

METHODS FOR THE AUTOMATIC GEOMETRIC REGISTRATION OF TERRESTRIAL LASER SCANNER POINT CLOUDS IN FOREST STANDS

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ABSTRACT:

A combined analysis of multiple terrestrial laser scanner point clouds recorded from different positions requires a geometric registration of these scans. In most applications of terrestrial laser scanning, artificial tie points, which can be recognized automatically by proprietary scanner software, are placed in the scanning area. In this case, the scan positions have to be chosen in a way that they ensure a clear view to the tie points. These pre-scanning tasks may be often labour-intensive and time-consuming. Therefore, an automatic registration process without pre-assigned artificial tie points is aspired.

This paper will discuss two methods for the registration of terrestrial laser scanner point clouds in forestry applications: In a first step, our automatic registration procedure on the basis of an intensity image of a laser scanner data will be presented. The tie points (in this case white spheres) are detected in the intensity image. Corresponding points are found by calculating a distance pattern of all detected spheres on the basis of their centres derived from the range data. In a second step towards avoiding artificial tie points, a novel method to register two laser scanner datasets on the basis of extracted tree axis and only one tie point is introduced. Finally the results of three different registration processes (interactive, sphere detection, tree axes) are compared and discussed.

1. INTRODUCTION

To ensure a scan of a large object without shading zones, different laser scanner positions are necessary. Each scan position defines a local co-ordinate system. The point clouds of each viewpoint are referred to this local frame. Analysing different laser scanner positions requires a common reference system. This transformation process of all local systems into a common reference system is called registration. Often a central viewpoint defines the common reference system.

Much work has been done on the geometric registration of terrestrial laser scanner point clouds in the past few years. Two types of registration are distinguished: A marker based registration and a marker free registration (feature based) registration.

The marker based registration is a reliable and precise method, but sometimes time-consuming. Before scanning the targets have to place inside the scanning area. Afterwards they have to be collected and a manual or automatic recognition have to be done to define corresponding points for the registration. Almost all application software of terrestrial laser scanners provide the registration of different scan positions by the use of artificial 2D or 3D targets (e.g. retro reflective targets, spheres, cylinders) to match the different scan positions. Thereby the extracted centre points of the artificial tie points are used as input for the registration process. Herein two processing steps can be distinguished: The identification of the marker and the matching algorithm to find homologue points between two scan scenes. Akca (2003) presents a fully automatic registration on the base of flat markers. The marker detection is done in a 2D intensity image of a laser scan by the use of a cross-correlation matching method. For each point in the target reference system all combinations with the enclosed space angle and its two distances is calculated and compared with the space angle-

distance combinations of the other system. The point belongs to its matching partner if a compatible 3D triangle exists.

The most famous marker free registration algorithm is the iterative closest point (ICP) introduced by Besl & McKay, 1992. Hereby two overlapping point clouds are registered iteratively, based on the minimum Euclidean distance. Many variations of this algorithm exist. A feature based registration makes use of extracted natural features, such as points, edges, planes or cylinders, in the point cloud. Böhm & Becker (2007) and Kang et al. (2008) use the SIFT algorithm to extract distinctive points in intensity images. Applying RANSAC (Böhm & Becker, 2007) homologue points can be detected in different images. Kang et al. (2008) calculate a Delaunay Triangulated Irregular Network to use the distance relation of the triangles to detect corresponding points. Other groups handle cylinders and planes (Rabbani et al., 2006; Brenner et al., 2008) to register the scans.

Registration also plays an important role when using a terrestrial laser scanner in forestry applications. Most users, for instance Thies et al. (2004), Hopkinson et al. (2004) and Wezyk et al. (2007), use artificial targets to register forest scenes. Henning & Radtke (2006) present a registration algorithm for use in forestry applications, which deals with estimated centre points of tree stem profiles. An ICP procedure uses these distinctive points to transform one scan to the other. A modified method is reported in Henning & Radtke (2008). Besides the estimated centre points, matched tie points from the ground are used to avoid singularities in Z-direction.

The registration process in forest stands goes along with occlusions caused by ground vegetation and trees. So the placement of the markers (tie points) is restricted by the trees and vegetation. An optimum placement of the tie points can only be reached by a time-consuming pre-scanning analysis. Therefore the goal of the work presented here was to develop a method which allows an automatic geometric registration in

forest stands. In the following section the study area will be outlined. The papers focus is on the registration of laser scanner point clouds in forest stands. Methods for the geometric registration via artificial tie points or tree axes are presented in Section 3. In Section 4, the paper will show the results from the dataset. Finally a discussion completes this article.

2. STUDY AREA AND RECORDING

2.1 Dataset

In August 2008, terrestrial laser scanner data were acquired on two plots in a spruce stand in the Tharandter Wald, Saxony, Germany (N 50°57'49", E 13°34'01"). The stand has an age of 120 years, no understorey and flat terrain (Figure 1).

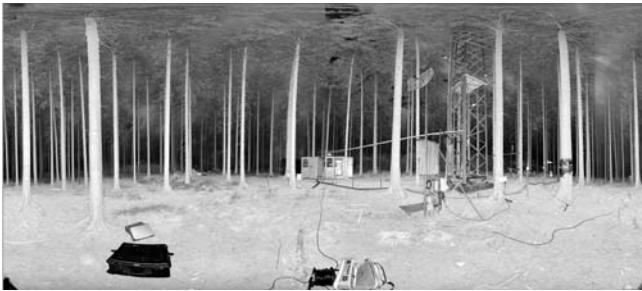


Figure 1. Intensity image of the study area

2.2 Data recording

A Faro LS 880 laser scanner was used with a scan resolution of 0.036°. The scanner was levelled with a built in circular bubble. By measuring up to 120,000 points per second and a field of view of 360° x 320°, the scan process needs about 6 minutes. The range finder works on the principle of phase shift measurement and achieves a range measurement precision of ± 3 mm in an ambiguity interval of 76 m (Faro, 2006).

The distance between both scanner positions was approximately 12 m. Figure 2 shows a horizontal slice through the point clouds after registration. The tie point positions are marked as black crosses and the trees as arcs. A total of 9 tie points (white spheres with a radius of 7.25 cm) were placed in the scan area.

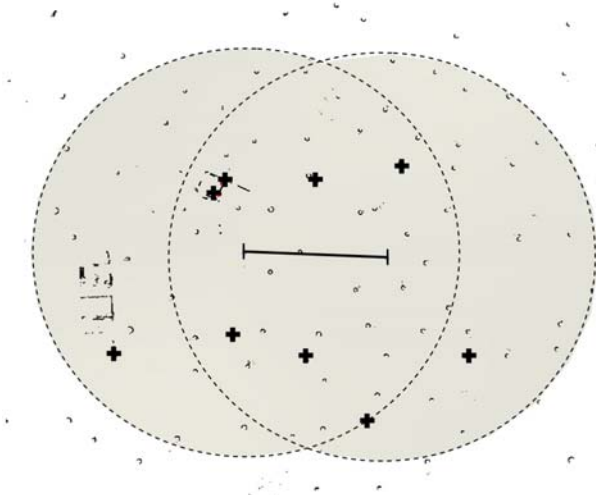


Figure 2. Scheme of the plot configuration (plot radius 18 m) with tie point position (black cross) and base between viewpoints (black line)

All tie points have a 3D distance d_1 between $6 \text{ m} \leq d_1 \leq 20 \text{ m}$ to the first viewpoint and 3D distances d_2 between

$8 \text{ m} \leq d_2 \leq 24 \text{ m}$ to the second viewpoint. A deviation of the vertical axis of 0.024° (viewpoint 1) and 0.025° (viewpoint 2) were recognized with the built-in inclinometer.

3. METHODS

3.1 Manual registration with *Faro Scene*

A software to handle point clouds recorded with a Faro scanner is *Faro Scene*. This software provides a wide range of point cloud processing tools. Besides the data management of different scan projects, the visualisation and analysis of point clouds is a fundamental tool. Also an object fitting of spheres, planes and cylinders is possible. The sphere fitting algorithm is used to detect tie points and transform the different point clouds in common reference systems.

As described in Section 2.2, the used tie points were white spheres with a radius of 7.25 cm. The registration process is done by marking all tie points in *Faro Scene* in each 2D intensity image. Corresponding spheres are identified by the user itself and obtain identical names. Two options are given for calculating the centre point of each sphere. First the sphere fitting in the range data with a fixed radius (7.25 cm) and second a sphere fitting by adjusting the radius as well. Afterwards a transformation with the fitted centre points is done. One of the two co-ordinate systems acts as common reference system.

3.2 Automatic registration with spheres

3.2.1 Sphere detection: The automatic sphere detection, which was implemented in the course of the work described in this paper, works on the basis of the intensity image, where each pixel represents the intensity of the backscattered laser pulse. The X,Y,Z co-ordinates, the intensity (value range: 0 to 255) and the pixel co-ordinates are exported from *Faro Scene*. The workflow is divided in three parts. In the first step, an inverse binary intensity image is prepared by thresholding. All light areas with a grey value greater than 242 are contained as black pixels (value: 0, e.g. parts of trees, ground and tie points (Figure 4, left)) and the remaining pixels as white pixels (value: 1) in the binary array.

The spheres appear as a closed circular area in the binary image. To eliminate points, which do not belong to the sphere surface, an erosion operation is performed. A 3x3 square structure element moves over the array and it is placed on each filled object. If the middle element is not completely surrounded by filled elements, the element is removed and its value is set to 1 (Figure 3, right and Figure 4, right).

The last part of the workflow is the cluster search. For that purpose a modified 2D cluster search algorithm, as described in Scheller & Schneider (2006) and Maas et al. (2008), is used. A square structure element with a size s (10 elements) searches for clusters in the array. All cluster points are fed into a sphere fitting routine, where a sphere with a fixed radius is fit into the XYZ co-ordinates of the cluster points. This procedure minimises the sum of squares of the Euclidean distances of the laser scanner points from the adjusted sphere. After the sphere fitting, the residual of each point to the sphere is analysed. The point with the largest residual larger than a preset threshold (typically $r_{max} = 1.0$ cm) will be deleted and the routine starts again. If the largest residual is smaller than the threshold r_{max} the procedure stops and the centre co-ordinates define the centre point. The cluster accepted as a sphere (tie point) if the following conditions are fulfilled:

- The cluster contains more than n_{min} points
- The standard deviation of unit weight σ_0 is smaller than a preset threshold $\sigma_{max} = 0.008$ m
- The cluster contains no gaps (empty pixels) inside

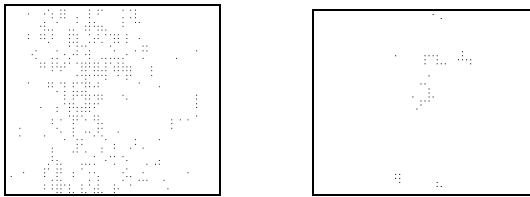


Figure 3. Stem section after thresholding with gaps (left) and stem section after erosion (right)

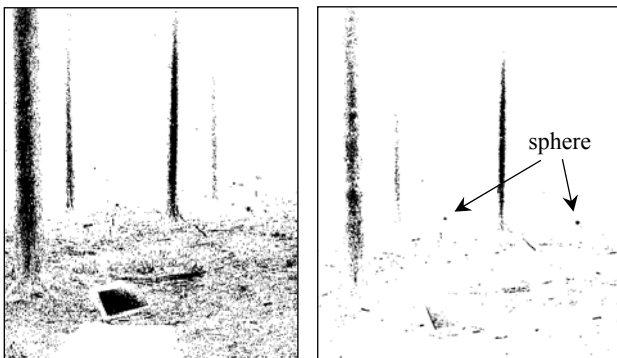


Figure 4. Detailed view of an inverse binary image after thresholding (left) and eroded image (right)

3.2.2 Corresponding tie point assignment: By calculating all possible distances S_{ij} between the detected spheres, the assignment of the corresponding tie points is done. The distance pattern is used to analyse all distances from co-ordinate system 1 with all distances from co-ordinate system 2 in an iterative manner. Figure 5 and Table 1 give an example of a simple distance pattern with 4 points. Assigning the first point of system 1 (Table 1, left), each distance combination of this point (first row) is compared with all distance combinations (row-wise) of system 2 (Table 1, right). Distance differences ΔS below a pre-setting threshold t_{dis} increase a counter. The corresponding point to point 1 of system 1 will be the point (row) with the maximum count in system 2. Afterwards the counter is set to zero and the algorithm starts again with the other rows, by skipping already assigned points.

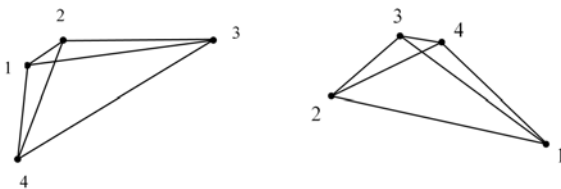


Figure 5. Example for distances S_{ij} between detected spheres (left – system 1; right – system 2)

S_{ij} [m]	j			
	1	2	3	4
1		2.51	9.06	5.8
2	2.51		7.14	7.57
3	9.06	7.14		11.22
4	5.8	7.57	11.22	

S_{ij} [m]	j			
	1	2	3	4
1		11.22	9.06	7.13
2	11.22		5.79	7.58
3	9.06	5.79		2.52
4	7.13	7.58	2.52	

Table 1. All distance combinations S_{ij} [m] of co-ordinate system 1 (left) and co-ordinate system 2 (right)

Applying a Helmert transformation with three translations and three rotations (the scale m is given by the scanner and is fixed to $m=1$) the common reference system is built (Equ. 1). At least 3 corresponding tie points have to exist to solve the equation system. In case of an overdetermined equation system (more observations than unknowns), a least squares adjustment have to be applied.

$$\bar{X} = X_0 + m * R * \bar{X} \quad (1)$$

where X_0 ... translation vector [m]
 m ... the scale factor [], $m = 1$
 R ... rotation matrix [radians]
 \bar{X} ... initial vector

3.3 Automatic registration via tree axes

In this section an approach to register forest laser scanner point clouds by the knowledge of only one corresponding point and extracted tree axes is shown. Two approaches were investigated. The basic idea is to use the normal vectors of the planes, produced by:

- Approach A1: The mean centre point of all profiles of the lower tree axis and a perpendicular axis through the tie point, given that the scanner was levelled while scanning (Figure 7).
- or
- Approach A2: The adjusted stem axis of the lower stem part and the known tie point.

As precondition one corresponding tie point (sphere) and an overlapping area of two point clouds have to exist with at least one corresponding tree for approach A1 and two trees for approach A2. In the following section approach A1 is described.

After a tree detection algorithm as described in Bienert et al. (2007), all profiles between breast height diameter (DBH) and a stem height up to 4 metre are calculated. The interval of two neighbouring profiles is 10 cm, while the profile thickness is 6 cm. With all centre points of the determined profiles the mean centre point (X_m, Y_m, Z_m) is calculated. For each tree the calculation of the normalized normal vector of the planes \vec{n}_i is performed by applying the cross product (input: mean centre point and direction vector $n_z=(0,0,1)$) (Figure 6).

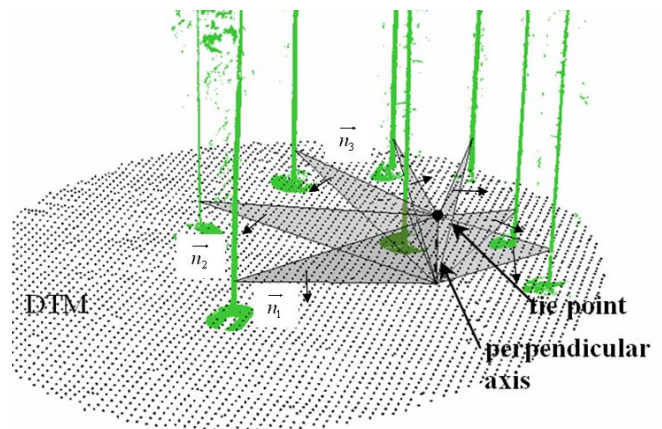


Figure 6. Extracted planes (vertical alignment) through the mean centre point of the tree axis and the tie point with direction vector n_z

Because of different viewpoints, different views to the stems are possible. Given that the stem surface show natural variations in the shape and architecture, the mean centre point describes in some cases not the same axis. Minimizing such errors the standard deviation of the mean centre point is used to filter reliable mean centre points. Only those mean centre points with a standard deviation σ_x and σ_y smaller than 1 cm are used.

In a second step the length s_i of the normal vector is set to the 2D distance detected between the mean centre point and the sphere. By shifting the normal vectors in the sphere (Figure 7), the end points of the normal vectors define new virtual points. With all virtual points of system 1 and system 2 the tie point assignment (Section 3.2.2) and subsequently a Helmert transformation is performed.

In case of straight standing trees all virtual points will define approximately a plane. A stabilisation in respect to the Helmert transformation is performed by adding one more point along the direction vector n_z 10 m below, placed in the sphere (Figure 7).

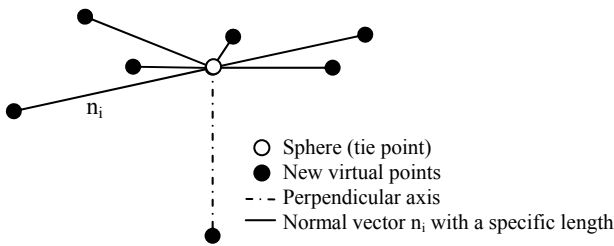


Figure 7. Principle of the determination of the virtual points of one point cloud

Approach A2 works in the same way as described for approach A1 in the upper part, but with a different determination process of the planes. With all centre points of the determined profiles the spatial direction of the stem axis is calculated by the eigenvector which corresponds to the largest eigenvalue of the matrix B. Applying the cross product the stem axes and the tie point define the planes with the normal vectors \vec{n}_i .

$$A = \begin{bmatrix} X_i - X_M & Y_i - Y_M & Z_i - Z_M \\ \dots & \dots & \dots \\ X_n - X_M & Y_n - Y_M & Z_n - Z_M \end{bmatrix}$$

$$B = A^T A$$

where X_M, Y_M = co-ordinates of the mean centre point
 X_i, Y_i = co-ordinates of the centre points

All virtual points will approximately lie on a plane. A stabilisation point to spread the virtual point cloud, as introduced in approach A1, is not considered. The outcome will be a coarse registration.

4. RESULTS

In the following, practical results obtained from the application of the methods described in Section 3.2 and Section 3.3 are presented. For comparison, an interactive registration was also performed.

4.1 Manual registration

The spheres detected manually using *Faro Scene* have different number of points $n1_i$ (scan 1) and $n2_i$ (scan 2) which were used for fitting. Their values depend on the scan resolution and the distance to the scanner. The used number of points is between

$12 \leq n1_i \leq 209$ for scan 1 and $14 \leq n2_i \leq 102$ for scan 2. The standard deviation of the position σ_{Pos} per sphere S is between $1.00 \text{ mm} \leq \sigma_{Pos} \leq 5.10 \text{ mm}$ for scan 1 and $1.05 \text{ mm} \leq \sigma_{Pos} \leq 6.12 \text{ mm}$ for scan 2. The registration parameters are shown in Table 4.

4.2 Automatic sphere detection and registration

The automatic sphere detection was done with both datasets. Therefore the inverse binarised intensity image (size: 9628 x 4305) was produced with a preset threshold. A previous analysis of all grey values of the spheres was done to define a threshold. 62% of all sphere pixels had a grey value greater than 242. The threshold was set to 242, to compromise the maximum number of sphere points with a minimum number of other object points. 2.2% (scan 1) and 2.7% (scan 2) of all pixels from the intensity image are declared as object elements (bright areas – Figure 4, left). After erosion, only 0.48 % (scan 1) and 0.39 % (scan 2) of all elements remain (Figure 4, right). The minimum point count n_{min} , which was used in the cluster search algorithm was $n_{min} = 20$. Only clusters with a point number greater than n_{min} are detected. Finally 13 objects in each scan were found, which were accepted as spheres. Table 2 shows the results of the standard deviation of the position σ_{Pos} per sphere S and the used number of point of the correct fitted spheres (no type II errors included in Table 2). The parameters d_1 and d_2 in Table 2 are the 3D distances from the spheres to the scanner.

S	Scan 1			Scan 2		
	d_1 [m]	$n1_i$	σ_{Pos} [mm]	d_2 [m]	$n2_i$	σ_{Pos} [mm]
1	20.90	-	-	11.01	136	0.62
2	18.02	24	3.76	14.54	55	1.25
3	10.99	163	0.78	11.39	126	0.77
4	7.69	326	0.58	14.81	-	-
5	14.07	48	2.78	24.43	-	-
6	6.89	540	0.45	15.93	27	3.11
7	10.26	275	0.72	17.56	21	2.99
8	8.81	227	1.04	9.07	253	0.43
9	15.53	24	5.52	8.53	273	0.44
mean	12.57	203.38	1.95	14.15	127	1.37

Table 2. Overview of the automatic fitted sphere parameters (without type II errors)

	Scan 1	Scan 2
Number of visible spheres	9	9
Sphere detection	13	13
Correct detected spheres	8	7
Type I error	1	2
Type II error	5	6

Table 3. Results of the automatic sphere detection

The results of the sphere detection are presented in Table 3. Type I errors define spheres which were not detected and type II errors define a false detection (small bright areas on stem or ground surface). The search for corresponding points with the distance pattern as described in Section 3.2.2 was performed with all detected spheres (also type II errors) and a distance threshold t_{dis} of 4 mm was used.

4.3 Registration via tree axes

For all trees inside a plot radius of 18 m the calculation of the DBH, tree height and profile determination was done

automatically with the methods described in Maas et al. (2008). Finally 32 trees are detected in the overlapping area of 562 m². 15 trees in scan 1 and 18 trees in scan 2 had a standard deviation of the mean centre point smaller than 1 cm. The normal vectors of the planes, determined with approach A1, are used to calculate the new points for registration. Finally, with a distance threshold $t_{dis} = 5$ mm, 12 corresponding virtual points (tree pairs) are found. Approach A2 was also tested. The registration was done with 7 corresponding points and a $\sigma_0 = 2.43$ cm was obtained. The results are sufficient for a coarse registration (Figure 8). A detailed presentation of the results will not present.

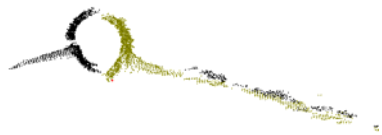


Figure 8. Coarse registration with approach A2 (registered tree profile)

4.4 Registration parameters

Table 4 shows the registration parameter of the different methods. The column of MAN I and II presents the transformation parameter of the manual sphere detection and registration. Thereby method I uses all spheres, which were well distributed in Z-direction ($\Delta Z = Z_{max} - Z_{min} = 9.98$ m), because 4 spheres are placed at the tower, fence and containers, whereas the other spheres are placed at the ground. Method II simulates the ordinary tie point distribution in forest stands ($\Delta Z = Z_{max} - Z_{min} = 0.84$ m). In forest applications the tie points are placed mostly on the ground or on sticks (Wezyk et al., 2007) with a minimal difference ΔZ between the Z coordinates.

	Method	MAN I	MAN II ¹	AUTO ²	Tree axes A1
	Number	9	4	6	12
Translation	X [m]	11.501	11.503	11.504	11.501
	σ_X [mm]	1.547	1.195	2.154	2.762
	Y [m]	-3.480	-3.480	-3.479	-3.477
	σ_Y [mm]	1.844	1.411	2.389	2.796
	Z [m]	-0.819	-0.816	-0.821	-0.824
	σ_Z [mm]	2.055	2.367	2.922	2.185
Rotation	ω [°]	0.0509	-0.0179	0.0344	0.0023
	σ_ω [°]	0.000087	0.000081	0.000121	0.000049
	ρ [°]	0.0739	0.0392	0.0969	-0.0018
	σ_ρ [°]	0.000082	0.000186	0.000148	0.000045
	κ [°]	-56.895	-56.897	-56.895	-56.8873
	σ_κ [°]	0.000056	0.000055	0.000086	0.000067
	σ_0 [mm]	4.555	2.338	4.940	4.697

¹ tie point distribution in Z, $\Delta Z = 9.98$ m

² tie point distribution in Z, $\Delta Z = 0.84$ m

Table 4. Registration parameters

The last both columns present the results of the registration with an automatic sphere detection algorithm (AUTO) (Section 3.2.1 and 3.2.2) and the registration via tree axes (Section 3.3).

Figure 8 shows a profile which was registered with the four different methods presented in Table 4. The black points are the

points from scan system 1 and the coloured points show the different registration methods. The tree was placed 5 m from scan position 1 and 16 m from scan position 2 and the profile is located at a height of 15 m. To visualize the registration results also a vertical view of a branch is shown (Figure 10 a. and b.) By regarding the detailed view of a branch (Figure 10b.) the manual registration with 9 tie points (dark blue points) and the automatic registration with 6 tie points (light blue points) reveal the best alignment.

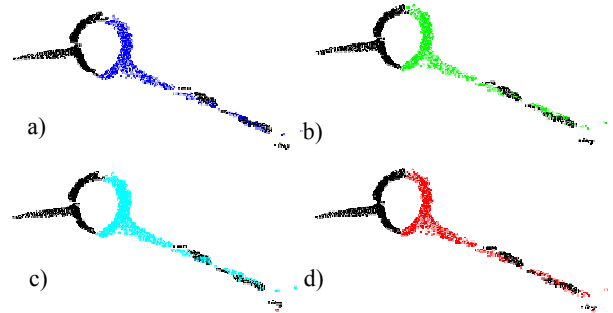


Figure 9. Registered tree profile – a.) manual registration with 9 tie points; b.) manual registration with 4 tie points; c.) automatic registration with 6 tie points; d.) tree axes based registration with 12 corresponding points

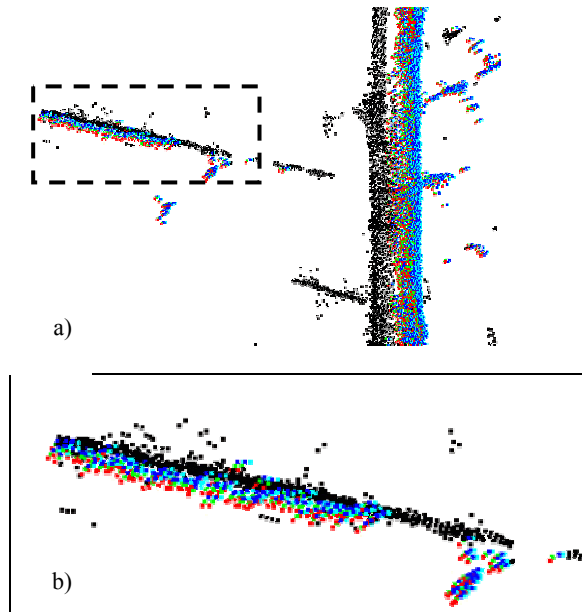


Figure 10. Stem part of a combined view of all registration methods (a); detailed view of a branch (b)

5. DISCUSSION

Two registration methods for terrestrial laser scanner point clouds were presented. First a method based on artificial white spheres are introduced. The sphere detection was done by thresholding and erosion. Therefore the information of a 2D intensity image and also the 3D information (X,Y,Z) was used. After thresholding a cluster search algorithm was performed in the inverse binary image. Applying the cluster search algorithm in a 2D array the processing time is very low. Also a cluster search in 3D space is possible but this is very time consuming and needs special filter operations to minimize type II error clusters.

In comparison with the manual sphere detection and registration as presented in Section 3.1., the automatic registration process is an objective and fast method. The used point number for the automatic sphere fitting is in contrast to the manual registration always larger. This leads in better standard deviations of the position, with some exceptions. But type I and type II errors are obtained. By tuning the parameters (minimum points n_{min} and standard deviation σ_{max}) type I errors can be avoided but at the expense of an increasing number of type II errors. Overall the tie points should be located within approximately 15 metre to ensure enough points on the sphere surface.

Due to the applied erosion, valid sphere points on the edge are deleted. The outcome is a lower point number and a missed detection of spheres located far away from the scanner (type I error). Maybe after the cluster search and before sphere fitting a dilatation can be done, to add valid sphere points. By using a fixed radius in the sphere fitting algorithm, type II errors are minimized. Remaining falsely detected spheres (type II errors) are filtered in the point assignment method (distance pattern) by setting a fixed threshold t_{dis} . A more robust method can be obtained by additionally considering of the space angles and variable distance threshold t_{dis} defined as the multiple error of distance invariance as suggested in Kang et al. (2007). Some cluster points, which describe a sphere, contain points from the neighbourhood (ground), because of their similarly large intensity and the thresholding. Applying the erosion, edge points and also some points from the ground are deleted. Also the removing of large residuals in the sphere fitting procedure reduces the number of noisy and ground points. To avoid an edge fusion of ground and sphere points, it might help to place the spheres on an artificial black background.

In a second step a novel method for the geometric registration with the help of tree axes was presented. Two approaches are possible. Approach A2 can be used as a coarse registration in forest scenes, when no levelled scanner was used. Approach A1 deliver better results and can be applied for point clouds recorded from a levelled scanner. If the point clouds are corrected with the detected inclinometer parameters the method will give better results. The datasets presented in this paper were not corrected, that means a vertical axis error is included (0.024° and 0.025°), which was caused by the setting accuracy of the circular bubble. An increase in the accuracy can be obtained by using a bubble tube instead of a circular bubble.

As shown in Figure 10 and Table 4 similar results are reached with 6 and 9 tie points and a good vertical distribution. In this test site the vertical distribution was realized with the help of available tower and containers inside the stand, which is unusual for forest plots. So the registration process in forest stands is a difficult task to solve. Finally the number of tie points and their vertical arrangement play a huge role. Also the environmental conditions (like wind and ground vegetation) influence the registration results. Overall the presented sphere detection method can be used as fine registration method, while the tree axes methods realize a coarse registration.

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