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An automated method to register airborne and terrestrial laser scanning point clouds

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ABSTRACT

Laser scanning techniques have been widely used to capture three-dimensional (3D) point clouds of various scenes (e.g. urban scenes). In particular, airborne laser scanning (ALS) and mobile laser scanning (MLS), terrestrial laser scanning (TLS) are effective to capture point clouds from top or side view. Registering the complimentary point clouds captured by ALS and MLS/TLS provides an aligned data source for many purposes (e.g. 3D reconstruction). Among these MLS can be directly geo-referenced to ALS according to the equipped position systems. For small scanning areas or dense building areas, TLS is used instead of MLS. However, registering ALS and TLS datasets suffers from poor automation and robustness because of few overlapping areas and sparse corresponding geometric features. A robust method for the registration of TLS and ALS datasets is proposed, which has four key steps. (1) extracts building outlines from TLS and ALS data sets independently; (2) obtains the potential matching pairs of outlines according to the geometric constraints between building outlines; (3) constructs the Laplacian matrices of the extracted building outlines to model the topology between the geometric features; (4) calculates the correlation coefficients of the extracted geometric features by decomposing the Laplacian matrices into the spectral space, providing correspondences between the extracted features for coarse registration. Finally, the multi-line adjustment strategy is employed for the fine registration. The robustness and accuracy of the proposed method are verified using field data, demonstrating a reliable and stable solution to accurately register ALS and TLS datasets.

1. Introduction

Laser scanning has developed rapidly since it collects dense three-dimensional point clouds of object surfaces quickly and accurately. Laser scanners mounted on different platforms (e.g. airborne, vehicle-borne, terrestrial platforms) are widely applied to various fields such as Digital Elevation Model (DEM) generation (Ma, 2005), landslide monitoring (Corsini et al., 2013), power line inspection (Melzer and Briese, 2004), 3D reconstruction (Kedzierski and Fryskowska, 2014), and hydrologic survey. Generally, the data captured by any one method covers only certain parts of a scene. Taking airborne laser scanning (ALS) data as an example, façade data is largely omitted. On the other hand, façade data is easily captured by mobile laser scanning (MLS) or terrestrial laser scanning (TLS), providing a good complement to ALS data.

Compared with TLS, MLS is more suitable for large area scanning or wide region operations. The registration between ALS and MLS can be fulfilled based on the equipped position systems. Nevertheless, the registration between ALS and TLS is a non-trivial issue. To make full use of the data captured by ALS and TLS, corresponding geometric features need to be matched, registering the datasets. However, in addition to the different scanning views, some other differences exist. The point densities of the ALS and TLS differ obviously. ALS has about 1–8 points per square meter and the overlapping region of adjacent strips has more points. This density is enough to model the building roof, but difficult to model small objects like chimney and roof window. On the other hand, TLS has higher point density and millions of points can be obtained per scan position; For ALS, scanning region of each time is wide since strip width is few hundred meters. However, the scanning region of single terrestrial position is narrow and a dozen stations are often needed to record one building. Compared with the relatively complete building roof data collected by ALS, the building façades of TLS are easily influenced by occlusions, causing more difficulties for automatic and robust registration.

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To match corresponding geometric features in TLS and ALS datasets robustly, we construct the spectral space of the extracted geometric features and identify the corresponding features according to spectral graph theory. Experiments of datasets with obvious eaves, uneven ground surface, or differences between geometric features show the robustness of the proposed method.

The rest of the paper is structured as follows: Section 2 reviews the related literature regarding ALS and TLS data registration. Section 3 describes our proposed system to determine geometric feature correspondences based on spectral graph theory, and thereby allow accurate registration of ALS and TLS data. We report the outcomes of a number of experiments undertaken to demonstrate the validities and effectiveness of the proposed method in Section 4. Finally, in Section 5 we draw our conclusions and describe future research directions.

2. Literature review

Extensive studies have attempted to register different laser scanning systems. Existing solutions can be classified into three categories: namely, registration of ALS strips, registration of multi-station TLS data, and registration of ALS and TLS data (Cheng et al., 2013).

2.1. Registration of ALS strips

Registration of ALS data attempts to reconcile system location errors between GPS, inertial navigation systems (INS), and the laser scanner to eliminate discrepancies between neighboring strips. Consequently, the quality of registration of ALS data depends on the calibration of system components spatial relationship as defined by the bore-sight parameters, or the distortion correction of the ALS strips. Skaloud and Lichti (2006) presented a self-calibration method for bore-sight error of ALS system, which is based on the modeling of direct geo-referencing equations considering the systematic sensor errors for target points. Practical examples show the good accuracy and robustness. Unlike this method, Bang et al. (2008) took control features extracted from the TLS data as the reference to calibrate the bore-sighting parameters of ALS data after coarse registration of ALS and TLS data. Real data test shows that existing bore-sight parameters are improved after calibration. Favalli et al. (2009) estimated and corrected systematic errors within ALS data by minimizing displacements between different strips. Tie points of strips are used instead of ground control points. Rentsch and Krzystek (2009) used a strip adjustment procedure considering the systematic errors of each strip with intersecting roof ridge lines and roof planes which are automatically reconstructed in overlapping strips.

2.2. Registration of TLS point clouds

In terms of registration between TLS data sets, extensive studies have been carried out from different fields. These methods can be generally classified into two categories: pair-wise registration and multi-station registration. Popular pair-wise coarse registrations include artificial marker, auxiliary data (e.g. Wang and Brenner, 2008; Arguilera et al., 2009; Weinmann et al., 2011), and geometric features (e.g. Gruen and Akca, 2005; Bae and Lichti, 2008; Brenner et al., 2008; He et al., 2013; Yang and Zang, 2014) based methods. When initial orientation parameters are provided by coarse methods, fine registration methods are needed to improve registration accuracy. Many fine registration methods have been proposed like dynamic genetic algorithm (Chow et al., 2004), signed distance fields algorithm (Masuda, 2002), iterative closest point (ICP) algorithm (Besl and McKay, 1992; Chen and Medioni, 1992). To distribute the accumulative errors caused by pair-wise registration reasonably, multi-station registration is necessary. Williams and Bennamoun (2001) proposed a simultaneous multi-station registration method. A constant matrix encoding the point correspondence information was constructed to calculate the optimal transformations by an iterative algorithm. Different from this simultaneous method, Huber and Hebert (2003) introduced a multi-step method, which defines visibility consistency to eliminate incorrect matches and constructs a sub-graph to guide the computation of transformations between stations. To process large data sets, Pulli (1999) applied the virtual point pairs instead of the concrete pairs of points. This method is efficient and less likely to get stuck into a local minimum.

2.3. Registration of ALS and TLS Data

Registration of ALS and TLS data attempts to fuse scans from top and side view for complete representation of object surfaces. Many studies have attempted registration using external devices (e.g. GPS receiver). Böhm and Haala (2005) mounted a GPS receiver and a digital compass on the top of a terrestrial laser scanner to determine the position and orientation of the scanner. TLS data can then be directly geo-referenced to the ALS data. In addition to the high precision GPS system, Hauglin et al. (2014) measured the initial position of a terrestrial laser scanner with a recreational-grade GPS receiver, and then used the positions of individual trees and tree stems to register the ALS and TLS data. However, if trees clustered together, individual tree will be difficult to extract. Another kind of method making use of geometric features has also been proposed. Cheng et al. (2013) combined feature lines and corner points to register ALS and TLS data semi-automatically. Nevertheless, this method mainly focuses on the extraction of geometric features from the cuboid-shaped buildings. A similar solution was proposed by Wu et al. (2014), which considered the buildings whose roof extents are larger than façade extents. Both methods have low automation grade. Jaw and Chuang (2008) constructed a feature-based transformation model integrating point, line, and plane models to calculate the transformation parameters. This method can afford higher degree of flexibility and higher accuracy application. The emphasis is on the parameter calculation rather than geometric feature extraction or matching. Hansen et al. (2008) proposed automatic registration method by identifying the correspondence between extracted feature lines. Then orientation histograms were applied for the rotation, and generate-and-test scheme was used for the translation parameters. This method does not need prior knowledge. However, many useless feature lines from the TLS façade were also extracted. Other solutions include target based registration methods (e.g. Hohenthal et al., 2011).

Successfully registering ALS and TLS data depends on extracting and identifying corresponding geometric features (i.e., points, lines, patches) between the scans. Many studies have explored identifying corresponding geometric features by incorporating the neighboring shape context of geometric features (Belongie et al., 2001; Gelfand et al., 2005; Huang et al., 2006). However, the shape context of features between ALS and TLS data sets is difficult to model because there are few overlapping areas between top and side views. On the other hand, reliable corresponding geometric features determination has been demonstrated based on the spectral graph theory (e.g., Damiand et al., 2009; Raynal et al., 2009). Therefore, this paper proposes an automated and robust method based on spectral graph theory to address the discussed drawbacks and successfully register ALS and TLS data.

3. Methodology

The proposed method encompasses four key components: extracting building outlines from ALS and TLS data, initial building