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Deformation measurement using terrestrial laser scanning data and least squares 3D surface matching

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Abstract

The use of Terrestrial Laser Scanning (TLS) data for deformation measurement is gaining increasing interest. This paper is focused on a new procedure for land deformation monitoring based on repeated TLS scans. The kernel of the procedure is the least squares 3D surface matching proposed by Gruen and Akca [Gruen, A., Akca, D., 2005. Least squares 3D surface and curve matching. ISPRS Journal of Photogrammetry and Remote Sensing 59 (3), 151−174]. This paper describes the three main steps of the procedure, namely the acquisition of the TLS data, the global co-registration of the point clouds, and the estimation of the deformation parameters using local surface matchings. The paper briefly outlines the key advantages of the proposed approach, such as the capability to exploit the available high data redundancy using advanced analysis tools, the flexibility of the proposed solution, and the capability of providing fully 3D deformation measurements, including displacement vectors and rotations. Furthermore, it illustrates the performance of the proposed procedure with a validation experiment where a deformation measurement scenario was simulated and TLS and topographic data were acquired. From the analysis of this experiment, interesting features are highlighted: the validation errors below 1 cm in the displacements and below 1 gon in the rotations of small targets measured at a distance of 134 m; the increase by factor two of the errors when the same scene is measured from a distance of 225 m; and the importance of an accurate global co-registration in order to avoid systematic errors in the estimated deformation parameters. It is interesting to note that the above results were achieved under non-optimal conditions, e.g. using non-calibrated data and sub-optimal targets from the matching viewpoint. Besides the simulation experiment, the validation results achieved on landslide test site are briefly discussed.

Keywords: Laser scanning; TLS; Point cloud; Estimation; Matching; Error; Landslides

1. Introduction

In the last few years there has been an increasing interest in exploiting the Terrestrial Laser Scanning (TLS) data for deformation measurement and monitoring purposes. This concerns both engineering geodesy measurement tasks and, thanks to the capabilities of long-range TLS, other relevant geological and geotechnical applications, like landslide monitoring. This interest is certainly due to the key advantages of TLS, such as the direct measurement of 3D coordinates, the high degree of automation, the easy-to-use hardware, and the massive sampling capability, which can be exploited to counter-balance the relatively poor quality of the single TLS points.

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It is worth noting that the exploitation of the high redundancy provided by TLS tools is a key to achieving good deformation measurement performance with TLS data, and often requires the development of ad hoc tools. In the following, we focus on the main data analysis procedures for carrying out TLS-based deformation measurements, which are described in the literature. Useful additional references include a review of TLS (Pfeifer and Lichti, 2004), a survey of the commercially available TLS systems (Lemmens, 2004), a classification of terrestrial laser scanners (Fröhlich and Mettenleiter, 2004), and an analysis of the quality of the points recorded by laser scanners (Boehler et al., 2003).

Some authors, like Bitelli et al. (2004) and Hesse and Stramm (2004), perform deformation studies by directly comparing Digital Elevation Models (DEM) from different TLS campaigns. An analogous case is described in Schäfer et al. (2004). Though this approach is easy to implement using commercial software, it has two important limitations. Firstly, it has limited sensitivity to small deformations, which makes it unsuitable for measuring subtle displacements. Secondly, since the DEMs are typically defined on a 2D support, i.e. $z=f(x,y)$, the difference between DEMs basically provides a 1D deformation measurement, in the z direction. Given the 3D nature of the TLS point clouds, this represents an important limitation of this approach. This aspect is discussed later in this paper.

Another type of method makes use of suitable surface models, which are fitted to the TLS point clouds. The key idea is to overcome the limited precision of the single TLS points by taking advantage of the high redundancy of the observations, i.e. the 3D points and the geometric characteristics of the observed surfaces. Van Gosliga et al. (2006) use a cylinder parameterization to model a tunnel, while Alba et al. (2006) follow this approach for the structural monitoring of a large dam by fitting a 3D polynomial surface to the surveyed TLS point cloud. Other interesting work concerning dams can be found in Rudig (2005). Another example of this type of method is described in Schneider (2006), for the deformation analysis of a television tower. In order to determine its bending line, the point cloud is cut in N thin layers and projected on to planes, thus transforming the 3D fitting problem into N 2D fitting problems. The bending line is given by connecting the centre points of the circles, which are estimated through a circle-fit least squares (LS) adjustment applied to each of the N layers. The main advantage of this type of method is the high quality of the deformation parameters of interest with respect to the quality of the original TLS data. A limitation of these methods is related to the need to rely on a specific surface model, which requires a context-dependent analysis, applicable only to objects with specific geometric characteristics. Furthermore, if deformation is derived by computing the differences between surface models estimated in different epochs, e.g. see Alba et al. (2006), the estimated deformation field is basically 1D. This is the same limitation mentioned in the previous type of method. It is, however, important to note that the impact of this limitation clearly depends on the type of application at hand. In fact, in some application cases the 3D information is not needed or does not make sense.

A particular class of model-based deformation analysis is described in Gordon et al. (2004), which make use of a physical model that represents the deflection of a loaded beam. In this work the authors achieve high precision in estimating small deformations. A limitation of the approach is that such models can only be used in particular deformation analysis cases.

An original procedure is described in Girardeau-Montaut et al. (2005), which, however, is focused on change detection on building sites or inside facilities, where displacement measurement precision is not the key parameter. They make use of an efficient octree structure for the point clouds, and different cloud-to-cloud comparison algorithms. Some of them are suitable for quick, rough change assessments, which can be useful for in situ verification. The proposed procedure is useful for all applications based on complex environments, and where the speed of the data analysis plays a critical role. From the viewpoint of this work, the main limitation of this approach is the limited precision of the derived displacement maps.

Finally, it is worth mentioning another approach, proposed by Lindenbergh and Pfeifer (2005), which is based on a statistical deformation analysis for deformation detection. This approach involves the segmentation of the scene into planar patches, the LS adjustment of a planar model for each patch, the LS computation for each patch of the epoch-to-epoch deformation, and a statistical analysis of the derived deformation parameters. The key advantage of this approach is the capability to detect deformations with magnitudes that are well below the nominal single point precision. The main disadvantage of the technique is the need to explicitly model the surface patches, which cannot be applied in different applications, such as those involving many natural targets. This aspect is further discussed in the following section.

This paper presents a new approach to deformation measurement using repeated TLS acquisitions over the same scene. Although this has not been tested yet, the proposed approach could be also applied on point cloud