A WRAPPED-SURFACE RECONSTRUCTION METHOD OF LIDAR POINTS TO IDENTIFY TREE CROWN ATTRIBUTES

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ABSTRACT

Identifying tree attributes from aerial photos or high resolution satellite images is difficult due to shading effects and image distortion. This research employed small footprint Light Detection and Ranging (LIDAR) data to derive precise tree crown structural parameters. LIDAR provides three-dimensional point distributions which captures structural measurements of trees and other objects. The conventional approach fitted assumed geometric shapes over a set of discrete LIDAR points using a regression approach. Differences between observed and geometrically fitted values can be significant, especially with asymmetrical or irregular crown structures. In this study, we took a graphical approach and created a wrapped surface over LIDAR points through implicit surface reconstruction to identify irregular tree crown shapes and corresponding shape parameters. We applied this method in Washington Park Arboretum in Seattle, WA, for which two different point densities of LIDAR data (from 1 pt up to 20 pts per square meter) have been collected. The tree species in the arboretum are common to the Pacific Northwest region. The value of high and low density LIDAR point data were compared as inputs to the method. The wrapped surface method results in better crown shape parameter estimation for tree height and crown volume. Using high point density LIDAR data as an input to the wrapped-surface method identifies unique crown structural attributes that are unrecognized using standard geometrical shape models.

INTRODUCTION

Light Detection and Ranging (LIDAR), active remote sensing technology, has been widely used from creating Digital Terrain Models (DTMs) to forestry and ecological application; squirrel habitat analysis (Nelson *et al.,* 2005), carbon content (Patenaude *et al*., 2004) and LAI (Lefsky *et al*., 2002, Riaño *et al.*, 2004).

Prior to LIDAR use in forestry application, one of the finest remotely sensed data, were aerial photographs. In photogrammetry, the object which is reconstructed in stereo should be clearly seen on both stereo pairs, however, a clear view of an object is not always possible from the two perspectives. Sometimes vegetation on the ground obscures the view of the solid object such as buildings from one perspective point and makes it difficult to measure the height of the objects and reconstruct them in three dimensional spaces. Moreover, automatic tie point generation during ortho-rectification process cannot identify accurate tie points automatically over vegetated area between two stereo photos because of irregular shades and shadow pixels on the image. LIDAR can compensate for the drawbacks of the photogrammetric approach, because LIDAR can transmit the scanning laser pulses to reach and be reflected from any objects on the ground without any shadow effect.

Forest inventory practitioners use LIDAR in delineating tree crowns for their field sampling (Maltamo *et al*., 2004). In their study, a few sampled tree parameters collected in the field are regressed against LIDAR point distribution to estimate all trees in a large area. Regression approach of a stand level estimation has been applied to Norwegian forest (Næsset, 1997, 2002, Næsset *et al.* 2002) and different kinds of tree shape (Nelson, 1996). Regression approach is, however, locally accepted but not globally applied. More globally applicable approach is required for future sampling schemes which overcome local variability. Furthermore, building regression models for different species and tree shapes require excessive numbers of sampling which can characterize the general shape of tree for certain species in their targeted area. In the case of managed forest, all trees have been fitted well with the regressed model from a few sampling. In highly mixed species forest which has highly variable and irregular shape of trees, however, does not fit the regressed model at all. The urban forest is a good example of this and unmanaged, tropical, and temperate forest also needs to be analyzed by a different approach for their ecological studies using LIDAR.

Crown volume, one of the most difficult to obtain tree parameters, is needed for bird habitat analysis (Hinsley *et al*., 2002) and forest fire simulation (Finney, 1998). Crown volume has been estimated using fitted explicit geometric equation such as cone and ellipsoid with diameter at breath height (dbh), field measured basal area, crown diameter, and tree height. It also requires characterizing the crown curvature (Nelson, 1996, Sheng *et al*. 2001). Again, modeled equations do not fit exactly for all types of tree shapes, even within the same species.

Identifying crown formation of different species is difficult from the field. LIDAR can capture the shape of trees as point cloud, but cannot distinguish species well even with their intensity values (Brandtberg *et al.*, 2003, Holmgren *et al.,* 2004) unless intensity values are calibrated well (Brandtberg *et al.*, 2007). For mixed species plot, stand level tree parameters have been derived with different remotely sensed images. Popescu and others used hyperspectral images to differentiate tree species and derive individual crown parameters (Leckie *et al*., 2003, Popescu *et al*,. 2003a, 2004a, 2004b) In most situations, it is rare to capture LIDAR data with different remotely sensed data at the same time. More practical application which uses only LIDAR data to derive tree parameters is still needed.

With using only LIDAR to derive tree parameters in stand level, the points should be extracted for a single tree. There have been several segmentation methods that can be applied on discrete LIDAR points. Morsdorf *et al.* (Marsdorf *et al.* 2004) and Riano *et al.* (Riano *et al.*, 2004) used K-means method to segment LIDAR points. The accuracy of segmentation results depend on the number of iteration and the initial location of input seed points. The method is unique, but not promising. Since LIDAR returns come from exposed surface of objects directed towards the sensor, the algorithm developed by Hyyppä *et al.* (Hyyppä *et al.*, 2001) is more suitable to segment LIDAR points. Hyyppä and co-authors used Gaussian filter convoluted over the local maximum height of LIDAR points to make Digital Surface Models (DSMs). Expanding this technique, watershed segmentation method (Chen *et al*, 2006, Sollie, 2003) has been applied to delineate crown and extract LIDAR points for a single tree. A marker controlled watershed segmentation improves the accuracy of segmentation (Chen *et al*, 2006). The marker for watershed segmentation can be set manually (Hyyppä *et al.*, 2001), by semi-automatic process using morphological filtering (Anderson *et a*., 2001), and by full automatic process using level set method (Kato *et al*., 2006) and local convex shape identification (Kato *et al.*, 2007a). The watershed segmentation is suited to segment LIDAR points in two dimensional spaces, three dimensional segmentation (vertically overlapped trees), however, requires another approach using median filtering (Holmgren *et al.*, 2004).

In order to estimate globally applied crown volume and identify tree parameters, we take a computer graphic approach to wrap LIDAR discrete points at a stand level using Radial Basis Functions (RBFs).

Radial Basis Functions (RBFs) has been used for the reconstruction of surface from scattered points in three dimensional spaces (Bishop 2005, Carr *et. al.* 1997, 2001, 2003, Kato *et al*., 2006, 2007b, Wendland *et. al.* 2005). RBFs are used to reconstruct DTMs from scattered points as well (Pouderoux *et al*., 2004, Tobor *et al*., 2004). This function, therefore, is applied to make DTMs and wrapped surface in this study.

Field validation of LIDAR has not been discussed well in previous research. The selection of instrument is important to validate LIDAR derived tree parameters. Previous research validated mainly tree heights with field equipment using laser range finder with clinometers (Brandtberg *et al*., 2003), Vertex Forestor (Hoglof Inc., Sweden; Maltamo *et al*., 2004), Vertex Ⅲ hypsonometer (Hoglof Inc., Sweden; Riano *et al.*, 2004), *Sunto* hypsonometer (Sunto Inc., Finland; Holmgren *et al*., 2003), handheld laser impulse (Laser Technology Inc., USA; Clark *et al.*, 2004) or the total station (Nicon Inc., USA) for tree height (Andersen *et al.*, 2006) and stem location (Holmgren *et al*., 2004). The technique of field measured crown formation has not been developed yet and it requires accurate horizontal and vertical angular measurement. Handheld laser impulse with Mapster (Laser Technology Inc., USA) is the most commonly used to measure these angles efficiently in a large area. LIDAR, however, has the most accurate three dimensional coordinate. Human manual error, therefore, should be minimized to validate LIDAR derived tree parameters. In this study, the total station is utilized to validate LIDAR derived tree parameters and crown profiles. Moreover, we compute field measured crown volume from crown profiles (the edges of tree crown shapes) from four different cardinal angles. The field based crown volume is compared with the volume graphically given by the wrapped surface.

Objectives

Wrapping surface can provide tree crown attributes from LIDAR points. The field measured tree parameters are given by the total station with high accuracy. This paper, therefore, is aimed at:

1) comparing crown volume and the other tree attributes derived from a wrapping surface with field measured those using the total station; and,
2) indentifying crown volume effect between two different LIDAR point cloud densities.

DATA

Research Site

The research area is located in the Washington State Park Arboretum (founded in 1934) at the south end of University of Washington and at the east end of downtown Seattle, WA. The total area is 230 acres. The arboretum collection is diverse from shrubs to trees and contains 5,500 different kinds of species mainly from the Northwest region.

Field Data

In this study area, some areas have sparse stands and other areas are dense, thus, 55 relatively open canopy coniferous trees are randomly selected. The selected trees are 27 Douglas-Fir (*Pseudotsuga menziesii*), 11 Pine (several kinds of genus family), 10 Western Red Ceder (*Thuja plicata*), and 7 other species. Their stand conditions are 39 open stand trees without understory and 16 co-dominant trees which have clearly exposed canopy with understory trees and shrubs.

Field Measurement

The crown profiles are measured with a surveying total station (Nikon DTM-420). The accuracy of the total station measurement is 1/1000 feet. The edge points that comprise the tree crown profile are observed from eight cardinal directions in terms of the stem location. The eight directions are N, S, E, W, NE, NW, SE, and SW (each direction has 45 degrees range). The trees are assumed to be symmetric from one side of view and 180 degree opposite side of view. Therefore, four cardinal directions are used instead of eight directions. From the observation points, the edge of crown shape are recorded vertically every fixed 5 degrees, beginning with the crown base height. In addition to the points, the location of treetop and trunk base height is recorded. Crown base height is defined as the edge of the lowest branches. The location of all points is calculated trigonometrically from the vertical and horizontal angle. From one observation point, two crown profiles are taken and each crown profile is created by linearly interpolated lines. Eight profiles require measurement from four observation points. To get the total volume of a tree, the vertical profile is integrated every 45 degrees for each profile. The sum of them is a total volume for a tree. In order to get more precise volume, the volume enclosed between live crown base height and crown base height is subtracted from the total volume in this research.

To achieve this field measurement, the location of the total station requires clear view of an entire tree from four cardinal angles. The total station has limitation of vertical angle, (less than 55 degrees), which need enough distance to capture the top of tree crown. In order to get clear view of coniferous trees, they are captured during leaf-off season (between February to March 2007) to minimize the effect of deciduous leave interception of the view from the observation points. All observation points are tied with accurate GPS location collected by Trimble Pathfinder Pro XR GPS units (Trimble Inc.). All GPS points are differentially corrected during post processing.

LIDAR Data

Small footprint LIDAR data were acquired two times over this research site in 2004 and 2005. LIDAR sensor characteristics for each mission are shown in Table 1. The coordinates of the LIDAR points are UTM zone 10 and NAD83. In this analysis, the DTM values were subtracted from the ground elevation of all LIDAR points to make Digital Canopy Height Model (DCHM) to remove any slope effect and measure tree parameters from the wrapped surface.

Table 1. LIDAR sensor system settings

Date of acquisition	August 30th 2004	March 17th, 2005
Laser sensor	Optech ALTM 30/70	Optech ALTM 3100
Flying height	1200 m	900 m
Impulse frequency	71 kHz	100 kHz
Laser point density range	2 to 5 points/m^2	3 to 20 points/m^2

METHODOLOGY

Classification of LIDAR Points

The vendor did not classify LIDAR points for last returns to create DTMs, the last returns are selected using our own algorithm using the local minimum elevation models of LIDAR returns and Radial Basis Functions (RBFs). Local minimum height points are collected within 1m by 1m square grids to make the local minimum elevation models. A 6m by 6m minimum filer is convoluted over the minimum elevation models. The minimum filter, however, could not remove the returns from the top of the building and contained a few returns from the trunk or lower brunches. The mean and one standard deviation of the elevation models are applied to filter out non-ground returns. With the filtered ground points, the initial DTMs are created.

The resulting surface is used to select more ground points which are close to the initial DTMs for the second iteration; because RBFs make a more realistic surface if there are more input points for this function. Finally, the final DTMs are created with selected ground points. The resulting surface and selected ground returns are shown in Figure 1.

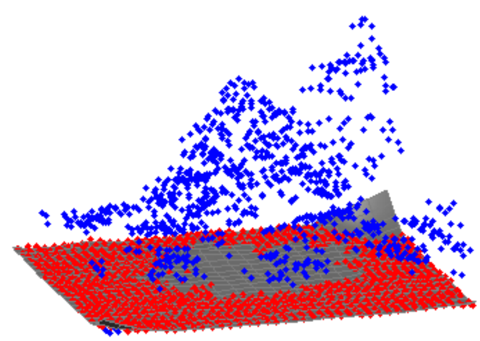

Figure 1. Classification of LIDAR points for last and first returns; last returns (red), first returns (blue) and DTM (gray).

Segmentation of LIDAR Points

To segment LIDAR points, tree top locations are identified using a level set method (Kato *et al*., 2006, 2007b). Based on the tree top location, a marker-controlled watershed segmentation method is implemented.

First of all, a level set method is used to identify the local peaks of the local maximum elevation models. In order to find good location of local maximum peaks, the elevation models need to be smoothed. The local maximum height models are created by local maximum height points within 1m by 1m square grids and smoothed by a Gaussian filter (Hyyppä *et al*., 2001). The smooth surface is sliced at a certain height by a flat plane. For each sliced plane, a value of 0 is assigned for the pixels whose height is less than the height of the plane and 1 for the other to create a binary image. Based on this binary image, a connected component analysis is implemented to label and classify the pixels. This sliced plane is created for all height with interval 0.1m from the bottom to the top of the smooth surface. In order to identify the peaks, one sliced image at a certain height is compared with the other of the next height plane to see the difference between them. If a total number of labeled pixels decrease from one image to the other, the plane passes a local peak of trees and the locations of the missed regions are recorded with the height. The missed location is the tree top location for one tree.

After identifying all local peaks of the surface, a gradient flow analysis in eight neighboring pixels is used to determine which peak the surrounding pixels belonged to. All pixels are labeled based on an identifying number given by each local peak. From the classified pixels, all discrete LIDAR points whose locations are fallen into the labeled pixels are assigned as the same identified numbers to segment as individual trees.

Selection of Points on the Surface

After LIDAR points representing individual trees are clustered, their returns come from not only the surface of tree crowns, but also from the interior of the tree crown. For the wrapping purpose, only the points from the surface of tree crowns are required. To remove the points inside the crown, a two-dimensional convex hull algorithm was used at selected height locations. Although the convex hull could get most of the point that outlined the crown shape, outlier points still remained. To remove the outliers, a cylinder, which was defined by the mean and one standard deviation distance from the center of tree stem coordinates, are applied.

Creation of the Implicit Surface Wrapping the Tree Crown

A nonparametric interpolating surface is constructed from the selected surface points for individual trees by radial basis functions (RBFs). As a first step toward creating a wrapped surface, the Euclidean distance, which is defined as the distance between any arbitrary points in the space and the closest point on the surface, is calculated by RBFs. After calculating Euclidean distance for all the points in the space, isosurface is used to display closed and wrapped surface created for nonparametric tree shapes with zero level set surfaces.

Radial Basis Functions

Radial Basis Functions (RBFs) are one of the interpolation methods in three dimensional spaces. RBFs in this research are used for creating DTMs from the last returns and creating a wrapping surface from first returns. General formula of RBFs is:

$$s(x) = \sum_{i=1}^{N} \lambda_i \Phi(\|x_i x_j\|) + \pi(x) \qquad (1)$$

where $\pi(x)$ is a polynomial term for point $x \in \Re^3$ $x_i x_j$ is the Euclidian distance.

λ_i is the weighting coefficient.

N is the number of initial points.

The radial basis function Φ used in this study is $\Phi(r) = r$ (linear)

In order to make DTMs, elevation values are the function of s(x). For a wrapping surface, we use fourth dimension to create a wrapping surface for the function of s(x). LIDAR data has three dimensional point location; X, Y, and Z coordinates. The fourth dimension is a distance. The distance from any arbitrary point in the space to the closest point on the surface of tree crowns. The wrapped surface is then given by the set of points for which $s(x) = 0$. For this study, we don't use the polynomial term of the equation (1), because resulting interpolated surface should go through all initial points.

With only zero distance which is on the surface of tree crown, all coefficient λ_i of the left hand side of the equation (1) are zero. Using the points on the surface, we are able to construct two additional sets of points at a distance 1 and –1 from the desired surface. We generated additional points for the distance 1 and -1 and the total 3N points are used to solve the linear system. With the coefficients λ_i given by 3N points, the distance of any arbitrary points $x \in \Re^3$ in the space can be calculated the formula below:

$$s(x) = \sum_{i=1}^{3N} \lambda_i \left\| x_i - x \right\| \qquad (2)$$

where x is any points in $\Re^3$

Crown Volume from the Wrapped Surface

To compute the volume enclosed by the zero level set, calculus divergence theorem is used. The crown volume using calculus divergence theorem requires the normal vector and the area of facets which compose a wrapping surface. The formula of calculus divergence theorem is:

$$Volume = \int_{\partial C} F\vec{n}dS = \sum_{j=1}^{m} \vec{n}_j^x \int_{T_j} xdS \qquad (3)$$

RESULTS AND DISCUSSION

In this section, the tree parameters given by a wrapped surface are compared with field measured tree parameters. Crown volume calculated from a wrapped surface is compared with the crown volume derived from field measured crown profiles. The difference of the crown volume between two different LIDAR point densities is discussed afterwards.

Tree Parameters

Tree height & volume. Tree height derived from a wrapped surface for all 55 trees and crown volume of only 39 stand-alone mixed species coniferous trees was compared with field measured those. Tree height has R^2 value of 0.91 and crown volume has R^2 value of 0.84, which is highly significant between them.

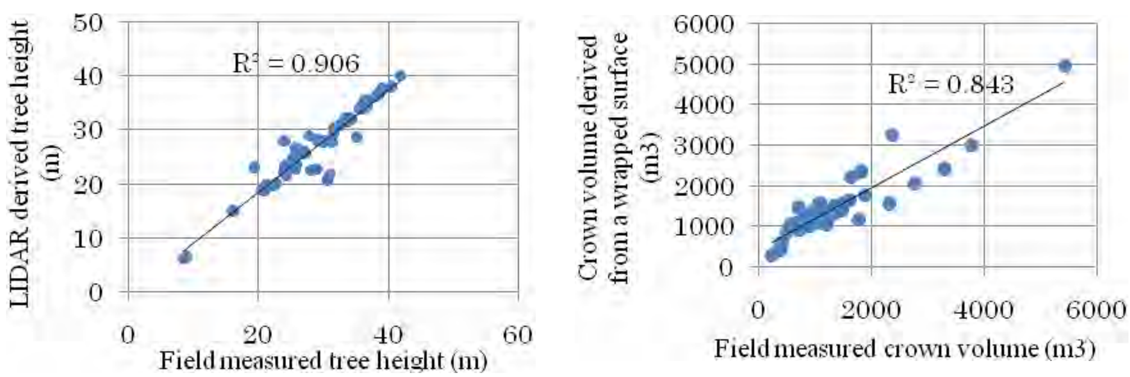

Figure 2. Comparison of tree height (on the left) and crown volume (on the right) between field and LIDAR measurement. LIDAR derived tree height is given by a wrapped surface.

Maximum crown diameter & crown base height. Crown base height, the maximum crown diameter of all 55 trees were compared with field measured those in Figure 3.

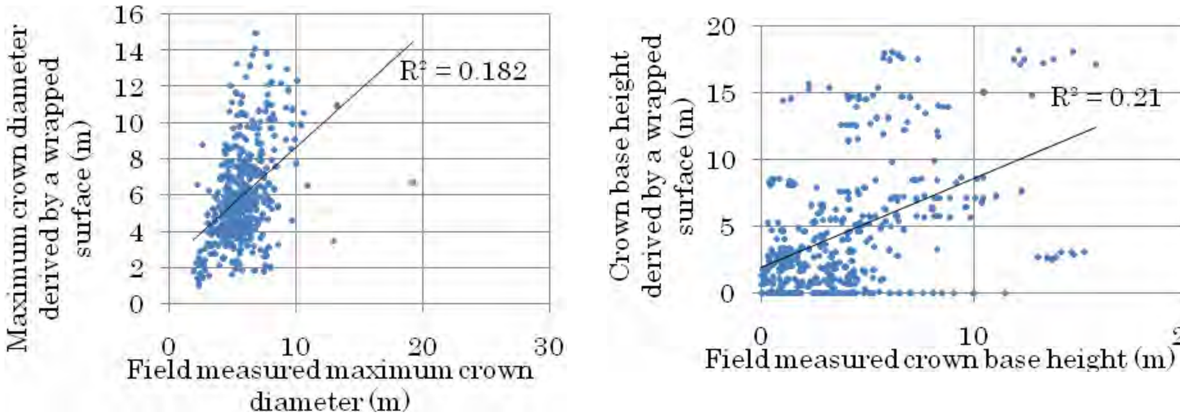

Figure 3. Comparison of maximum crown diameter (on the left) and crown base height (on the right). They are compared between field and LIDAR measurement sampled at the same angle with the field observation points from a wrapped surface.

From Figure 2, tree height and crown volume are significantly correlated between field and LIDAR measurement, because LIDAR returns have high precision from the top of canopy and are reflected from upper part of canopy. From figure 3, LIDAR measurement tends to miss the returns from the crown base height, which influences the values of maximum crown diameter. Even though crown diameter and crown base height are not significantly correlated with actual field measurement, the crown volume is highly correlated between them. Crown volume is not directly influenced by crown diameter and crown base height for most irregular shape of trees used in this study. Based on this result, it is found that crown shapes and tree height are more influential factors to estimate crown volume.

Influence on LIDAR point density. To show the difference of crown volume between two different LIDAR sensor settings, Figure 4 shows wrapped surfaces of two different (2004 and 2005) LIDAR data. They have different point density and season to capture the data (leaf-on at 2004 and leaf-off at 2005).

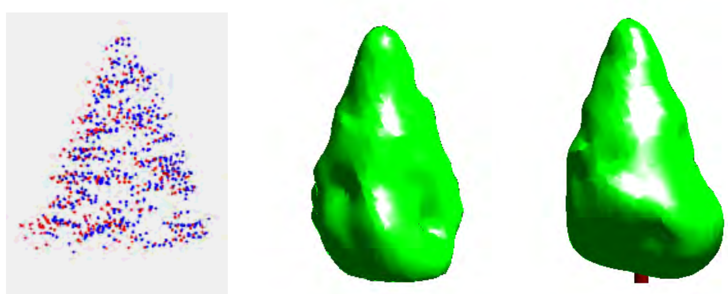

Figure 4. 2004 LIDAR point distribution (red points on the left), 2005 LIDAR point distribution (blue points on the left), a wrapped surface for 2004 data (at the center), and a wrapped surface for 2005 data (on the right). Crown volume from a wrapped surface of 2004 data, that of 2005 data, and field measured crown volume are $1052m^3$, $894m^3$, and 1018 m^3 respectively. Their relative errors are 3% for 2004 and 12% for 2005.

We use the same technique for both year, crown volume calculated by 2004 data (lower point density), however, is bigger than that of 2005 data. If the point density is getting less, the estimated volume is getting bigger and relative error based on field measured crown volume is getting smaller. Because the sampling numbers of points are different among 2004 LIDAR points, 2005 LIDAR points, and field measured crown profile, more points LIDAR sensor receive, less crown volume is estimated, but more irregular shape of crown is captured. Field sampled crown profiling has the least number of sampling, tends to overestimate crown volume. The rest of 16 co-dominant trees need to be analyzed by better segmentation technique to extract a single tree to wrap. The trees we used in this research are all coniferous. The condition of leaves between leaf-off and leaf-on, therefore, did not influence so much for crown volume estimation. The difference of crown volume between two different LIDAR dataset mainly comes from LIDAR point density.

CONCLUSION

Conventional tree attributes and crown volume estimation has been achieved through regression analysis using field measured crown diameter, tree height, and crown curvature. The regression approach only works for managed and homogeneous stands locally. Urban forest areas have irregular shapes within the same species, our graphical approach is superior to derive tree attributes easily and crown volume more accurately in these conditions. Maximum crown diameter and crown base height are less influential factors to estimate crown volume from our analysis. As our next step, the crown formation characterized by our wrapped approach is analyzed and used for species identification.

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REFERENCES

Andersen, H.E., Reutebuch, S.E., and Schreuder, G.F., (2001). Automated Individual Tree Measurement Through Morphological Analysis of a LIDAR Based Canopy Surface Model.*Proceedings of the first international Precision Forestry Symposium, Seattle WA*: 11-22.

Andersen, H.E., Reutenbuch, S.E., and McGaughey, R.J., (2006). A rigorous assessment of tree height measurements obtained using airborne lidar and conventional field methods. *Canadian Journal of Remote Sensing* 32(5): 355-366

Bishop, C. M. (2005). *Neural Networks for Pattern Recognition*. Oxford University Press, NY.

Brandtberg, T., Warner, R.E., Landenberger, R.E., and McGraw, J.B. (2003). Detection and Analysis of Individual Leaf-off Tree Crowns in Small Footprint, High Sampling Density LIDAR Data from the Eastern Deciduous Forest in North America. *Remote Sensing of Environment* 85: 290-303.

Brandtberg, T. (2007). Classifying individual tree species under leaf-off and leaf-on conditions using airborne lidar. *ISPRS Journal of Photogrammetery & Remote Sensing* 61:325-340.

Carr, J.C., Fright, W.R., and Beatson, R.K. (1997). Surface Interpolation with Radial Basis Function for Medical Imaging. *IEEE Transactions on Medical Imaging* 16 (1): 96-107.

Carr, J.C., Beatson, R.K., Cherrie, J.B., Mitchell T.J., Fright, W.R., McCallum, B.C., and Evans, T.R. (2001). Reconstruction and Representation of 3D objects with Radial Basis Functions. *ACM SIGGRAPH 2001*, Los Angeles, CA: 67-76.

Carr, J.C., Beatson, R.K., McCallum, B.C., Fright, W.R., McLennan, T.J. and Mitchell, T.J. (2003). Smooth Surface Reconstruction from Noisy Range Data. *ACM GRAPHITE 2003,* Melbourne, Australia: 119-126.

Chen, Q., Baldocchi, D., Gong, P., and Maggi, K. (2006). Isolating Individual Trees in a Savanna Woodland Using Small Footprint LIDAR Data. *Photogrammetric Engineering and Remote Sensing* 72 (8): 923-932.

Clark, M.L., Clark, D. B., and Roberts, D.A., (2004). Small-footprint lidar estimation o sub-canopy elevation and tree height in a tropical rain forest landscape, *Remote Sensing of Environment* 91:68-89.

Finney, M. A. (1998). FARSITE: Fire Area Simulator-Model Development and Evaluation. *RMRS-RP-4.* Ogden, UT: USDA Forest Services.

Holmgren, J., Nilsson, M., and Olsson, H. (2003). Estimation of Tree Height and Stem Volume on Plots Using Airborne Laser Scanning. *Forest Science* 49 (3): 419-428.

Holmgren, J. and Persson, Å. (2004). Identifying Species of Individual Trees Using Airborne Laser Scanner. *Remote Sensing of Environment* 90 (4): 415-423.

Hyyppä, J., Kelle, O., Lehikoinen, M., and Inkinen, M. (2001). A Segmentation-Based Method to Retrieve Stem Volume Estimates from 3-D Tree Height Models Produced by Laser Scanners. *IEEE Transactions on Geoscience and Remote Sensing* 39 (5): 969-975.

Hinsley, S., Hill, R.A., Gaveau, D.L.A., and Bellamy, P.E. (2002). Quantifying woodland structure and habitat quality for birds using airborne laser scanning. *Functional Ecology*, 16: 851-857.

Kato, A., Calhoun, D., Schreuder, G. F., and Schiess, P. (2006). Estimating Crown Volume through Implicit Surface Reconstruction from LIDAR Points for Forest Fire Simulation. *Proceedings of MAPPS/ASPRS 2006 Fall Conference*, San Antonio, TX.

Kato, A and Schiess, P. (2007a). LIDAR Derived Tree Parameters for Optimal Cable logging System Design. *Proccedings of the International Mountain Logging and 13th Pacific Northwest Skyline Symposium*, Corvallis, OR, April 2007.

Kato, A., Schreuder, G. F., Calhoun, D., Schiess, P., and Stuetzle, W. (2007b). Digital Surface Model of Tree Canopy Structure from LIDAR Data through Implicit Surface Reconstruction. *Proceedings of ASPRS 2007 Annual Conference*, Tampa, FL, May 2007

Leckie, D., Gougeon, F., Hill, D., Quinn, R., Armstrong, L., and Shreenan, R. (2003). Combined High-density LIDAR and Multispectral Imagenery for Individual Tree Crown Analysis. *Canadian Journal of Remote Sensing* 29 (5): 633-649.

Lefsky, M.A., Cohen, W.B., Cohen, Parker, G., and Harding, D.J. (2002). Lidar Remote Sensing for Ecosystem Studies, *BioScience* 52(1): 19-30

Maltamo, M., Eerikäinen, K., Pitkänen, J., Hyyppä, J., and Vehmas, M. (2004). Estimation timber volume and stem density based on scanning laser altimetry and expected tree size distribution functions, *Remote Sensing of Environment* 90: 319-330.

Morsdorf, F., Meier, E., Koetz, B., Itten, K. I., Dobbertin M., and Allgower, B. (2004). LIDAR-based Geometric Reconstruction of Boreal Type Forest Stands at Single Tree Level for Forest and Wildland Fire Management. *Remote Sensing of Environment* 92 (3): 353-362.

Næsset, E. (1997). Estimating Timber Volume of Forest Stands Using Airborne Laser Scanner Data. *Remote Sensing of Environment* 61: 246-253.

Næsset, E. (2002). Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data, *Remote Sensing of Environment* 80: 88-99

Næsset, E. and Økrand, T. (2002). Estimating tree heights and tree crown properties using airborne scanning laser in a boreal nature reserve, *Remote Sensing of Environment* 79 (1): 105-115.

Nelson, R. (1997). Modeling Forest Canopy Heights: The Effects of Canopy Shape. *Remote Sensing of Environment* 60 (3) : 327-334.

Nelson, R., Keller C., and Ratnaswamy, M. (2005). Locating and estimating the extent of Delmarva fox squirrel habitat using an airborne LiDAR profiler, *Remote Sensing of Environment* 96: 292-301.

Patenaude, G., Hill, R.A., Milne, R., Gaveau, D.L.A., Briggs, B.B.J., and Dawson, T.P. (2004). Quantifying forest above ground carbon content using LiDAR remote sensing, *Remote Sensing of Environment* 93: 368-380.

Popescu, S.C., Wynne, R.H. and Nelson, R.F. (2003). Measuring Individual Tree Crown Diameter with LIDAR and Assessing Its Influence on Estimating Forest Volume and Biomass. *Canadian Journal of Remote Sensing* 29(5): 564-577.

Popescu, S.C., and Wynne, R.H. (2004a). Seeing the Trees in the Forest: Using LIDAR and Multispectral Data Fusion with Local Filtering and Variable Window Size for Estimating Tree Height. *Photogrammetric Engineering and Remote Sensing* 70 (5): 589-604.

Popescu, S.C., Wynne, R.H., and Scrivani, J.A. (2004b). Fusion of Small-Footprint Lidar and Mutispectral Data to Estimate Plot-Level Volume and Biomass in Deciduous and Pine Forests in Virginia, USA. *Forest Science* 50(4): 551-565.

Pouderoux, J., and Gonzato, J.C. (2004). Adaptive Hierarchical RBF Interpolation for Creating Smooth Digital Elevetion Models. *Proceedings of GIS'04*, Washington, DC.

Riaño, D., Chuvieco, E., Condés, S., González-Matesanz, J., and Ustin, S. L. (2004). Generation of crown bulk density for *Pinus sylvestris* L. from LIDAR. *Remote Sensing of Environment* 92 (3): 345-352.

Sheng, Y., Gong, P., and Biging, G.S. (2001) Model-Based Conifer-Crown Surface Reconstruction from High-Resolution Aerial Images. *Photogrammetric Engineering and Remote Sensing* 67 (8): 957-965.

Sollie, P. (2003). *Morphological Image Analysis Principles and Applications.* Springer NY.

Tobor, I., Reuter, P., and Schlick, C. (2004). Efficient Reconstruction of Large Scattered Geometric Datasets using the Partition of Unity and Radial Basis Functions. *Journal of WSCG* 12(3).

Wendland H. (2005). *Scattered Data Approximation.* Cambridge Monographs on Applied and Computational Mathematics, Cambridge University Press, Cambridge, UK.