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# Sensitivity of tree volume measurement to trajectory errors from a terrestrial LIDAR scanner

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ABSTRACT

The use of terrestrial LIDARs in agriculture enables the measurement of structural parameters of the orchards such as the volume of the trees. The sequence of two-dimensional scans performed with a LIDAR attached to a tractor can be interpreted as the three-dimensional silhouette of the trees of the grove and used to estimate their volume. In this work, the sensitivity of the tree volume estimates relative to different error sources in the estimated spatial trajectory of the LIDAR is analyzed. Tests with pear trees have demonstrated that the estimation of the volume is very sensitive to errors in the determination of the distance from the LIDAR to the center of the trees (with errors up to 30% for an error of 50 mm) and in the determination of the angle of orientation of the LIDAR (with errors up to 30% for misalignments of 2°). Therefore, any experimental procedure for tree volume estimate based on a motorized terrestrial LIDAR scanner must include additional devices or procedures to control or estimate and correct these error sources.



## 1. Introduction

The measurement of vegetation structure on a farm can be used to optimize the application of pesticides and fertilizers in a grove treatment (Hislop, 1987). For example, the instantaneous dose of pesticides applied with sprayers to a fruit tree can be reduced or increased depending on the volume or foliage covered by the cone of the different sprayers used. The benefits of this optimization are direct for growers because the use of agrochemicals is reduced (relative to a uniform application dose), but also for the environment because of the reduction in the pollution originated by the residuals (Hiroaki et al., 2002). The measurement of tree canopy structural characteristics, such as volume, foliage and leaf area index, can be carried out by several detection approaches, such as image analysis techniques, stereoscopy photography, analysis of the light spectrum, ultrasonic sensors, and light detection and ranging (LIDAR) laser sensors.

Image-based canopy measurement (Leblanc et al., 2005; Ryu et al., 2010a) requires elaborate algorithms and fast computational resources to operate in real-time (Chen et al., 2002). Ultrasonic sensors have been used to measure canopy volume for pesticide applications (Tumbo et al., 2002; Zaman and Salyani, 2004) although the divergence angle of the ultrasonic waves limits the spatial resolution and accuracy of these measurements.

LIDAR is a remote laser range sensor based on the measurement of the elapsed time between the transmission of a pulsed laser beam and the reception of its echo from a reflecting object; this time-of-flight (TOF) is used to estimate the distance between the laser and the object. The advantage of the laser light relative to the ultrasonic waves is that the measurement beam is thinner and less divergent and can be combined with a scan mechanism to obtain a bi-dimensional scan pattern (Wehr and Lohr, 1999) to report information about a large area. Both airborne and terrestrial LIDAR are now used in characterizing canopy structure for different applications (e.g. forestry, agriculture). Airborne LIDAR scanners produce information with lower resolution than terrestrial scanners because the different point of view and the different laser pulse sampling and geometry used.

Airborne LIDAR scanners combined with precise global positioning system (GPS) and additional inertial measurement units (IMU) are widely used in forestry and agriculture to estimate and characterize general environmental target parameters such as the canopy height (Ritchie et al., 1993; Tanaka et al., 2004), tree surface (Holmgrena and Persson, 2004), tree height and volume (Nilsson, 1996), and to estimate the effective leaf area index (LAI) (Richardson et al., 2009). The airborne LIDAR information can be combined with high-resolution airborne images to increase the accuracy of the extraction of structural parameters of the forest (Huang et al., 2009).

Terrestrial LIDAR scanners are usually used standalone in agriculture. Walklate et al. (2002) used a LIDAR to study the relationship between orchard tree crop structure and the performance char-

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acteristics of an axial fan sprayer, with good correlation between spray deposit and foliage density. Tumbo et al. (2002) compared the performance of ground ultrasonic and laser sensors for measuring citrus canopy volume obtaining good correlations with manual data. Wei and Salyani (2005) used a terrestrial LIDAR to measure tree height, width and volume, giving a coefficient of variation of 5.4% and a relative error of 4.4% in the estimation of the volume of the trees. Hosoi and Omasa (2006, 2007, 2009) used a terrestrial LIDAR at different known static positions and with different laser beam inclinations to create a three-dimensional (3D) voxel-model of the canopy to evaluate the probability of beam penetration of sunlight through the vegetation. The voxel-model can be used to estimate the leaf area density (LAD) and accumulative LAI accurately (Zheng and Moskal, 2009) when multiple vertical and horizontal scans can be obtained with different LIDARs positioned at fixed points of view. However, this method cannot be extended to the case of a row of adjacent trees where the LIDAR is moved constantly because only translated vertical scans of one-side of the trees are available.

The relationship between the volume of the trees and the leaf area was analyzed in Palacín et al. (2007) where the volume of some trees, estimated with a terrestrial LIDAR, was used to estimate the total foliage surface with an average relative error less than 6% when compared with manual foliage measurements. In Ehlert et al. (2008), the relationship between LIDAR measurements and crop biomass density was compared under field conditions with very good correlations. In Van der Zande et al. (2009), a Holm oak was scanned with a terrestrial LIDAR to obtain a 3D model to estimate the interception of the radiation depending on the distribution of the plant biomass. Rosell et al. (2009a) used the volume estimate obtained with a terrestrial LIDAR to calculate the LAI for apple and pear orchards and vineyards. Ryu et al. (2010b) uses the estimate of the effective LAI to reveal information on clumping effects. In Rosell et al. (2009b), the volume estimate obtained with a LIDAR was correlated with manual measurements of the volume obtaining good correlations ($R^2 = 0.97$). Good correlations ($R^2 > 0.8$) were also obtained with manual measurements of the foliage surface for pear, apple, and citrus orchards and vineyards. In such analyses, the good correlation between the volume and leaf area implies that the leaf area density is approximately constant. This effect can be originated by the growers because they tend to prune the orchards to obtain good light penetration into the crop.

One advantage of the tree volume estimate is that it can be easily georeferenced to perform temporal analysis using the trees as implicit landmarks or using an additional GPS. For example, the wood volume can be estimated during winter and subtracted with volume estimates taken in spring to get an unbiased estimate of the leaf volume.

Two main factors affect the tree volume estimate from the raw data obtained with a moving terrestrial LIDAR: the uncertainty in the set of distances measured and the uncertainty in the 3D positioning of the reference axis of the scan. Few published works reported the measurement error originated by these factors in the estimations performed in standalone agricultural applications. In Van der Zande et al. (2006), the influence of the geometric measurement pattern of the laser in the accuracy of the estimation of the structural parameters of an artificial tree was studied. They demonstrated that even in controlled artificial conditions, where the exact position and orientation were known, the registered data needed manual correction for an accurate 3D interpretation. In Palacín et al. (2007), the volume of some trees was estimated in a controlled environment identifying the following error sources: measurement outliers, grass interpreted as tree biomass, inaccurate mechanical fixing of the LIDAR on the tractor (Fig. 1), and trajectory uncertainties accumulated during the forward movement. However, no sensitivity study was performed for the identified error sources. In Rosell et al. (2009a), the cloud of points of both sides of a tree-row obtained in two different passes were combined to get an accurate volume estimate. However, they reported that the trajectory of the LIDAR needed fine adjustments in the positioning and in the relative angle of orientation of the individual scans to improve the matching of the cloud points corresponding to both sides of a tree-row.

**Fig. 1.** LIDAR placed on the back of a tractor.

The main contribution of this work is a sensitivity analysis of the estimation of the volume of some trees relative to different trajectory errors originated during the displacement of a LIDAR in a typical agricultural application. The volume will be estimated from the 3D interpretation of the raw data obtained with a terrestrial LIDAR attached to an agricultural tractor (Fig. 1). The sensitivity analysis will be focused in the errors caused by the uncertainty in the estimation of the position and orientation of the LIDAR during the scanning of the tree-row. In this first approach, the errors on the spatial trajectory of the LIDAR will be analytically simulated in reference scans of a pear orchard. The reference scans have been obtained under controlled conditions and close supervision assuming no error in the distances measured or in the spatial trajectory of the LIDAR. Then, these reference scans will be analytically modified to simulate the effect of a specific error in the trajectory of the LIDAR and the new volume estimate will be compared with the reference volume to evaluate the sensitivity to this error source. In future work, this analysis will be repeated experimentally using a dedicated and specialized robotized facility to incorporate deterministic and random positioning errors in the trajectory of a terrestrial LIDAR.

## 2. Tree volume estimate

The tree volume estimate is obtained by interpreting the raw data provided by the LIDAR as a 3D description of the crop (Palacín et al., 2007). The LIDAR is attached to a tractor unit (Fig. 1) and traverses the crop following a straight line in parallel to a row of trees. In normal farm operation, the LIDAR is moved forward with a constant speed that is previously adjusted in the closed loop speed control of the tractor. The LIDAR provides vertical slices (Fig. 2) corresponding to different positions along the tree-row that can be processed or stored for offline analysis.

The LIDAR used in this work is a low-cost general-purpose LMS-200 model (SICK, Düsseldorf, Germany), a fully-automatic divergent laser scanner based on the measurement of the TOF with an accuracy of ±15 mm in a single measurement and 5 mm stan-