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MISALIGNMENT CALIBRATION OF MULTISENSOR SYSTEMS FOR HORIZONTAL DIRECTIONAL DRILLING

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A new method was developed for calibration a multi-sensory system which contains one tri-axial accelerometer and two tri-axial magnetometers. The system is used for navigation of horizontal direction drilling. The method calculates the misalignment error (angular and offset) to mutually align all sensors. Specific rotations of the whole system are carried out and the errors are calculated by the optimization method from the recorded sensor data. By applying of correction matrices into the navigation algorithm, the error of the navigation unit was reduced to 0.5 meters in the 30-meter distance.

Keywords: horizontal drilling, magnetometer, accelerometer, calibration

1 INTRODUCTION

Principle of a magnetic tracker [1] is to identify a mutual position of two drill heads used in the horizontal directional drilling. A slight modification of the tracker [2] is able to establish absolute positions of the drill heads with respect to a reference point. Such a navigation system is divided into two parts - an excitation (coil) unit and a sensor (magnetometer) unit. The sensor unit measures response of the magnetic field during coil excitation and the measurements are values that are processed with a calculation algorithm and the position of the both unit is established. The precision of the navigation strongly depends on the precision of the sensors and their mutual alignment.

The sensor unit of the magnetic tracker consists of three sensors which are typically one MEMS tri-axial accelerometer and two tri-axial fluxgate magnetometers in 1-meter distance. Although the placement of the sensors with respect to the drill head housing is mechanically limited (app. ±3 deg), it is necessary to calibrate the direction of each sensor axes with respect to other sensors as well as with respect to drill head housing because sensor alignment errors have also the crucial influence on accuracy for a long distance magnetic localization (up to 40 meters).

The orthogonality, sensitivities, offsets of the individual sensors within each sensor triplet are calibrated in the first step using scalar calibration described in [3] or [4]. The methods assume free rotations of the calibrated sensor within reference frame that can be either measured by a reference sensor or can be set in precise steps but this type of calibrations is not the subject of this work.

The presented work focuses on calibration of a mutual misalignment error among all three sensors since each sensor could have its own orientation (misalignment). Possible methods, with principles described in [5] and even [3], can solve the situation.

The principle coming from [3] assumes precise rotations of the whole multi-sensory system. The rotations has to be carried out at many different orientation to cover a tri-dimensional space. During the rotations the sensor data are stored to be further included into a linear correction model. The error misalignment angles are consequentially calculated from the model.

The algorithm described in [5] even makes use of a probabilistic model and it obtains the calibration parameters as a solution to a minimum probability problem. This method also includes compensation of the error of a static magnetic distortion which would be advantageous in many applications.

Nevertheless, all these methods have assumptions which cannot be easily satisfied when the HDD sensor unit is calibrated due to the weight of housing pipes.

Therefore, we decided to apply a similar method that was published in [6] and originally it is exploited for calibration of electronic compasses. Our approach, however, does not use any expensive or a high accuracy demanding equipment which measures the orientation of the reference frame.

2 THEORY

The situation of the calibration problem is depicted in Fig. 1. Each sensor triplet is individually oriented with respect to the reference frame and the metal pipe housing.

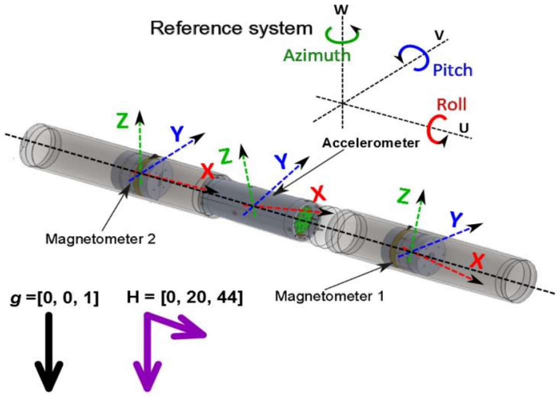

Fig. 1. Multi-sensors navigation unit - sensor arrangement (error illustration)

The method, therefore, establishes all nine orientation of three sensors and it is based on specific rotations of the whole unit in the stationary field. The reference field is

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gravity in case of the accelerometer and the Earth's magnetic field for the magnetometers. The stability and homogeneity of the reference magnetic field in test location is the crucial point in terms of the accuracy of the calibration because the homogeneity would cause the difference of the magnetic vector at magnetometer one and magnetometer two positions. Nevertheless, if these influences (noise, gradient of magnetic field) are suppressed down to 10 nT, the uncertainty of calibration of misalignment angles should reach 0.2 degree.

2.1 Accelerometer calibration.

As it was mentioned, three error angles (roll, pitch, and azimuth) have to be corrected for all sensors in the unit. The azimuth error and pitch error angles can be found when a rotation of the roll in the reference system is performed. The roll and pitch angle can be determined when the unit is rotated in the reference azimuth. Since influences of static field magnitude had been also supposed, we have to add also an offset compensation of each axis which represent the $\mathbf{A}_{OFF}$ matrix.

Then the situation during the roll rotation is described by the equation

$$\mathbf{A}_R = \mathbf{A}_{OFF} + \mathbf{T}_{E\gamma}\mathbf{T}_{E\delta}\mathbf{T}_{E\varepsilon}\mathbf{T}_{ROLL}\mathbf{g} \tag{1}$$

where $\mathbf{A}_R$ contains values measured by an accelerometer, $\mathbf{A}_{OFF}$ is a offset vector $[A_{off,X}, A_{off,Y}, A_{off,Z}]$, $\mathbf{T}_{ROLL}$ is the calibration rotation, the matrices **T** with index *E* represent the searched error rotations transformation that are further use for compensation and **g** is a vector of the gravity field.

$$\mathbf{T}_{E\gamma} = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \approx \mathbf{T}_{AZIMUTH}$$

$$\mathbf{T}_{E\delta} = \begin{bmatrix} \cos\delta & 0 & -\sin\delta \\ 0 & 1 & 0 \\ \sin\delta & 0 & \cos\gamma \end{bmatrix}$$

$$\mathbf{T}_{E\varepsilon} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varepsilon & \sin\varepsilon \\ 0 & -\sin\delta & \cos\gamma \end{bmatrix}$$

The equation for the azimuth rotation corresponds in similar way

$$\mathbf{A}_A = \mathbf{A}_{OFF} + \mathbf{T}_{E\gamma}\mathbf{T}_{E\delta}\mathbf{T}_{E\varepsilon}\mathbf{T}_{AZIMUTH}\mathbf{g} \tag{2}$$

where $\mathbf{A}_A$ is a matrix of collected sensor data during the azimuth $\mathbf{T}_{AZIMUTH}$ calibration rotation.

It is obvious that the $\mathbf{T}_{E\varepsilon}$ transformation matrix cannot be expressed from the equation (1) and on the other hand, the $\mathbf{T}_{E\gamma}$ would not be possible to calculate from (2). Therefore, the calculation of all error parameters is solved by a combination of both equations. Additionally, due to the offset errors, the variation of magnitude of a measured vector is included as a criteria.

When the accelerometer sensor is not perfectly aligned with the reference coordinate system which is defined by the gravity vector and by housing of the navigation unit, the pitch and azimuth error will appear as a sinus wave in *x* component of the recorded data of the matrix $\mathbf{A}_R$. The pitch and roll error will be propagated to the *x* and *y* components of the recorded data of the matrix $\mathbf{A}_A$ and it will be presented as an offset in the corresponding components. The *z* component is also influenced but it cannot be used as the criteria for optimization method since the real magnitude of the vector *g* is not precisely known due to the possible offsets.

To make the statement valid, the unit has to be at least approximately aligned with the reference gravity vector. That means the component of matrix $\mathbf{A}_R$ should be very close to the normal vector [0 0 1] at zero pitch and zero roll orientation.

When the data are collected from the both calibration rotations then six error parameters (defined here as $\boldsymbol{x}=[\gamma, \delta, \varepsilon, x_{off}, y_{off}, z_{off}]$) are evaluated. The solution is very complex and cannot be performed analytically and so the only possibility is to use the numerical optimization method which seeks the best fit of the searched parameters. We want to minimize influenced sensor components according the problem derived in equation (1)

$$\mathbf{P}_A = \underset{x}{\arg\min}\begin{pmatrix} (\mathbf{A}-\mathbf{A}_{OFF})\mathbf{T}_{E\gamma}\mathbf{T}_{E\delta}\mathbf{T}_{E\varepsilon}[1,0,0] \\ \operatorname{stdev}\left(\operatorname{norm}(A)\right) \end{pmatrix} \tag{3}$$

The **A** matrix is composed as $[\mathbf{A}_R\ \mathbf{A}_A]$. For our purpose, the minimization problem was solved with Levenberg-Marquart method which is able to accept an overdetermined set of non-linear equations. The number of the measured data effects the calculation, the calibration rotation should consist whole rotation with at least the 15 degree division to declare convergence of the optimization method. The more measured data are collected the more efficient the method is.

2.2 Magnetometer calibration

During magnetometer calibration the reference vector has a different proportion ($\boldsymbol{h}$ = [0 20 44] μT *in Middle Europe*) in opposite to the gravity vector because the Earth's magnetic field has two non-zero components at the reference plane. Nevertheless, the principle is the same: to suppress the sinus waves or a bias in the matrix components which should not be influenced in a specific rotations. The offset matrix $\boldsymbol{M}_{OFF}$ in the equation (4) represents influence of the hard magnetic parts in the unit and it has to be in the equation because the unit contains small magnetized parts.

To align the magnetometers with the accelerometers, the transformation matrix of the accelerometer $\mathbf{T}_{ACC}$ is added to equations. This matrix transfers both magnetometer coordinates into the accelerometer frame. Expressions which are derived for re-alignment of the magnetometers are

$$\mathbf{M}_R = \mathbf{M}_{OFF} + \mathbf{T}'_{E\gamma}\,\mathbf{T}'_{E\delta}\,\mathbf{T}'_{E\varepsilon}\,\mathbf{T}_{ROLL}\mathbf{T}_{ACC}\mathbf{h} \qquad (4)$$

$$\mathbf{M}_A = \mathbf{M}_{OFF} + \mathbf{T}'_{E\gamma}\,\mathbf{T}'_{E\delta}\,\mathbf{T}'_{E\varepsilon}\,\mathbf{T}_{AZIMUTH}\mathbf{T}_{ACC}\mathbf{h} \qquad (5)$$

where $\mathbf{M}_R$ consists of values measured by a magnetometer sensor at the roll alignment and $\mathbf{M}_A$ at the azimuth rotation.

Values, recorded during both calibration rotations, are solved by the same optimization method as it was mentioned in the accelerometer case but the minimization conditions slightly differs because the vector of the magnetic field has two non-zero components. The minimizing problem splits into the two separates matrices according to the rotations (roll, azimuth). In the roll calibration, the *x* component is optimized to be zero. In the azimuth calibration, the offset of the *x* axis is minimized to be zero and *z* component should have zero dispersion, otherwise the sinus wave is presented when the error angles effect the rotation.

$$\arg\min_{x} \left(\begin{array}{c} (\mathbf{M}_R - \mathbf{M}_{OFF})\mathbf{T}'_{E\gamma}\,\mathbf{T}'_{E\delta}\,\mathbf{T}'_{E\varepsilon}[1,0,0] \\ \mathrm{stdev}\left(\mathrm{norm}(\mathbf{M})\right) \\ \mathrm{stdev}\left[(\mathbf{M}_A - \mathbf{M}_{OFF})\mathbf{T}'_{E\gamma}\,\mathbf{T}'_{E\delta}\,\mathbf{T}'_{E\varepsilon}[1,0,0]\right] \end{array} \right) \qquad (6)$$

Here also the Lavenberg-Marguate method is applied to solve the problem and the same requirements for the minimal sample count are valid.

3 EXPERIMENTAL RESULTS

The proposed method was tested on the system which was presented in [2]. The system has huge error in a desired range (see Fig. 3).

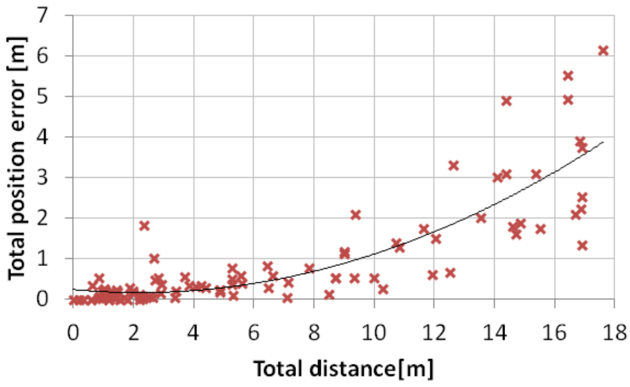

Fig. 3. The error of non-calibrated navigation unit

3.1 Procedure

Calibration procedure of the described method start with a preparation state.

It is very important to carry out the calibration in magnetically clean environment to avoid the gradient in the magnetic field caused for example by reinforcement steels in floor concrete etc. The housing of the calibrated unit is leveled into the zero pitch and the axial direction pointed to West. This requirement is due to defining the reference coordinate system with respect to the gravity and the Earth's magnetic field.

The procedure starts with the roll rotation in usual step of 15 degree in the whole range from 0 to 360 deg. The typical data are shown in Fig. 4. There can be see the misalignment because the *x* component is non zero and even it has a sinus shape.

After finishing the roll calibration, the unit is again settled into the start position. The unit is rotated in the azimuth in the range of 0-360 degrees. The recorded data of accelerometer are depicted in Fig. 5. Also here the misalignment of the axis are clearly visible: *x* component is not zero.

The roll and azimuth data of magnetometer are presented in Fig. 6 and Fig. 7.

The recorded data are transferred to the calculation software which establishes all misalignment parameters. For the experiment, we carried out, the parameters are in Table 1.

Table 1. Established misalignment error.

	Azimuth (deg)	Pitch (deg)	Roll (deg)
Accelerometer	-2.4	0.1	0
Magmeter 1	0.6	1	-3
Magmeter 2	-0.1	0.2	3.1

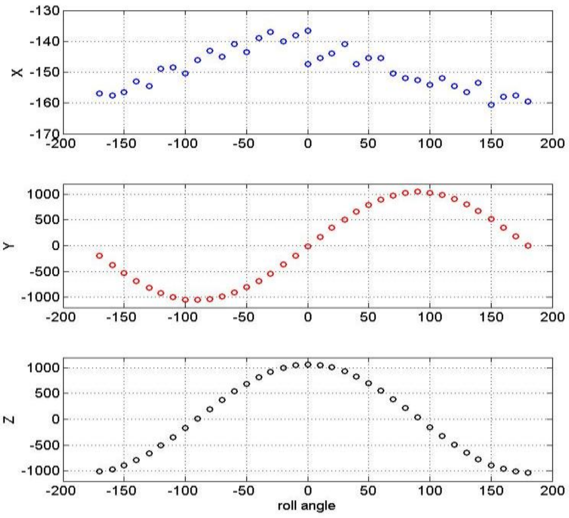

Fig. 4. The components of the accelerometer data (mG) during the roll rotation - experimental data

5 CONLUSIONS

By the described calibration method, the misalignment angles can be calculated based on the specific rotation and using optimization method. The method mainly servers to align the multi-sensor system (containing accelerometer and magnetometer). When the correction angles, established by the method, was applied into the calculation algorithm of the navigation unit of horizontal directional drilling, the precision was substantially improved which is proved by comparing of Fig. 3 and Fig. 8. The calibrated system can estimate positions of the units with the precision 0.5 meters in the 30-meter distances.

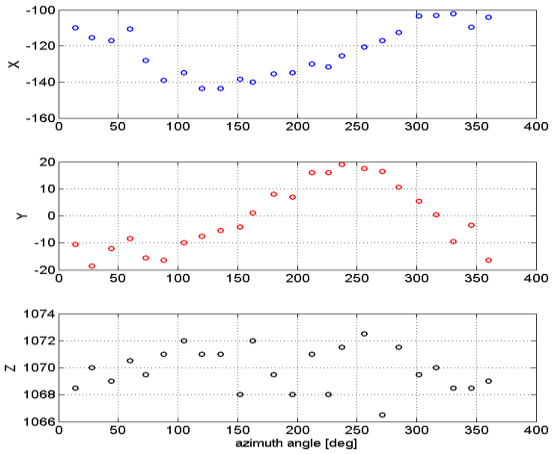

Fig. 5. The components of the accelerometer data (in mG) during the azimuth rotation - experimental data

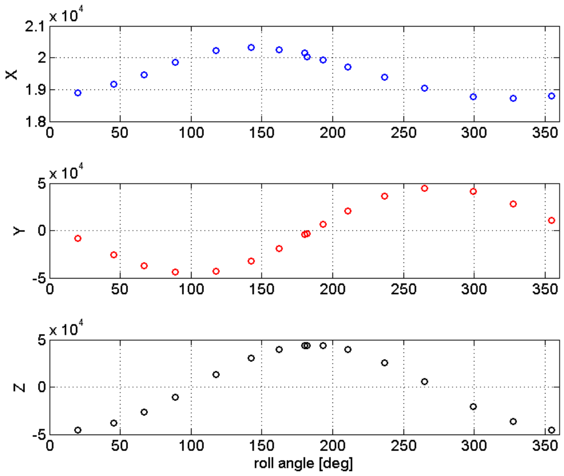

Fig. 6. The components of the magnetometer data (in nT) during the roll rotation - experimental data

The main source of the uncertainty is the stability of the Earth's magnetic field. Other affecting factors are presence of the metal part which can distort the magnetic field. From practical point of view, the method relatively takes a long time.

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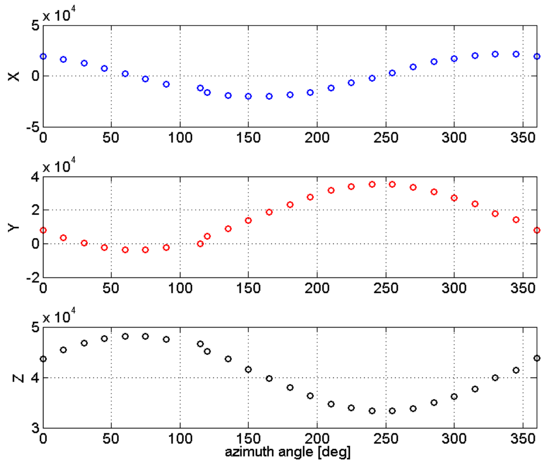

Fig. 7. The components of the magnetometer data (in nT) during the azimuth rotation - experimental data

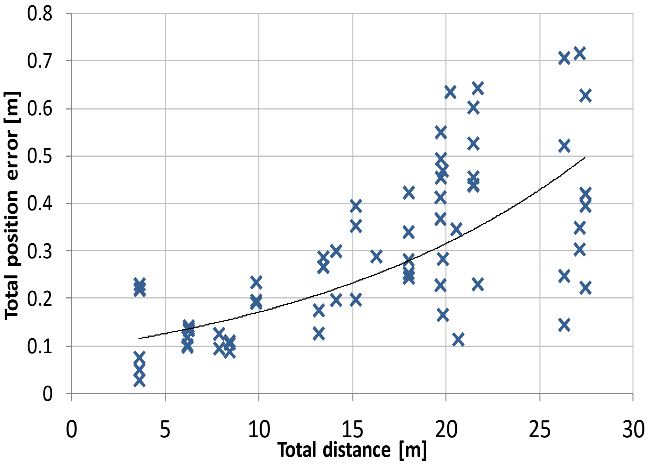

Fig. 8. The error of calibrated navigation unit

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