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A rigorous cylinder-based self-calibration approach for terrestrial laser scanners

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ABSTRACT

Existing self-calibration methods for terrestrial laser scanners are predominantly point-based and plane-based. In this paper, we present a new cylinder-based self-calibration method with its variants for several scanners having different architectures and scanning mechanisms. The method not only increases the flexibility of in situ self-calibration, but also its rigor because of reduced functional dependencies between adjustment parameters. Based on the analysis of linear dependencies between columns of the design matrices for both the cylindrical and planar models, it is shown that using the vertical cylindrical model is advantageous over using the planar model as some high linear dependencies can be avoided. The proposed method and its variants were first applied to two simulated datasets, to compare their effectiveness, and then to three real datasets captured by three different types of scanners are presented: a Faro Focus 3D (a phase-based panoramic scanner); a Velodyne HDL-32E (a pulse-based multi spinning beam scanner); and a Leica ScanStation C10 (a dual operating-mode scanner). The experimental results show that the proposed method can properly estimate the additional parameters with high precision. More importantly, no high correlations were found between the additional parameters and other parameters when the network configuration is strong. The overall results indicate that the proposed calibration method is rigorous and flexible.

1. Introduction

In situ self-calibration is essential for terrestrial laser scanners (TLSs) to maintain high accuracy for many applications such as structural deformation monitoring (Lindenbergh, 2010). This is particularly true for aged TLSs and instruments being operated for long hours outdoors with varying environmental conditions. Presently, the most common in situ self-calibration approaches utilize either signalized target points (e.g. Lichti et al., 2011; Reshetyuk, 2010; García-San-Miguel and Lerma, 2013; Abbas et al., 2014) or planar features (e.g. Dorninger et al., 2008; Glennie and Lichti, 2010, 2011; Glennie et al., 2013; Chow et al., 2013) as calibration references. For point-based self-calibration, there is a need for users to manually install a number of signalized target points and then extract the point coordinates with multiple estimation and transformation steps (Chow et al., 2010). These steps are not very straightforward and are labour intensive. Moreover, the point-based calibration can incur problems of high parameter correlations which hinder the calibration accuracy unless tilted scans, which require a special scanner mount, are incorporated (Lichti et al., 2011; Chow et al., 2013). Furthermore, spinning beam instruments featuring a set number of laser rangefinders mounted in fixed intervals rather than a beam deflection mechanism, such as the Velodyne scanner series, have low vertical angle resolution. This architecture makes accurate position determination of target points almost impossible. As a result, the calibration of scanners must rely on planar features instead of target points (e.g. Muhammad and Lacroix, 2010; Atanacio-Jiménez et al., 2011; Glennie and Lichti, 2010, 2011; Chen and Chien, 2012; Glennie et al., 2013; Gong et al., 2013).

Although the plane-based methods are now widely adopted for TLS calibration, they also suffer from the problem of high parameter correlation when there is a low diversity in the plane orientations (Chow et al., 2013). In practice, not all locations possess large and smooth planar features that can be used to perform a calibration. Even though planar features are available, their planarity is not always guaranteed.

Because of the drawbacks to the point-based and plane-based calibrations, an alternative geometric feature, namely circular

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cylindrical features, should be considered and incorporated into the self-calibration procedure. Cylinders are readily found in most built environments (both indoor and outdoor), can be automatically segmented and provide strong geometric constraints for the calibration adjustment. Cylindrical features can be easily found as structural pillars, metallic poles, gas/water pipes and in other forms. They are also one of the most important geometric primitives of many industrial sites (Rabbani and van den Heuvel, 2005). Since structural pillars are the most commonly-found among the above mentioned examples, vertical cylindrical features and their model will be the main focus of this paper. Two models for horizontal cylinders are also presented for completeness.

Even though using cylindrical features for scanner self-calibration is a new concept, cylindrical features are well studied by a number of researchers in terms of fitting algorithms (e.g. Shakarji, 1998), point cloud registration (e.g. Rabbani et al., 2007) and segmentation strategies (e.g. Pfeifer et al., 2004; Luo and Wang, 2008). In particular, cylindrical pole-like objects in highway corridors captured by terrestrial mobile mapping systems are one of the most popular features being investigated worldwide (e.g. Pu et al., 2011; Lehtomaki et al., 2010; Yokoyama et al., 2011; Nurunnabi et al., 2012; El-Halawany and Lichti, 2013; Cabo et al., 2014). The advances in cylinder segmentation methods can benefit and automate cylinder-based sensor calibration (Chan et al., 2013).

In this paper, a new multiple feature-based calibration method with vertical cylindrical features as the primary input is demonstrated. The method combines TLS observations of cylindrical features and planar features to estimate the exterior orientation parameters (EOPs), the features' parameters and the scanner's additional parameters (APs) simultaneously using the Gauss-Helmert Model according to the weighted least-squares criterion. The proposed method is verified with both simulated data and real datasets captured by three different types of scanners.

The paper is organized as the follows. The calibration models are first described in Section 2. The advantage of using vertical cylinder features over planar features for self-calibration is shown by analysing the linear dependence of columns of the calibration design matrices in Section 3. This is followed by descriptions of the simulated and real data experiments in Section 4. Eleven calibration experiments were performed in total. Section 5 provides analyses of the calibration estimates and the corresponding correlation matrices. In Section 6, a summary of the paper is provided.

2. Functional models for the calibration

2.1. Point observation model for the TLS

For the self-calibration of a panoramic scanner (Chow et al., 2013) or a scanner operated in panoramic scanning mode, the coordinates of point i lying on feature k captured from station j are related by the rigid body transformation:

$$\begin{bmatrix} X_{ijk} \\ Y_{ijk} \\ Z_{ijk} \end{bmatrix} = \mathbf{M}_j^{\mathrm{T}} \begin{bmatrix} (\rho_{ijk} - \Delta\rho)\cos(\alpha_{ijk} - \Delta\alpha)\cos(\theta_{ijk} - \Delta\theta) \\ (\rho_{ijk} - \Delta\rho)\cos(\alpha_{ijk} - \Delta\alpha)\sin(\theta_{ijk} - \Delta\theta) \\ (\rho_{ijk} - \Delta\rho)\sin(\alpha_{ijk} - \Delta\alpha) \end{bmatrix} + \begin{bmatrix} X_{s_j} \\ Y_{s_j} \\ Z_{s_j} \end{bmatrix} \tag{1}$$

where $\mathbf{M}_j = \mathbf{R}_3(\kappa_j)\mathbf{R}_2(\phi_j)\mathbf{R}_1(\omega_j)$ is the product of rotation matrices, $\mathbf{R}_1$, $\mathbf{R}_2$ and $\mathbf{R}_3$ which are associated with the rotation angles, ω_j, ϕ_j and κ_j about the X-, Y- and Z-axes, respectively. In this paper, only the following basic correction terms are considered (Lichti, 2010):

$$\Delta\rho = a_0 \tag{2}$$

$$\Delta\theta = b_1 \sec(\alpha_{ijk}) + b_2 \tan(\alpha_{ijk}) \tag{3}$$

$$\Delta\alpha = c_0 \tag{4}$$

where a_0 is the rangefinder offset, b_1 and b_2 are the collimation axis error and the trunnion axis error, respectively; and c_0 is the vertical circle index error. The details of the correction terms can be found in Lichti (2007). These models are applicable to the self-calibration of the Faro Focus 3D (a panoramic scanner) and the Leica ScanStation C10 (a dual mode scanner that can be operated in panoramic scanning mode).

2.2. Point observation model for the multi-beam spinning scanner – Velodyne HDL-32 scanner

The proposed calibration method has been applied to the Velodyne HDL-32E LiDAR system. The HDL-32E is neither one of the three well-defined types (camera, panoramic and hybrid) of the TLS (Staiger, 2003). It consists of 32 individual one-dimensional (1D) laser rangefinders which are radially oriented on a vertical panel that rotates about the Z-axis continuously for point capture when the instrument receives power. It has approximately 41.3° and 360° fields of view (FOV) in the vertical and horizontal directions, respectively. Its nominal vertical and horizontal angular sampling intervals are 1.33° and 0.15°, respectively. It can capture approximately 700,000 points per second (Velodyne, 2013). More details about the internal architecture of the HDL-32 and also the applications of the HDL-32E can be found on Chan et al. (2013).

As the individual lasers are oriented radially with fixed vertical angles, only the range (ρ) and the horizontal angle (θ) are considered as observations. The coordinates of the scanner space point i lying on feature k captured from station j and collected by laser n (n = 1, 2, ..., 32) are related by the rigid body transformation:

$$\begin{bmatrix} X_{ijkn} \\ Y_{ijkn} \\ Z_{ijkn} \end{bmatrix} = \mathbf{M}_j^{\mathrm{T}} \begin{bmatrix} (\rho_{ijkn} - \Delta\rho_n)\cos(\alpha_n)\sin(\theta_{ijkn} - \Delta\theta_n) \\ (\rho_{ijkn} - \Delta\rho_n)\cos(\alpha_n)\cos(\theta_{ijkn} - \Delta\theta_n) \\ (\rho_{ijkn} - \Delta\rho_n)\sin(\alpha_n) \end{bmatrix} + \begin{bmatrix} X_{s_j} \\ Y_{sj} \\ Z_{s_j} \end{bmatrix} \tag{5}$$

where

$$\Delta\rho_n = a_{0_n} \tag{6}$$

$$\Delta\theta_n = b_{0_n} \tag{7}$$

and a_{0_n} is the rangefinder offset and b_{0_n} is the horizontal angle offset (Glennie and Lichti, 2010) for laser n. For experiments reported herein, the horizontal angle offset and the vertical angle of one laser were kept constant for the calibration adjustment to define the scanner space and thus 32 rangefinder offsets, 31 horizontal angle offsets and 31 vertical angles were considered as calibration parameters. In general, a higher number of input features and also scan stations are needed for the Velodyne scanners since they do not observe the vertical angles (Glennie and Lichti, 2010; Chan et al., 2013).Tilted scans are also required but they can be readily achieved by using regular camera mounts due to the compact size and light weight of the HDL-32 scanner (Chan and Lichti, 2013).

2.3. Geometric model for the calibrations

The transformed object space coordinates, $[X_{ijk} \quad Y_{ijk} \quad Z_{ijk}]^{\mathrm{T}}$ in Eq. (1) or $[X_{ijkn} \quad Y_{ijkn} \quad Z_{ijkn}]^{\mathrm{T}}$ in Eq. (5), are constrained to lie on the corresponding geometric feature models for calibration. Without loss of generality, we only show the case of the panoramic scanning system. Cylindrical features have five degrees of freedom (Rabbani et al., 2007) and they can be modelled with five parameters in three different ways depending on the approximate position and orientation of the central axis of the cylinder (Chan and Lichti, 2012). For point i lying on a nominally vertical cylindrical feature k (cylinders have