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Automatic forest inventory parameter determination from terrestrial laser scanner data

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Terrestrial laser scanners find rapidly growing interest in photogrammetry as efficient tools for fast and reliable three-dimensional (3D) point cloud data acquisition. They have opened a wide range of application fields within a short period of time. Beyond interactive measurement in 3D point clouds, techniques for the automatic detection of objects and the determination of geometric parameters form a high priority research issue. With the quality of 3D point clouds generated by laser scanners and the automation potential in data processing, terrestrial laser scanning is also becoming a useful tool for forest inventory. This paper presents a brief review of current laser scanner systems from a technological point of view and discusses different scanner technologies and system parameters regarding their suitability for forestry applications. Methods for the automatic detection of trees in terrestrial laser scanner data as well as the automatic determination of diameter at breast height (DBH), tree height and 3D stem profiles are outlined. Reliability and precision of the techniques are analysed on the basis of several pilot studies. In these pilot studies more than 97% of the trees could be detected correctly, and DBH could be determined with a precision of about 1.8 cm.

1. Introduction

Forest inventory, management and planning tasks require, besides other parameters, the measurement of several parameters describing the geometry of trees. In the simplest case, these parameters are limited to the tree height and diameter at breast height (DBH). In some tasks, many more geometry parameters, such as stem profiles, open stem height (the timber-relevant height between the bottom and the first branch), stem ovality, damage or branch diameters are required. As full area coverage is an unrealistic goal in forest inventory using conventional techniques, inventory schemes based on data acquisition in isolated plots and statistical inference methods have been developed.

Several studies have been published on applying airborne laser scanning and model-based automatic processing tools to acquire large-area forest inventory data (e.g. Næsset 1997, Schardt *et al.* 2002). Airborne laser scanning offers the advantage of efficient large-area coverage, but the precision and reliability potential of the technique depends on the validity of assumptions made in models applied to derive inventory-relevant parameters from point clouds. In most cases, processing is

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limited to the determination of standwise average parameters rather than individual tree parameters.

Terrestrial laser scanning, combined with automatic data processing techniques, may provide an interesting tool to bridge the gap between conventional inventory techniques and airborne laser scanning data processing schemes and to facilitate the data acquisition for three-dimensional (3D) individual tree geometry parameters in large plots. Figure 1 gives an impression of the information content of terrestrial laser scanner point clouds. Several studies on the applicability of terrestrial laser scanners in forest inventory tasks have been published. Simonse *et al.* (2003) used a 2D Hough transform to detect trees in point clouds and to determine diameter at breast height (DBH) after height reduction in the digital terrain model. This approach was extended to the determination of diameters at different heights by Aschoff and Spiecker (2004). Gorte and Winterhalder (2004) and Gorte and Pfeifer (2004) generated tree topology skeletons by projecting point clouds into a voxel space, where stems and major branches were extracted by morphology operations using 3D structure elements and connectivity analysis. Pfeifer and Winterhalder (2004) modelled the stem and some major branches of a tree by a sequence of cylinders fitted into the point cloud. Thies and Spiecker (2004) described the results of a pilot study based on the works mentioned above. They reported a fairly low rate of 22% of the trees detected in single scans and 52% detection rate in multiple scans. Although the stem position could be determined with fairly high precision, DBH values showed a standard deviation of about 3.5 cm, obtained from a comparison of laser scanner data processing results with conventional tape measurements. The standard deviation of tree height determination was 5.6 m and thus not satisfactory. Henning and Radtke (2006) showed the Iterative Closest Point (ICP) automatic registration of three scans of a group of nine trees using the stem centres detected in the trees at different heights and reported a precision of 1–2 cm for stem diameters determined at different heights.

The aim of this study was to validate and verify the precision and reliability of terrestrial laser scanner data processing schemes in forest inventory applications on the basis of five pilot studies covering different types of forests, scanners, different data acquisition schemes and seasons. In section 2 we provide a brief overview of the

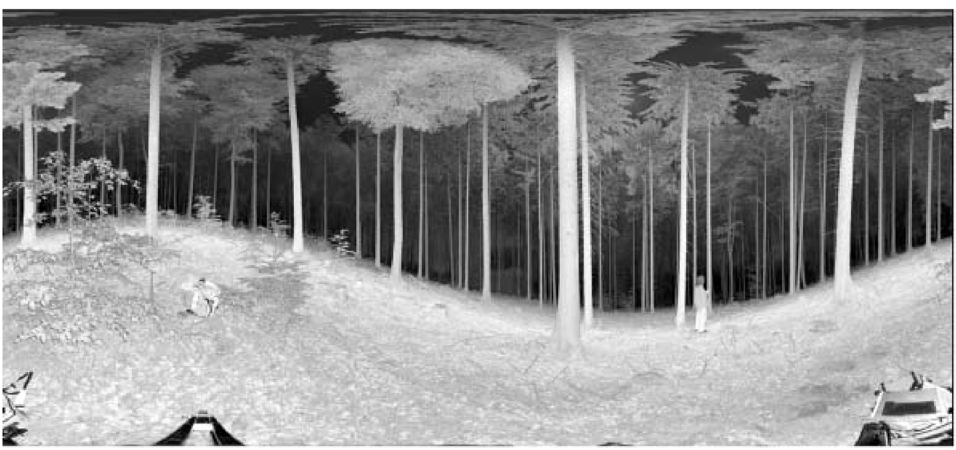

Figure 1. Terrestrial laser scanner data of a forest inventory plot (panoramic projection of point cloud intensity).

technology and performance parameters of different types of terrestrial laser scanners. Section 3 outlines the techniques used for automatic tree geometry parameter extraction from laser scanner point clouds. The results of five different pilot studies are presented and discussed in section 4.

2. Terrestrial laser scanner instruments and data acquisition

Terrestrial laser scanning has been used increasingly in geodesy and photogrammetry over the past few years. Laser scanners can be considered as a bridge between engineering geodesy and photogrammetry, combining tachymeter-like instrument design principles with data processing methods mostly derived from photogrammetric image analysis techniques. Laser scanners generate 3D point clouds consisting of several million 3D points densely representing an object surface in a polar measurement mode by scanning in two directions and measuring distances. These 3D point clouds can be considered either as an end-product or as a basis for generating value-added structured data products.

2.1 *Laser scanner instrument categorisation*

Laser scanner instruments that are currently on the market can be categorised according to the following criteria:

- *Range measurement principle*. Most scanners use time-of-flight measurement for range determination. The precision of time-of-flight measurement is usually limited to 5–10 mm. Some scanners use phase modulation techniques to achieve a higher range measurement precision of 1–3 mm. This principle comes with the disadvantage of a limited range due to wave number ambiguities. The highest precision, however, at a rather limited range, can be achieved by scanners following the triangulation principle with a laser source and a position-sensitive receiver delivering an angular measurement arranged at a fixed base.
- *Beam deflection principle*. Laser scanners scan an object surface sequentially in two scanning directions, with the beam deflected by galvanometric mirrors, polygon wheels, rotating elliptical mirrors, rotation of the instrument or combinations thereof.
- *Field of view*. Most laser scanners offer a panoramic 360° horizontal field of view with a vertical opening angle between 80° and 135°, with the latter offering the possibility of hemispheric scans. Some scanners offer a camera-like rectangular field of view.

Further differentiating factors may be the maximum range (between less than 20 m for triangulation scanners and more than 1000 m for some time-of-flight scanners) or the data rate (2000 to 625 000 points per second with current instruments). Some instruments offer an integrated camera, allowing for the simultaneous acquisition of co-registered high-resolution colour image data and for the fusion of point cloud and image data processing.

A laser scanner to be used in typical forest inventory applications should have a maximum range of at least 50 m to allow for scanning typical forest inventory plots with a radius of 12–15 m with trees of height up to 40 m. The data rate should be at least 10 000 points per second to allow for time-efficient operation. For flexibility in data acquisition, a scanner should offer a panoramic or hemispheric field of view.

The range measurement precision should be better than 10 mm to allow for an adequate precision in stem diameter determination. Special consideration has to be given to problems caused by multiple echoes obtained from a single pulse, such as from twigs partially occluding each other. All range measurement principles may produce ghost points (data points between objects with no physical justification) in these cases (Böhler and Marbs 2004), which have to be considered in the development of data processing schemes.

2.2 *Plot data acquisition*

In the stationing of the instrument, single scan and multiple scan set-ups can be distinguished. While multiple scan set-ups provide the best plot coverage, panoramic single scan set-ups are preferred from an economic point of view (Thies *et al.* 2003). The data processed in the studies presented here were acquired with two state-of-the-art terrestrial laser scanner instruments (Riegl LMS Z420i and Faro LS 800 HE80, figure 2). Laser scanner instrument specifications are given in table 1. The scanner is assumed to be levelled. If this is not accomplished by an integrated sensor in the scanner, point clouds have to be levelled by a transformation onto levelled control points.

Five pilot studies were performed to validate the quality of terrestrial laser scanner data and to verify the performance of automatic data processing schemes. The studies include coniferous forest and deciduous forest as well as mixed forest scanned in both single scan (figure 1) and multiple scan modes with three instrument positions (figure 3).

3. Data processing methods

Terrestrial laser scanners are often used as pure 3D point cloud generation tools with the goal of interactive measurement of relevant parameters in the point cloud, thus shifting the survey interpretation task from the field to the office. Of greater interest from a scientific and economic point of view, however, are techniques for

Figure 2. Riegl LMS Z420i and FARO LS 800 HE80 terrestrial laser scanner instruments.

Table 1. Laser scanner instrument specifications.

	Riegl LMS-Z420i	Faro LS 800 HE80
Laser class	1	3b
Range finder	Time-of-flight	Phase shift
Field of view (°)	360 × 80	360 × 320
Measurement range (m)	2–800	up to 80
Distance accuracy (mm)	5–7	3
Points per second	12 000	120 000
Beam divergence (mrad)	0.25	0.25
Weight (kg)	14.5	14.5
Speciality	W-LAN-operable, mountable camera	Integrated PC

the automatic derivation of task-relevant parameters from point clouds. In the following, we show a fully automatic point cloud processing scheme with the aim of extracting forest inventory relevant parameters from terrestrial laser scanner point clouds. In the first step, a segmentation is performed with the aim of detecting and extracting stems from terrestrial laser scanner data after a terrain model reduction. Subsequently, tree heights, DBHs and stem profiles are determined from the segmented point clouds representing individual trees.

3.1 *Digital terrain model reduction*

Determination of tree height and DBH requires the determination of a local digital terrain model. Point clouds produced by terrestrial laser scanners include a large number of ground points. A simple height histogram analysis searching for maxima in predefined XY-meshes of the laser scanner data, followed by a neighbourhood consistency check and bilinear interpolation in the meshes, proved to be sufficient to provide a suitable terrain model for height reduction (Bienert *et al.* 2006). At the same time, the analysis performed well in removing ghost points far below the terrain surface, which were found in the FARO scanner data.

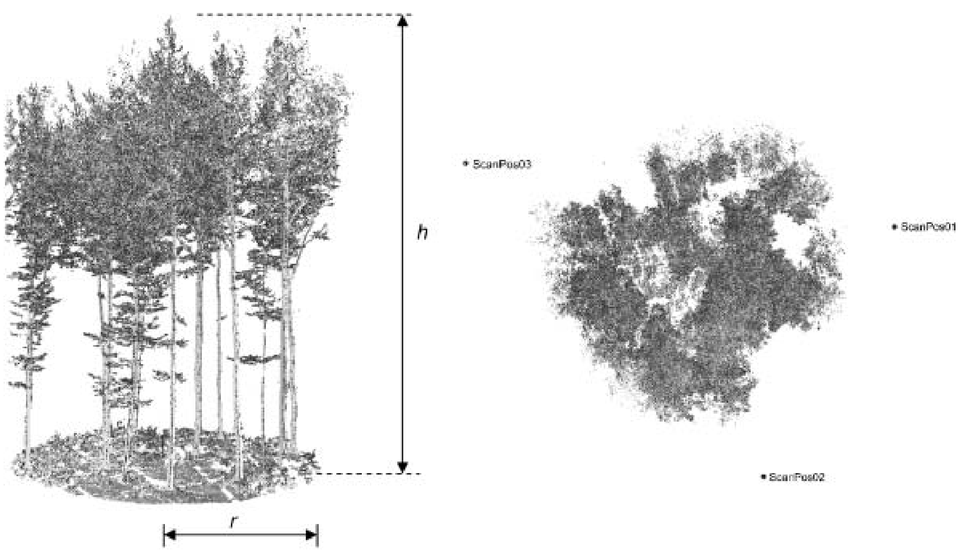

Figure 3. Multiple scan data from three instrument positions (side and top view).

3.2 *Detection of trees*

The tree detection process is based on mathematical morphology techniques (Serra 1982), extended from raster image analysis to irregularly distributed points in horizontal slices of the laser scanner data. A horizontal slice with a predefined thickness d (typically 5 cm) is cut out of the point cloud at a predefined height H_{slice} above the ground after digital terrain model reduction. Then a square structure element with a size s (typically 20 cm) is moved in steps of $s/2$ over the XY-projection of the points in the slice, starting at an arbitrary point. If the structure element covers more than a preset number of n_{min} points at a position, all points within the structure element are considered to belong to a cluster. The algorithm then moves the patch by $s/2$ in each direction if the respective quadrant of the patch contains data points (figure 4). It stops and moves to a new starting point if no more points are detected. Clusters are separated when they are more than $s/2$ apart. In the next step, a circle is fit into the cluster. The cluster is accepted as a tree if the following conditions are fulfilled:

- The cluster contains more than n_{min} points.
- The radius r of the fitted circle is above a threshold r_{min} (to avoid the detection of smaller objects such as bushes, etc.).
- The standard deviation σ_P of the cluster points to the fitted circle is smaller than a preset maximum σ_{max}.

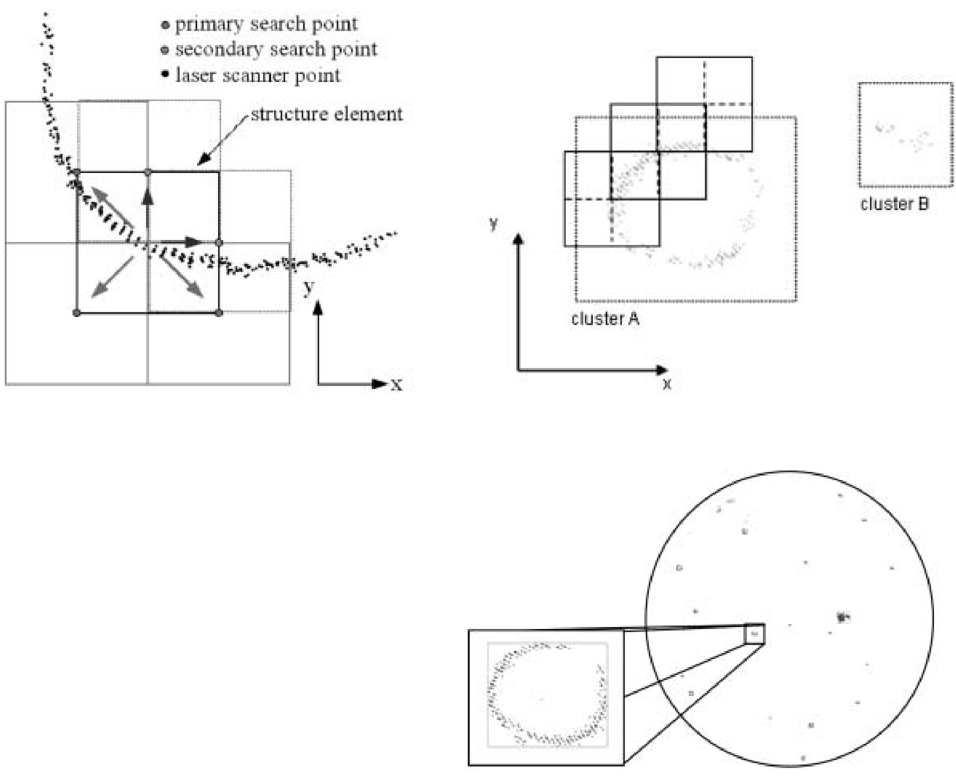

Figure 4. Cluster search procedure with a square structure element.

If the conditions are fulfilled, the centre of the fitted circle defines the (X,Y) coordinates of a detected tree. The technique, which is described in more detail by Bienert *et al.* (2006) and Scheller and Schneider (2006), can be applied to multiple scan data delivering full circles as well as to single scan data delivering only about 160° sectors of tree cross-sections. Optionally, the whole procedure can also be applied in multiple slices at different heights, exploiting the redundancy in the dataset to improve the reliability of the detection process. In that case, a cluster will only be accepted as a tree if the stem is consistently detected in all slices.

3.3 *DBH determination*

DBH is defined as the diameter 1.3 m above the finished grade at the end of the trunk. Therefore, a vertical cylinder placed at the (X,Y) position of a detected tree is used to extract the data points on the stem and the neighbouring terrain points. Based on the tree position, the radius and the slope of the terrain at the tree obtained from the local digital terrain model (see section 3.1), a representative ground point on the hillside of the stem can be calculated (Bienert *et al.* 2006). Figure 5 (left) shows the representative ground point of a tree on sloped terrain.

Each tree will be separated by cutting a vertical cylinder with a radius r_2 (typically 1.5 m) out of the scan dataset to reduce processing time. The DBH is determined by cutting a horizontal slice with a thickness d at a height of 1.3 m above the representative ground point. If the slice contains more than a preset number of $n_{\min}$ points, an adjusting circle is fit into the 2D projection of the points of that slice (figure 5). After the circle fitting, the residual of each point to the circle is analysed. Points with a residual greater than a preset threshold $d_{\max}$ will be deleted. The circle fitting procedure, which is similar to the one described by Henning and Radtke (2006), is applied recursively. As a result, an improved tree position and the DBH are obtained. In addition, the adjustment procedure delivers the standard deviation of unit weight as well as the standard deviation of the position and the DBH, which can be used for quality checking. Robust estimation techniques allow gross errors in the data points to be eliminated, which may for instance be caused by twigs, leaves, neighbouring vegetation or instrument errors (section 2.1), thus warranting high reliability of the method.

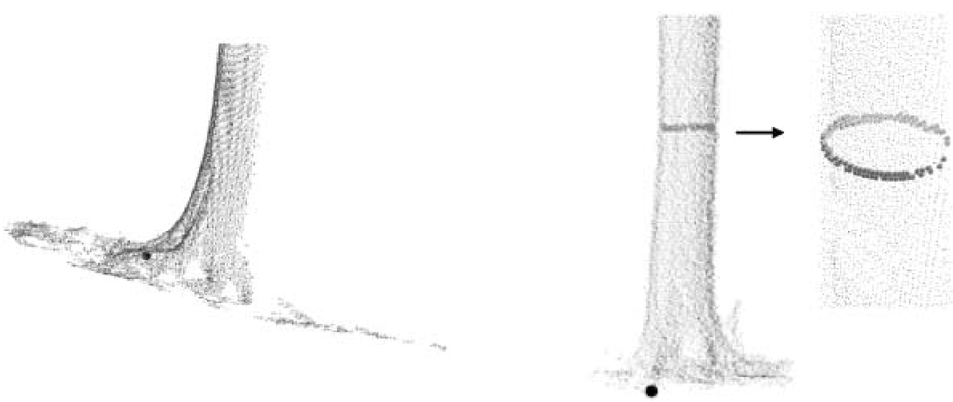

Figure 5. Ground point of the tree on sloping terrain (left), circle in data points representing diameter at breast height (right).

3.4 *Tree height determination*

Tree height is calculated as the height difference between the highest point of the point cloud of a tree and the representative ground point as outlined in section 3.3, similar to the procedure described by Hopkinson *et al.* (2004). The tree top is defined as the highest point in a vertical cylinder of a radius r_2 (figure 6). As a consequence of the undersampling character of laser scanner data, this procedure probably leads to a slight underestimation of the tree height. Moreover, the highest point of the point cloud may not be representative for the tree height as a consequence of occlusions, thus further limiting the precision potential of tree height determination. In dense forests, a vertical slice analysis of the points in the vertical cylinder should be performed to reduce the probability of finding points belonging to neighbouring trees.

3.5 *Stem profiles*

Repeating the technique of stem position and DBH determination as outlined in section 3.3 for predefined height intervals at the same (X,Y) location, stem profiles can be determined straightforwardly. These profiles contain information on the

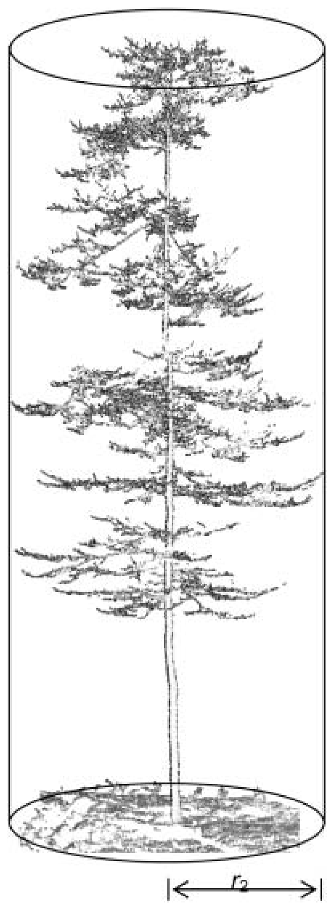

Figure 6. Tree height determination cylinder.

shape, uprightness and straightness of the stem. Using knowledge on the tapering of the stem in a subsequent filtering operation, the probability of gross errors in the diameter determination can be further reduced. A reliable automatic stem profile extraction technique is of particular interest for use in inventory applications involving large, high-value trees, where errors in estimating upper-stem dimensions could be costly.

4. Practical results

The methods of automatic laser scanner data processing as outlined in section 3 are operational and were tested in several pilot studies using data from different scanners in test regions in Germany, Austria and Ireland. In the following, results from five different test plots in closed forest stands are presented and analysed. Table 2 gives an overview on the test plots. For all plots (except for the Irish plot), reference data on the number of trees, tree height and DBH were taken using conventional forest inventory techniques.

The studies contain three plots in an Austrian forest scanned in spring using the Faro LS 800 HE80 in single scan mode. The plots are located in hilly terrain with sparse ground vegetation. Plot 1 (figure 1) includes 100-year-old spruce trees (78%) as well as some fir (11%) and beech (11%) trees. Another test site (plot 2) mainly consists of spruce (66%), larch (17%) and Douglas fir (17%). The stand age was 65 years. In addition, a plot with 105-year-old beeches was recorded (plot 3). One plot (plot 4) was scanned in multiple scan mode using the Riegl LMS Z420i. The scanner was placed at three positions outside of the plot with a distance of 40 to 60 m between the positions. The individual point clouds were automatically co-registered by using retro-reflective targets that can be detected in the laser scanner data based on their intensity. Homologous targets in multiple scans can be identified in a combinatorial approach based on their 3D distance patterns. They form the basis for a 3D coordinate transformation between multiple local coordinate systems. The test site consists of 140-year-old beeches on sloped terrain with a steepness of 5.5° and was scanned in winter.

Table 2. Characteristics of test plots.

	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Characteristic	Leaf-on, hilly terrain	Leaf-on, hilly terrain	Leaf-on, hilly terrain	Leaf-off, sparse ground vegetation, slope terrain, snow	Flat terrain, no understorey
Tree population	Spruce (78%) Beech (11%) Fir (11%)	Spruce (66%) Larch (17%) Douglas fir (17%)	Beech	Beech	Sitka spruce
Age (years)	100	65	105	140	35
Recording season	Spring	Spring	Spring	Winter	Autumn
Scan mode	Single scan	Single scan	Single scan	Multiple scan	Single scan
Scanner	Faro	Faro	Faro	Riegl	Faro
Plot radius (m)	15	15	15	12	15
Data points	3 018 916	15 257 069	17 562 118	2 363 221	5 473 340

Another plot (plot 5) was acquired in a 35-year-old Sitka spruce plantation in Ireland on flat terrain with no understorey. This plot was also scanned in single scan mode using the Faro LS 800 HE80. For this test site harvester data were retrieved. Harvester machines are equipped with sensors to measure the length of a tree bole and the diameter along the stem.

4.1 *Tree detection*

Table 3 gives an overview on the results of tree detection. Type I errors (trees that were not detected) are mostly caused by full or partial occlusions of stems in single scan data. Taking into consideration that type II errors (false detections) can largely be eliminated by checking the tree height or by an analysis of the stem profile, the overall success rate is 97.5%. Future work will aim at further improvement in the detection rate mainly by applying the multilayer consistency check detection technique as suggested in section 3.2.

4.2 *DBH determination*

Table 4 shows the results of automatic determination of DBH compared to conventional calliper measurements. Overall, a root mean squared (RMS) error of 1.8 cm could be obtained from the comparison, with the multiple scan data in plot 4 (beeches) showing slightly better results (1.5 cm), and the worst results (3.2 cm) obtained from the single scan data in plot 3 (beeches). For plots 1, 2 and 3 recorded with the Faro scanner, the interior standard deviation of DBH determination, obtained from the circle fit procedure on a large number of data points, was 0.3 cm; the standard deviation of unit weight (here: single data point coordinate precision) was 0.5 cm. Plot 4 (recorded with the Riegl scanner) has an interior standard deviation of DBH determination of 0.5 cm and a standard deviation of unit weight of 1.4 cm (table 4), The standard deviation of unit weight contains the instrument precision as well as deviations of the stem from circularity. The results in table 4

Table 3. Results of tree detection.

	Plot 1	Plot 2	Plot 3	Plot 4
Number of trees	15	29	24	14
Segmented objects	15	30	26	15
Detected trees	13	29	24	14
Type I error	2	0	0	0
Type II error	2	1	2	1

Table 4. Differences between DBH from laser scanner data and calliper measurements in cm.

	Plot 1	Plot 2	Plot 3	Plot 4
Minimum difference	−0.01	0.21	0.08	0.0
Maximum difference	2.50	−4.43	−6.17	−3.30
Arithmetic mean	−0.67	0.49	1.58	0.93
RMS error	1.80	1.80	3.25	1.48
Average number of points for DBH fitting	187	540	510	175
Arithmetic mean of standard deviation of the diameter determination	0.6	0.2	0.1	0.5
Arithmetic mean of standard deviation of unit weight	0.5	0.5	0.4	1.4

show that the precision of data recorded by a time-of-flight measurement scanner is worse than the precision obtained by a laser scanner based on phase-shift distance measurement. The internal precision parameters for DBH determination are not confirmed by the external accuracy verification based on calliper measurement comparison, which is significantly worse than the internal precision for plots 1, 2 and 3. This may also be attributed to the fact that the calliper measurement does not qualify as a perfect reference for the verification of the precision of diameters derived from laser scanner point clouds. Generally, both scanners show a measurement precision potential that is sufficient for DBH determination at centimetre accuracy.

It should also be noted that plots 1, 2 and 3 were scanned in a single scan set-up, leading to perimeter coverage of the order of 160°. This coverage turned out to be sufficient for determining the DBH for stems with a circular or almost circular cross-section. Only plot 4 has 360° point coverage of the stem, which would be a prerequisite for the determination of ovality of the stem cross-section. As can be seen from the results in table 4, plot 4, although captured by a time-of-flight scanner, shows the best accuracy. This indicates that the number of scans (and thus the point coverage on the stem) has a larger influence on DBH accuracy than the distance measurement principle of the scanner. A slight overestimation of the stem diameter, which was found for three plots, can be expected as a consequence of the beam diameter of the laser scanner, which is about 10–12 mm for both scanners. This might be compensated in the future by a distance and beam divergence-dependent correction term, thus further improving the precision of tree diameter determination.

4.3 *Tree height determination*

The results of the tree height determination are summarized in tables 5 and 6. Table 5 lists hand-held tachymeter height measurements for one tree from each species in each plot, compared to height values that were derived automatically from the laser scanner point cloud as described in section 3.4. The mean value of the differences is −0.64 m and is thus in agreement with the expected underestimation of tree height, but the RMS error is 4.55 m and thus much too large. Even if two outliers are removed from the dataset, the RMS error is still 2.07 m.

Table 5. Comparison of tree heights (in metres) derived from laser scanner data with tree heights measured by a hand-held tachymeter.

Plot	Species	Measured	Scanner	Difference
1	Spruce	28.00	25.49	−2.51
1	Fir	29.00	26.79	−2.21
1	Beech	30.00	19.47	−10.53
2	Spruce	32.00	38.74	6.74
2	Larch	32.00	34.17	2.17
2	Douglas fir	34.00	31.07	−2.93
3	Beech	36.00	37.80	1.80
4	Beech	29.70	31.17	1.47
4	Beech	32.10	32.32	0.22
Mean value				−0.64
RMS error				4.55

Table 6. Comparison of tree heights (in metres) derived from laser scanner data with tree heights estimated by applying uniform height curves.

	Plot 1	Plot 2	Plot 3	Plot 4
Number of trees	6	9	7	12
Minimum difference	0.22	−1.11	0.75	−0.09
Maximum difference	−6.39	9.30	−6.90	7.76
Arithmetic mean	−0.02	1.58	−0.48	2.25
RMS error	4.00	3.95	3.86	3.24

The mean tree heights (h_m) of each species per plot from table 5 and their diameter at breast height (d_{bh}) were used to extrapolate the heights (h) of the remaining trees in the respective plots, following a standard forest inventory procedure of uniform height curves with species-specific coefficients b_0, b_1 and b_2 (Hradetzky 1999) as shown in equation (1).

$$h = (h_m - 1.3)\exp(b_0 + b_1 h_m + b_2 d_{bh})\left(\frac{1}{d} - \frac{1}{d_{bh}}\right) + 1.3 \qquad (1)$$

Table 6 compares the tree heights derived from the laser scanner point clouds and the extrapolated heights and shows the RMS error, mean, maximum and minimum values of the heights of plots 1, 2, 3 and 4. The RMS error is between 3.20 m and 4.00 m. It should be noted that the RMS error is influenced by the reliability of the laser scanner data processing as well as by the tachymetric reference height determination and the plot extrapolation scheme. Plot 4 has the smallest RMS error and the smallest systematic difference to the reference measurements. This can be explained by the better point coverage achieved by the multiple scan mode applied in plot 4 and by less occlusions because the data were obtained in winter.

In conclusion, the precision and reliability of processing the data with these simple methods is currently too poor to encourage the professional use of the technique for tree height determination in forest inventory. Further work will have to address the information content of the point cloud itself to assess the effect of occlusions and to verify the presence of treetop points in the point cloud. If these points are not present in the point cloud, the acquisition scheme should be modified. If they are present, the data processing scheme for tree height determination should be improved, as suggested in section 3.4.

4.4 *Stem profiles*

Applying the circle fit procedure as described in section 3.3 at multiple height steps, vertical stem profiles can be derived. To assess the accuracy of profile fitting, harvester data were retrieved for plot 5. Figure 7 shows a comparison between a stem profile derived from laser scanner data and the harvester data for the same stem. The RMS error of the profile differences over the whole tree is 4.7 cm. As can be seen in figure 7, some larger differences occur in the lower and upper parts of the stem. The differences in the lower part of the stem can be explained by the non-circularity of this part of the stem. The deviations in the upper part are mainly caused by branches and could be removed by a model-based filtering of the profile. In the most relevant part of the stem from the beginning of the trunk at 0.70 m up to a height of 7.70 m, the RMS error is only 1.0 cm.

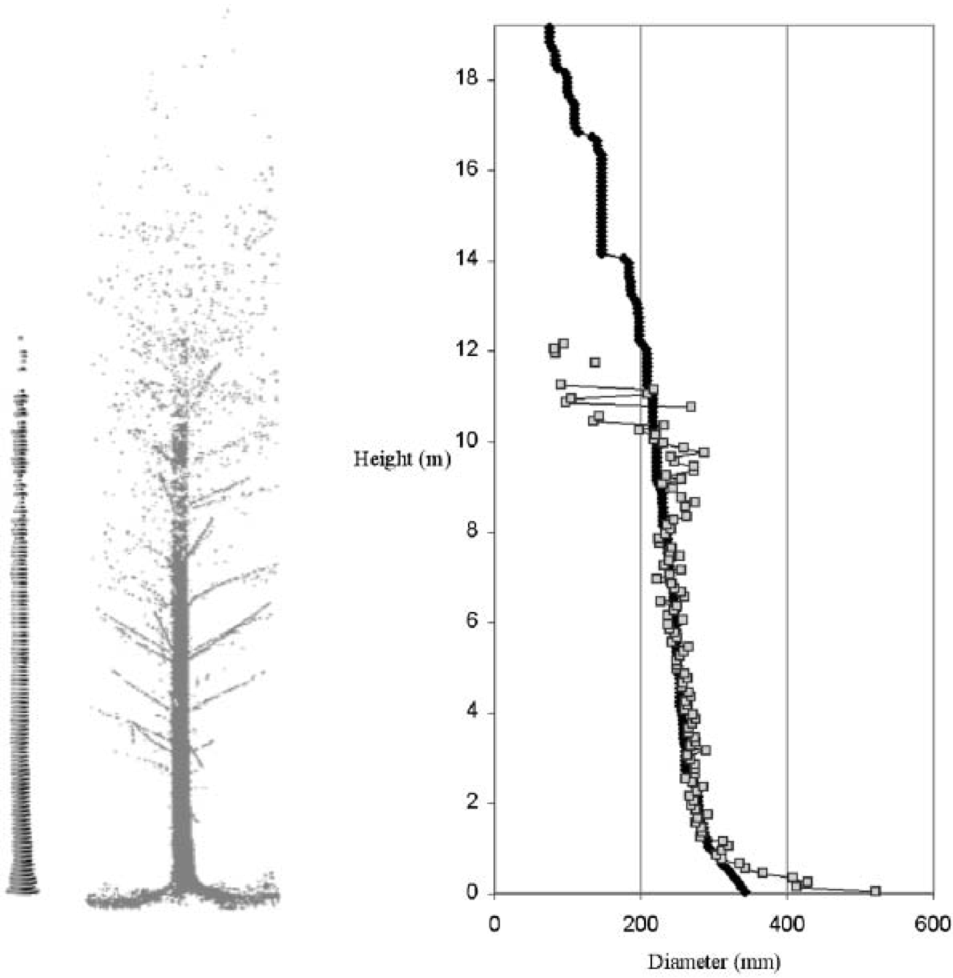

Figure 7. Scanned Sitka spruce (plot 5) with profiles, comparison between diameters derived from laser scanner data (light grey) and diameters determined by a harvester (black).

5. Discussion and conclusions

Although the results presented here are only the outcome of pilot studies that can be improved in several aspects, they show the application potential of terrestrial laser scanning in forest inventory and forest management tasks. Whereas conventional inventory techniques are based on distributed small plots and have to rely on statistical extrapolation techniques, airborne laser scanning acquires full area data, but is limited to the determination of tree parameters that can be derived from terrain and crown height models by applying suitable models (Næsset 1997, Schardt *et al.* 2002). Terrestrial laser scanning, combined with automatic data processing tools, delivers extended capabilities at fine scales and may bridge the gap between conventional inventory techniques and airborne laser scanning. Airborne laser scanner data processing delivers digital terrain model information at 10–20 cm height precision and canopy height model data at about 1 m precision (Maas 2005), whereas terrestrial laser scanning delivers precise and reliable stem geometry information in an efficient manner. Obviously, there are limitations for the use of terrestrial laser scanning in dense forests with intensive ground vegetation; the technique is much better suited for commercial forests with less complex structure and little understorey. An optimised data acquisition workflow might be achieved by mounting a scanner on an all-terrain vehicle, such as a quad.

The methods shown and analysed in sections 3 and 4 are operational but can be further improved by using multiple layer techniques to optimise the tree detection process and by improving the procedure of slicing the cylinders used for tree height determination to avoid points of neighbouring trees affecting height determination. In addition to the tree geometry parameters discussed in section 3, further parameters such as ovality of the stem, open stem height, tree topology, branch angles, branch diameters or structure and damage to the bark can be determined by an extension of the techniques. Using shape and image information derived from laser scanner data in combination with classification techniques applied to images of an integrated camera, an automatic tree species recognition as a prerequisite for biodiversity analysis may be envisaged. Because of the character of an automated, objective measurement technique, the method is also well suited for change detection tasks in multitemporal scans.

One option for a reduction in the effort of data acquisition is provided by novel range cameras, which will soon be commercially available. Range cameras (see, for example, Oggier *et al.* 2003) are based on Complementary Metal Oxide Semiconductor (CMOS) sensors, with each pixel acting as an electro-optical rangefinder. They deliver a greyscale image plus a range image with a distance measurement for each pixel. Range cameras are very compact, hand-held devices and their price will be much lower than the price of a terrestrial laser scanner system. Current prototypes show several technical limitations such as a sensor format of only up to 176×144 pixels, a maximum range of 7.5 m and a distance precision of about 1% of the measured distance. Once these limitations are overcome, range cameras combined with a Global Positional System (GPS) receiver could well be used for fast and flexible data acquisition in forestry tasks.

Acknowledgements

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