ISPRS Journal of Photogrammetry and Remote Sensing 125 (2017) 146–155

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

An intensity-based stochastic model for terrestrial laser scanners

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ARTICLE INFO

Article history:
Received 8 September 2016
Received in revised form 13 December 2016
Accepted 15 December 2016
Available online 1 February 2017

Keywords:
Terrestrial laser scanning
Rangefinder
Stochastic modelling
Precision
Individual point quality

ABSTRACT

Up until now no appropriate models have been proposed that are capable to describe the stochastic characteristics of reflectorless rangefinders - the key component of terrestrial laser scanners. This state has to be rated as unsatisfactory especially from the perception of Geodesy where comprehensive knowledge about the precision of measurements is of vital importance, for instance to weigh individual observations or to reveal outliers. In order to tackle this problem, a novel intensity-based stochastic model for the reflectorless rangefinder of a Zoller + Fröhlich Imager 5006 h is experimentally derived. This model accommodates the influence of the interaction between the emitted signal and object surface as well as the acquisition configuration on distance measurements. Based on two different experiments the stochastic model has been successfully verified for three chosen sampling rates.

1. Introduction

Terrestrial laser scanners (TLS) have reached a high level of acceptance in the field of Geodesy and are consequently used in various fields of applications, for instance kinematic laser scanning (Böder et al., 2010), deformation monitoring (Lindenbergh and Pietrzyk, 2015), cultural heritage (Böhler and Marbs, 2004) and bio mass estimation (Tilly et al., 2013). As for all other surveying instruments, the achievable precision or measurement noise is used, among other characteristics, to decide whether a specific sensor is suitable to fulfil a particular task or not. Furthermore, this information is also vital for identification of outliers, statistically significant identification of deformation, comparison of different laser scanners, and weighting of individual observations in an adjustment. For these reasons, the assumed precision of observations is gathered within the stochastic model.

Regarding the noise of TLS observations it is emphasised that after more than a decade of intensive research no appropriate stochastic model has been published (e.g. Böhler et al., 2003; Soudarissanane, 2016) - a circumstance which has to be rated as unsatisfactory from a geodetic point of view. The reason why the stochastic properties are not well understood up to this point can be associated to the component that lead to the development of laser scanners, namely reflectorless rangefinders (RL-RF) that are also referred to as electro-optic distance measurement units (RL-EDM). The advantage of these RL-EDMs is that distances can be determined between an instrument and an object point without the necessity of bringing artificial reflectors, such as prisms or markers, into the object space. Yet, some requirements exist for reflectorless rangefinders namely, that the object is not translucent and that a certain amount of the emitted signal has to be reflected by the object's surface.

Moreover it can be established that the emitted laser signal is subject to various falsifying effects during its way on an uncontrolled optical path. Soudarissanane et al. (2011) declare four main categories that influence the quality of individual points captured by TLS, namely:

- the instrument mechanism;
- the atmospheric conditions;
- the properties of the object's surface; and
- the acquisition configuration.

While various authors do not distinguish between systematic and random errors in their contributions (see next paragraph), this article will strictly focus on stochastic signals in reflectorless rangefinders. Hence, effects are analysed that are caused by the last two categories.

1.1. Related work

The use of appropriate stochastic models is of particular importance for tasks such as sensor calibration of terrestrial laser

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http://dx.doi.org/10.1016/j.isprsjprs.2016.12.006

scanners (Lichti, 2007), registration of point clouds (Grant et al., 2012), direct georeferencing of TLS (Scaioni, 2005) or propagating the uncertainty of a mobile mapping system (Mezian et al., 2016). While the two latter contributions consider an extended error budget that involves several sensors, this article will solely analyse the stochastic behaviour of a TLS's rangefinder. Regarding the registration problem discussed by Grant et al. (2012) it has to be emphasised that the spatial sampling uncertainty of TLS should also be considered in their stochastic model, as it may surpass the precision of observations (Wujanz et al., 2016).

As it is well known that constant weights cannot be assumed for ranges observed by terrestrial laser scanners (Soudarissanane, 2016), methods have been developed to address this issue. In early publications on the subject Böhler et al. (2003) derive the noise of a TLS's rangefinder from residuals to an adjusted plane which has been previously scanned. A similar approach has been proposed by Heister (2006) who chose spherical targets instead of planes. Both procedures are subject to several influences that can notably falsify the outcome, for instance:

- accuracy of angle encoders;
- spatial resolution of the data as well as redundancy;
- accuracy of the applied geometric primitives; and
- processing software.

Even though the listed aspects appear to be self-explanatory at first glance, some remarks should be made. As Böhler et al. (2003) and Heister (2006) aim to describe the noise of rangefinders, only observed ranges should be considered. The adjustment of scanned geometric primitives in order to derive these stochastic measures is unfavourable as the stochastic properties of the angle encoders will interfere with the ones of the rangefinder. In addition, the result of an adjustment is influenced by the redundancy, the sampling of points in object space and potential outliers that are likely to occur on the boundary of an object. The most critical item in the list is the accuracy of the measured primitives as their geometric characteristics have to be more accurate than the precision of TLS measurements. If this is not the case, the imperfections of the primitive will lead to larger residuals that exceed the scanner's noise. Consequently, the evaluation of the rangefinder performance would be too pessimistic. Concerning the software for adjusting geometric primitives various commercial solutions or self-implemented code may be applied to compute the desired stochastic measures of an EDM. As it is usually unclear how a certain adjustment was implemented, for instance which functional model has been chosen or if and how outliers are automatically rejected, generated results are not necessarily comparable.

Even though usage of scanned geometric primitives is disadvantageous due to the aforementioned negative impacts, the majority of authors still follows this path, e.g. Voegtle et al. (2008), Soudarissanane et al. (2011). An alternative method is pursued by Zámečníková et al. (2014) who derive deviations between reference measurements recorded on a baseline to observations of a TLS captured within the 2D profile mode. Another commonality of contributions on the subject is that various influences are separately considered for instance:

- object distance (Elkhrachy and Niemeier, 2006);
- surface properties (Zámečníková et al., 2014); and
- varying incidence angles (Soudarissanane et al., 2011).

Regarding a suitable stochastic model this means that all listed impacts would have to be considered individually. While this is feasible for the object distance, the surface properties for individual points are usually not known. Incidence angles for single points can be computed from adjacent points yet are not very reliable as the ratio between local point density and noise is usually unfavourable. In summary it can be concluded that a separate consideration of various influences is not practical as the majority of effects cannot be explicitly modelled due to the fact that they are unknown.

Soudarissanane et al. (2011) remark in their contribution regarding the incidence angle that an unfavourable signal-to-noise ratio (SNR) yields to a loss of precision of the range measurement. A similar conclusion is drawn by Zámečníková et al. (2014) who state that the received signal strength should be considered in laser scanner error models. These statements are a step into the right direction as they link the precision of range measurements to the quality of the signal. A vital optical element in TLS is the receiving photo diode (Vosselmann and Maas, 2010, p. 14; Mettenleiter et al., 2015, p. 16 ff.) that derives the distance between scanner and object as well as the signal's strength, which is also referred to as intensity (Höfle and Pfeifer, 2007), based on the reflected signal. Mettenleiter et al. (2015, p. 51) presume that the noise of a rangefinder is dependent to the strength of the received signal, which forms the theoretical basis for this article.

1.2. Motivation

The mentioned relationship between SNR and achievable precision of measurements is also widely known for other surveying techniques, e.g. photogrammetry (Ackermann, 1984). Yet, a causal separation of influencing factors on the SNR in the context of TLS cannot be made. This leads to the motivation to develop a stochastic model for rangefinders of TLS that inherently considers the acquisition configuration as well as the reflectance properties of an object. Thus, raw intensity values recorded by TLS serve as input for the proposed stochastic model as they capture the effects that are caused by the acquisition configuration as well as interdependencies between emitted signal and object surface.

Another important factor is that the proposed stochastic model should only describe the characteristics of the rangefinder of a TLS, as this is its key component. As distance measurements are, in addition to direction and tilt angle, elementary observations, only input parameters should be used to develop the stochastic model that are independent of the other elementary observations or derived quantities such as Cartesian coordinates. As a consequence, only observed ranges are used to model the stochastic properties of the TLS's distance measurements. By this course of action influences provoked by the accuracy of the angle encoders, the spatial resolution of acquired 3D-data, the quality of the applied geometric primitives as well as the processing software are ruled out. In summary three arguments lead to the motivation for this article:

Argument 1: The input parameters for the stochastic model should be independent to other elementary observations or derived quantities such as Cartesian coordinates.
Argument 2: All previously mentioned influences have an impact onto the signal's strength and hence the precision of distance measurements. A causal separation of influencing factors cannot be made.
Argument 3: Raw intensity values are capable of capturing those influences provoked by the acquisition configuration as well as radiometric properties of a sampled surface. Hence, intensity values should be suitable to assign stochastic properties to rangefinders, if a characteristic behaviour can be observed.

The second mentioned argument is demonstrated with a simple example: The noise level on a light surface that was scanned under a "bad" incidence angle far away from the scanner can be