On the Tracking of a Laser Scanner for Geo-Referencing Tasks by Means of Geodetic Sensors

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Abstract

For several terrestrial laser scanning applications, it is important to register different static 3D laser scans with locally different coordinate systems in one standard coordinate system. This paper deals with a sensor fusion, which consists of a terrestrial laser scanner (TLS) and additional sensors for an efficient direct geo-referencing of such laser scans. An efficient way to determine the transformation parameters –position vector and orientation– is the direct observation of these parameters with geodetic positioning sensors. While the determination of the position vector by GNSS or tacheometry measurements is an easygoing task, the determination of the orientation is challenging. In order to determine this orientation information the constant rotation of the TLS about its vertical axis is used with a synchronous high frequency 3D tracking of a characteristic point on the TLS, e.g., the antenna reference point of the GNSS antenna or a prism. The 3D track is evaluated within an adaptive extended Kalman Filter approach. As a result we obtain the filtered positions and the orientation of all three axes. To show the potential of the described procedure for the direct geo-referencing a practical experiment is performed with simultaneous tracking of the TLS by GNSS and tacheometry measurements. The results for the geo-referencing of the captured laser scans are compared with each other as well as with the results determined by the classical geo-referencing with artificial control points.

Keywords

Terrestrial Laser Scanning, Geo-referencing, Kalman Filtering, Tracking

1 INTRODUCTION

The terrestrial laser scanning technique has been established nowadays in the engineering geodesy. The benefit of this technique is the immediate data acquisition in 3D space with a high spatial resolution as well as with a very high frequency. However, the gathered 3D point cloud is given generally in a relative or local sensor-defined coordinate system, which could be disadvantageous for several applications in engineering geodesy. Hence, there is a basic necessity for estimation of the single fixed translation and orientation of the terrestrial laser scanner (TLS) in relation to an absolute or global coordinate system. This is the typical registration and/or geo-referencing task in the static scanning domain. Whenever a combination of several scans from locally different stations into one standard coordinate system (registration) is required, the transformation parameters for each scan have to be estimated. This can be done by iterative algorithms, e.g., the Iterative Closest Point (ICP) algorithm [Besl & McKay, 1992], or by identifying several artificial control points in each scan. For an additional link to an absolute or global coordinate system (geo-referencing), control points with a known geodetic datum are indispensable. If the geodetic datum of the control points has also to be determined, the procedure would be complex and time-consuming due to an additional and independent surveying.

A well-known procedure from the kinematic scanning domain can be used to find an efficient way for the geo-referencing task of a static laser scanner station. Typically 2D profiles with time-dependent translation vector and orientation are observed in kinematic scanning applications. The transformation parameters for each 2D profile are acquired by the tracking of the TLS with navigation sensors such as, e.g., GNSS equipment and inertial measurement unit, and are estimated in a Kalman Filtering process [Vennegeerts et al., 2008].

It is possible, however, to transfer the above mentioned procedure from the kinematic scanning domain to the static scanning. At first there is the tracking of the position and orientation, which can be derived by the orbital motion of the fixed laser scanner station. Therefore a multi-sensor system (MSS) is built by a laser scanner, navigation sensors, and geodetic positioning sensors, which is comparable to the setup of a MSS for kinematic scanning applications (known as mobile mapping system) [Vennegeerts et al., 2008]. For the estimation of the transformation parameters, which are constant for the whole 3D laser scan, a Kalman filtering process is initiated. These parameters may also be used as appropriate start values with variance information for iterative algorithms for registration tasks without the need of any control points.

The paper is organized as follows. Section 2 describes the concept for geo-referencing of terrestrial 3D laser scans by the tracking of a TLS-based MSS by means of geodetic positioning sensors. Also a brief overview about the modelling within a Kalman Filter as well as an overview of the analysis strategy are given. In Section 3 the realization of a prototype implementation is presented. Furthermore practical investigations with different geodetic positioning sensors as well as a comparison of these results with the results determined by the classical geo-referencing with artificial control points is given. Finally, Section 4 summarizes the results and gives an outlook for future work.

2 CONCEPT FOR GEO-REFERENCING OF TERRESTRIAL 3D LASER SCANS

In Section 1 the clear advantages of tracking a laser scanner for geo-referencing by means of geodetic sensors in comparison with the traditional way by using control points was already shown. The main benefit is the direct observation of the required transformation parameters from the local sensor-defined coordinate system, given by the MSS, to a global coordinate system. This 3D transformation is defined by a translation vector, which is equal to the position of the MSS, and a rotation matrix. This matrix contains the orientations of the three axes of the MSS, comparable to roll, pitch and yaw angle known from aeronautics. This transformation has at least six degrees of freedom (dof) which have to determined by observation and estimation. Because of the fixed terrestrial MSS, which can be orientated to the center of gravity, the spatial rotations (roll and pitch) about the X- and Y-axis of the MSS can be minimized. However, four of the six dof, the position vector as well as the azimuthal orientation (yaw), are essential for the 3D transformation.

The straightforward task of determining the position vector of the TLS has also been treated by commercial manufacturers of laser scanners such as, e.g., Leica Geosystems and Riegl [Web1, Web2]. Riegl uses an integrated L1 GPS receiver while Leica Geosystems gives the option to adapt standard surveying equipment such as the Leica GPS SmartAntenna or prism holder. The just mentioned 3D positioning sensors are centrically adapted on top of the TLS. The field of view (fov) of the Leica scanner is limited in the overhead area whereas the fov of the Riegl scanner is not influenced. Note that both manufacturers do not provide a direct azimuthal orientation with the adapted sensors. Therefore additional artificial control points with known coordinates nearby the scanning area are needed. Both manufacturers have integrated inclination sensors so that an orientation of the sensor to the center of gravity is possible.

Hence, a strategy for direct geo-referencing of a TLS is needed which overcomes all limitations mentioned above. At the Geodetic Institute of the Leibniz Universität Hannover (GIH) an adapted sensor-driven method is developed to determine the 3D transformation for a static TLS station.
An efficient way of scanning huge objects from several static stations can be achieved by mounting the MSS on a mobile platform. Please note that the data acquisition is only performed statically on selective stations in contrast to classical mobile mapping applications where the data acquisition is done in motion. The strategy can be divided into a hardware part dealing with the aspects of the sensor fusion in the MSS and a software part dealing with the different algorithms for the transformation parameters estimation.

2.1 Hardware part: Sensor fusion in the MSS

The developed MSS is composed by of a sensor fusion of a phase-based TLS, which is the main sensor, and of additional geodetic positioning and navigation sensors which are required to observe the transformation parameters. While developing the MSS, several issues have to be considered. The operation of the laser scanner should neither be restricted nor disturbed by any of the enlisted additional sensors. Hence, one has to take advantage of the individual characteristic of any sensor. Here one can point out the usage of the constant rotation of the laser scanner about its vertical axis as time and orientation reference. This is a major difference compared with the commercial realizations which are discussed in a subsequent section. The TLS characteristic of a high frequency data acquisition rate with in general more than 10 Hz for the used phase-based TLS demands adequate data rates for the additional positioning and navigation sensors to derive reliable transformation parameters. If the data rate of the positioning sensor differs significantly from the data acquisition rate of the TLS an appropriately good motion model of the TLS and a suitable interpolation method for the positioning data are required, respectively. Indispensable in the MSS is the synchronization of all enlisted sensors so that the individual measurements could be temporally related to each other. For this reason, it is useful to define a unique time reference in the MSS. The most suitable way is to use GPS time as reference because GNSS equipment is usually one of the enlisted sensors in the MSS. For further details about the time synchronization in the MSS please refer to [Paffenholz & Kutterer, 2008].

As a minimum number of additional sensors for tracking the orbital motion of the fixed laser scanner station one geodetic positioning sensor is required. This sensor is adapted eccentrically on top of the laser scanner. Nevertheless, if one or two positioning sensors are used, the trajectory of a characteristic point on the TLS is a space curve which is described by the orbital motion of the laser scanner (cf. Figure 2). The case of mounting two positioning sensors at the same time on top of the laser scanner may lead to different approaches within the scope of the pre-processing of the 3D tracking data. We can sum up that the used geodetic positioning sensor for the 3D tracking of the orbital motion of the TLS is a flexible choice depending on the environment of the laser scanner station. For instance GNSS equipment or a tacheometer can be used. In such a case the characteristic point on top of the TLS will be equipped with a GNSS antenna or with a prism, respectively.

This minimum number of additional sensors especially for the tracking of the orbital motion leads to the fact that only four of the six dof are determinable. If the MSS can be mounted horizontally, any residual divergence of the orientation to the center of gravity can be neglected in first approximation. This is feasible if the integrated inclinometers are used to mount the fixed MSS station with respect to the center of gravity before the measurements.

In [Paffenholz et al., 2010] an optimization of the direct geo-referencing strategy is described by further sensor modifications in the MSS. In addition to the positioning sensors, navigations sensors (inclinometers) to estimate the remaining two dof (the spatial rotations about the X- and Y-axis of the MSS) were integrated in the MSS. For synchronization purposes an external process computer with integrated analogous-digital converter is used. The challenge of using the integrated inclinometers is the synchronization of the data because a parallel way of synchronization to the external sensors is not available at the moment.

Besides the briefly described modification, the horizontal motor steps of the laser scanner were introduced to the algorithm as additional information about the orbital motion of the laser scanner. The synchronization of this new data source is instantaneously available by the general synchronization pulse of the laser scanner which corresponds to the progress in the horizontal rotation of the laser scanner about its vertical axis.

2.2 Software part: Transformation parameters estimation

The described sensor modification and additionally available data sources lead to significant modifications of the algorithm for the estimation of the transformation parameters given in [Paffenholz et al., 2009]. In addition, and due to the consideration of all dof of the transformation from the local to the global coordinate system, a more accurate estimation of the unknown parameters is expected. This subsection gives a brief overview about the algorithmic part of the transformation parameters estimation. For a detailed discussion of the algorithmic part please refer to [Paffenholz et al., 2010].

The current algorithm was developed in a closed form on basis of a Kalman Filter (KF), which determines the required transformation parameters as an output. The first algorithm to derive the transformation parameters [Paffenholz & Kutterer, 2008] was separated in two parameter estimations which are computed by means of a least-squares adjustment. First, a projection onto a best-fitting plane for all 3D positions is determined. Second, an estimation of a best-fitting circle through the projected positions is computed. The main drawback of the mentioned two-step model is that the data acquisition must be finalised before the processing steps can be performed. In addition, a setup of two separated adjustments with extra outlier detection is required.

The current algorithm based on a KF resolved the above mentioned disadvantages. On the one hand the KF allows a real-time processing. On the other hand the parameter estimation is less sensitive against outliers. The main aim of a KF is the optimal combination of given physical information for a system and external observations of its state. The modelling of the orbital motion of the static MSS is comparable to the general modelling of trajectories of moving vehicles, which often leads to nonlinearities in the system equations of the KF. The functional relationship between the vehicle (MSS) coordinates and the other state parameters is generally nonlinear [Simon, 2006]. However, the state estimation within a KF is optimal only in case of linear state space systems. The extended Kalman filter (EKF) is the most widely-used technique for solving nonlinearities in the system and measurement equations. Further details about the EKF, which is based on an approximation of the nonlinear functions by a Taylor series expansion, can be found in, e.g., [Simon, 2006]. The EKF algorithm is additionally supplemented with adaptive parameters. These system specific parameters are time-invariant with well known initial values. The adaption with additional parameters in the dynamic model might improve the filtering and brings the model closer to reality [Eichhorn, 2007].

The algorithm part of the strategy -from the data acquisition to the estimation of the transformation parameters- can be divided into five parts:
Part I deals with the data acquisition in the MSS. In detail this is the scanned scene by the TLS, the 3D tracking data gathered by the geodetic positioning sensors -GNSS equipment or tacheometer with prism-, additional navigation sensors -external inclinometers-, and the synchronization information registered by a real-time process computer.
In part II the unique time reference for the MSS, the GPS time is introduced for all data sources.
Part III deals with the data fusion of all gathered data sources. For each 2D profile of the 3D point cloud the corresponding 3D tracking position as well as inclination has to be determined by an interpolation with respect to the time stamp of each 2D profile.
Part IV treats the core of the algorithm. By an EKF with adaptive parameters (AEKF) the estimation of the transformation parameters is performed. Besides the already mentioned observations, three system parameters are integrated into the AEKF as adaptive parameters. These time invariant parameters are determined in an independent procedure with high accuracy by a laser tracker. For more details about the modelling of the motion of the MSS, the system equations elements, and the measurement model please refer to [Paffenholz et al., 2010].
The final part V deals with the transformation of the 3D point cloud from the local sensor-defined to a global coordinate system.

3 PRACTICAL INVESTIGATIONS

The practical experiment was performed in front of the Welfenschloss, the main building of the Leibniz Universität Hannover (Figure 1). The scan object is the "Lower Saxony Steed" (Lower Saxony’s landmark). The acquisition of the laser scans is carried out with a Zoller+Fröhlich (Z+F) Imager 5006 in normal 3D mode at two different stations in front of the steed with 15 m distance from the object. As a typical scan parameter “high, low noise” has been used for horizontal positions from 0° up to 365°. The scanning time was approximately 15 minutes per station.

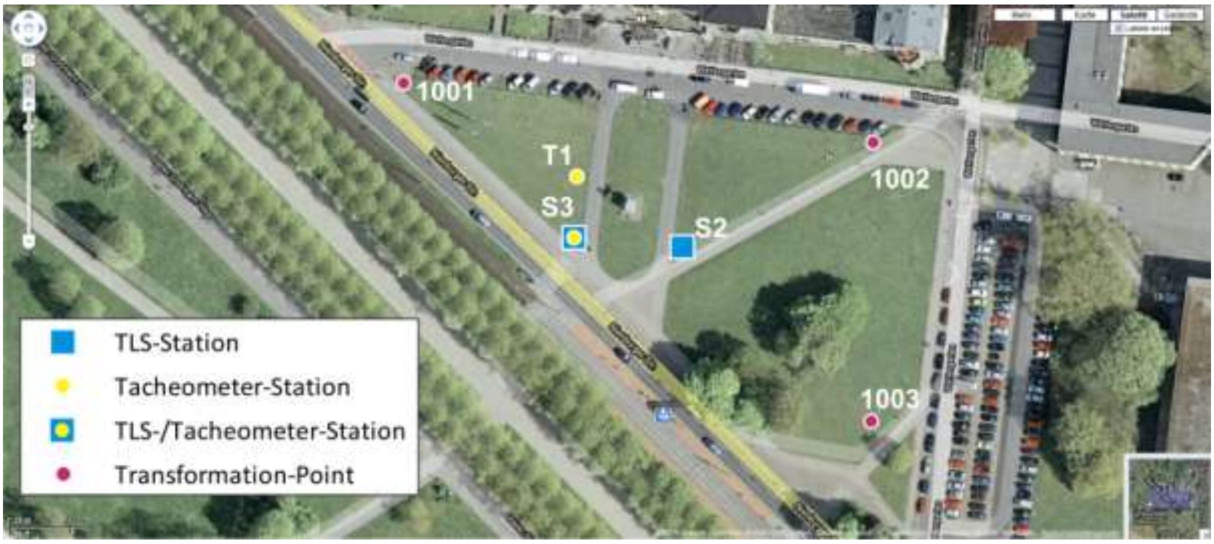

Figure 1: Configuration of the practical experiment in front of the Leibniz Universität Hannover (Image by Google Maps)

The orbital motion of the laser scanner was observed with different geodetic sensors, installed on top of the laser scanner. As previously described, various positioning sensors may be used for this task. Considering a possible application in a standard engineering office, classical geodetic sensors should be used as far as possible. Hence, it can be assumed that GNSS equipment and tacheometers are available.

In positive Y-axis direction of the laser scanner a JAVAD GRANT G3T GNSS antenna was adapted. The corresponding JAVAD GNSS receiver Delta G3T operated with a data rate of 100 Hz. In addition, a Leica GRZ4 360 degree prism was installed in negative Y-axis direction of the TLS. This prism was tracked by a Leica TS30 robot tacheometer. For this purpose the tacheometer was set to the "lock mode" and polled twice per second the measurements. Furthermore two navigation sensors (Schaevitz single axis inclinometers) were mounted on top of the laser scanner to explore any tumbling. Each of them observed one spatial rotation about the X- and Y-axis, respectively (cf. Figure 2). To obtain precise 3D positions for the orbital motion of the antenna reference point a GNSS reference station (Leica GRX1200GGPRO receiver with Leica AT504GG antenna at 20 Hz data rate) on top of the GIH (about 625 m from the scanning area) was used.

The merging of the different data sources was realized by means of an external real-time process computer. In this way, time synchronization for the 3D tracking positions, inclinometer measurements and the 3D point cloud could be guaranteed.

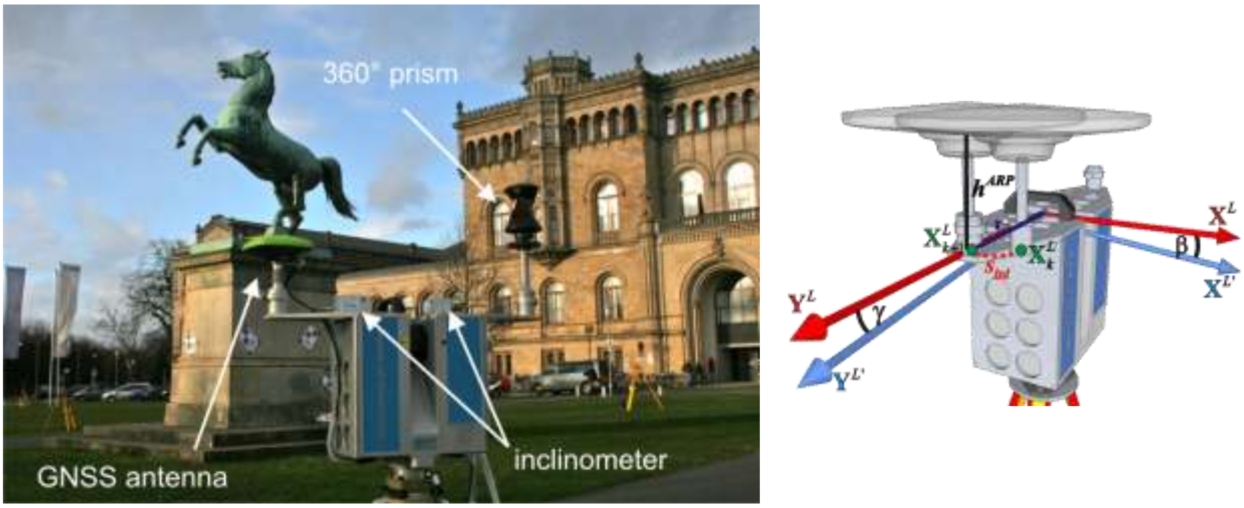

Figure 2: MSS prototype; left: MSS in front of the scanning object; right: sketch of the MSS

The traditional way of georeferencing static terrestrial laser scans was implemented by the scanning of control points with known coordinates. The determination of those control point coordinates was realized by tacheometry. For a direct comparison of the different geo-referencing technologies, all measurements have to be in the same coordinate system. For this purpose a geodetic network in a global earth-centred earth-fixed (ECEF) coordinate system was defined. Static GPS measurements and several sets of tacheometer measurements on three homologous points (1001, 1002, 1003) were accomplished. These data sets allowed the transformation of any other local tacheometer measurements to the ECEF coordinate system.

3.1 Comparison of GNSS and tacheometry trajectories

Figure 3 shows a comparison of the observed (red) and filtered (green) trajectories in an ECEF coordinate system. The blue triangle in the middle of each trajectory represents the center point of the filtered positions or translation vector of the MSS, respectively. On the left side of Figure 3, the trajectory is illustrated which is derived by the GNSS measurements. The AEKF effect is clearly visible. The right side of Figure 3 shows the trajectory derived by the tacheometer measurements. In contrast to the GNSS trajectory, the tacheometer trajectory is smooth. This difference is caused by the different data acquisition rates and different 3D position accuracies.

The noisy GNSS trajectory is resulting from the single 3D position accuracy of about 1 cm and the short observation interval of about 15 minutes only. For the GNSS analysis the software Wa1 by Lambert Wanninger [Web3] was used. The satellite configuration consists of 13 GPS and Glonass satellites. In the following work the filter will be improved by an integration of a data aggregation step to smooth the 100 Hz positions data according to the TLS data rate of 12.5 Hz.

The 3D positions of the smooth tacheometer trajectory have a 3D position accuracy of a few millimetres. To align the 2 Hz tacheometer measurements with the TLS data rate a wide range of 3D positions have to be interpolated. This is feasible if the motion model of the characteristic point on top of the TLS is well known. Furthermore, a higher-order interpolation method which takes into account the known motion model should be used in order to minimize the interpolation error. Nevertheless, in the current state of the MSS only a linear interpolation method is used to show the potential of the strategy. In future work an advanced interpolation method will be implemented; in addition, a higher data rate for the tacheometer measurements should be provided.

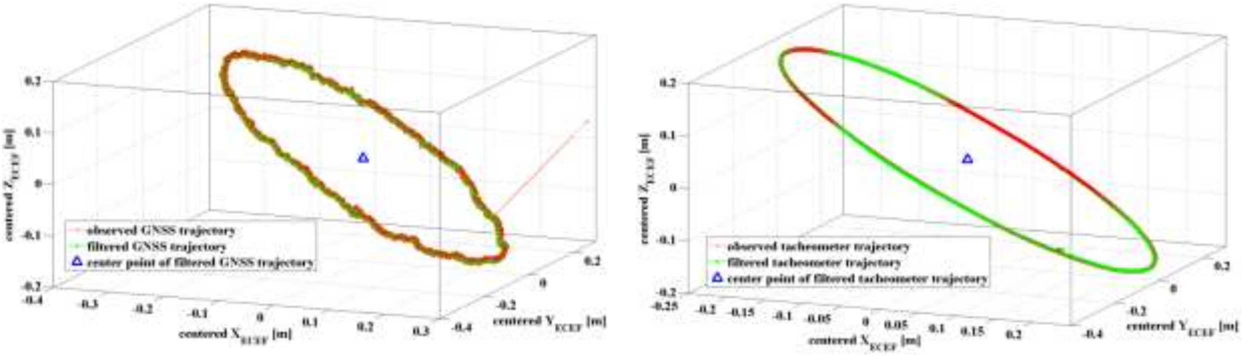

Figure 3: Comparison of the observed and filtered trajectories in an ECEF coordinate system; left: derived by GNSS; right: derived by tacheometer

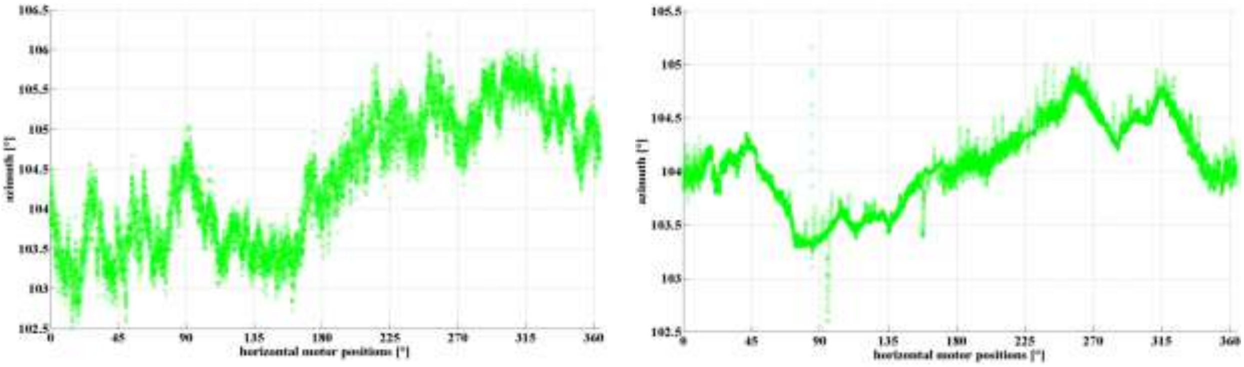

Figure 4: Comparison of MSS orientation; left: derived by GNSS; right: derived by tacheometer

Figure 4 shows the different orientations derived by GNSS and tacheometer. The orientation angles are reduced to the X-axis of the TLS for direct combination with the vertical 2D profiles of the 3D point cloud. Apart from the noise of the orientation parameters, systematic effects can be seen.

In case of the GNSS-derived orientations one can see the higher noise in comparison to the orientations derived with the tacheometer. This noise is linked to the estimated trajectories which are the input data for the orientation calculation.

In case of the tacheometer orientations, it can be assumed that the systematic effect is due to the prism rotation about its vertical axis during the 3D scan. Because of the rotation symmetry of the 360°-prism, repetitions of variations as a function of a periodic reflector orientation can be expected. The used Leica GRZ4 is built up from two sets of three nested prisms; so it can be assumed that the frequency is an integer multiple of three [Favre et al., 2000]. As it is obvious that the observed frequency of the systematic effect is not an integer multiple of three, further investigation is required.

The final azimuth for the MSS is calculated as the mean of the single orientations for the approximately 10100 2D profiles. This leads to a precision for the mean azimuth of a few milli-degree. The offset between the GNSS and tacheometer azimuth of about 0.3° was reproducible for both stations in repeated measurements. We assume that these two azimuths are located exactly alternate (180° to themselves). One can conclude that this assumption is incorrect and has to be proved by further investigations under laboratory conditions.

3.2 Impact of the derived orientations on the object

For the assessment of the available accuracy the positions of several artificial control points were compared which are derived from the different techniques and from different stations. The following figure shows two point clouds of the steed including the different control points (marked with standard TLS-targets).

Figure 5: 3D point clouds of the steed with artificial control points; left: station S3; right: station S2

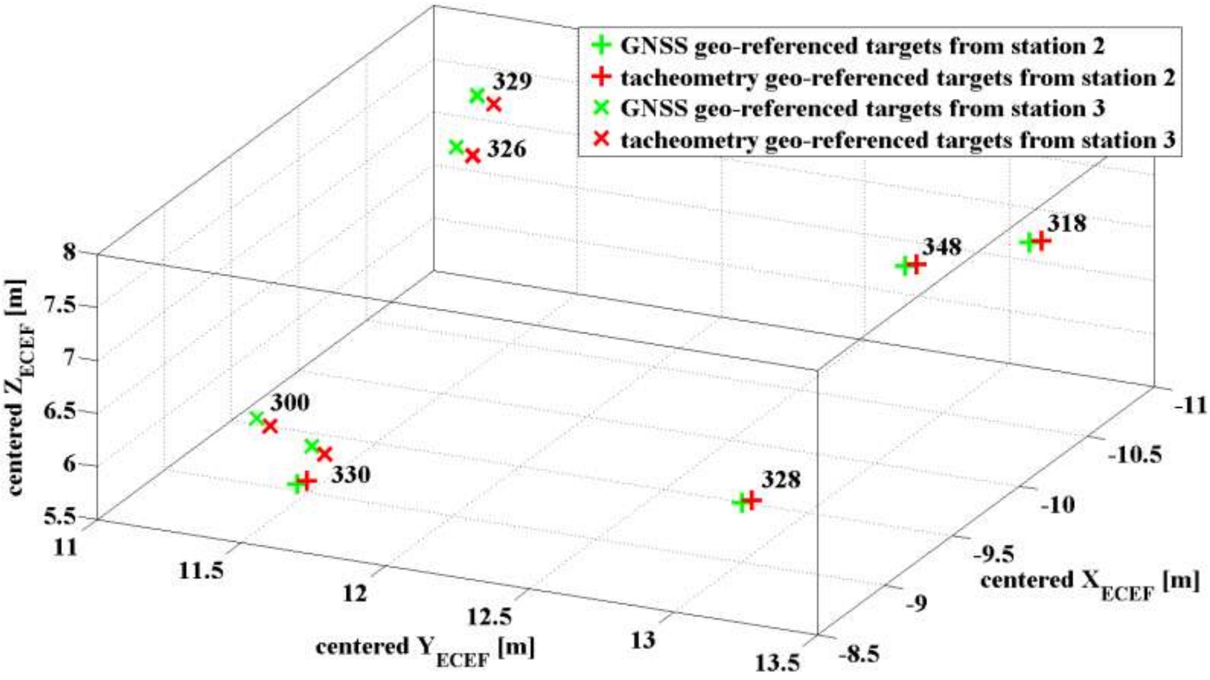

Figure 6: Centered ECEF coordinates of the control points of both stations determined by GNSS (green) and tacheometer (red)

Figure 6 shows a plot of estimated target coordinates. Green marks indicate the GNSS geo-referencing and the red ones illustrate the tacheometry geo-referencing from station 2 and station 3 in an ECEF coordinate system. Station 2 is illustrated with a plus and station 3 with a cross for each sensor.

Table 1: Coordinate differences for the control points

station	point nr	GNSS - tacheometry			
		dx [m]	dy [m]	dz [m]	ds [m]
S2_r3	328	-0,002	-0,034	-0,038	0,051
	348	-0,001	-0,041	-0,038	0,056
	318	-0,001	-0,042	-0,038	0,057
	330	-0,003	-0,033	0,042	0,053
S3_r1	330	-0,074	-0,078	-0,026	0,111
	300	-0,072	-0,079	-0,027	0,110
	326	-0,072	-0,089	-0,027	0,110
	329	-0,072	-0,090	-0,026	0,118

Table 1 gives an overview of the numerical values of the coordinate differences and spatial distances of all seven TLS-targets (compare to Figure 3). The distance between the stations and the seven targets is about 16 m. The displayed data sets are measured on two stations.

As one can see both sensors come nearly to the same result. The differences between the coordinates are less than one decimetre. Furthermore, it can be noticed that the spatial distance is almost the same for each station. This results from the uncertainty of the estimated azimuth per station, which is used for all targets. The large differences of the spatial distances on station 3 could be caused eventually by the transformation of the tacheometer measurements to the ECEF coordinate system.

Nevertheless, the abovementioned results show the operability of the georeferencing strategy independent on the operating geodetic sensor. A comparison of global reference control points and the coordinates resulting from the direct geo-referencing shows significant larger differences. An increasing of almost 1.5 times can be determined. Further investigations would explain the disturbances within station 3 as well as the significant global differences.

4 CONCLUSION AND FUTURE WORK

This paper gives an overview about a direct geo-referencing strategy of terrestrial laser scans developed at the GIH. We have shown that this is an efficient way to determine the transformation parameters –position vector and azimuth– which are directly observed by tracking the TLS by means of geodetic sensors. The estimation of the position vector is straightforward while the calculation of the orientation is challenging.

In a case study, the results of the tracking of the TLS by GNSS and a tacheometer are analysed. These first results for the completely performed geo-referencing procedure show the potential as well as the current limitations regarding the reachable accuracy of the azimuth. To show the precision of the strategy, a set of artificial control points is compared with each other which is geo-referenced by the two sensors.

The topics of the ongoing research are the improvement of the filter regarding the evaluation of the GNSS positions. Therefore, a data aggregation step to smooth the 100 Hz positions data according to the TLS data rate of 12.5 Hz should be developed. Also the interpolation method for low frequent position data such as the tracked prism positions of 2 Hz should be enhanced. In addition, an optimization of the observation strategy with initialization measurements for the global azimuth is an important problem to tackle. Besides this an inclination plane should be obtained.

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