Remote Sensing of Environment 123 (2012) 368–380

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Tree species classification and estimation of stem volume and DBH based on single tree extraction by exploiting airborne full-waveform LiDAR data

Wei Yao [a,*], Peter Krzystek [a], Marco Heurich [b]

[a] Dept. of Geoinformatics, Munich University of Applied Sciences, 80333 Munich, Germany
[b] Bavarian Forest National Park, 94481 Grafenau, Germany

A R T I C L E I N F O

Article history:
Received 23 August 2011
Received in revised form 19 March 2012
Accepted 24 March 2012
Available online 3 May 2012

Keywords:
Airborne full-waveform LIDAR
3D segmentation
Single tree extraction
Species classification
Forestry
Stem volume
DBH estimation

A B S T R A C T

The paper highlights recent results of forest structure analysis at single tree level based on analyzing airborne full waveform LiDAR data. Single trees are automatically detected by a 3D segmentation technique applied directly to laser point clouds, which uses the normalized cut segmentation combined with a stem detection method. A subsequent classification identifies tree species using salient features that are defined on single 3D tree segments and utilize the additional information extracted from the reflected laser signal by the waveform decomposition. The stem volume and diameter at breast height (DBH) are estimated by a multiple linear regression analysis which uses tree shape parameters derived from the 3D model of the trees. Experiments were conducted in the Bavarian Forest National Park with full waveform LiDAR data. The data were captured with the Riegl LMS Q-560 system at a point density of 25 points/m^2 under leaf-off and leaf-on conditions. The analysis of waveform data in the tree structure shows that the intensity and pulse width discriminate stem points, crown points and ground points significantly. The unsupervised classification of deciduous and coniferous trees is in the best case 93%. If a supervised classification is applied the accuracy is slightly increased to 95%. Concerning stem volume estimation, in the case of coniferous trees the study shows a low RMSE of about 0.46 m^3 to 0.43 m^3 both for the watershed segmentation and the new normalized cut segmentation. In the case of deciduous trees RMSE has increased by 14% in leaf off condition and by 4% in leaf on condition for the normalized cut segmentation. A similar trend can be confirmed for DBH estimation as well, even demonstrating a larger benefit from 3D segmentation. The study results proved that the 3D segmentation approach is not only capable of detecting more small trees in the lower forest layer but also can allow to derive more promising features of single trees used for yielding better performance in species classification and estimation of forest structural parameters, especially for deciduous trees.

1. Introduction

The development of new approaches to forest inventory utilizing LiDAR remote sensing data has been an important research issue in the past (Hyyppä et al., 2008; Koch, 2010; Lim et al., 2003; Nelson et al., 1988). Besides area based methods (Næsset, 2002, 2007), techniques for tree extraction from LiDAR data have been investigated for mapping forests at the tree level and identifying important structural parameters, such as tree height, crown size, crown base height, tree species, and stem volume etc. (Hyyppä & Inkinen, 1999; Hyyppä, Kelle, et al., 2001; Hyyppä, Schardt, et al.2001; Persson et al., 2002; Holmgren & Persson, 2004; Heurich, 2006; Yu et al., 2011; Korpela et al., 2010). Recent advances in LiDAR technology have generated new full waveform scanners that provide a higher point density and additional information about the reflecting characteristics of trees. Important issues like the calibration and the decomposition of full waveform data with a series of Gaussian functions, as well as the detection and classification of vegetation have been investigated by Wagner et al. (2006), Jutzi and Stilla (2006), Stilla et al. (2007), Reitberger et al. (2008a) and Yao and Stilla (2010). Novel methods for single tree detection tackle conceptually the segmentation problem with a 3D approach instead of using only the crown height model (CHM) (Wang et al., 2008). In combination with full waveform data the strategy proposed in Reitberger et al. (2009) could successfully demonstrate that the detection rate of single trees could be much improved in overall terms using a 3D segmentation technique based on the normalized cut segmentation. Interestingly, the improvement was found to mostly happen in the lower forest layers with 20%.

The single tree approach has advantages over the area-based approach with respect to providing accurate forest attributes for mixed stands by developing species-specific models, while errors in the tree detection could limit the accuracy of plot-level estimates (Heurich & Thoma, 2008; Hyyppä, Kelle, et al., 2001; Hyyppä, Schardt, et al., 2001; Yu et al., 2010). Consequently, recent studies

* Corresponding author. Tel.: +49 89 1265 2632; fax: +49 89 1265 2698.
E-mail address: yao@hm.edu (W. Yao).

0034-4257/$ – see front matter
doi:10.1016/j.rse.2012.03.027

from Breidenbach et al. (2010) made an attempt to compensate for the non-detected trees by connecting non-detected trees in the field data to nearby segments and got good results. Additionally, Lindberg et al. (2010) and Vastaranta et al. (2012) have proposed to combine the single tree and area based methods for a more unbiased forest inventory. Obviously, full waveform LiDAR data render possible new approaches to reconstruct and classify objects, such as trees. It will be interesting to find out how newly developed methods for extracting single trees from full waveform LiDAR data can contribute to the accuracy of the forest inventory significantly.

Regarding tree species discrimination with LiDAR parameters Brandtberg et al. (2003) as well as Holmgren and Persson (2004) have made early studies about tree species classification based on single tree analysis from LiDAR data. More recently, Heurich (2008) demonstrated that classification of Norway spruce and European beech is possible with an overall accuracy of 97% in leaf-off situation. This study was based on area-based method to process LiDAR data with a mean point density of 10 points/m^2 and clearly showed that desirable forest features such as young regeneration could not be detected. Reitberger et al. (2008a) demonstrated the first strong evidence for the correlation between laser pulse width and species for tree species classification using full-waveform data. The pulse width is a function of the length of the emitted pulse and its different reflections. Mean pulse width of single reflections within a beam reveals as the main factor. In addition, Höfle et al. (2008) reported that mean width of laser echo pulse is able to separate larch from broadleaved (i.e. oak and beech). Orka et al. (2009) demonstrated an accuracy of 73% when classifying conifers and deciduous trees solely based on pulse intensity. In combination with canopy structure parameters, which are derived from height distributions, they attain only an improvement of 4%. Korpela et al. (2010) reported a comprehensive study on the effects of various parameters including forest stand properties, size of training set, intensity normalization etc. on the tree species discrimination, which showed that the intensity features were dependent on the absolute and relative sizes of trees and can contribute to a classification accuracy of 88% between Scots pine, Norway spruce, and birch. Most recently, Heinzel and Koch (2011) have exploited various full waveform features in an attempt to identify most promising LiDAR-derived features for the classification of up to six tree species.

Thus, it seems that the fusion of 3D techniques and full waveform data pushes the single tree approach to a new level of completeness and accuracy. Consequently, parameters such as the estimation of the stem volume might be enhanced using the 3D information of segmented trees. Recently, stem volume estimation was investigated by several groups. Hyyppä et al. (2005) combined ALS first/last pulse data with CIR orthophoto and get random errors of 25 to 30% in terms of the estimation of individual tree volume based on a semi-automatic method. For smaller tree groups the random error amounts to 34 to 40%. Heurich (2006) used in his experiments first/last pulse data acquired by the TopoSys system at a nominal point density of 10 points/m^2. Based on 2D watershed segmentation, the multiple regression ends up with a relative RSME of 27% for coniferous trees and 35% for deciduous trees. The study of Maltamo et al. (2006) showed that stem volume can only be estimated with about 30% RMSE accuracy at plot-level if derived as a function of the tree height and the crown diameter. Furthermore, Vauhkonen et al. (2010) reported on a relative RSME of 31% for imputing stem volume of single trees using tree height, intensity and alpha shape metrics. Additionally, DBH has become one of essential parameters for forest inventory which can be predicted from airborne laser scanning measurements. The early work of Persson et al. (2002) has reported that DBH can be estimated by using the laser-measured tree height and crown diameter with an error of 10% of the mean value. Popescu (2007) attempted to derive DBH of individual pine trees with tree parameters that are extracted based on a 2D segmentation of CHM generated from airborne LiDAR data. Breidenbach et al. (2008) showed that the mean of DBH distributions can be estimated with a RMSE of 2.44 cm by applying area-based sample plot method to airborne LiDAR data. One should keep in mind that it is common for all reports that the imprecision of the field data could affect the results significantly.

In this paper we present and evaluate results of tree species classification and estimation of stem volume and DBH with full waveform data based on normalized cuts segmentation technique. The objectives of this paper are (i) to review an innovative method of singe tree detection with the normalized cut segmentation using full waveform LiDAR data, (ii) to analyze and define physical and geometric features of the single tree structure for species classification and regression analysis, (iii) to present and evaluate species classification results of a) deciduous and coniferous trees and b) spruces and fir trees, finally, (iv) to present and evaluate results of the estimation of stem volume and DBH at single tree level by regression analysis.

2. Methodology

2.1. Waveform decomposition and calibration

Due to its importance in processing laser data and extracting features towards forest inventories the decomposition and calibration of laser waveforms will be first discussed. In this study the LiDAR waveform data are decomposed by fitting a series of Gaussian pulses to the waveform which contains N_R reflections (Fig. 1).

The vector $X_i^T = (x_i, y_i, z_i, W_i, I_i)(i = 1, \ldots, N_R)$ is provided for each reflection i with (x_i, y_i, z_i) as the 3D coordinates. Additionally, for each point X_i the width $W_i = 2 \cdot \sigma_i$ and the intensity $I_i = \sqrt{2 \cdot \pi} \cdot \sigma_i \cdot A_i$ of return pulses with σ_i as the standard deviation (= half pulse width at $A_i/\sqrt{e}$) and A_i as the amplitude of the reflection i are given (Jutzi & Stilla, 2006; Reitberger et al., 2008b). Basically, each reflection can be detected by the waveform decomposition. Hence, neighboring targets with a minimum distance of $v_g \tau/2$ in the direction of the laser beam can be separated, where v_g is the group velocity of the laser pulse in the atmosphere and τ is the pulse duration of the ALS system (Wagner et al., 2006). For example, the pulse duration of 4 ns of the Riegl LMS-Q560 scanner leads to a minimum distance of 0.6 m. This is remarkable since most conventional LiDAR systems recording at most five reflections have a dead zone of about 3 m within these systems and effectively blind after a reflection.

The sensor data are calibrated by referencing W_i and I_i to the pulse width W^e and the intensity I^e of the emitted Gaussian pulse and

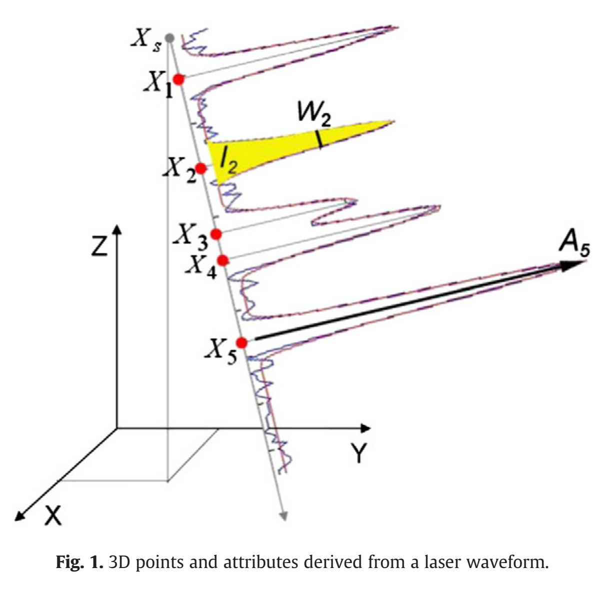

Fig. 1. 3D points and attributes derived from a laser waveform.