A Concept for the Calibration of Terrestrial Laser Scanners

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Key words: Laser Scanner, Calibration, Adjustment, Planes

SUMMARY

In order to eliminate the influence of instrumental errors the consideration of calibration parameters is a very important issue for laser scanning instruments in practice. A new concept for the determination of the calibration parameters for different types of instruments has been derived based on adjustment planes.

This paper deals with the new concept for the calibration of geodetical instruments which provide polar measurements, like laser scanners or total stations where the distance measurements are collected without using reflectors.

Using plane parameters instead of point coordinates for the parameterization of the special calibration model, an extended Gauß-Markov-Model of quaternion transformations allows to solve for these parameters. Following the assumption that the instrumental error types of laser scanners coincide to the types of instrumental errors of tacheometers the approach of determining the calibration parameters is based in the same adjustment model. In this paper we will present a calibration example in order to show the power of the proposed method in addition to the concept.

ZUSAMMENFASSUNG

In diesem Beitrag wird ein Modell zur Kalibrierung von scannenden Messinstrumenten, die nach dem Theodolitmessprinzip arbeiten, vorgestellt. Dabei wird auf den Einsatz von diskreten Punkten als Passpunkte (Kugeln, Zieltafeln, o.ä.) verzichtet. Die Bestimmung der Kalibrierparameter des Messsystems und eine Abschätzung der Genauigkeiten der einzelnen Komponenten erfolgt in einem dreidimensionalen Testfeld, welches aus Ebenen besteht. Neben der Erläuterung des allgemeinen Fehlermodells für diese Art der polaren Messinstrumente und der Vorstellung des mathematischen (funktionalen) Modells, welches der Kalibrierung zu Grunde liegt, wird auf den an der TU Berlin realisierten Versuchsaufbau sowie auf den Ablauf der Kalibrierung eingegangen und die Ergebnisse der Kalibrierung eines Testobjektes werden vorgestellt.

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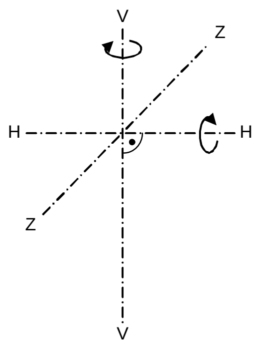
1. INTRODUCTION

Remaining systematic instrumental errors of scanning instruments (laser scanners, reflectorless measuring tacheometers, …) might cause a significant falsification of the measurement results. The results derived from these sensors are point clouds $(X, Y, Z)_i$, which afterwards will be structured to geometrical primitives. In order to minimize the systematical influence of instrumental errors, instruments have to be calibrated and the observations have to be corrected on the basis of the calibration parameters (INGENSAND et al. 2003). Calibration makes it furthermore possible to specify the observational accuracy of the sensor in use and to validate the specifications of the producer (BOEHLER et al. 2003).

2. MODEL OF INSTRUMENTAL ERRORS

The geometrical model of calibration is based on the assumption that the instrumental errors of the considered typical laser scanner corresponds to those of a totalstation. The local polar coordinate system of the instrument derived from the typical radiated station observables is represented by a vertical axis (VV), a horizontal tilting axis (HH) and the laser beam (ZZ). The relative spatial positions of these three axes can be expressed by 6 parameters – three translations and three rotations. The three angles are measured in a plane parallel to the two regarded axes.



e_{vh} :	orthogonal distance vertical axis – tilting axis
e_{vz} :	orthogonal distance vertical axis – laser beam
e_{hz} :	orthogonal distance tilting axis – laser beam
α_{vh} :	Angle between vertical axis and tilting axis
α_{vz} :	Angle between vertical axis and laser beam
α_{hz} :	Angle between tilting axis and laser beam

For the angles the following relationships are valid:

$\alpha_{vh} + v_{vh} = 100\text{gon}$	v_{vh} : trunnion axis error	
$\alpha_{vz} = \zeta + v_\zeta$	v_ζ : vertical index error,	ζ : measured zenith angle
$\alpha_{hz} + v_{hz} = 100\text{gon}$	v_{vh} : horizontal collimation error	

For the distance measurement unit an addition constant and a scale factor were modelled:

$$d_{expected} = a + d_{measured} \cdot m$$

$d_{expected}$	: expected distance
a	: addition constant
$d_{measured}$	: measured distance
m	: scale factor

The purpose of the instrumental calibration is to determine the parameters e_{vh}, e_{vz}, e_{hz}, v_{vh}, v_ζ, v_{hz}, a and m their significance level as well.
The components of the vertical axis direction, ξ and η, are not considered as specific instrumental errors. They are station specific orientation parameters in the proposed model, and will therefore be determined separately for each setting up of the instrument.

3. FUNCTIONAL MODEL

3.1 Rotation with Quaternions

The present model applies quaternion algebra for the functional description of rotations. This encompasses the rotational calibration parameters v_{vh}, v_ζ, v_{vh} as well as the orientation parameters ξ, η and ω of each station.

Quaternions are a generalisation of complex numbers. They were developed 1843 by Sir William Rowan Hamilton. For the representation two notations are in use:

$$\dot{q} = s + ix + jy + kz \quad \text{or} \quad \dot{q} = \left[s, \begin{pmatrix} x & y & z \end{pmatrix}^{\mathrm{T}}\right] \tag{1}$$

For the formulation of rotations the polar notation of quaternions is relevant:

$$\dot{q} = |\dot{q}| \cdot (\cos\Phi + i\sin\Phi + j\sin\Phi + k\sin\Phi) \tag{2}$$

If $\dot{q}$ is a unit quaternion it can be written in a simplified way as

$$\dot{q} = [\cos\Phi, n \cdot \sin\Phi], \tag{3}$$

were n is a vector of length 1. A rotation is expressed then by a quaternion multiplication of the type

$$\dot{x}_P' = \dot{q} \cdot \dot{x}_P \cdot \dot{q}^* \quad \text{mit} \quad |\dot{q}| = 1. \tag{4}$$

The components of the position vector $\mathbf{x}_P$ of the point P correspond to the vector components of the quaternion $\dot{x}$. The scalar component of the quaternion $\dot{x}$ is zero.
From a geometrical point of view the components of a rotation quaternion can be interpreted as vector and a rotation angle (see fig 2).

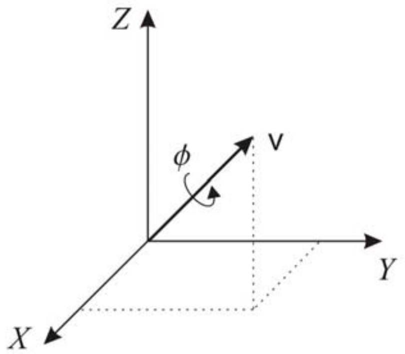


Fig. 2: Geometrical Interpretation of a Rotation Quaternion

In comparison to conventional rotation matrices, the application of quaternions for the description of rotations provides essential advantages. A rotation can be expressed by just 4 parameters. Only one degree of freedom remains which can easily be eliminated by normalizing the quaternion. The resulting condition equations are bi-linear; therefore it is possible to calculate the adjusted parameters without providing any proximity values. A unit quaternion of the following structure proved to be a sufficient initial value:

$$\dot{q}_0 = \left[0.5, \begin{pmatrix}0.5 & 0.5 & 0.5\end{pmatrix}^{\mathrm{T}}\right]. \tag{5}$$

3.2 Adjustment Approach

Usually the systematic falsification caused by remaining axis errors of theodolites will be eliminated by measuring to discrete points in two instrumental faces. However due to restrictions in the construction of laser scanners such a measuring configuration is not feasible because discrete positions of the laser beam can not be reproduced in a second instrumental face. One way out is the use of spherical targets whose centres are discrete points again. But this solution can lead to problems because of the unfavourable reflection behaviour at the margin of the spheres. Furthermore the high measuring density of the laser scanner will not be exploited at all in that case.

In the proposed procedure here a different measuring configuration will be used. Instead of identical points, identical planes will be referenced from different scanner stations. Exploiting the large amount of observations, precise adjusted parameters for the planes, the scanner stations and the scanner calibration can be calculated.

Observables:

$$\left.\begin{array}{ll} d & \text{Distances} \\ r & \text{Directions} \\ \zeta & \text{zenith angles} \end{array}\right\} \mathbf{l}$$

Unknown Plane Parameters:

$$\left.\begin{array}{ll} \mathbf{n}_{\mathrm{g}} & \text{normal vector} \\ d_g & \text{orthogonal distance to the origin} \end{array}\right\} \mathbf{x}_{\mathrm{E}}$$

Unknown Station Parameters:

$$\left.\begin{array}{ll} \mathbf{t}_{\mathrm{g}} & \text{station coordinates} \\ q & \text{quaternion} \rightarrow \text{orientation, vertical axis inclination} \end{array}\right\} \mathbf{x}_{\mathrm{S}}$$

Unknown Calibration Parameters:

$$\left.\begin{array}{ll} v_{vh} & \text{trunnion axis error} \\ v_{\zeta} & \text{vertical index error} \\ v_{hz} & \text{horizontal collimation error} \\ a & \text{additive constant} \\ m & \text{scale factor} \\ e_{vh} & \text{eccentricity vertical axis – tilting axis} \\ e_{vz} & \text{eccentricity vertical axis – laser beam} \\ e_{hz} & \text{eccentricity tilting axis – laser beam} \end{array}\right\} \mathbf{x}_{\mathrm{I}}$$

The model is in a way comparable to a photogrammetric bundle adjustment. However the orientation parameters of a direction bundle based on identical points will not be determined but the orientations of polar station coordinate systems based on identical planes instead. The global coordinates of a referenced point can be expressed as a function of the defined observables and unknowns.

$$\mathbf{x}_g = \mathrm{g}(\ \mathbf{l}, \mathbf{x}_{SP}, \mathbf{x}_I) \tag{6}$$

For the adjustment the Gauss-Helmert-Model – condition adjustment with unknowns and restrictions between the unknowns – will applied. The restrictions are responsible for the normalization of the quaternions and the normal vectors.

$$\begin{aligned} \mathrm{f}(\bar{\mathbf{l}}, \bar{\mathbf{x}}) &= s_1 \\ \mathrm{h}(\bar{\mathbf{x}}) \quad &= s_2 \end{aligned} \tag{7}$$

The condition equations in this case are form equations of planes with the point coordinates $\mathbf{x}_g$ and the plane parameters $\mathbf{x}_E$ as arguments.

$$\begin{aligned} &\vec{n}_g \cdot \vec{x}_g - d = 0 \\ &\mathrm{f}(\mathbf{x}_g, \mathbf{x}_E) \end{aligned} \tag{8}$$

The substitution of (6) in (8) results in

$$\mathrm{f}\left(\ \mathrm{g}(\ \mathbf{l}, \mathbf{x}_{SP}, \mathbf{x}_I\ ), \mathbf{x}_E \right) = 0\ . \tag{9}$$

After linearization the unknowns can be calculated according to

$$\mathbf{x} = \left(\mathbf{A}^T \underbrace{\left(\mathbf{B}^T \mathbf{Q}_{ll} \mathbf{B}\right)^{-1}}_{\mathbf{P}} \mathbf{A} \right)^{-1} \mathbf{A}^T \underbrace{\left(\mathbf{B}^T \mathbf{Q}_{ll} \mathbf{B}\right)^{-1}}_{\mathbf{P}} \mathbf{w} \quad \Rightarrow \quad \mathbf{x} = \left(\mathbf{A}^T \mathbf{P} \mathbf{A}\right)^{-1} \mathbf{A}^T \mathbf{P} \mathbf{w}\ . \tag{10}$$

The partial derivatives of (9) to the observables and unknowns lead to very complicated terms, therefore in the program the differentiation is realised in a numerical way. The predefinition of the datum is taken care of by setting the orientation parameters of one of the stations to be fixed.

In addition to the determination of calibration parameters of the scanner a further problem is to determine its observational accuracy. To ascertain the observation accuracy a variance component estimation and tests of significance for the calibration parameters will be performed in the adjustment. Their result can be used to update the a priori standard deviations. The results of the calculation process are significant calibration parameters as well as standard deviations for the observational groups *directions*, *distances* and *zenith angles*.

4. MEASURING CONFIGURATION

4.1 Test Field

For the determination of calibration parameters of polar measuring instruments a test field at the TU Berlin was installed, which is composed of 15 planar calibration panels. The calibration panels are customary chipboards (grey, 19mm) and they are distributed over different parts of the test room to cover the hemisphere as complete as possible (see fig. 3). The calibration panels have a size of approximately 1,0m x 1,3m, the area of the test room amounts ca. 60m^2 and the height of the room is 3,2m.

Fig. 3: Test Field at the TU Berlin (detail)

4.2 Procedure of Calibration

The procedure of calibration is performed in different steps, see Fig. 4:

The measurement for calibrating the instrument takes place "on-site" in the test field at the test room at the Technical University of Berlin. (ALDER 2003) recommends to use 4 different evenly distributed instrumental positions with varying heights. The original observational data from the scanning process are 3D polar coordinates – horizontal directions, vertical directions and distances. The local coordinate system of the particular station is defined by the temporary position and orientation of the scanner.

After transferring the data into the post processing part, the first calculation task consists of refering the points measured to their planes. This will be done in an automatic plane detection process, by a suitable evaluation of the point clouds (LANGE 2003), followed by an adjustment of these planes.

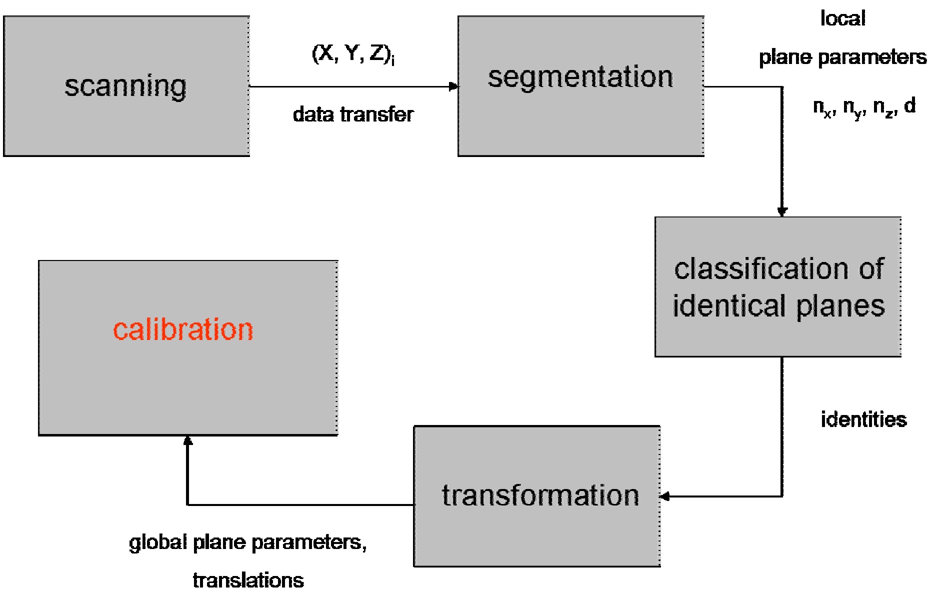


Fig. 4: Overview over the Calibration Procedure

The task of plane detection is to aggregate points to subsets which represent a parameterized surface and to estimate their corresponding parameters. These steps take place for every station and for every visible calibration panel. The results of this step are the local plane parameters, the normal vectors $\mathbf{n}_i = (n_x, n_y, n_z)^T$ and the orthogonal distances d_i between the planes and the origin.

For the second step of processing – finding identical planes– two different approaches could be considered. The first approach would be based on a manual selection of the interesting planes which can be done after the visual perception in a viewer, like a VRML-PlugIn, in combination with an Internet-Browser. However it would be difficult to locate these identical planes in a feasible time, because the user would have to move actively into the procedure.
The second approach is an automated procedure which is based on homogenous coordinates, projective geometry and robust Monte-Carlo-Methods. The robustness of these methods could be achieved using GASAC (RODEHORST 2004), a genetic algorithm sampling consensus.

The planes which are detected and proved to be significant will be used to transform different stations into a common system or into the global reference frame. If an object, consisting of at least three non parallel planes, being surveyed from two stations, then both station frames can be transformed into each other (THIENELT 2003).

Process automation, favourable error propagation and efficient blunder detection are the main characteristics of this step (RIETDORF & GIELSDORF 2003). The parameters received from the previous transformation will be used as proximity parameters for the last module, the calibration and estimation of the instrumental errors.

5. RESULTS

As a reference example a calibration of the laser scanning device developped as a prototype at TU Berlin has been done. The measuring device shows significant systematic instrumental errors due to constructive restrictions (RIETDORF & GIELSDORF 2003).

Abb. 3: Prototype Laserscanner

Statistics of adjustment:
Observable: 6326
Redundancy of the system: 6251
Instrumental errors:
Additive constant: 72,6 mm ± 0,1 mm
Trunnion axis error: -0,034 gon ± 0,003 gon
Horizontal collimation error: -0,304 gon ± 0,014 gon
eccentricity of instrumental axes:
a_x: -0,4 mm ± 0,1 mm
a_y: 1,1 mm ± 0,1 mm
a_z: not significant

The expected instrumental errors were confirmed by the calibration process shown above. No scale parameter has been determined in this process, as the scale factor could be determined beforehand via direct comparison to exactly determined distance measurements from high precision tacheometers. Based on the variance component estimation of the calibration process an estimated sensor precision was derived which resulted in 0.1gon for the horizontal and vertical angular measurements and 1mm for the distance measurements.

6. OUTLOOK

In this paper a powerful method for the calibration of polar measurement instruments has been presented. The determination of the calibration parameters is based on a calibration field, which consists of suitably arranged planes different special positions. The computational procedure analyses the measurements to these planes and does not require any identical point information. The planes are detected from the point clouds, their parameters and all calibration parameters are derived from an automated adjustment process, and, via variance component estimation, the precision of all parameters are determined. Thus the quality of the individual sensor components becomes visible. For determining the scale additional distance information is required, i.e. achieved measuring the distances between the instrumental positions.

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