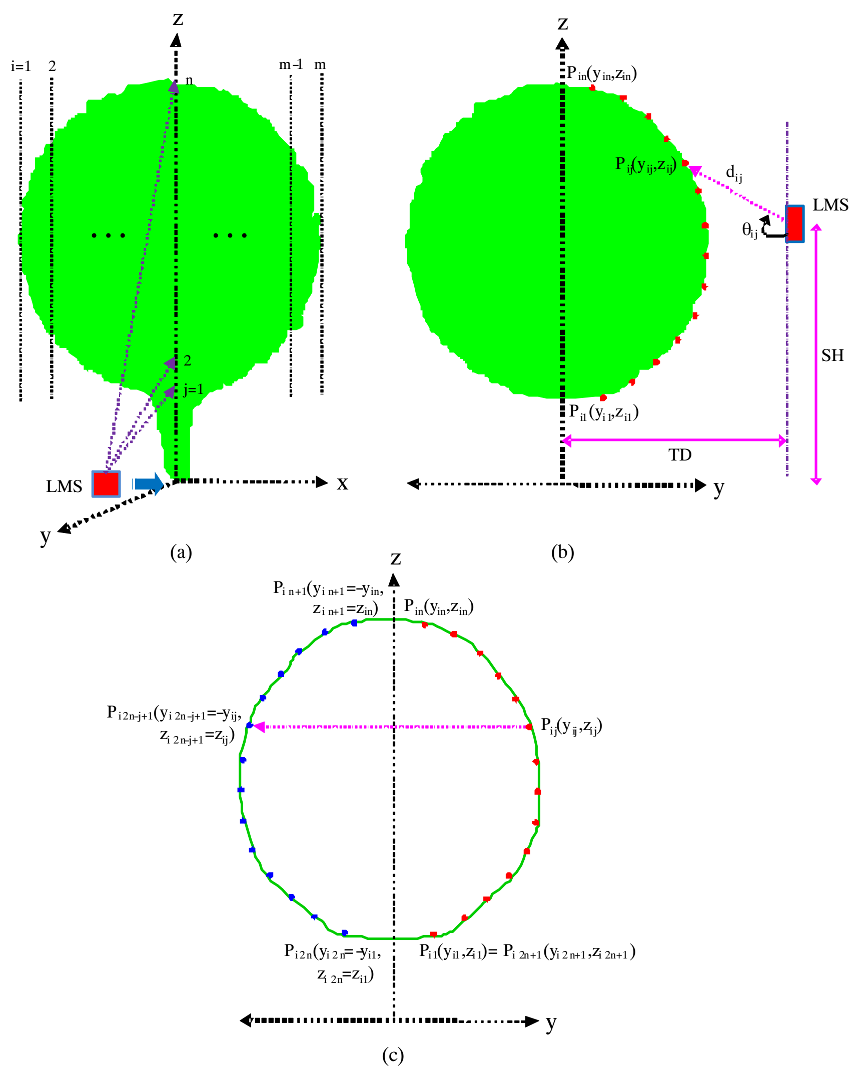


Figure 4. (a) Laser scanning on-the-go, (b) illustration of the scan of the i^{th} slice in the y-z plane, and (c) laser scanning points in the y-z plane for the i^{th} slice.

Table 2. Measurements of tree canopy height, width, surface area, and volume at the two travel speed measurement methods.

Tree Geometric Characteristics[b]		Travel Speed Measurement[a] By Two-pole Method DF[c] (m, m^2, m^3)	RE[d] (%)	SD of RE[e] (%)	By GPS at 5 Hz DF[c] (m, m^2, m^3)	RE[d] (%)	SD of RE[e] (%)
Height		-0.01	-0.37	0.38	-0.01	-0.37	0.38
Width		0[f]	0.01	1.87	0.16	5.37	3.51
Surface area	Original data	115.72	699.62	33.99	118.29	715.20	13.72
	Convex hull data	-0.33	-1.99	2.45	0.10	0.61	2.69
	Savitzky-Golay filter data[g]	0.13	0.78	2.41	0.50	3.02	2.86
Volume	Original data	-1.47	-13.04	3.18	-1.35	-11.93	2.28
	Convex hull data	0.67	5.96	3.70	0.86	7.61	2.73
	Savitzky-Golay filter data[f]	-1.66	-14.70	3.16	-1.53	-13.59	2.24

[a] The average travel speed was 0.63 m/s. The angular resolution of the laser was 0.25°. The tree canopy surface area and volume were estimated by three data sets: an original laser data set, a data set processed by the convex hull method, and a data set processed by the Savitzky-Golay filter. The DF and RE values are the averages of five replications.
[b] Manual measurements: 2.40 m for height, 2.97 m for width, 16.54 m^2 for surface area, and 11.29 m^3 for volume.
[c] DF = laser measurement - manual measurement; the unit is m for height and width, m^2 for surface area, and m^3 for volume.
[d] RE = (DF/manual measurement) × 100.
[e] Standard deviation of RE.
[f] Absolute value is less than 0.005 m.
[g] The window size of the filter was 31 and the polynomial degree was 1.

a slice should be calculated as the perimeter of the slice (eq. 10). Therefore, the surface area estimation by the original data set must be greater than the manual measurement because the manual measurement was carried out under the assumption that the tree canopy surface was solid without any gaps. In addition, the virtual tree canopy solid surface for the manual measurement was assumed to be located on the top portion of the fluctuating data points. This caused the volume estimation by the laser scanner to be smaller than the manual measurement.

The surface area and volume estimations by the data set processed by the convex hull method were relatively close to the manual measurements. The convex hull data points were located on the boundary of the tree canopy on which the data points for the manual measurement were also located (fig. 5).

The Savitzky-Golay filter has two independent variables: a window size and a polynomial degree. With the trial and error method, the window size was determined to be 31 and fixed during the surface area and volume estimations. Only the polynomial degree was changed. As the polynomial degree increased, the values of the data points processed approached the values of the laser scanner data points (fig. 5); the data points were close to the average values of the window when the polynomial degree decreased. The polynomial degree of the filter used for the surface area and volume estimations in table 2 was one. The surface area estimations (RE = 0.78% and 3.02% for the two-pole method and the GPS method, respectively) from the data set processed by the filter were close to the manual measurements, but the volume

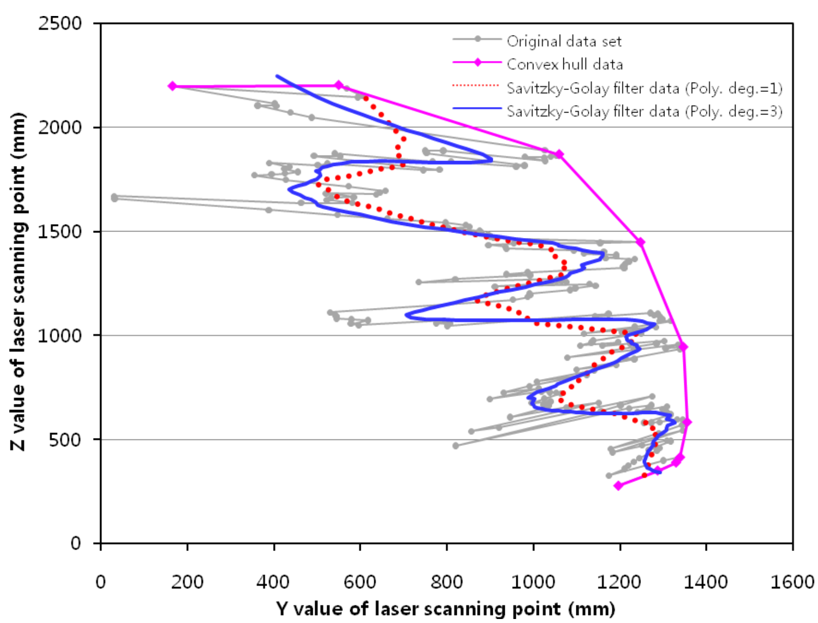


Figure 5. Three data sets at a single slice used for the estimations of tree geometric characteristics: an original laser data set, a data set processed by the convex hull method, and a data set processed by the Savitzky-Golay filter. The window size of the filter was 31.

estimations (RE =-14.70% and -13.59%) were smaller than the manual measurements. This can be verified in figure 5.

Effect of Travel Speed Variation

Using the two-pole method, a single travel speed was calculated by measuring the travel time between the two poles under the assumption that there was no speed variation during the scanning of the tree. The travel speed information was applied for the tree canopy width, surface area, and volume estimations (eqs. 12, 11, and 9, respectively). Therefore, it could be assumed that the laser scanned the tree at a constant horizontal interval and hence the widths of the tree slices scanned must be same. In fact, the actual travel speed measured by the GPS was not constant during the scanning as shown in figure 6. The change in the travel speed caused the variation in the width of the tree slice scanned. The variation of the travel speed might increase the errors in the tree canopy width, surface area, and volume estimations. The degree of the error was different based on the pattern of the travel speed variation. The variation of the travel speed might cause the standard deviation of the RE to increase.

The GPS used in this study could track the travel speed of the test vehicle at 5 Hz. The sampling frequency of the GPS was lower than the laser scanning frequency of about 19 Hz at the angular resolution of 0.25°. Therefore, the data sets obtained at three or four scanning cycles were recorded with the same travel speed information. This low sampling frequency of the GPS for travel speed measurement might increase the errors of the tree canopy width, surface area, and volume estimations.

As shown in equations 12, 11, and 9, the travel speed information is an essential parameter for tree canopy width, surface area, and volume estimations. The accuracy of the travel speed measurement can directly affect the accuracy of the tree canopy characteristics measurements. Therefore, it is believed that measuring the travel speed accurately by a GPS with a higher sampling frequency or by an encoder with a fast response time and making the laser sensor travel at a constant speed may improve the accuracy of the measurements of the tree canopy characteristics.

Effect of Different Data Processing Methods

The data sets processed by the convex hull method and the Savitzky-Golay filter were used for the tree canopy surface area and volume measurements. The estimations by the convex hull method were close to the manual measurements in general. The advantage of the convex hull process was that it used a small number of data points to estimate the tree geometric characteristics. In figure 5, only 10 data points chosen by the convex hull method from the 210 original data points were used for the surface area and volume estimations. The small amount of data necessary for the convex hull method will shorten the data processing time. Therefore, the convex hull data processing method will be useful for real-time applications. Although the surface area and volume estimations by the original laser scanning data set, and the Savitzky-Golay filter data set deviated further from the manual measurements, the data sets could describe the profile of the tree in detail with a higher spatial resolution. The data sets may provide more useful information in predicting tree growth and productivity.

Measurements at Different Laser Angular Resolutions and Travel Speeds

Tables 3, 4, and 5 show the tree canopy height, width, surface area, and volume estimations by the laser scanning system at the average travel speeds of 0.63, 1.00, and 2.21 m/s, respectively. The laser angular resolution was set to 0.25° and 0.5° at each travel speed. For the width, surface area, and volume measurements, the travel speed information was measured using the two-pole method. The surface area and volume were determined by the data set processed by the convex hull method. The DF and RE values in tables 3, 4, and 5 are the averages of five replications.

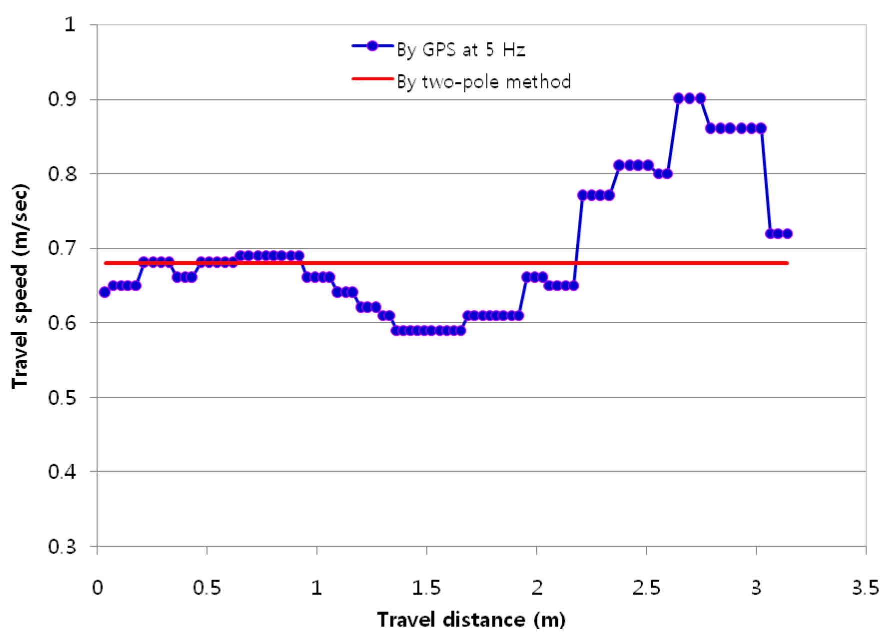


Figure 6. Travel speed variation measured by the GPS at 5 Hz and by the two-pole method during the scanning of the tree. The average travel speed of the two methods was about 0.68 m/s.

Table 3. Measurements of tree canopy height, width, surface area, and volume at the average travel speed of 0.63 m/s.[a]

Tree Geometric Characteristics[b]	Angular Resolution (°)					
	0.25			0.5		
	DF[c] (m, m^2, m^3)	RE[d] (%)	SD of RE[e] (%)	DF[c] (m, m^2, m^3)	RE[d] (%)	SD of RE[e] (%)
Height	-0.01	-0.37	0.38	-0[f]	-0.13	0.05
Width	0[f]	0.01	1.87	0.03	0.85	5.03
Surface area	-0.33	-1.99	2.45	-0.51	-3.09	3.12
Volume	0.67	5.96	3.70	0.62	5.49	2.36

[a] The forward travel speed of the vehicle was measured by the "two-pole method." The tree canopy surface area and volume were estimated by a data set processed by the convex hull method. The DF and RE values are the averages of five replications.
[b] Manual measurements: 2.40 m for height, 2.97 m for width, 16.54 m^2 for surface area, and 11.29 m^3 for volume.
[c] DF = laser measurement - manual measurement; the unit is m for height and width, m^2 for surface area, and m^3 for volume.
[d] RE = (DF/manual measurement) × 100.
[e] Standard deviation of RE.
[f] Absolute value is less than 0.005 m.

Table 4. Measurements of tree canopy height, width, surface area, and volume at the average travel speed of 1.0 m/s.[a]

Tree Geometric Characteristics[b]	Angular Resolution (°)					
	0.25			0.5		
	DF[c] (m, m^2, m^3)	RE[d] (%)	SD of RE[e] (%)	DF[c] (m, m^2, m^3)	RE[d] (%)	SD of RE[e] (%)
Height	-0[f]	-0.15	0.59	-0[f]	-0.06	0.37
Width	0.07	2.43	2.94	0.05	1.71	2.96
Surface area	0.10	0.61	3.80	-0.16	-0.95	1.77
Volume	0.88	7.80	4.28	0.59	5.23	0.92

[a] The forward travel speed of the vehicle was measured by the "two-pole method." The tree canopy surface area and volume were estimated by a data set processed by the convex hull method. The DF and RE values are the averages of five replications.
[b] Manual measurements: 2.40 m for height, 2.97 m for width, 16.54 m^2 for surface area, and 11.29 $m^3$for volume.
[c] DF = laser measurement - manual measurement; the unit is m for height and width, m^2 for surface area, and m^3 for volume.
[d] RE = (DF/manual measurement) × 100.
[e] Standard deviation of RE.
[f] Absolute value is less than 0.005 m.

Table 5. Measurements of tree canopy height, width, surface area, and volume at the average travel speed of 2.21 m/s.[a]

Tree Geometric Characteristics[b]	Angular Resolution (°)					
	0.25			0.5		
	DF[c] (m, m^2, m^3)	RE[d] (%)	SD of RE[e] (%)	DF[c] (m, m^2, m^3)	RE[d] (%)	SD of RE[e] (%)
Height	0[f]	0.15	0.49	0.03	1.19	0.28
Width	0.17	5.68	6.83	0.16	5.46	5.96
Surface area	2.72	16.47	9.71	0.17	1.00	4.20
Volume	2.92	25.87	8.83	0.84	7.40	3.65

[a] The forward travel speed of the vehicle was measured by the "two-pole method." The tree canopy surface area and volume were estimated by a data set processed by the convex hull method. The DF and RE values are the averages of five replications.
[b] Manual measurements: 2.40 m for height, 2.97 m for width, 16.54 m^2 for surface area, and 11.29 m^3 for volume.
[c] DF = laser measurement - manual measurement; the unit is m for height and width, m^2 for surface area, and m^3 for volume.
[d] RE = (DF/manual measurement) × 100.
[e] Standard deviation of RE.
[f] Absolute value is less than 0.005 m.

At the angular resolution of 0.5°, the change in the relative errors of all the tree geometric characteristics was generally minor as the travel speed increased. The change of the relative errors at the angular resolution of 0.25° was not significant at travel speeds of up to 1 m/s, but it was noticeable at 2.21 m/s. The relative errors of the surface area and volume measurements were pronounced at the travel speed of 2.21 m/s.

As shown in table 1, the horizontal resolution of the laser scan is determined by the laser angular resolution and the travel speed of the laser, and the vertical resolution is determined by the angular resolution and the distance between the laser sensor and the tree. When the distance is relatively small (i.e., about 2 m), the change of the vertical resolution at the different angular resolutions is minor, compared to the change of the horizontal resolution at the different angular resolutions and the different travel speeds. Since the relative errors of the surface area and volume measurements at the combination of a 0.25° angular resolution and a 2.21 m/s travel speed were largest and quite different from those at other combinations, the experimental setup with a 0.25° angular resolution and a 2.21 m/s travel speed could be considered as the worst combination. The horizontal resolution at the worst combination was about 10 cm and the horizontal resolution at other combinations was less than about 5 cm. Therefore, it is believed that the effect of a tree horizontal profile change of up to 5 cm on the accuracy of tree surface area and volume measurement is minor, while a horizontal profile change of 10 cm significantly affects the measurement accuracy.

Analysis of variance (ANOVA) was used to evaluate the effect of laser forward travel speed and angular resolution variations on the measurement of the tree height, width, surface area, and volume. ANOVA was carried out using a statistics toolbox of MATLAB. The results were not significant at a level of 0.05 except for the effect of travel speed variation on the width measurement (p value of 0.0287). It can be concluded that in general, the effect of laser travel speed variation up to 2.21 m/s and two different laser angular resolutions (0.25° and 0.5°) were not significant on the measurements of the tree geometric characteristics using the laser scanning system except for the width measurement under the condition of various laser travel speeds.

Effect of the Distance Error between the Laser Sensor Travel Line and the Tree Row Line

For the estimations of tree geometric characteristics from the laser scanning data, the first step was to transform the scanning data which existed in the polar coordinate to the data in the Cartesian coordinate using equations 5 and 6. These equations include two essential parameters: the distance (TD) between the laser sensor travel line and the tree row line, and the height (SH) of the laser above the ground. While laser sensors scan trees on-the-go in a real orchard, SH can be set at a constant level, but TD can vary because there are no markers or reference lines for the driver of the vehicle. In order to examine the effect of the variation of TD on the accuracy of the surface area and volume measurements, the distance errors of 2%, 4%, 6%, 8%, and 10%, which correspond to 5.7, 11.1, 17.1, 22.9, and 28.6 cm, respectively, were made intentionally when the surface area and volume were calculated. Figure 7 shows the relationship between the distance errors, and the errors of the surface area and volume measurements that were obtained with the data processed by the convex hull method and the travel speed information obtained by the two-pole method. The slopes of the trend lines for the surface area and volume were 0.40 and 0.92, respectively. This indicates that a distance error of 10 cm can cause errors of 4.0% and 9.2% in surface area and volume measurements, respectively. The errors of the surface area and volume estimations by the algorithms developed in this study were very sensitive to the distance between the laser sensor travel line and the tree row line.

Future Studies

The laser sensor scanned one side of the tree and the tree geometric characteristics were estimated from the laser data based on the assumption that the tree was symmetric. Therefore, the measurement error may increase under field conditions where the trees are asymmetric. To reduce the error caused by asymmetrical tree shapes, a new setup with multiple laser scanners needs to be considered. The test vehicle on which the laser was mounted traveled on relatively even terrain. The roll and pitch angles of the vehicle were small so that the effect of the angles on the laser data was negligible. However, there may be a situation in an orchard in which the vehicle undulates due to uneven terrain. For this condition, the algorithms must be modified to correct the laser data based on the roll and pitch angles. The effect of the distance error between the laser sensor travel line and the tree row line on the measurement accuracy was significant. To reduce the measurement error caused by the variation of the distance under field conditions, it may be helpful to equip the test vehicle with an auto-steering and lightbar guidance system that can keep the distance uniform.

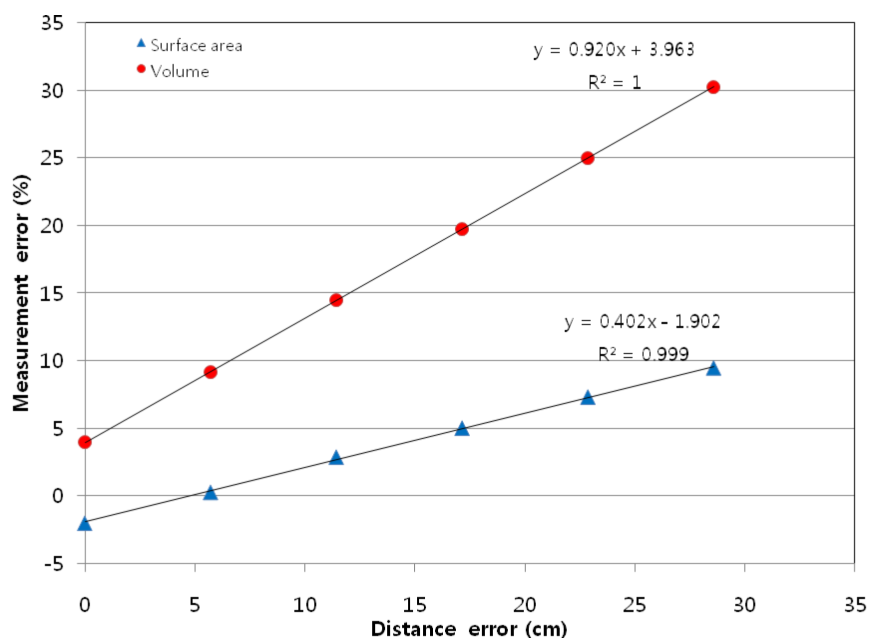


Figure 7. The relationship between distance error (distance between laser sensor travel line and row line) with respect to measurement error of the tree surface area and volume.

CONCLUSIONS

The following conclusions can be drawn from the experiments:

- Under the experimental condition of a 0.63 m/s travel speed and a 0.25° angular resolution, the relative errors using the two-pole method were -0.37% and 0.01% for height and width measurements, respectively; and -1.99% and 5.96% for surface area and volume measurements, respectively, using the convex hull method.
- The estimations of the tree geometric characteristics with the data set processed by the convex hull method were close to the manual measurements in general. Although the estimations by the original laser data set and the Savitzky-Golay filter data set deviated further from the manual measurements, the data sets could describe the profile of the tree in detail with a higher spatial resolution.
- The relative errors of the measurements of the tree geometric characteristics at the combination of a 0.25° angular resolution and a 2.21 m/s travel speed were largest and quite different from those at other combinations. The horizontal resolution at the above combination was about 10 cm and that at other combinations were about 5 cm. Therefore, it is believed that the effect of a tree horizontal profile change of up to 5 cm on the measurement accuracy is minor, while a horizontal profile change of 10 cm significantly affects the measurement accuracy.
- The distance error of 10 cm between the laser travel line and the tree row line caused errors of 4.0% and 9.2% in surface area and volume measurements, respectively. To reduce the distance error, the test vehicle needs to be equipped with an auto-steering and lightbar guidance system that can help keep the distance between the laser and trees constant.
- Test results indicated the laser scanner based measurement system developed in this study measured the tree geometric characteristics with a relatively good accuracy. However, it needs to be noted that the test results were obtained on a tree that was symmetric with respect to a vertical line on the tree trunk; therefore, the measurement errors may increase under field conditions where the trees may be asymmetrical.

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NOMENCLATURE

k = horizontal slice index of the tree in the manual measurement. k = 1 and k = t mean the horizontal slices at the bottom and top of the tree crown, respectively.

h = distance between the horizontal slices in the manual measurement.

L_k = circumference of the k^{th} horizontal slice.

D_k = diameter of the k^{th} horizontal slice.

A_k = area of the k^{th} horizontal slice.

V_m = total volume of the tree canopy by the manual measurement.

S_m = total surface area of the tree canopy by the manual measurement.

i = vertical slice index of the tree in the laser measurement. i = 1 and i = m mean the vertical slices at the left- and right–most edges of the tree canopy, respectively.

j = laser scanning spot index at each vertical slice in the laser measurement. j = 1and j = n mean the spots at the lowest and highest positions, respectively.

p_{ij} = spot position at the i^{th} vertical slice and the j^{th} spot.

y_{ij} = y value of P_{ij} in the Cartesian coordinate system.

z_{ij} = z value of P_{ij} in the Cartesian coordinate system.

d_{ij} = diagonal distance between the laser sensor and a spot at the i^{th} vertical slice and the j^{th} spot.

θ_{ij} = scanning angle of the laser sensor to a spot at the i^{th} vertical slice and the j^{th} spot.

TD = distance between the laser sensor travel line and the tree row line.

SH = height of the laser sensor above the ground.

α = approximate clearance between the tree skirt and the ground.

A_i = area of the i^{th} vertical slice.

TS = forward travel speed of the test vehicle, i.e. the forward travel speed of the laser sensor.

Δt = time interval between two consecutive vertical scans.

T_i = elapsed time at the i^{th} vertical slice.

P_i = perimeter of the i^{th} vertical slice.

V_L = total volume of the tree canopy by the laser measurement.

S_L = total surface area of the tree canopy by the laser measurement.

W_L = width of the tree canopy by the laser measurement.

H_L = height of the tree canopy by the laser measurement.