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Error model of direct georeferencing procedure of terrestrial laser scanning

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ABSTRACT

Processing of raw point cloud data obtained as a result of terrestrial laser scanning (TLS) sometimes involves georeferencing, i.e. transformation of point cloud data to an external coordinate system. This paper focuses on defining the error model of point positions obtained through a "station-orientation" procedure of direct georeferencing. The original error model presented by the authors relevant in this field is partly altered. All modifications are explained in detail within the paper and the reported model is statistically verified based on the carefully conducted experiment using Leica ScanStation P20 scanner.
The obtained values of the uncertainty measures of direct georeferencing which are of a few millimetre magnitude prove that this procedure can be efficiently used for planning and carrying out even more demanding surveying tasks, including those during monitoring and maintenance of constructed facilities. Additionally, traversing capabilities of terrestrial laser scanners tightly connected with direct georeferencing should contribute to mass introduction of laser scanning into the construction industry thanks to its similarities to the highly automated procedures of polar surveying and traversing which are traditionally employed among surveyors.

1. Introduction

Terrestrial laser scanning (TLS) is a method for mass 3D data acquisition. The result of its application is a point cloud of the observed object [1]. Great amount of highly accurate spatial data obtained this way provide a possibility to build quality models of various structures and, consequently, monitor and maintain them in an efficient manner. Positional uncertainties of scanned points propagate through the processes of registration and/or segmentation into final 3D as-built models or structural monitoring results [2]. The first and critical step in such a workflow is to provide quality data. If a registered point cloud features low accuracy and resolution, it is impossible to achieve high quality of 3D model or any other product or information based on that point cloud [3].

Although the issue of realization of TLS-aided engineering tasks related to monitoring and maintenance of various structures has already been treated widely by various authors [4–14], not much was done in the field of investigating possibilities of planning these tasks. Fan addressed the possibility of planning TLS measurements for monitoring a slope stability [15], while Soudarissanane and Lindenbergh reported on optimizing a number and spatial distribution of scanner stand-points for fully covering a particular scene [16]. Here we tried to contribute to these issues of planning certain engineering tasks by giving an error model of one particular TLS procedure.

Despite the fact that a raw point cloud can be used for some investigations, an in-depth analysis of scan data requires a "little more" effort regarding data processing. The first processing steps are usually scan registration and/or georeferencing. And while the scan registration involves transforming multiple scans acquired from several station points into a common coordinate system (usually a coordinate system of one of the scans), georeferencing means transforming the scan data from an arbitrary coordinate system (CS) to an external CS or, more precisely, CS of a geodetic control network [17].

A method of point cloud (scan) georeferencing is determined on the basis of predefined experiment methodology [18]. Accordingly, it is distinguished between indirect and direct approach to point cloud georeferencing. The main difference between these two is reflected in the fact that indirect georeferencing requires additional post-processing of scan data in the office in order to get point coordinates in the CS of a geodetic control network. Direct georeferencing on the other hand means that scan data are transformed to the CS of a geodetic control network during fieldwork. There are several

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approaches within this direct method that have been developed so far [17,19-22]. This paper focuses on the method that mimics tacheometric method of surveying. It means that the scanner is centred and levelled over a point with known coordinates and elevation, the height of the scanner above the point is measured and the scanner is oriented towards another "known" point.

While error sources in TLS have generally been widely investigated so far [23–27], very few authors worked on deriving an error model of direct georeferencing. The original work was presented in 2004 by Lichti and Gordon [28], followed by the paper they published with Tipdecho in 2005 [29]. Scaioni [30] expanded the model, while Reshetyuk [21,31] mainly cited previous authors. In this paper we partly altered the original model by introducing some modifications that are mainly methodological in nature and rely on the classical theory of errors in surveying. Firstly, we discussed centring and pointing errors and their impact on determining precision of the position of a georeferenced point. The original model was modified to reflect the nature of this impact, which means that certain components of the model were altered to either exclude or include the influences of the centring and pointing errors.

After introducing these modifications we endeavoured to develop a model which could be tested against data acquired in a field test. Namely, [28], [29] and [30] describe situations when the original model is used to simulate point position precision in some of the common scanning scenarios and then to assess point position precision for point clouds obtained in cultural heritage environment. Model-derived errors, theoretical by nature, were then compared with point position errors given in the scanner specifications issued by the manufacturer, although these can also be considered theoretical. Despite the fact that figures given in the specifications are obtained after thorough instrument testing and calibration in metrological laboratories, they do not always reflect real-world situations. So our intention was to develop a model which could be tested against truly experimental data. In order to be able to do that, we had to additionally modify the original model which was tailored for situations when precision of the position of a single point from the point cloud is assessed, rather than of a target. Nevertheless, the initial assumption stayed the same: the precision of point coordinates georeferenced through direct method is affected by the instrument errors and precision of determination of the transformation parameters.

Like the original paper, this one is also mainly theoretical, but with additional verification of its adequacy based on the carefully conducted experiment. Certain restrictions originating from the nature of TLS data inevitably exist, but the real data confirms the validity of the reported error model to a great extent. The values of the uncertainty measures, obtained both from the theoretical model and in the field test, which are in the order of magnitude of a few millimetres make us optimistic in terms of possibility of using direct georeferencing of a point cloud even for more demanding surveying tasks during construction process, quality monitoring and risk management of buildings or infrastructure. At the same time, since traversing using laser scanners means employing essentially the same procedure as traversing using total stations which is the procedure traditionally employed by surveyors, this should contribute to the faster introduction of laser scanning into the construction industry. Of course, in order to carry out reliable traversing using laser scanners, these instruments must feature the ability of high precision centring, levelling and instrument height measuring.

It is important to emphasize that one should always be aware of the fact that specific uncertainty measures of a terrestrial laser scanner as a geodetic instrument enter the error model as a priori values. The lack of ISO standards in declaring these uncertainty measures (ISO 17123-9 is currently under development) introduces a potential problem in the practical application of the reported model for planning TLS measurement data errors.

2. Direct georeferencing method

Georeferencing involves transforming point cloud data from an arbitrary coordinate system (scanner CS to be exact) to an external CS (CS of a geodetic control network). The general form of this transformation is given by

$$\mathbf{X_e} = \mathbf{X_0} + s \cdot \mathbf{R_{se}} \cdot \mathbf{x_s}, \tag{1}$$

with

- $\mathbf{X_0}$ being the vector of coordinates of the scanner CS origin (scanner electro-optical centre) in the external CS,
- s being the scale factor,
- $\mathbf{R_{se}}$ being the rotation matrix between the scanner CS and the external CS,
- $\mathbf{x_s}$ being the vector of point coordinates in the scanner CS,
- $\mathbf{X_e}$ being the vector of point coordinates in the external CS.

The scale factor is only taken into account in some special scanner performance investigations, otherwise it is neglected (it is considered to be equal to 1). Additionally, since the "station-orientation" procedure of direct georeferencing is investigated within this paper, assuming that the scanner is equipped with a dual-axis compensator Eq. (1) is further simplified [32]:

$$\mathbf{X_e} = \mathbf{X_0} + \mathbf{R_{se}}\,(\kappa) \cdot \mathbf{x_s}. \tag{2}$$

Here (κ) indicates that the rotation matrix between the scanner CS and the external CS depends solely on the azimuth from the scanner station point to the backsight target, i.e. the scanner CS is rotated only about its z-axis. Rotation angles about x- and y-axis (ω and φ) are de facto equal to zero when the scanner is precisely levelled using a built-in dual-axis compensator (Fig. 1).

Possessing the aforementioned dual-axis compensator is not the only prerequisite the scanner has to meet in order to enable a successful direct georeferencing. The scanner must be equipped with other devices common for a total station (optical or digital plummet, circular, plate or digital level). Besides, it must possess adequate built-in software routines and enable accurate measuring of the instrument height. Nearly all major terrestrial laser scanner manufacturers recently started providing their high-precision surveying-intended instruments with this potential, which was not the case just a decade ago. For example, Leica HDS3000 scanner which was manufactured until 2006 is equipped only with a circular level with common sensitivity of about 8 arc-minutes installed on a classical tribrach. Furthermore, the lack of a dual-axis compensator which is typical of the older generation scanners leads to a significant point cloud delevelling, as well as to a centring error which even reaches the values of several millimetres if scanner is set up on a pillar [33]. Another important thing to notice is that although some scanners are equipped with a telescope which can be used for pointing towards a backsight target, most of them use standard TLS targets and algorithms for automatic target recognition and target centre determination.

Direct georeferencing of a point cloud using "station-orientation" procedure is completely analogous to a polar method of surveying. The application of this method in geodetic engineering is limited by the fact that the instrument height measurement error, centring error, levelling error and azimuth error significantly contribute to the total error of georeferenced point cloud data. Thus, instrument height measurement, centring, levelling and backsighting should be carefully conducted if increased georeferenced data accuracy is required.

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