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An architectural model of trees to estimate forest structural attributes using terrestrial LiDAR

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ABSTRACT

Terrestrial lidar (TLiDAR) has been used increasingly over recent years to assess tree architecture and to extract metrics of forest canopies. Analysis of TLiDAR data remains a difficult task mainly due to the effects of object occlusion and wind on the quality of the retrieved results. We propose to link TLiDAR and tree structure attributes by means of an architectural model. The proposed methodology uses TLiDAR scans combined with allometric relationships to define the total amount of foliage in the crown and to build the tree branching structure. It uses the range (distance) and intensity information of the TLiDAR scans (i) to extract the stem and main branches of the tree, (ii) to reconstruct the fine branching structure at locations where the presence of foliage is very likely, and (iii) to use the availability of light as a criterion to add foliage in the center of the crown where TLiDAR information is sparse or absent due to occlusion effects. An optimization algorithm guides the model towards a realistic tree structure that fits the information gathered from TLiDAR scans and field inventory. The robustness and validity of the proposed model is assessed on five trees belonging to four different conifer species from natural forest environments. This approach addresses the data limitation of TLiDAR scans and aims to extract forest architectural metrics at different structural levels.

1. Introduction

Monitoring forest ecosystems is a critical activity for efficient resource management (e.g. Hunter, 1999; Ferguson and Archibald, 2002; Garcia-Gonzalo et al., 2007), fire risk modelling (e.g. Arroyo et al., 2008), habitat mapping of wildlife species (e.g. McRae et al., 2008), and understanding ecological processes (e.g. Gustafson, 1998), to name a few applications. Remote sensing remains an essential tool for continuous monitoring of the state and evolution of forest ecosystems. Numerous methods exist based on satellite remote sensing for mapping forest attributes from local to global scales (e.g. Pohl and Van Genderen, 1998; Drake and Weishampel, 2000; Zenner and Hibbs, 2000; Lefsky et al., 2002; Chen et al., 2003; Widlowski et al., 2004; Frazer et al., 2005; Leblanc et al., 2005; Jonckheere et al., 2006; Omasa et al., 2007; Verstraete et al., 2007). Several studies propose generalized measurement methods for forest attributes, but their applicability is often limited to small areas or specific scenarios (Holmgren and Thuresson, 1998). The main constraint on method development is not linked to the quality of remote sensing sensors, but to our inability to handle the structural complexity inherent to forest canopy architecture.

Forest canopy architecture refers to the 3D organization (i.e. position, orientation, dimension and shape) of vegetation elements (Ross, 1981). The 3D architecture of a forest canopy is a highly heterogeneous and dynamic system at all scales. Spatial heterogeneity can result in clumping in the distribution of (i) standing trees in a canopy, (ii) branches and leaves within crowns and (iii) needles within conifer shoots. The temporal dynamics of the architecture range in scale from seconds/minutes (e.g. wind), days, seasons to years. Therefore, neglecting the importance of structural factors can yield to inconsistencies when evaluating: the radiative regime within a forest canopy (e.g. Govaerts and Verstraete, 1998; Smolander and Stenberg, 2003; Pinty et al., 2004), temporal/dynamic changes (e.g. Waring and Running, 2007; Weber et al., 2008), or scale dependencies (e.g. Reich et al., 2004; Zenner and Peck, 2009). The impact of the arrangement of fine-scale elements becomes more decisive when examining the mechanisms occurring at small and local scales (Widlowski et al., 2007; Omasa et al., 2007). An architectural model providing explicit details is

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difficult to develop due to the complexity of forest canopies and the great number of measurements required (Fournier et al., 1997). Regardless, the development of architectural models remains an ongoing challenge to improve our ability to estimate forest attributes with monitoring methods at the local scale. Numerous approaches to reconstruct canopy architecture exist and selecting the most suitable model depends on the requirements of the application in terms of accuracy and level of detail. For example, remote sensing and forest ecology applications used a 3D tree architecture model at local scales to simulate the signal from a forest canopy measured by a remote sensing instrument (Disney et al., 2006; Morsdorf et al., 2009) and to characterize the geometry of plants (Boudon et al., 2006). Other applications would benefit from such models to estimate tree structure at finer scales: e.g. to assess wood quality (Houllier et al., 1995; Chave et al., 2009). This requires that the architectural model be capable of describing tree structure down to the shoot or leaf cluster level. Moreover, the representation of the architecture should contain [i] *decomposition* information describing the different tree components including their types [ii] *topological* information describing how the components are (hierarchically) connected together, and [iii] *geometric* information describing the shape and spatial position of each component (Godin, 2000).

Architectural models have been developed as a practical simplification of the 3D canopy architecture, assuming that a fully detailed description is not possible through ground-based measurements (e.g. Côté, 2010). One of the simplest approaches represents the distribution of the elements in a spatial continuum where all foliage elements are assumed to be randomly distributed inside an infinite homogeneous layer (e.g. Pinty et al., 2006). This simplified analysis may be suitable for representing uniform canopies with small gaps. Refinement of this spatial representation was accomplished by modelling the geometrical parameters of tree crown envelopes with the branch and shoot elements distributed like a turbid medium within the crowns (e.g. Cescatti, 1997). Those models are well adapted to representing sparse canopies but fail to describe the intricate distribution of material within the crowns. Another series of architectural models is capable of reproducing plant physiological processes and fine-scale architecture by making use of (i) plants' geometric/topologic information from explicit measurements (e.g. Landry et al., 1997; Sinoquet and Rivet, 1997) and (ii) knowledge on growth processes and plant genetics (e.g. Měch and Prusinkiewicz, 1996; Perttunen et al., 1996; Godin et al., 1999). However, representing tree architecture remains a challenging task, particularly when dealing with mature trees in complex environments. Architectural models need to identify irregularities in recursive branching, branch mortality, and adaptive branch development from available light, and include factors significant to tree growth (e.g. crown shyness, rules for the mechanical expansion of branches) (Runions et al., 2007). Therefore, two major aspects need to be addressed to develop fine-scale 3D architectural models of forest canopies: (1) reliable measurements of the 3D structure of the forest canopy, and (2) adaptation of detailed algorithms for the representation of tree architecture.

Terrestrial light detection and ranging (TLiDAR) systems are adapted to acquire detailed measurements corresponding to the 3D distribution of canopy components (e.g. Lovell et al., 2003; Chasmer et al., 2006; Omasa et al., 2007). Point cloud data sets resulting from TLiDAR scans provide a raw view of the distribution of canopy elements in 3D, but do not provide specific information on the canopy structure. Therefore, a way to synthesize and quantify the spatial information in a useful format is still required. The quality of TLiDAR data depends on the amount of object occlusion and external environmental factors, such as wind or relative humidity (e.g. presence of fog or light rain). TLiDAR scans made in natural forest environments must deal with different levels of occlusion among the various vegetation components (Hopkinson et al., 2004). The amount of occlusion depends on the width of the light beam, the point cloud density, and the use of the first or last return (if a pulse detection laser is used). Resulting point clouds can also be altered by the presence of mild to moderate wind conditions if the scanning time exceeds a few seconds because of the erratic motion of the smaller tree constituents. In the case of multiple scans from different viewpoints, geometric scan registration adds another level of complexity to data pre-processing, but reduces the adverse effects of object occlusion since it over-samples some areas. Other aspects that influence the quality of point cloud data as input to architectural models include (i) the presence of structural elements at a finer level than that which can be resolved by the laser scanner, e.g. individual needles on a conifer shoot, (ii) the lack of a priori information about leaf or shoot/needle inclination, and (iii) the difficulty in distinguishing wood and foliage from point cloud data. In cases where a TLiDAR data set is used, the 3D modelling of tree architecture is highly dependent on the scan acquisition parameters and data quality. For instance, the assessment of the spatial distribution of wood and foliage is greatly limited when the 3D point clouds are of insufficient quality. These constraints have been limiting efforts to model 3D tree architecture and are particularly aggravating for evergreen coniferous species because they can never be scanned without their foliage.

Selecting a suitable model to describe 3D architecture depends on the importance placed on structural levels imbedded in the canopy architecture: e.g. crown, branch, leaf clumps, and leaf. The use of TLiDAR data sets is conducive to modelling tree architecture at levels as fine as the leaf/shoot. The selected model should distinguish between wood and foliage elements. Some efforts have been made to reconstruct tree stem and branch structures (e.g. Hyyppa et al., 2001; Gorte and Pfeifer, 2004; Gorte and Winterhalder, 2004; Pfeifer et al., 2004; Thies et al., 2004; Reitberger et al., 2009; Cheng et al., 2007) and to produce polygonal models of trees (Xu et al., 2007) from TLiDAR scans. These models all depend on the quality of TLiDAR scans. Côté et al. (2009) developed a model to improve radiative transfer validation schemes by reconstructing plausible 3D tree architectures from a series of TLiDAR scans. This model can deal with the adverse effects influencing TLiDAR data sets, such as object occlusion, and can improve the detection of wood and foliage components from point clouds. However, the labour-intensive parameterization was based only on the visual aspects of the tree, thus preventing the operational use of the model for the interpretation of TLiDAR data.

This paper arises from two weaknesses in the work of Côté et al. (2009) whose main purpose was to model the 3D architecture of trees from point cloud data collected with TLiDAR scans. In our previous study, the proposed model was only briefly described and the parameterization of the model was done interactively/visually. Here, we propose first to describe our architectural model at a level sufficient to make it reproducible. Second, we extended the original model by adding an automated procedure to assess the accuracy of the generated tree architecture. This architectural model will be referred to as *L-Architect* (*L*idar data to tree *Architect*ure). *L-Architect* is designed to provide a practical method to synthesize and quantify the spatial distribution of tree components from TLiDAR point clouds, resulting in an explicit description of 3D tree architecture. *L-Architect* uses geometrically registered TLiDAR scans of individual trees to reconstruct their geometric and topological structure, which in turn allows the retrieval of detailed tree structural attributes. It also aims to minimize the requirement for destructive measurements in forest ecology and resource management. A specific objective of *L-Architect* is to address the main limitations of the use of TLiDAR data sets, namely the effects of object occlusion