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Capturing tree crown formation through implicit surface reconstruction using airborne lidar data

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ABSTRACT

Forest structure data derived from lidar is being used in forest science and management for inventory analysis, biomass estimation, and wildlife habitat analysis. Regression analysis dominated previous approaches to the derivation of tree stem and crown parameters from lidar. The regression model for tree parameters is locally applied based on vertical lidar point density, the tree species involved, and stand structure in the specific research area. The results of this approach, therefore, are location-specific, limiting its applicability to other areas. For a more widely applicable approach to derive tree parameters, we developed an innovative method called 'wrapped surface reconstruction' that employs radial basis functions and an isosurface. Utilizing computer graphics, we capture the exact shape of an irregular tree crown of various tree species based on the lidar point cloud and visualize their exact crown formation in three-dimensional space. To validate the tree parameters given by our wrapped surface approach, survey-grade equipment (a total station) was used to measure the crown shape. Four vantage points were established for each of 55 trees to capture whole-tree crown profiles georeferenced with post-processed differential GPS points. The observed tree profiles were linearly interpolated to estimate crown volume. These fieldwork-generated profiles were compared with the wrapped surface to assess goodness of fit. For coniferous trees, the following tree crown parameters derived by the wrapped surface method were highly correlated ($p<0.05$) with the total station-derived measurements: tree height ($R^2=0.95$), crown width ($R^2=0.80$), live crown base ($R^2=0.92$), height of the lowest branch ($R^2=0.72$), and crown volume ($R^2=0.84$). For deciduous trees, wrapped surface-derived parameters of tree height ($R^2=0.96$), crown width ($R^2=0.75$), live crown base ($R^2=0.53$), height of the lowest branch ($R^2=0.51$), and crown volume ($R^2=0.89$) were correlated with the total station-derived measurements. The wrapped surface technique is less susceptible to errors in estimation of tree parameters because of exact interpolation using the radial basis functions. The effect of diminished energy return causes the low correlation for lowest branches in deciduous trees ($R^2=0.51$), even though leaf-off lidar data was used. The wrapped surface provides fast and automated detection of micro-scale tree parameters for specific applications in areas such as tree physiology, fire modeling, and forest inventory.

1. Introduction

The accurate measurement of tree crown parameters is critical for fields such as wildland fire dynamics (Agee, 1993; Finney, 1998), plant physiology (Maguire & Hann, 1989; Oohata & Shinozaki, 1979; Shinozaki et al., 1964) forest health monitoring (Zarnoch et al., 2004; Schomaker et al., 2007), and habitat analysis (Lowman & Rinker, 2004). The shape and size of tree crowns are typically related to photosynthesis, nutrient cycling, energy transfer (evapotranspiration and respiration) and light transmittance to understory vegetation. Obtaining precise crown information is, however, a challenging task, because the irregularity of many crown shapes is difficult to capture using standard forestry field equipment. Tree crown shapes have attracted the interests of artists as well. Christo and Jeanne-Claude used fine fabric to wrap actual trees and emphasize the complexity of the crown shape (Fig. 1). Their artistic approach to visualize the complexities of tree crowns prompted us to attempt the same but relying on mathematical and computer graphic techniques applied to light detection and ranging (lidar) point clouds.

Lidar systems have been used for ecological applications, change detection studies, forest inventory applications, and single-tree based methods (Carson et al., 2004). There are two kinds of lidar systems that have been used in previous research: discrete-return devices (DRD) and full wave recording devices (WRD) (Lefsky et al., 2002;

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Fig. 1. Visualization of tree crown formation captured by the artwork of Christo and Jean-Claude. (Christo and Jeanne-Claude, Wrapped Trees, Fondation Beyeler and Berower Park, Riehen, Switzerland 1997–98, Photo: Wolfgang Volz, ©Christo 1998).

Patenaude et al., 2004). WRD research focuses primarily on plot-level estimation of canopy structures because of the larger footprint size. The process of validation with field-measured tree parameters relies on summarizing field data at the plot level and varies with user interpretation (Mean et al., 1999). Since DRD captures returns from individual structures, it can provide more direct measurement of individual tree crown parameters. Most DRD data, however, has been analyzed with regression analysis of canopy quantile lidar metrics (Lim & Treitz, 2004; Næsset & Økrand, 2002) or the fitting of an assumed geometric shapes to derive crown parameters such as height or crown width (Andersen et al., 2002; Persson et al., 2002; Riaño et al., 2004). These approaches had two main drawbacks. First, information specific to the tree species related to their unique crown shape was required to quantify crown parameters from lidar-derived metrics. Species identification from remotely sensed data is still under development. Thus, a species-invariant approach should be considered for lidar applications. Second, regression models for fitting crown shapes were derived and applied on a local basis. The modeled regression cannot be applied to the other areas without risking errors of extrapolation. Thus, a widely applicable, individual tree-specific approach to derive tree parameters is highly advantageous for further automated detection of crown geometry from lidar measurement.

A number of commonly employed tree parameters are tree height, crown width, basal area, crown base height, and crown volume. Previous research on the determination and utilization of these parameters from DRD data is reviewed in the following paragraphs of this paper according to each tree parameter, because sensor settings and data characteristics differ between DRD and WRD.

Lidar-derived tree height information has been used for tree growth estimation and stem location (Hopkinson, 2007; Yu et al., 2004), detection of single or multi-story stand condition (Zimble et al., 2003), estimation of carbon density (Patenaude et al., 2004), biomass estimation (Bortolot & Wynne, 2005), and modeling the distribution of understory vegetation (Gobakken & Næsset, 2004, 2005; Maltamo et al., 2004). Generally, tree height and stem location are derived from a Digital Canopy Height Model (DCHM) which is the elevation difference between Digital Surface Models (DSMs) and Digital Terrain Models (DTMs). Convex shapes of the DCHM were assumed to be crown structure and were used to detect tree tops. The location and height of the tree tops were key factors for determining stem location and stand density (Hyyppä et al., 2001). The measurement of tree height depends on the quality of Digital Terrain Models (DTMs) (Andersen et al., 2006; Yu et al., 2004). Since tree height is generally a more accurately determined parameter than other crown or canopy parameters, tree height is preferred to detect change in tree growth studies.

Crown width and basal area have been derived from lidar data with the use of regression models (Means et al., 2000) or the segmentation method (Morsdorf et al., 2004; Persson et al., 2002; Popescu & Zhao, 2007). Means et al. (2000) used stepwise regression analysis for 50 m × 50 m field plot to get R^2 of 0.95 (R^2: correlation coefficient) for basal area between field and lidar measurement. For individual trees, Persson et al. (2002) used the active contour technique to retrieve crown diameter from lidar-derived DCHM to achieve an R^2 of 0.76, while Popescu and Zhao (2007) used a voxel-based method to get R^2 of 0.51.

Crown base height has been estimated with stepwise regression models (Næsset & Økrand, 2002) to achieve R^2 of 0.53 for individual trees. Alternatively, a median filter was applied to the vertical lidar point distribution (Holmgren & Persson, 2004) to get an R^2 of 0.71, while a voxel-based method (Popescu & Zhao, 2007) yielded R^2 values between 0.73 and 0.78. The accuracy of crown width and live crown base measurements relies on the precise segmentation of points for individual trees, both horizontally and vertically.

Crown volume, one of the most difficult tree parameters to obtain, is required for avian habitat analysis (Hinsley et al., 2002), estimation of the fractal dimension of trees (Zeide & Pfeifer, 1991), and forest fire simulation (Finney, 1998). Crown volume has been estimated using fitted explicit geometric equations (e.g., cones and ellipsoids) using diameter at breast height (DBH), field-measured basal area, crown diameter, and tree height as the independent variables. It also requires characterization of crown curvature (Nelson, 1997; Sheng et al., 2001). Riaño et al. (2004) computed crown volume using a relative crown height profile given by vertical lidar point density and distribution. None of these modeled equations are capable of exact fitting to all types of tree shapes, even within the same species.

To estimate those tree parameters, tree canopy shapes have been reconstructed by three different ways: implicitly, explicitly, and parametrically. The parametric reconstruction has been approached by regression statistical analysis, and the explicit reconstruction has been done using mathematical explicit functions such as cone, ellipsoid, parabolic and a combination of those. The implicit reconstruction has been accomplished with a "marching cubes" method with the implicit function (Angel, 2003).