Computers & Geosciences 83 (2015) 54–64

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Error in target-based georeferencing and registration in terrestrial laser scanning

Lei Fan[a,*], Joel A. Smethurst[a], Peter M. Atkinson[b], William Powrie[a]

[a] Faculty of Engineering and The Environment, University of Southampton, University Road, Southampton SO17 1BJ, UK
[b] Faculty of Science and Technology, Lancaster University, Lancaster LA1 4YR, UK

ARTICLE INFO

Article history:
Received 12 October 2014
Received in revised form
24 June 2015
Accepted 27 June 2015
Available online 6 July 2015

Keywords:
Terrestrial laser scanning (TLS)
Accuracy
Error
Georeferencing
Registration
Point clouds

ABSTRACT

Terrestrial laser scanning (TLS) has been used widely for various applications, such as measurement of movement caused by natural hazards and Earth surface processes. In TLS surveying, registration and georeferencing are two essential steps, and their accuracy often determines the usefulness of TLS surveys. So far, evaluation of registration and georeferencing errors has been based on statistics obtained from the data processing software provided by scanner manufacturers. This paper demonstrates that these statistics are incompetent measures of the actual registration and georeferencing errors in TLS data and, thus, should no longer be used in practice. To seek a suitable replacement, an investigation of the spatial pattern and the magnitude of the actual registration and georeferencing errors in TLS data points was undertaken. This led to the development of a quantitative means of estimating the registration- or georeferencing-induced positional error in point clouds. The solutions proposed can aid in the planning of TLS surveys where a minimum accuracy requirement is known, and are of use for subsequent analysis of the uncertainty in TLS datasets.

1. Introduction

Terrestrial laser scanning (TLS) has been used increasingly for topographical surveying (e.g. Gallay et al., 2013), monitoring natural hazards (e.g. Jaboyedoff et al., 2012; Barnhart and Crosby, 2013) and investigating Earth surface processes (e.g. Schürch et al., 2011; Montreuil et al., 2013; Day et al., 2013). In these applications, TLS data usually need to be transformed into an external coordinate system for data fusion or the derivation of surface movement. This process is known as georeferencing. Another important process in TLS surveying is registration, which is the joining of multiple scans from different scan locations to form an integrated point cloud. An introduction on the registration methods used in TLS surveying can be found in Lichti and Skaloud (2010).

At present, the common practice for georeferencing/registration in TLS surveying is the target-based method. In this method, targets placed over a scan scene are surveyed by a scanner from successive scan locations for registration, or are measured by a second instrument for georeferencing. The instruments used for georeferencing mainly include differential global positioning systems (DGPS) and total stations. For TLS surveying in a natural environment, DGPS seems more popular (e.g. Schürch et al., 2011; Montreuil et al., 2013).

Surface matching is another well-known georeferencing/registration method, which is usually based on the iterative closest point (ICP) algorithm developed by Besl and McKay (1992) and Chen and Medioni (1992). An overview of the surface matching strategies can be found in Gruen and Akca (2005). The ICP method is more widely used for registration. Although some researchers (e.g. Prokop and Panholzer, 2009) have used this method to georeference multi-temporal TLS datasets, it is less popular for georeferencing, probably because of the concern that overlapping areas (required for surface matching) in sequential TLS data may have changed over time, especially in a natural environment.

Another georeferencing approach in TLS surveying is direct georeferencing. A number of researchers (Lichti et al., 2005; Mohamed and Wikinson, 2009; Reshetyuk, 2010) have investigated the accuracy of directly georeferenced TLS data. However, the use of this approach is still relatively rare in practice, probably due to its comparatively low accuracy.

Georeferencing is a crucial step for deformation measurement. Georeferencing error will result in relative positional error between multi-temporal TLS data, leading to a proportion of the detected surface variations being the georeferencing-induced error. Accurate registration is also important in TLS surveying, as registration error can cause misalignments between point clouds acquired from different scanner locations. Some empirical

* Corresponding author.
E-mail address: lei.fan@soton.ac.uk (L. Fan).

http://dx.doi.org/10.1016/j.cageo.2015.06.021
0098-3004/

experiments (e.g. Bornaz et al., 2003; Schuhmacher and Böhm, 2005; Alba and Scaioni 2007) and numerical studies (e.g. Bornaz et al., 2003; Scaioni, 2012) have been carried out to investigate the accuracy of georeferencing/registration in TLS surveying. However, assessment of TLS georeferencing/registration quality is still poorly understood (Scaioni, 2012), which is reflected by the statements in the following paragraph.

In data processing, target-based georeferencing/registration is usually carried out using software provided by scanner manufacturers. After georeferencing/registration, the software can report an estimated georeferencing/registration error, based on how well the target constraints are matched. For example, Leica Cyclone® reports a mean absolute error for registration and a residual error for each target constraint in its registration diagnostics report. The same or similar statistics are used by other software. It is currently common practice in the laser scanning industry to quote directly these error statistics as a quality control standard or for an uncertainty analysis. This approach has also widely been adopted by researchers (e.g. Barnhart and Crosby, 2013, Lague et al., 2013; Montreuil et al., 2013; Day et al., 2013). They are single and spatial uniform statistics per point cloud. Although TLS users may have appreciated from their experience that these statistics are not adequate descriptors, the statistics are still used routinely, probably because there are no alternative suitable solutions in the literature.

A part of this paper is devoted to demonstrating that the statistics used routinely in current practice are incompetent measures of the actual georeferencing/registration-induced positional error in TLS point clouds. To seek a suitable replacement, the spatial pattern and the magnitude of the georeferencing/registration-induced positional error in point clouds were explored using numerical simulations in this paper. Based on the simulation results, a set of equations were proposed for estimation of the georeferencing/registration-induced error in point clouds. These equations provide a quantitative means of estimating the georeferencing/registration-induced positional error in TLS data points.

Although the target arrangement strategy for a higher georeferencing/registration accuracy is well appreciated in engineering surveying, it is not always possible to achieve an optimal target arrangement due to site constraints. The solutions proposed in this paper provide a simple tool for assessing if the target arrangement is acceptable for a given accuracy requirement associated with TLS data points. It also enables the analysis of the trade-off between the factors affecting the georeferencing/registration-induced positional error. Hence this paper can serve as a useful reference for TLS survey planning. It is also of use to subsequent analysis of positional uncertainty in TLS data points. Unless clearly specified, georeferencing/registration in the rest of this paper refers to target-based georeferencing/registration.

2. Methods

2.1. Coordinate transformation problem

Target-based georeferencing/registration involves two steps: (i) estimation of the transformation parameters based on control/tie points of known correspondences, and (ii) application of transformation to point clouds. In the context of TLS surveying, a rigid body transformation is usually used. If there is any reason to believe a scale difference is present, a similarity transformation can be used. In this paper, only the rigid body transformation is considered. This operation is expressed in Eq. (1), in which the point clouds in Space B are transformed into Space A using the transformation parameters **R** and *T*.

$$\mathrm{A}_i = \mathbf{R}\mathrm{B}_i + T \tag{1}$$

where A_i and B_i represent the same points in Space A and Space B, respectively; **R** is the rotation matrix; *T* is the translation vector.

The transformation parameters are estimated by minimising the squared differences shown in Eq. (2) (i.e. a least-squares approach).

$$\varepsilon^2 = \sum_{j=1}^{n} \left\| \mathrm{A}_j - \left(\mathbf{R}\mathrm{B}_j + T\right) \right\|^2 \tag{2}$$

where A_j and B_j represent the same set of targets in Space A and Space B, respectively; n is the number of target constraints; ε^2 is the squared differences to be minimised; **R** is the rotation matrix to be estimated; *T* is the translation vector to be estimated.

Iteration is usually required for solving a non-linear least-squares problem such as that given in Eq. (2). Meanwhile, closed-form solutions have been developed for estimating the transformation parameters, including the singular value decomposition method (Arun et al., 1987), the unit quaternion method (Faugeras and Hebert, 1986; Horn, 1987) and the orthonormal matrix method (Horn et al., 1988). Eggert et al. (1997) compared these closed-form algorithms and found no discernible differences in accuracy or stability for practical applications. In this paper, the Horn's unit quaternion method is used.

2.2. Levelled point clouds

Many latest laser scanners are equipped with an accurate dual-axis (tilt) compensator. When it is enabled during scans, the scanner automatically corrects the deviation of the scanner standing axis from the plumb line. Some researchers (Silvia and Olsen, 2012) have investigated the accuracy of the dual-axis compensators of several scanners. If a scanner is levelled and its dual-axis compensator is enabled, its vertical orientation is effectively plumb. This leads to a levelled point cloud.

For levelled point clouds, a 3D rigid body transformation can be simplified into a 2.5D case, including a 2D rigid body transformation (i.e. a rotation about the *Z* axis and translations along the *X* and *Y* axes) and a vertical translation. As the vertical translation can be determined by taking the average elevation differences between corresponding targets, a 2D transformation is effectively required for levelled point clouds. For example, levelled ScanWorlds (a ScanWorld represents all point clouds obtained from a scanner position) are the default setting for registration in Leica Cyclone®.

To reduce the georeferencing/registration error, targets should be arranged in such a way that they can cover the full volume of a scan scene. However, it is usually more difficult to do so in the vertical direction due to site constraints. The use of an accurate dual-axis compensator can effectively remove such a requirement in the vertical direction. In addition, forcing scan data to be tied to a plumb vertical orientation eliminates some degrees of freedom for georeferencing/registration, and hence reduces the need for the targets for the same degree of georeferencing/registration accuracy. Therefore, it is beneficial to level a scanner and to enable its dual-axis compensator. In fact, it is common practice to enable the dual-axis compensator by professional surveyors.

2.3. Definition of error

The problem investigated in this paper is essentially an error propagation problem in the context of Geographic Information System (GIS). The study of errors in GIS has been extensive and diverse (e.g. Zhang and Goodchild, 2002; Foody and Atkinson, 2002). Leung et al. (2004) proposed a framework for error analysis