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Efficient registration of terrestrial LiDAR scans using a coarse-to-fine strategy for forestry applications

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ABSTRACT

Terrestrial Laser Scanning (TLS) plays an increasing role in acquiring 3-dimensional forest structure information. Obstructions and stem density often need multiple scans, making the registration procedure vitally important. Since natural features are difficult to find, traditional registration methods often use artificial reflectors as tie points in forest areas. However, the placement of reflectors reduces the scanning efficiency, especially in forest stands with severe obstructions. In this paper, an efficient registration method using a coarse-to-fine strategy is proposed to overcome the challenge of placing artificial targets so as to improve the scanning efficiency. The coarse registration step utilizes the backsighting orientation approach to form a coarse alignment. Unlike other backsighting research used in urban areas, we solely rely on a TLS system with an internal compass and a built-in inclination sensor. In the fine registration step, stem center locations are calculated in each individual scan. Then, corresponding stem center pairs are found between adjacent scans with the help of the coarse registration results. They are used as tie points to perform a rigid-body transformation for the fine registration. The proposed coarse-to-fine registration method was tested at two forest sites in northeast China. The registration accuracy is approximately 1.5 cm. Results also show that the diameters at breast height (DBHs) extracted from registered TLS data sets are highly correlated with field-measured DBHs (coefficient of determination (R^2): 0.92, root mean square error (RMSE): 0.27 cm). Considering both the scanning efficiency and accuracy, the proposed coarse-to-fine registration method provides a feasible and effective way for forest measurements.

1. Introduction

Forest structure information is essential in forest measurements. It is an important indicator of ecosystem change (Patenaude et al., 2005; Pothier, 2002) and terrestrial resources conservation (Kim et al., 2009). Traditional field measurements are time-consuming and labor-intensive in acquiring forest structural parameters. Other forest measurements mostly used hemispherical photography to measure structural information (Chen et al., 1991; Jonckheere et al., 2005). However, these methods cannot fully capture 3-D forest information.

Terrestrial Laser Scanning (TLS) is an active technology that acquires 3-D point clouds with high spatial resolution (Liang et al., 2014). In the last few years, it has been widely used in different forestry applications, such as stem position determination (Henning and Radtke, 2006b; Hopkinson et al., 2004; Pueschel et al., 2013), diameter at breast height measurements (Bienert et al., 2007; Brolly and Kiraly, 2009; Srinivasan et al., 2015), tree height estimation (Király and Brolly, 2007; Olofsson et al., 2014; Srinivasan et al., 2015) and forest biomass inversion (Greaves et al., 2015; Keightley and Bawden, 2010; Seidel et al., 2012; Srinivasan et al., 2014; Watt and Donoghue, 2005; Yao et al., 2011). It has also been applied to calculate canopy gaps and the Leaf Area Index (LAI) in forest stands. Results have shown good agreement between these TLS methods and hemispherical photography (Danson et al., 2007; Lovell et al., 2003). In recent years, some researchers have also developed multi-wavelength, full-waveform LiDAR instruments to overcome the limitations of commercial LiDAR systems for spe-

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cific forest measurements (Danson et al., 2014; Douglas et al., 2012; Gaulton et al., 2013; Strahler et al., 2012).

However, during the scanning, some limitations exist which are caused by the TLS system and the complex environmental conditions. Unlike airborne LiDAR systems, in each TLS scan, most laser returns are collected near the scan position. This makes it difficult to estimate forest parameters for an entire site from a single scan. In addition, obstructions caused by different vegetation elements commonly impede the scanning process, especially in natural forest stands (Hopkinson et al., 2004; Van der Zande et al., 2006). These obstructions can lead to partial observations and missing features in an individual scan (Hilker et al., 2010), resulting in the underestimation of plot-level forest parameters (Kelbe et al., 2015). To mitigate these effects and measure the entire 3-D structure of a forest site, TLS data acquired from multiple scans are required. The position of a single scan with respect to another can be described by a transformation matrix. It includes three translation vector coordinates in the X, Y and Z directions and three rotation angles around each axis. To align all scans, a registration procedure is needed. The registration's accuracy directly affects forest parameter extraction results, making this procedure vitally important (Cifuentes et al., 2014).

In most research areas, commercial TLS scanners, such as Riegl, Leica, and Faro, provide reflectors with various shapes (circular, cylindrical, etc.) to be placed in each scan for registration purposes. The registration process then calculates the transformation matrix between adjacent scans using corresponding reflector pairs. However, for certain purposes, such as urban surveying and mapping, more accurate registration is required. In these cases, the backsighting orientation approach is applied to estimate the position and orientation between two scans. To obtain an accurate position of the backsighting target, a total station and Differential Global Positioning System (DGPS) are generally needed (Guarnieri et al., 2012; Hoffmeister et al., 2012; Pirotti et al., 2013).

In forestry applications, three main challenges impact the registration process: 1) Most TLS instruments are heavyweight (for example, the total weight of the Riegl VZ-1000 scanner and accessories used in our experiments is more than 15 kg). In addition, natural forest sites are usually difficult to access. Moreover, occlusions create complex environmental conditions that are often difficult to navigate. For these reasons, carrying additional measuring instruments (e.g., a total station or DGPS) into a forest plot is not preferred. It is recommended to use only the TLS system for accurate registration. In recent studies, a low-cost, portable lidar system was introduced to overcome the limitations of low mobility and long scan time in forest areas (Kelbe et al., 2015). However, it is a non-commercial system with low resolution in forest scanning. 2) GPS performs poorly with low spatial accuracy under dense forest canopies. As a result, it is unreliable for accurate registration purposes. 3) In contrast to urban sites with many architectural features, few natural tie points can be found in forests. As a result, artificial reflectors are widely used as tie points for registration (Hilker et al., 2012; Hilker et al., 2010; Tansey et al., 2009; Watt and Donoghue, 2005; Zheng and Moskal, 2012). Using these artificial reflectors, high registration accuracy can be achieved. However, obstructions often make the placement of artificial reflectors labor-intensive and time-consuming. Moreover, the working hours of the TLS are limited by environmental conditions (such as the weather) and the battery life of the scanner, further reducing the efficiency of data acquisition. Therefore, the number of artificial reflectors in forest scans should be reduced to increase the scanning efficiency.

Some reflector-free registration methods have been applied to overcome the difficulties in placing artificial reflectors. In these methods, researchers have extracted natural features (such as ground surface points and stem centers) as tie points to replace the artificial reflectors in the registration process (Aschoff and Spiecker, 2004; Henning and Radtke, 2006a). One of these methods applied the iterative closest point (ICP) procedure to register range images from three scans using the stem centers estimated at multiple heights on nine trees (Henning and Radtke, 2006a). The results showed that the registration error (the mean of the post-registration tree-center paired point distances) was better than 2.1 cm in all registration scan pairs. To obtain the initial values for the ICP method, corresponding reflective tapes affixed to each stem were extracted for coarse alignment. However, placing all the reflective tapes throughout a natural forest site is still time-consuming. In addition, the study did not consider the accuracy of identifying stem centers. The registration result needs to be directly compared with the reflector-based method or field measurements. A modified method was reported in 2008 to record the position and orientation of the instrument in relation to the field measurement rather than using fixed reflective tapes (Henning and Radtke, 2008). This method used tie points on the ground surface to align the Z axes between adjacent scans. However, some manual steps were still required to extract tree stems in this method.

Another reflector-free registration method was proposed to address the difficulties in determining tie points (Ni et al., 2011). With the help of an inclinometer, two rotation parameters (rotation angles around the X and Y axes) were measured before registration. To acquire other transformation parameters, the central positions of trunks were extracted. Then, the similarity of the triangles formed by these trunk positions between the two scans was used for registration. The similarity of two triangles was determined by comparing the lengths and directions of all corresponding sides. Ground surface points were extracted to adjust the offset in the vertical direction. In this study, the mean horizontal registration error was 3.0 cm. For comparison purpose, we further calculated the average 3-D registration error as the average of $\sum_{i=1}^{n} \sqrt{\Delta x_i^2 + \Delta y_i^2 + \Delta z_i^2}$ (where n is the number of stations, is the registration error in the X, Y and Z directions) using the data listed in this paper. Results showed that the average 3-D registration error was 8.5 cm. This method offers a new way to determine tie points. However, it still has some limitations. Many parameters used in the registration step need to be adjusted based on the features of each forest site. In addition, although the initial values of the transformation parameters are acquired during the field measurement, they are not used to narrow the search area of the tie points.

In this paper, we propose a coarse-to-fine registration method that achieves accurate registration results with high efficiency at a forest site. The backsighting orientation approach is used in the coarse registration step. Unlike other research, we rely solely on a TLS system for the backsighting orientation. No other measuring instrument is needed. After the coarse registration, corresponding stem positions are extracted as tie points to perform a rigid-body transformation in the fine registration process. To evaluate our method, we compared it with the reflector-based method. For further comparison in forestry applications, we also extracted the DBHs of 21 sample trees in Plot 1 to compare with field measurements.

Our main objective is to develop this two-stage registration method that highly improves the scanning efficiency in the forest and extracts high accurate structural parameters. Using only one reflector as the backsighting target between two scans, our registration method overcomes the difficulty in setting up many artificial reflectors in the reflector-based methods. In this paper, we also aim to improve the efficiency and accuracy of the registration method. Unlike other reflector-free registration methods, initial transformation parameters are automatically obtained using the coarse registration algorithm. These parameters highly improve the