ALGORITHMS AND METHODS OF AIRBORNE LASER SCANNING FOR FOREST MEASUREMENTS

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ABSTRACT:

Extracting forest variables from airborne laser scanner has less than 10 years of history. During that time, however, a new area in the field of forest studies has emerged. This paper describes existing algorithms and methods of airborne laser scanning that are used for forest measurements. The methods are divided into the following categories: 1) extraction of DTM (digital terrain model), 2) extraction of canopy height, 3) extraction of statistical variables from laser data, 4) extraction of individual tree information using image processing techniques, 5) integrating aerial image data with laser scanner, 6) use of intensity and waveform information, and 7) use of change detection methods.

1. INTRODUCTION

About 100 years ago, forest mensuration was considered to deal with the determination of the volume of logs, trees, and stands, and with the increment and yield. Since then forest mensuration has expanded to cover assessment of e.g. wildlife, recreation, watershed management and other aspects in multiple-use forestry. However, the essence of forest mensuration is still in obtaining information on volume and growth of trees, forest plots, stands and large-area forest inventory.

Airborne laser ranging/profiling developed rapidly in early and middle 1970's, especially in North America, with experiments for bathymetric and hydrographic applications. The studies of laser ranging for forest inventory started in around 1980 (Solodukhin et al., 1977; Nelson et al., 1984; Aldred and Bonnor, 1985; Maclean and Krabill, 1986). The first studies concentrated on using a profiling system for forest height, stand density, tree species and biomass estimation. The basics of using laser measurements for forest inventory were established at that time. In order to get more detailed description of the history of prior laser ranging measurements over forest, reader is referred to e.g. Nelson et al. (1997), Nilsson (1996), and Holmgren (2003).

In the late 1980's the use of GPS made accurate range measurements on a larger scale possible. In early 1990's, profiler where gradually replaced by scanners, and GPS was combined with INS, enabling the collection of 3D coordinates for the reflected points. First, the airborne laser scanning (ALS) systems had to collect separately first and last pulse. Today all systems are capable to record simultaneously at least the first and last pulse, and some are even capable to record multiple pulses, continuous waveforms and aerial photographs in parallel. Ackermann (1999), Wehr and Lohr (1999) and Wever and Lindenberger (1999) summaries the basics of laser scanning and gives an overview of the history of the first 10 years. An overview of future possibilities of ALS is given by Steinvall (2003).

The first application of ALS for forestry was the determination of terrain elevations (e.g. Kraus and Pfeifer, 1998), followed by standwise mean height and volume estimation (e.g. Næsset, 1997a,b), individual tree based height determination and volume estimation (e.g. Hyyppä and Inkinen, 1999; Brandberg, 1999), tree species classification (e.g. Brandtberg et al., 2003; Holmgren and Persson, 2004) and measurement of forest growth and detection of harvested trees (e.g. Yu et al., 2004). Laser scanning experiences in Canadian, Norwegian, Swedish and Finnish forestry can also be obtained in Wulder (2003), Næsset (2003), Nilsson et al. (2003) and Hyyppä et al. (2003a). A Scandinavian summary of laser scanning in forestry can be read from Næsset et al. (2004).

The objective of this paper is to review ALS methods and algorithms, developed within the photogrammetry and forestry societies, to forest mensuration.

2. EXTRACTION OF DTM

Since laser scanning can provide 3D characterization of forest canopies, the basics for modern ALS based forest measurements rely on the acquisition of the DTM (digital terrain model) and DSM corresponding to treetops. The errors related to DTM fluctuate also to tree heights.

Photogrammetricians have developed various methods to obtain DTM from laser scanning point clouds. Kraus and Pfeifer (1998) developed a DTM algorithm based on distinguishing laser points into terrain points and non-terrain points using a recursive prediction of the DTM and weights attached to each laser point depending on the vertical distance between the expected DTM level and the corresponding laser point. Pyysalo (2000) developed a modified recursive classification method for DTM extraction, where all points within 60 cm vertical distance from the lowest expected ground level were included equally in the next DTM model calculation. Axelsson (1999, 2000, 2001) developed a progressive TIN densification method where surface was allowed to fluctuate within certain values, controlled by minimum description length, constrained spline functions, and active countour models for elevation differences. Ground points were connected in a TIN. A sparse TIN was derived from neighbourhood minima, and then progressively densified to the laser point cloud. In every iteration, points are added to the TIN, if they are within defined thresholds. The method has been implemented to Terrascan software (see www.terrasolid.fi). Elmqvist (2001) estimated the ground surface by employing active shape models by means of energy minimization. The active shape model behaves like a membrane floating up from underneath the data points. The energy function is a weighted combination of internal and external forces. The start state is a plane below the lowest point in the data set. Sithole (2001) and Vosselman and Maas (2001) developed a slope-based filtering technique, which works by pushing up vertically a structuring element. In the method by Wack (2002) non-terrain raster elements are detected in a hierarchical approach that is loosely based on a block-minimum algorithm.

Describing height accuracy of laser derived DTMS with a bias and a standard error is in most cases not sufficient. Due to the integration of different sensors (GPS, INS, laser scanner), the height error budget of single laser point is a combination of several error components (Crombaghs et al. 2002). These errors can be roughly divided into four components: an error per point, strip section (covered during one GPS observation), strip and entire block. In forestry, the effect of the bias is not relevant, since the crown DSM is also affected by the same bias. Therefore, a random error including all previous error sources is adequate in forest studies to give a rough understanding of the quality of DTM and laser data. However, in addition to errors caused by the laser system and errors caused by applied methodology and algorithms (for algorithm comparison see Sithole and Vosselman, 2004), the quality of DTM derived from laser scanning is influenced by data characteristics (e.g. point density, first/last pulse, flight height, scan angle), as well as errors due to characteristics of the complexity of target (type of the terrain, flatness of the terrain, density of the canopy above). Test flights (TopoSys, 1996) have shown that at scanning angles of more than 10 degrees off-nadir, the amount of shadowed areas heavily increases, i.e., the number of measured ground hits decreases and gaps in the DTM occur more frequently. With respect to type of terrains and surfaces, Raber et al. (2002a) and Hodgson et al. (2003) found that land-cover types were a significant factor that influences the accuracy of laser DTM in forested areas. Terrain slope impact on laser DTM were examined by Hyyppä et al. (2000) and Hodgson et al. (2003). Raber et al. (2002a) suggested that when information about the terrain type or land cover are known, it can be used in the filtering to improve the accuracy of resultant DTM. Also, data obtained in leaf-off conditions were found more suitable to map the terrain surface than data obtained in leaf-on conditions (Raber et al., 2002b). Results from these earlier studies suggest that a better accuracy was obtained in open flat areas. With the increase of the vegetation cover or terrain slope, accuracy deteriorated. It seems that forest canopy and understorey vegetation cover are one of the major factors that affect the accuracy of laser DTMs in forested areas by preventing larger proportion of laser pulses from hitting the underlying ground. In Yu et al. (forthcoming) impact of forest cover, as well as the effect of interpolation errors, point density, the terrain slope and 'scanning' angle on laser DTM were studied.

Practical tests have shown that laser scanning data always includes low points under the ground level. These may be real returns or falsely interpreted elevation values from strong backscatterers (as reported with profiling microwave radar in Hyyppä, 1993). The filtering of low erroneous points is preferred procedure before final DTM calculation.

Kraus and Pfeifer (1998) reported an RMSE of 57 cm in wooded areas using ALTM 1020 and average point spacing of 3.1 m. Hyyppä et al. (2000) reported a random error of 22 cm for modulating forest terrain using Toposys-1 and nominal pulse density of 10 pulses per m^2. Within the EC-funded HIGH-SCAN project (1998-2001), three different DTM algorithms were compared in Finnish (test site Kalkkinen), Austrian (Hohentauern) and Swiss (Zumikon) forests. Obtained random errors varied between 22 and 40 cm (Hyyppä et al., 2001) using Toposys-1 and pulse densities between 4 to 10 pulses per m^2. Ahokas et al. (2002) compared three algorithms in forested hill in Finland and found random errors between 13 and 41 cm using Toposys-1. Reutebuch et al. (2003) reported random errors of 14 cm for clearcut, 14 cm for heavily thinned forest, 18 cm for lightly thinned forest and 29 cm for uncut forest using TopEye data with 4 pulses per m^2. However, in dense forests, errors up to 10 to 20 m can occur in the DTM estimation (Takeda, 2004).

Extraction of the DTM of forest canopies can be considered as well-established, at least in Europe. However, more research is needed in order to understand the quality of the DTM in various conditions, using various methods, and systems. Due to improvements in sensor technology, including new waveform recording, further work in the development of the DTM algorithms and analysis of the quality of the new systems are also required.

3. EXTRACTION OF CANOPY HEIGHT

Most usable technique to obtain DSM relevant to treetops is to calculate the TIN of the highest reflections (i.e. by taking the highest point within a defined neighbourhood) and interpolate missing points e.g. by Delaunay triangulation. The canopy height model (CHM) is then obtained by subtracting the DTM of the corresponding DSM. The crown DSM is typically calculated by means of the first pulse echo and DTM with the last pulse echo. In order to guarantee, that there are no systematic errors between first and last pulse data, calibration using flat, non-vegetated areas, such as roads, roofs, and sports grounds should be performed. Especially when laser scanning systems required separate first and last echo recordings and both echoes were used for separate models, this is a necessity.

It was already noticed in the 1980's that the use of a laser leads to underestimation of tree height (e.g. Aldred and Bonnor, 1985). With the use of profiling lasers, that was obvious, since it was expected that the laser was mainly hitting the tree 'shoulder' rather than the treetops. Thus, detection of the uppermost portion of a forest canopy is expected to require a sufficient density of laser pulse footprints to sample the tree tops and a sufficient amount of reflecting material occupying each laser pulse footprint to cause a detectable return signal (e.,g. Lefsky et al., 2002). If ground elevation and (or) the uppermost portion of a forest canopy are not detected, then canopy height will be underestimated. Lefsky et al. (2002) also expected that sampling density is the principal issue determining the possibility of canopy height underestimation with small-footprint ALS. Previously, tree height underestimation has been reported also for individual trees and for both deciduous and coniferous trees (Hyyppä and Inkinen, 1999; Persson et al. 2002; Gaveau and Hill, 2003; Leckie et al., 2003; Yu et al., 2004; Maltamo et al., 2004a). According to all these studies, it seems that the underestimation of tree height is affected by the density and coverage of laser pulses; the algorithm used to obtain the canopy height model; the amount and height of undervegetation; the algorithm used to calculate the digital terrain model; the sensitivity of the laser system and thresholding algorithms used in the signal processing as well as pulse penetration into canopy; and the tree shape and tree species. Finding a universal correction factor, however, for the underestimation may be difficult, since the correction appears to be dependent on the sensor system, flight altitude, forest type and the algorithm used. Gaveau and Hill (2003) used a terrestrial laser system to calibrate the underestimation, whereas Rönnholm et al. (2004) demonstrated the use of terrestrial image data in the calibration of the effect.

Examples of reported tree underestimation values from studies where errors have not been calibrated with reference data are given. Hyyppä and Inkinen (1999) reported individual tree height estimation with an RMSE of 0.98 m and a negative bias of 0.14 m (nominal pulse density about 10 pulses per m^2), while Persson et al. (2002) reported an RMSE of 0.63 m and a negative bias of 1.13 m. Both test sites were dominated by Norway spruce and Scots pine. Persson et al. (2002) further explained their greater average tree height underestimation as resulting from lower ALS sampling density (ab. 4 pulses per m^2). Naesset and Okland (2002) stated that the estimation accuracy significantly decreased by a lower sampling density. Gaveau and Hill (2003) reported the tree height estimation of broadleaf woodland, since the previous studies had concentrated on coniferous forests. A negative bias of 0.91 m for sample shrub canopies and 1.27 m for sample tree canopies was observed. Leckie et al. (2003) concluded that some of the 1.3 m underestimation could be accounted by the undergrowth. Yu et al. (2004) found a systematic underestimation of tree heights by 0.67 m for the laser acquisition carried out in 2000 and 0.54 m from another acquisition in 1998. The underestimation corresponded to 2 to 3 years annual growth of those trees. Out of that, the elevation model overestimation (due to undervegetation) was assumed to account about 0.20 m. Since the accuracy of conventional field inventories may not be adequate for detailed assessment of the bias, Maltamo et al. (2004a) used 29 pines accurately measured with a tacheometer, and found a 0.65-m underestimation of height for single trees, including annual growth that was not compensated for in the plot measurements. They also found that the precision of 0.50 m for individual tree height measurements was better than reported earlier (e.g. Hyyppä and Inkinen 1999, Persson et al. 2002).

Magnussen and Bouldewyn (1998) introduced a geometrical model that successfully predicted the mean difference between the laser canopy heights and the mean tree height. The model explained why estimation of stand heights from laser scanner data based on maximum canopy height value in each cell of a fixed area grid (e.g. Næsset 1997b) has been successful in practise. Magnussen, Eggermont and LaRiccia (1999) introduced two recovery models that could be used to obtain tree heights from laser height measurements.

Even though the canopy height estimation has been the major concern of ranging measurements over 20 years, the exact knowledge of the processes causing the underestimation of the height are not known, and no well-established calibration method exist. In the future, there should be focus on calibrating the underestimation as well as understanding of the reasons for height underestimation. The overestimation of tree heights reported by a few scientists can be caused by the errors of the DTM. Inclusion of the underground point into DTM will result in overestimation of the tree. Further initiatives, such as Holmgren (2003) using simulation for estimation of mean tree height and Rönnholm et al. (2004), to get more understanding of the tree height estimation are welcomed.

Structural characteristics of forest stands in relation to, e.g., carbon content and biodiversity issues are of special interest. Since, some of the laser pulses will penetrate under the dominant tree layer, it is also possible to analyse multilayered stands. In Maltamo et al. (2004b), the existence and number of suppressed trees was examined. This was carried out by analysing the height distributions of reflected laser pulses. Histogram thresholding method of Lloyd was applied to the height distribution of laser hits in order to separate different tree storeys. Finally, the number and sizes of suppressed trees were predicted with estimated regression models. The results showed that multilayered stand structures can be recognised and quantified using quantiles of laser scanner height distribution data. However, the accuracy of the results is dependent on the density of the dominant tree layer. Possibility to characterize suppressed trees is an area of new research. The use of original point clouds instead of DSMs or CHMs makes this possible.

4. EXTRACTION OF FOREST VARIABLES BY STATISTICAL METHODS

Extraction of the forest variables has been recently divided into two categories: inventories done at stand and plot level (also called as area-based methods) and individual tree based inventories. These categories relate to the need of the forestry information and from methodological point of view it is better to divide them into statistical and image processing based retrieval methods. In the statistical methods, features and predictors are assessed from the laser derived surface models and point clouds, which are directly used for forest parameter estimation, typically using regression or discriminant analysis. Image processing based techniques utilize more efficiently the neighbourhood information of point clouds and pixels of DSMs. Physical features, such as crowns, individual trees, group of trees, or the whole stands, can be delineated using image processing techniques. After that process, the forest and stand parameters are assessed using existing models and statistical methods.

Maclean (1982) demonstrated that the cross-sectional area of the forest canopy, i.e. the *canopy profile area*, is directly related to the logarithm of the timber volume. Maclean and Krabill (1986) showed that the modified canopy profile consisting of all laser height measurement above a certain exclusion limit would predict volume more accurately than the entire canopy profile.

Height percentiles of the distribution of canopy heights has been used as predictors in regressions models for estimation of mean tree height, basal area and volume (e.g. Lefsky et al., 1999; Magnussen et al., 1999; Means et al., 2000; Naesset, 1997a,b; Naesset and Okland, 2002; Naesset, 2002). In Means et al. (2000), a large-footprint scanning lidar SLICER was used in estimation of tree height, basal area, and biomass in Douglas-fir dominated forests, with tree height ranging from 7 to 52 m, with coefficient of determination values of 0.95, 0.96 and 0.96, respectively. In addition to canopy height information, *canopy reflection sum, ground reflection sum* and *canopy closure* were used. Canopy reflection sum is the sum of the portion of the waveform return reflected from the canopy, where as ground reflection sum is the sum of waveform return reflected from the ground multiplied by a factor correcting the canopy attenuation. Canopy closure was approximated by dividing the sum of the canopy and ground reflection sums. In Naesset (2002), several forest attributes were estimated using canopy height and *canopy density metrics* using a two-stage procedure and field data. Canopy height metrics included e.g. quantiles corresponding to the 0,10,…,90 percentiles of the first pulse laser canopy heights and corresponding statistics, where as canopy density corresponded to the proportions of both first and last pulse laser hits above the 0,10,…,90 quantiles to total number of pulses.

In Riano et al. (2003), several statistical parameters were defined for forest fire behavior modeling. *Tree cover* was calculated from the proportion of laser hits from tree canopy divided by the total number of laser hits. *Surface cover* was defined as the proportion of laser hits from the surface and the total number of hits. Crown bulk density was obtained from foliage biomass estimate and crown volume using an empirical equation for foliage mass. Crown volume was estimated as the crown area times the crown height after a correction for mean canopy cover.

In Holmgren and Persson (2004), a large number of height and intensity based variables were defined for tree species classification, for example *relative standard deviation of tree heights*, the *proportion of single returns* and the *proportion of first return*, *proportion vegetation points* as the number of returns that were located above the crown base height divided by the total number of returns from the segment, *crown shape* by fitting a parabolic surface to the laser point cloud, *mean intensity and standard deviation of both single and surface returns*. They showed an overall classification accuracy of 95 % between Scots pine and Norway Spruce. High classification accuracy was obtained by using the proportion of first returns and standard deviation of the intensity. There was also a strong correlation between the standard deviation of laser heights within a segment and the corresponding crown base height. Additionally, a strong correlation between the m*ean distance between first and last return of a double return* within a segment and the corresponding crown length were found.

5. EXTRACTION OF INDIVIDUAL TREE INFORMATION BY IMAGE PROCESSING METHODS

The rapid development of computer-related techniques has enabled the introduction of semi-automated forest inventory based on advanced image processing methods. As a relatively new field of research, forest variable extraction using image processing techniques can be divided into tree location and full crown delineation (see also Gougeon and Leckie (2003)) The methods used in laser scanning have been merely applied from similar studies using very high resolution aerial imagery.

Finding tree locations can be obtained by detecting image local maxima (e.g. Geogeon and Moore 1989). In laser scanning, the aerial image is replaced by the crown DSM or the canopy height model. Provided that the filter size and image smoothing parameters are appropriate for the tree size and image resolution, the approach work relatively fine with coniferous trees (see also Gougeon and Leckie, 2003). After finding the local maxima, the edge of the crown can be found using the processed canopy height model. In laser scanning the delineation always results in the so-called full individual tree crown isolation, since the upper top of the crown will be modelled in 3D. Such approach can provide tree counts, tree species, crown area, canopy closure, gap analysis and volume and biomass estimation (Gougeon and Leckie).

Hyyppä and Inkinen (1999) were the first to demonstrate the ITC based forest inventory using laser scanner using tree finding with maximas of the CHM and segmentation for edge detection. The method was tested together with two other segmentation algorithms in Finnish, Austrian and German coniferous forests and 40 to 50 % of the trees could be correctly segmented. Persson et al. (2002) improved the crown delineation and could link 71% of the tree heights with the reference trees. Other attempts to use DSM or CHM image for ITC isolation or crown diameter estimation have reported by e.g. Brandtberg et al. (2003), Leckie et al. (2003), Straub (2003), and Popescu et al. (2003).

Andersen et al. (2002) proposed to fit ellipsoid crown models in a Bayesian framework to the point cloud. Morsdorf et al. (2003) presented a practical two-stage procedure where tree locations were defined using the DSM and local maximas and crown delineation was performed using k-means clustering in the tree dimensional point cloud. Wack et al. (2003) first calculated the canopy height corresponding to all laser points and used sorted list to define a cone of the tree top. If the point located close to the cone, it was removed. The process was recursive. 93 % of the planted eucalyptus trees could be correctly delineated by this manner.

The methods for ITC isolation using laser scanner data are still under development and empirical studies on the quality of the approaches is needed. For that purpose a Tree Extraction comparison project has been initiated by the Finnish Geodetic Institute.

6. THE USE OF FUSED LIDAR AND AERIAL IMAGES

The integration of laser scanning and aerial imagery can be based on simultaneous or separate data acquisitions. Presently in the photogrammetric society, there is a strong interest to develop sensor integration methods for simultaneous laser and aerial image acquisition. Practical aspects, such as possibility to make laser measurements during nighttime, make separate acquisition of laser and aerial data an economically suitable solution. Separate acquisitions typically mean different imaging geometries and a more complex matching problem.

There is a high synergy between the high resolution optical imagery and laser scanner data for extracting forest information. Laser data provides accurate height information, which is missing in single optical images, and also supporting information of the crown shape depending on the applied pulse density, whereas optical images provide more details about spatial geometry and color information usable for classification of tree species and health. Both provide information on crown shape and size. Even though these aspects have been known quite a long time, a small amount of research has been published on the topic. Here are some example of proposed solutions and results obtained.

St-Onge (1999) used multi-spectral digital videography to verify the laser scanning accuracy for height estimation. The height of individual trees read from the laser-derived CHM at the center of the tree crowns visible on the overlaid multispectral imagery were compared with field observation consisting of the mean of the two height measurements for each GPS-positioned tree. Hyyppä et al. (2000) proposed to integrate aerial image with laser scanner by ortorectifying the aerial image using the digital crown model instead of the digital terrain model. By this mean, the crowns in the aerial photographs and laser-derived tree height model coincide. That could be then used to derive tree species information for individual tree crowns and to have a good link between laser and aerial data. St-Onge and Achaichia (2001) demonstrated the use of laser data to obtain DTM and the use of the historical series of aerial photography to analyze forest canopy height changes of the part decades. Persson et al. (2004) combined laser data with high resolution near infrared digital images using a segmented laser-derived CHM and camera position and orientation (roll, pitch and heading) of each aerial image to map each tree segment to the corresponding pixel in the aerial image. Leckie et al. (2003) applied valley following approach to individual tree isolation to both digital frame camera imagery and a canopy height model created from high-density lidar data. The results indicate that optical data may be better at outlining crowns in denser situations and thus more weight should be given to optical data in these situations. Lidar also easily eliminated most of the commission errors that often occur in open stands with optical imagery.

Today, integration methods between laser and aerial imagery for forest inventory require further studies even though there exist products, such as Terrascan, which can handle both image and laser data in the value adding chain.

7. USE OF INTENSITY AND WAVEFORM

The use of intensity in forest parameter estimation is limited to be used as a predictor e.g. for tree species classification (Holmgren et al. 2004) or for matching aerial imagery and laser scanner data. The more effective use of intensity values is missing partly due to the lack of techniques to calibrate them.

There are also full-waveform digitising lidar systems that have been developed, firstly as preparation for future satellite systems to survey earth topography and vegetation cover, and later for airborne laser scanners. Today, several manufacturers are announcing the use of airborne laser scanner capable to record digitised waveforms. In Drake et al. (2002) several statistical predictors, such as lidar canopy height, height of median energy, and ground return ration, using waveform information are depicted. According to Wagner et al. (2004) the use of full-waveform in airborne laser scanner offers a possibility to classify the data based on the shape of the echo. Another important advantage is that the detection of the trigger pulses can be applied after data capturing.

8. CHANGE DETECTION

Yu et al. (2004) and Hyyppä et al. (2003b) demonstrated the applicability of airborne laser scanners for the estimation of forest growth and monitoring of harvested trees. Object-oriented algorithms were developed for detecting harvested and fallen trees, and for measuring forest growth at plot and stand levels. About 75 % of field-checked harvested trees could be automatically and correctly detected. All mature harvested trees were detected. Forest growth was demonstrated at plot and stand levels using an object-oriented tree-to-tree matching algorithm and statistical analysis. The precision of the estimated growth, based on field checking or statistical analysis, was about 5 cm at stand level and about 10-15 cm at plot level.

9. CONCLUSIONS

The methods and literature for laser methods is rapidly developing. At the same time, technology is pushing new possibilities. There seem to be relatively good understanding of DTMs and CHMs as well as possible features that can be extracted from present laser data for forest inventory. On the other hand, proper use of intensity and waveform data, integration of laser and aerial data, complementary use of airborne and terrestrial laser scanning, change detection possibilities, and use of more advanced image processing techniques to original point clouds will shape the future of laser scanning forest measurements in the coming years.

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