Localized Registration of Point Clouds of Botanic Trees

Alexander Bucksch and Kourosh Khoshelham

***Abstract*—A global registration is often insufficient for estimating dendrometric characteristics of trees because individual branches of the same tree may exhibit different positions between two scanning procedures. Therefore, we introduce a localized approach to register point clouds of botanic trees. Given two roughly registered point clouds PC_1 and PC_2 of a tree, we apply a skeletonization method to both point clouds. Based on these two skeletons, initial correspondences between branch segments of both point clouds are established to estimate local transformation parameters. The transformation estimation relies on minimizing the distance between the points in PC_1 and the skeleton of PC_2. The performance of the method is demonstrated on two example trees. It is shown that significant improvements can be achieved for the registration of fine branches. These improvements are quantified as the residual point-to-line distances before and after the localized fine registration. In our experiment, the residual error after the local registration is on an average of 5 mm over 90 skeleton segments, which is about three times smaller than the average residual error of the initial rough registration.**

***Index Terms*—Automation, forestry, image registration, laser scanning, least squares, parameter estimation, skeletonization.**

I. INTRODUCTION

TERRESTRIAL laser scanning is an emerging technology for capturing the dendrometric characteristics of trees. Measurement of parameters such as tree height, trunk diameter, and crown width provides valuable information for several applications, including forest inventory, biomass estimation, and evaluation of carbon stock. These parameters can be derived from laser-scanned point clouds automatically or with little manual interaction [1], [2]. Recently, methods have been developed to further characterize trees in higher detail. A prime candidate to extract a 1-D representation of the branching structure is skeletonization. Such a representation allows us to extract geometric and topologic information of the branching structure [3].

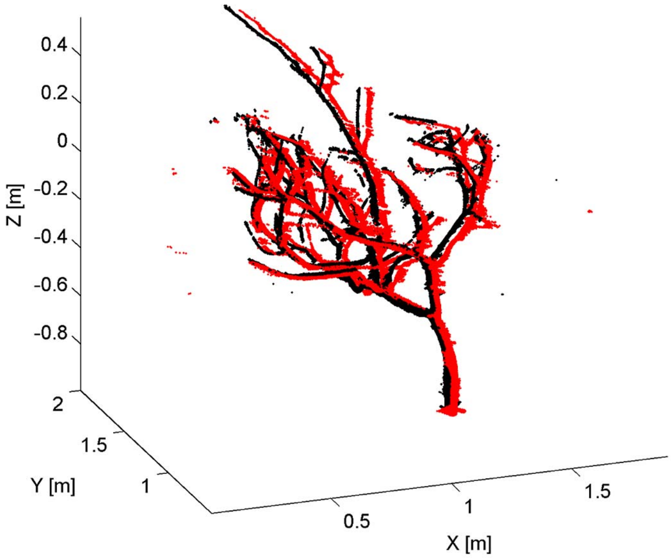

Fig. 1. Registration error on the branches.

Often, multiple scans of a tree are obtained from different locations around the tree. From each location, a point cloud is obtained from a different viewing angle. The obtained point clouds are combined into one common point cloud by a so-called registration process that estimates the transformation of the point clouds into one common coordinate system. The registration process is not problematic on tree trunks since trunks remain static during the scanning and contain most of the tree's surface area to be sampled by the scanner. The registration of finer branches, however, is a challenge. A change in environmental conditions between two scans (e.g., heat, rain, or different wind conditions) can change the bending of finer branches, which lets the same branch appear at different locations in registered scans. Such bending changes motivate our localized registration approach.

A manual registration approach, which requires the placement of markers (e.g., retroreflective spheres) to establish correspondences between the scans, is labor intensive. In particular, the placement of markers in the upper parts of the tree is impractical. Moreover, the established correspondences with markers cannot solve for the locally occurring changes. In applications targeting at the measurement of dendrometric parameters, the registration error, as shown in Fig. 1, can cause incorrect measurement results due to an overestimation of the number of branches that are present in the point cloud.

To overcome these problems, we propose a localized approach to register fine branches without using markers. We use a skeletonization method, which is called SkelTre [4], to derive

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A. Bucksch was with the Department of Geosciences and Remote Sensing, Delft University of Technology, 2628 Delft, The Netherlands. He is now with the School of Interactive Computing and the School of Biology, Georgia Institute of Technology, Atlanta, GA 30332 USA.

K. Khoshelham was with the Department of Geosciences and Remote Sensing, Delft University of Technology, 2628 Delft, The Netherlands. He is now with the Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, 7500 Enschede, The Netherlands.

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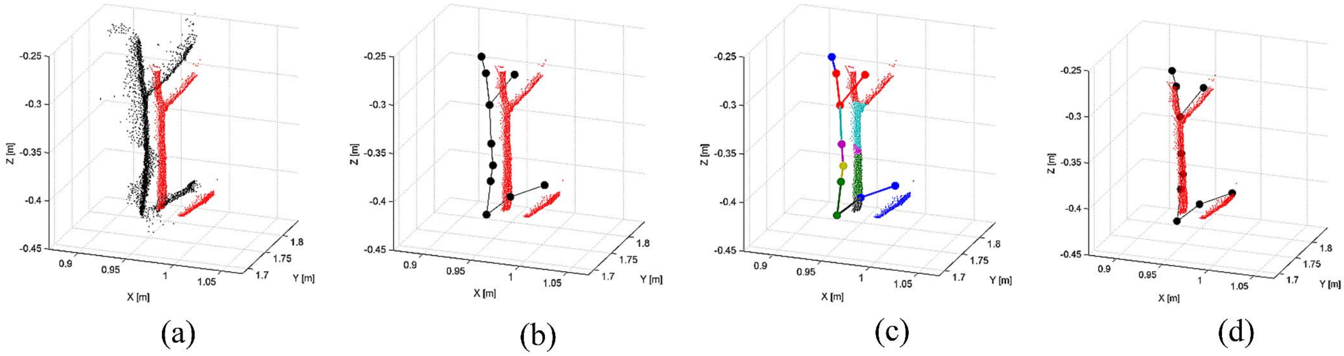


Fig. 2. Registration process. (a) Roughly registered point clouds of a branch. (b) Skeleton of the first point cloud. (c) Correspondence established between points in the second point cloud and the skeleton lines in the first one based on the minimum point-to-line distance. (d) Fine registration of the second point cloud to the skeleton.

the main structure of the branches. SkelTre is able to compute meaningful skeletons from undersampled fine branches that are less frequently sampled by the laser scanner. We improve an initial rough registration by minimizing the distances between the points in one point cloud and the SkelTre skeleton of the other point cloud. The registration is local, that is, for every pair of branch segments, a separate transformation is estimated. This localized approach guarantees a correct registration of the points on a branch level.

The following section reviews the related works and applications that can benefit from our localized registration approach. The main contribution of this letter is given in Section III, which introduces the registration method. Section IV describes the experimental results obtained by applying the method to point clouds of two example botanic trees.

II. RELATED WORKS

Over the last decades, the iterative closest point algorithm [5] and its variants [6] have become the quasi-standard to register point clouds obtained from different viewpoints of the same scene into one common coordinate system. These methods are based on minimizing the distance between corresponding point pairs that are iteratively updated to get an estimation of the registration parameters. Although a tree is scanned from several viewpoints, some parts of the crown are not sampled because the branches are occluding each other. In such unsampled parts of the canopy, it is impossible to establish point correspondences; however, a correspondence can be also established between the points and locally estimated surfaces. Chen and Medioni [7] minimized the distance between the points and the local surface of the target object. Newer methods operating on point-to-plane [8] and plane-to-plane correspondences [9]–[12] require larger planar surface segments. These types of correspondences are not suitable for registering point clouds of trees, as branches are not represented by large planar surfaces.

Forestry scenes were discussed by Henning and Radtke [13], who introduced an algorithm to register forest scenes containing multiple trees based on the trunk center. Nevertheless, they also pointed out the difficulty of selecting corresponding points in two scans of the same tree. Bienert and Maas [14] investigated automatic approaches to registering forest scenes, but the authors limited their discussion to the results achieved on the uncritical tree trunks and the first generation of branches. In applied studies, markers are usually placed under the tree, e.g., [15]. Such placement is insufficient for registering the complex structure of a tree because the height distribution of the marker points [16] causes the incorrect registration of finer branches in the canopy.

Registration on the branch level has the potential to be an essential step in existing applications and methods. Reconstruction methods, which use cylinder fitting to reconstruct the trunk and the branches, rely on accurate registration results, e.g., [17]. The reliable estimation of the wooden biovolume also relies on the extraction of dendrometric parameters from accurately registered point clouds of trees, e.g., [18] and [19]. Another potential application is the global network description of the branching structure by Horton–Strahler or Tokunaga ratios. Such network models are known to be sensitive to the younger branches representing the first order in such models [20]. An improvement in the local registration of the younger branches enhances the accuracy of such global network descriptions.

III. LOCALIZED REGISTRATION USING SKELETON LINES

The general workflow of our registration method is as follows. First, the two point clouds are manually roughly aligned by selecting feature points at branching locations. These roughly registered point clouds are then separately skeletonized and decomposed into segments by the branching nodes in the skeletons. Points in the source point cloud and their corresponding line segments in the destination point cloud are inputted to the localized fine registration algorithm. The correspondence between the points and the skeleton lines is established based on the minimum orthogonal distance between the points and all candidate lines in a skeleton segment. The localized fine registration is an iterative procedure. In every iteration step, a transformation is estimated between the points and the skeleton lines. The estimated transformation and the correspondences are updated until the residual point-to-line distances become minimal. Fig. 2 demonstrates the registration procedure for an internode segment of a branch. The following sections describe the skeletonization, the correspondence matching, and the transformation estimation.

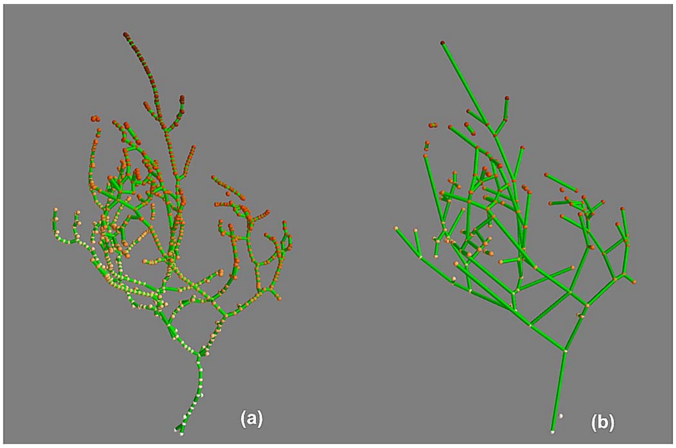


Fig. 3. (a) Skeleton of an unregistered single scan. (b) Reduced skeleton as input for the correspondence matching. The vertices are shown as spheres connected by green edges.

A. Extraction of the SkelTre Skeletons

The roughly registered scans of the tree, as shown in Fig. 3, are skeletonized by the SkelTre algorithm. In the following discussion, we briefly describe the SkelTre algorithm; a detailed description can be found in [4]. From each point cloud, an octree is created, which subdivides the point cloud into cubical octree cells. Each octree cell encloses a subset of the original point cloud. The face dual of the octree cells is the octree graph to be retracted to the 1-D SkelTre skeleton. The only required input parameter is the minimum cell size to terminate the octree subdivision. Embedding into the point cloud is achieved by placing every vertex of the octree graph at the center of the points enclosed by the corresponding octree cell. The retraction of the octree graph operates on locally suited vertex pairs, which are identified by the local connectivity and configuration of the graph vertices. Each pair defines the union of exactly two vertices, whose positions are averaged. This process is repeated until the final skeleton is derived. A useful property of this skeleton, in practice, is the correspondence between each vertex of the graph to a unique subset of points of the point cloud.

B. Matching

The skeletons derived from the roughly registered scans are matched in two steps. First, we reduce both skeletons [see Fig. 3(a)] such that no vertices with two incident edges are present in the skeleton [see Fig. 3(b)]. Then, we match the vertices of the source skeleton S_1 to the edges of the destination skeleton S_2 [see Fig. 4(a)] by finding the shortest distance between a vertex in S_1 and all edges of S_2. The correspondence between each vertex and a unique subset of the point cloud enables us to pair certain parts of the point cloud of S_1 locally with a skeleton edge of S_2 [see Fig. 4(b)]. These point–line pairs are not yet sufficient to estimate a full 3-D transformation, as the rotation around the edge cannot be determined. We make use of the fact that each vertex of the reduced skeleton represents either a tip or a branching point. Hence, the extension of each vertex of S_2 to all adjacent edges constrains all degrees of freedom in 3-D [see Fig. 4(c)] because each adjacent edge branches into a different direction. The point-to-line minimization uses the following as input: 1) the point cloud part of S_1 selected via the vertex correspondence; 2) the matched original unreduced part of the skeleton; and 3) the extended original unreduced part of the skeleton [see Fig. 4(d)].

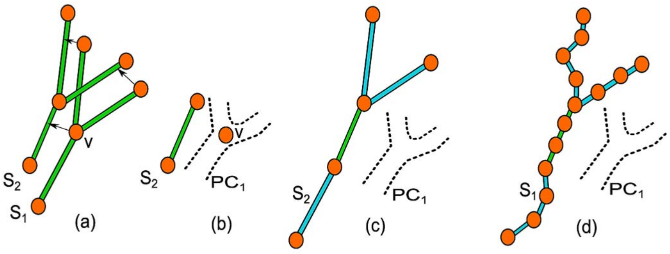


Fig. 4. Matching of the skeleton. (a) Matching the rough skeleton by means of the shortest distance between the vertex (orange) and the edges (green). (b) Vertex v of the source skeleton with its corresponding point cloud part PC_1 matched to an edge of S_2. (c) Extension of the matched edge to neighboring vertices (cyan) to reduce the degree of freedom in the registration. (d) Original fine skeletons of S_1 and PC_1 are the input to the point-to-line minimization.

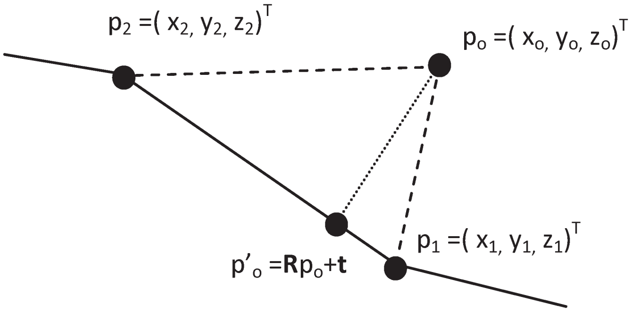


Fig. 5. Mapping a point to its corresponding line segment.

C. Local Transformation Estimation by Minimizing Point-to-Line Distances

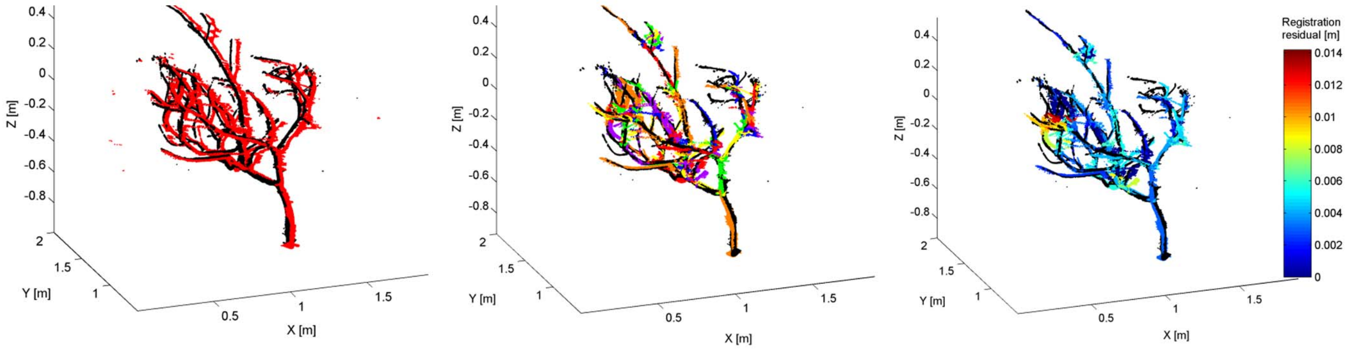
The registration of the branches is based on minimizing the distance between the points of the source point cloud PC_1 and their corresponding skeleton lines S_2 derived from the destination point cloud PC_2. The transformation between PC_1 and PC_2 is locally a rigid motion consisting of a 3-D rotation and a 3-D translation. As shown in Fig. 5, the transformation maps any point p_0 from PC_2 to its corresponding line segment connecting skeleton nodes p_1 and p_2. The condition that the mapping of p_0 is on the line segment p_1p_2 can be expressed as

$$\left\| \overrightarrow{p'_0 p_2} \times \overrightarrow{p_1 p_2} \right\| = 0$$

where

$$p'_0 = \boldsymbol{R}p_0 + \boldsymbol{t} = \begin{bmatrix} r_{11}x_0 + r_{12}y_0 + r_{13}z_0 + t_x \\ r_{21}x_0 + r_{22}y_0 + r_{23}z_0 + t_y \\ r_{31}x_0 + r_{32}y_0 + r_{33}z_0 + t_z \end{bmatrix}$$

is the transformed point, $\boldsymbol{R}$ is the 3-D rotation matrix with elements r_{ij}, and $\boldsymbol{t} = (t_x, t_y, t_z)^T$ is the translation vector. Expanding the cross product gives us two independent equations, as shown at the bottom of the next page.



(a) (b) (c)

Fig. 6. Results of the localized registration for the first example tree. (a) Rough registration of the two point clouds. (b) Localized fine registration of point cloud segments, where colors represent segments. (c) Visualization of the accuracy of the localized registration, where colors represent the residual point-to-line distances.

These equations are nonlinear with respect to the unknown rotation parameters. Therefore, they are first linearized using a Taylor expansion around an initial approximation of the unknown transformation parameters. Having a minimum of three line segments (which are not collinear) and their corresponding points, a system of linear equations of the form $AX = Y$ is obtained, in which A is a coefficient matrix containing derivatives of F_1 and F_2 with respect to the unknown parameters, X contains corrections to the unknowns, and Y contains F_1 and F_2 evaluated with the initial values of the unknowns. The estimated parameters are iteratively refined, until the corrections or the residual distances become minimal. The dependence of the estimation model on an initial approximation of the unknowns does not pose any limitation since the two point clouds are roughly registered, and the initial rotation and translation parameters can be safely assumed to be zero.

IV. EXPERIMENTAL RESULTS

We registered the point clouds of two example trees with diameters ranging from 8 cm at the trunk to less than 0.5 cm for the finest young branches. Both trees were scanned from two directions. The first tree was scanned with a FARO Photon laser scanner, whereas the second tree was scanned with a Zoller + Fröhlich Imager 5006. The registered point cloud of each tree contained roughly half a million points.

The roughly registered point clouds of the first example tree are shown in Fig. 6(a), where misalignments can be clearly seen on the upper branches. Fig. 6(b) shows the registered segments of the source point cloud, whereas the destination point cloud is shown in black. Fig. 6(c) shows the result of the localized registration, where the residual point-to-line distances color the points of the source point cloud.

Fig. 7 shows the residual point-to-line distances per segment before and after the localized registration. It can be seen that the residual distances significantly decrease after the localized registration. The average root-mean-squared (RMS) distance over all segments after the localized registration is 5 mm.

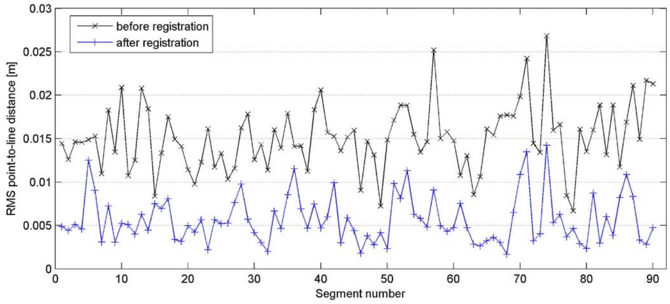


Fig. 7. Residual point-to-line distances per segment before and after the localized registration (first example tree).

Fig. 8 illustrates the application of the localized registration to the second example tree. The visualization of the residual point-to-line distances in Fig. 8(c) shows that the majority of branches have registration accuracy of 2 mm or better.

V. CONCLUSION

In this letter, we have presented a method for a localized registration of point clouds of trees. The method exploits the branching structure using the SkelTre skeleton to perform a localized fine registration without requiring the manual placement of markers. We have shown that significant improvement in the initial rough registration on the branch level is achievable by locally transforming the points to their corresponding skeleton lines. This improved registration is essential for the measurement of the length and number of branches. The localized registration approach can largely contribute to a more robust extraction of the branching structure and more accurate estimations of the wooden biovolume.

$$\begin{cases} F_1 = (y_2 - y_1)(r_{11}x_0 + r_{12}y_0 + r_{13}z_0 + t_x) - (x_2 - x_1)(r_{21}x_0 + r_{22}y_0 + r_{23}z_0 + t_y) - (x_1y_2 - x_2y_1) = 0 \\ F_2 = (z_2 - z_1)(r_{21}x_0 + r_{22}y_0 + r_{23}z_0 + t_y) - (y_2 - y_1)(r_{31}x_0 + r_{32}y_0 + r_{33}z_0 + t_z) - (y_1z_2 - y_2z_1) = 0 \end{cases}$$

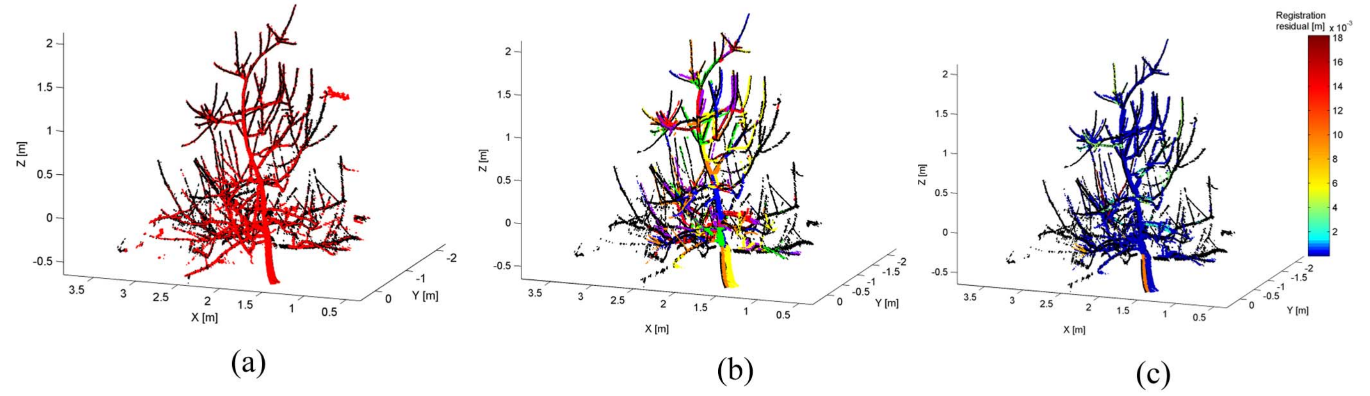


Fig. 8. Results of the localized registration for the second example tree. (a) Rough registration of the two point clouds. (b) Localized fine registration of point cloud segments, where colors represent segments. (c) Visualization of the accuracy of the localized registration, where colors represent the residual point-to-line distances.

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