Extracting tree crown properties from ground-based scanning laser data

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***Abstract*—The spatial organization of above-ground plant material plays an important role in controlling not only plant functional activities like photosynthesis and evapotranspiration, but also the photo-vegetation interactions. To improve our understanding of such interactions, the acquisition of highly detailed information about the 3D architecture of individual plants and communities of plants is required. Recently, Light detection and ranging (LiDAR) sensors, both at the ground and the airborne-level, have emerged as useful tools for mapping 3D plant structure. One such ground-based instrument is the Intelligent Laser Ranging and Imaging System (ILRIS 3D), which was developed at Optech Incorporated. This laser scanner, generates a 3D digital reconstruction of any scene, by actively emitting laser pulses and recording the time elapsed for the return of a pulse, thereby measuring the distance of any given object. It is the objective of this research to utilize the ILRIS 3D to measure structural, and biophysical information of individual trees for use as direct inputs into complex radiative transfer models. The key parameters under investigation are crown dimensions (i.e. shape, area, and volume), crown-level gap fraction (GF) and crown-level leaf area index (LAI). The ILRIS 3D was used to acquire 3D point clouds of an artificial 6' Ficus tree, in a controlled laboratory environment. Measured XYZ point cloud data was segmented to retrieve laser pulse return density profiles, which subsequently were used to estimate gap fraction and LAI . Gap fraction estimates were cross-validated with traditional methods of histogram thresholding of digital photographs (r^2 = 0.96). Crown LAI estimates were compared with the actual values (r^2 = 0.95, RMSE = 0.45). The next challenge was to implement the developed algorithms to real crowns, namely olive (*Olea europaea* L.) orchards in southern Spain. Individual tree-level ILRIS 3D data was collected from 24 structurally diverse crowns. Crown dimensional profiles were extracted for ILRIS data that was collected from a horizontal view (i.e ground-based) and a nadir view (i.e from platform 12 meters above ground). Preliminary retrievals from the olive orchards dataset is described here, while current ongoing field measurements are being conducted to validate the findings. Successful demonstration of extracting crown-level structural parameters like gap fraction and LAI from ground-based LiDAR will be important new information that can be used for detailed radiative transfer modeling in olive orchards and likely lead to more robust inversion algorithms.**

I. INTRODUCTION

Physically based radiative transfer models have been shown to have particular promise to accurately estimate vegetation canopy biophysical variables in open canopies from remote sensing observations, provided that canopy architecture and scene components are accurately considered. These algorithms use complex ray tracing techniques to simulate the three dimensional radiation regime within vegetated ecosystems. The accuracy of such models to predict canopy optical characteristics is highly dependent on prior knowledge of the spatial arrangement of vegetated elements at an individual tree-scale (i.e. leaves, branches) as well as a canopy-scale (i.e. plantation, homogeneous, open-clumped). Direct methods of measuring canopy structure involve destructive sampling, and thus spatially extensive *in-situ* measurements to characterize large-scale heterogeneity are not feasible [1]. As a result, insufficient detail about the vegetation structural architecture lead to errors in the modeling of the radiation and convective exchanges in a forest community. Recently, however, forest canopy structure have been measured using active remote sensing instruments at both the airborne [2] and ground-level [3], [4]. These LiDAR (Light Detection and Ranging) instruments use the Time-Of-Flight (TOF) principle to measure the distances of objects based on the time interval between laser pulse emittance and return, upon reflection from an object. More specifically, tripod-mounted ground-based LiDAR units, commonly used for mining, urban planning and surveying applications can now be deployed in a forest environment to quickly digitize structural information of tree crowns, potentially replacing laborious, time-consuming, and often relatively inaccurate manual field measurements. As a result, the challenge now lies in developing innovative and robust methodologies that utilize such highly specific 3D point cloud data to directly retrieve canopy structural attributes, which in turn will improve radiative transfer modeling of complex vegetated targets. This paper describes new methods of extracting crown-level biophysical parameters namely, gap fraction (GF), leaf area index (LAI) and crown physical dimensions, from ground-based laser scanning data. Experiments were conducted using an artificial tree, that was systematically pruned, for algorithm development. Next, ground-based laser scanner data was collected from olive (*Olea europaea* L.) stands to test the algorithms.

II. METHODOLOGY

A. Laboratory-Level

The Intelligent Laser Ranging and Imaging System (ILRIS 3D), developed by Optech Inc., was used to acquire 3D point clouds of an artificial 6' Ficus tree, in a controlled laboratory environment. ILRIS 3D is a tripod-mounted unit with a 40^o x 40^o field of view, with a scanning rate of 1500 laser pulses per second. The artificial tree was mounted on a rotating platform, allowing multiple perspectives of the tree from a stationary viewpoint. To provide a range of structural conditions, the tree was systematically defoliated to decrease the leaf count from 970 (full foliage) to 0 leaves, in 10 stages. At each defoliation step, the leaf inclination angle of all the pruned leaves were measured and ILRIS 3D data from four perspectives were acquired by rotating the tree platform in increments of 90^o. In addition, a digital photograph of the tree was acquired at each defoliation step.

The laser scans yield point cloud files that show the x-y-z coordinate of each detected point. The XYZ 3D point cloud was analyzed, by segmenting the data in vertical slices along the range direction. Next, the number of points in each vertical slice is tabulated, thereby yielding a point distribution profile as function of distance into the crown. Furthermore, using the Delaunay triangulation algorithm, topological triangles are drawn between detected points until all the points within a pre-defined slice are accounted for. Then the area of all the triangles are calculated and the radius of a circle with equivalent area is determined. Consequently, based on the number of points and the retrieval of slice area, we can calculate the laser pulse density as a function of distance into the crown. The subsequent step is to retrieve crown gap fraction from the measured laser pulse density. Despite the range dependency on the ability to detect gaps [4], the knowledge of sensor intrinsic properties, such as the degradation of angular (X-Y plane) resolution with distance, allows the normalization of this dependency. We can determine the theoretical returned laser pulse density of a solid object of 100% reflectivity at any range, given the knowledge of the scan parameters. This theoretical or maximum possible return density is then compared with the observed pulse density of the tree crown to determine laser pulse penetration through the crown or crown gap fraction (Equation 1& 2).

$$\frac{\text{cumulative laser pulse density}}{\text{theoretical pulse density}} = \%\ \text{cover} \tag{1}$$

$$1 - \%\ \text{cover} = \text{Gap Fraction} \tag{2}$$

ILRIS measured gap fraction estimates were compared with retrievals using traditional thresholding techniques of digital photographs. Next, Leaf Area Index retrievals from the laser 3D point clouds were extracted using gap fraction estimates, as well as measured leaf inclination distribution (Equation3).

$$\text{LAI} = -1/k\ \ln(\text{Gap Fraction}) \tag{3}$$

where:
k = extinction coefficient = G/cos(θ)
G = 0.5 (spherical) - based on leaf inclination measurements
The actual LAI of the artificial tree was determined by measuring the individual leaf areas of a subset of the foliage (n = 100), using a commercial flatbed scanner. LAI was then calculated, based on the individual leaf area, the number of leaves, and the crown's mean projected area.

B. Field-Level

To test the developed algorithm on real trees, ground-based laser scanning data was collected from olive (Olea europaea L.) orchards in Córdoba, Spain. ILRIS 3D data was acquired for 24 structurally variable trees in two modes: a) Nadir perspective mode, and b) Horizontal perspective mode. The nadir perspective data was obtained by mounting the ILRIS 3D sensor on a cherry picker, which was elevated to approximately 12 meters above the ground, in effect simulating an airborne scanner viewpoint. The advantage of this perspective is that we obtain a very high sample point density per crown as a result of the close range and relatively high scanning frequency. Complementing the nadir data, were horizontal perspectives of the trees, where the ILRIS unit was mounted on a tripod and positioned at two diametrically opposing viewpoints. Furthermore, the ILRIS 3D data will complement pre-existing high-spatial hyperspectral imagery acquired using the Compact Airborne Spectrographic Imager (CASI) over the sites. Also, current efforts are underway to collect in-situ measurements of crown structure using the Tracing Radiation and Architecture of Canopies (TRAC) instrument, the LAI-2000 Plant Canopy Analyzer as well as traditional mensuration measurements.

III. Results & Discussion

A. Crown Property Retrievals - Artificial Tree

Four viewpoints of the crown at 10 different stages of foliage cover resulted in a total of 40 ILRIS scan acquisitions. The XYZ data was processed to determine fractional laser pulse return as well as laser pulse return density as a function of distance into the crown (Figure 1). The location

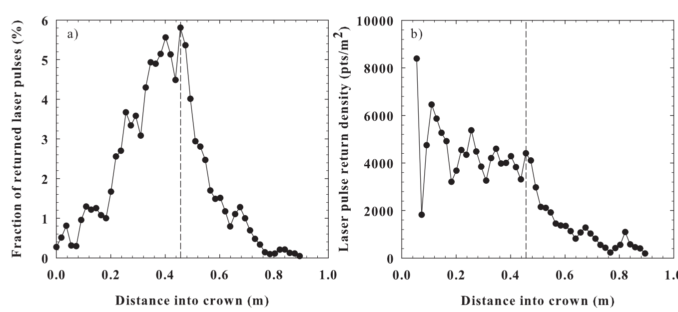

Fig. 1. Segmentation of the XYZ points (n = 48,876) of one ILRIS 3D scan into slices with a thickness of 2cm yields (a) laser pulse distribution as function of crown distance, as well as (b) the pulse return density with the appropriate determination of crown area. Dotted line indicates stem location

of the highest fractional point return for any given perspective corresponded with the stem location. Due to the relatively dense foliage within the crown, the number of pulses returned beyond the stem location was reduced, thereby decreasing the contribution of the back-side of the tree to the cumulative pulse density. As a result, the methodology to determine cumulative pulse density would sum the the return density from the front-side (up until stem location) of one perspective, with its opposing viewpoint, effectively joining two halves of the tree. Comparing this cumulative point density with the sensor intrinsic theoretical density at the same range, yields an estimate of crown gap fraction (Figure 2a). As

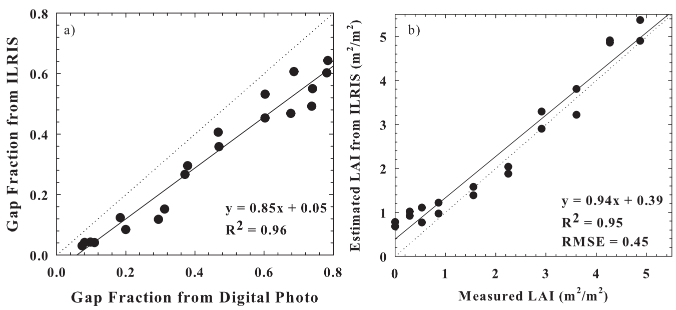

Fig. 2. Laser pulse density retrievals were used to determine a) gap fraction of the artificial tree for 10 stages of crown foliage density. Gap fraction from ILRIS data are compared with retrievals from estimates from digital photography. In addition, b) Leaf Area Index estimates from the laser pulse data, show close agreement with measured values, taking into consideration leaf angular distribution.

expected, gap fraction values increased as the leaf count of the crown decreased. Since, no truth measurement of crown gap fraction can be obtained, the results were cross-validated with gap fraction retrievals from digital photographs (r^2 = 0.96). Next, LAI estimates from the ILRIS data were obtained, while accounting for the leaf inclination angle distribution, and compared with the actual LAI (Figure 2b). The relatively low RMSE error, indicates that such an approach is feasible for LAI retrievals in the field provided, complete coverage of the crown (i.e no obscured regions) and sufficient ancillary information (i.e. leaf angular distribution) is available.

B. Crown Property Retrievals - Olive Trees

ILRIS 3D scans from a nadir view angle over select olive trees, illustrate highly specific XYZ point cloud data that can be used to reconstruct the crown biophysical properties (Figure 3). Collecting ground-based laser scanner with a nadir configuration is a unique top down approach that mimics the geometry of airborne LiDAR sensors, and yields a relatively high return point density. Crown dimensional estimates as well as laser pulse return density profiles were made on all 24 trees. Furthermore, the crown density profiles generated from horizontal scans of the two halves of the tree allow a completion of the 3D crown architecture characterization. The retrievals from the horizontal LiDAR data will be compared with the nadir view direction data. Current research is underway to validate the ILRIS retrievals using other in-situ measurements, using the LAI-2000, TRAC. In addition, high resolution multispectral and hyperspectral imagery was acquired over the selected crowns. It is the objective of the research to extract crown architecture from the ILRIS 3D data, and use the retrievals as direct inputs into FLIGHT [5], a Monte Carlo ray tracing model, which in turn will be validated with the measured optical data.

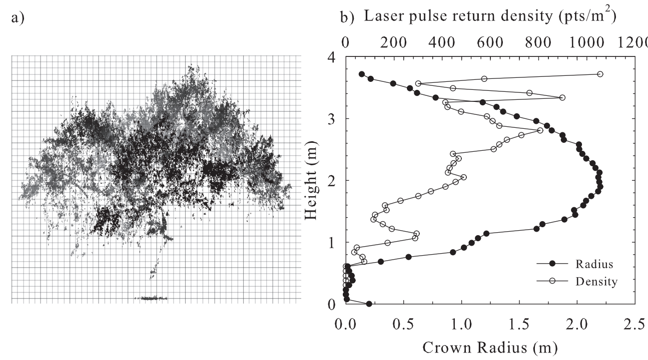

Fig. 3. The measured 3D point cloud data of an olive tree, presented here in a) with an oblique view , can be rapidly analyzed to generate estimates of b) crown profile and pulse return density.

IV. Conclusions

Extracting crown-specific parameters can help bridge the gap between coarse resolution *in-situ* data and highly detailed radiative transfer models. The methods described in this paper, show a simple approach to retrieving laser pulse return profiles to estimate gap fraction and LAI from ground-based LiDAR data. The caveat of such technology is that it provides data at higher accuracies then current field or "truth" measurements, thereby confounding validation issues. Experiments conducted on an artificial tree, show the potential for careful LiDAR data acquisition in the field to accurately estimate critical crown biophysical parameters.

V. Future Research

1) Additional strategies are being implemented to determine the variability of leaf area density and gap fraction within a given crown
2) Efforts are underway to utilize nadir viewing ILRIS data. to simulate waveform-like profiles of tree crowns for comparison with other models and measured airborne LiDAR data.

Acknowledgment

The authors would like to thank the members of the QuantaLab at the Instituto de Agricultura Sostenible for their efforts during the field data collection campaign.

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