INERTIAL AND MAGNETIC SENSORS: THE CALIBRATION ASPECT

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Abstract: A powerful procedure to calibrate and align the Micro Electro-Mechanical System inertial sensors and the Anisotropic-MagnetoResistive magnetic field sensors is presented. The suggested method is cost effective and suitable for the in-field calibration because it is based on techniques that do not need any complex mechanical platforms for the sensor manipulation.

To evaluate the calibration procedure, a modular Magnetic and Inertial Measurement Unit - consisting of three inertial sensor units, a magnetic sensor unit and a control unit - has been developed and calibrated according to the proposed method. The obtained results demonstrate accuracy and stability of the described calibration procedure.

Inercialni in magnetni senzorji: kalibracijski vidik

Kjučne besede: inercialna merilna enota, pospeškometer, žiroskop, elektronski kompas, kalibracija senzorjev

Izvleček: V prispevku je predstavljena kakovostna metoda za kalibracijo in poravnavo inercialnih MEMS (Mikro Elektro-Mehanski Sistem) in magnetnih AMR (Anizotropni MagnetoRezistivni) senzorjev. Predstavljena metoda je sestavljena iz kalibracijskih tehnik, ki so primerne za terensko uporabo, saj ne potrebujejo nikakršnih zapletenih mehanskih naprav za manipulacijo senzorjev.

Z namenom ovrednotenja kalibracijske metode je bila zgrajena modularna magnetna in inercialna merilna enota (MIMU), ki je sestavljena iz treh inercialnih senzorskih enot, ene magnetne senzorske enote ter centralne kontrolne enote. MIMU je bil uspešno kalibriran na podlagi predstavljene metode. Rezultati kalibracije pri sobni temperaturi pa izkazujejo natančnost in stabilnost kalibracijskega postopka.

1. Introduction

Several Integrated Circuit (IC) manufacturers (Analog Devices /1/, Freescale /2/, Honeywell /3/, etc.) are producing low-cost Micro Electro-Mechanical System (MEMS) inertial sensors and Anisotropic-MagnetoResistive (AMR) magnetic sensors that have allowed the full swing of the Inertial Measurement Unit (IMU) and the electronic compass systems. Low-cost miniature IMUs and electronic compasses are found in various applications like unmanned vehicles /4/, navigation devices /5/, human motion tracking /6/, virtual reality gadgets /7/ and many more.

However, the MEMS and the AMR sensors have one significant drawback. The electrical parameters of such sensors are not well defined and usually scatter for as much as 10%. Additional error sources are caused by the alignment problems during the IMU and electronic compass assembly. Therefore, each manufactured device using such sensors must be calibrated prior to the use or even recalibrated several times during the lifetime.

There are quite a few possible methods to calibrate the IMU and the electronic compass, but the majority of them involve complex mechanical platforms for the device manipulation or even the optical tracking systems /8/. These procedures are appropriate for the laboratory operation, but are completely unsuitable for the in-field calibration.

In this paper a new calibration procedure, which is based on the local Earth's gravitational and magnetic field, is presented. The procedure is a combination of calibration techniques which are simple to perform; they do not need any extra instruments and are convenient for the in-field use. Above all, the absence of any additional instrumentation leads to the reduction of the production costs and the final product price. For this reason, a miniature Magnetic and Inertial Measurement Unit (MIMU) has been developed /9/ to test and evaluate these calibration procedures.

2. Magnetic and inertial measurement unit

In order to study different degrees of sensor misalignment we have developed a modular system, where several detachable sensor units are connected to a central control unit. The MIMU consists of three inertial sensor units (ISU), one magnetic sensor unit (MSU) and a control unit (CU) (see Figure 1) which are enclosed in a cubic plexiglas casing /9/.

Each ISU contains two MEMS sensors: a single-axis angular rate gyroscope (ADXRS150, full-scale range of ±150 °/s) and a two-axis accelerometer (ADXL203, full-scale range of ±1.7 g), both made by Analog Devices. With the orthogonal positioning of three ISUs a complete six degrees-of-freedom (6 DOF) inertial measurement system was obtained.

MSU comprises two AMR sensors: a single-axis HMC1001 and a dual-axis HMC1002 (produced by Honeywell) with

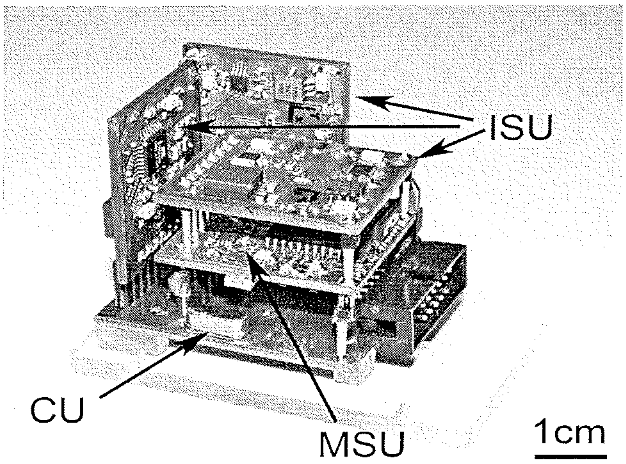

Fig. 1: Realized MIMU.

the full-scale range of $\pm 2 \cdot 10^{-4} \cdot$ T, forming a complete three-dimensional electronic compass. MSU also contains a high current flipping circuit for inverting the sensor's transfer function, which reduces the cross-axis effects and temperature drift.

During the development process, special attention was paid to the printed circuit board layout and analogue signal processing, to prevent coupling of additional noise and interferences to the sensor's output signals.

3. Sensor model

Prior to the calibration, the sensor model of accelerometer, gyro or magnetic field sensors must be known and the model parameters should be identified. The sensor model parameters can be divided in two groups: the electrical parameters and the mechanical parameters.

Each sensor's electrical characteristic is specified in its datasheet. Besides the sensor's sensitivity to the input physical quantity and the sensor's bias, there are also other unwanted effects specified, like the transfer function's nonlinearity and cross-axis sensitivity. However, these effects can be easily neglected, since they are suppressed by means of the system design. Thus it is adequate to determine only the sensitivities and the biases during the calibration procedure.

The other group members, i.e. the mechanical parameters, result from the fact that usually the three-dimensional IMU consists of several sensors with one or two sensitivity axes. These sensitivity axes should be perpendicular to each other in order to form the orthogonal sensor triplet. To achieve adequate sensor orthogonality advanced precise assembly procedures must be employed /10/, but these procedures are time consuming and above all present considerable augmentation in production costs. The next error source is the misalignment of the sensor triplet to the sensor system casing and the mutual misalignment of various sensor triplets, which are also critical because they cause system errors. These two subjects - the orthogonalization and the misalignment - are also considered in the sensor model with the intention to be compensated in the software.

According to the previous sections, we can put down the sensor model as:

$$\vec{y}_k = S_k \cdot T_k \cdot R_k \cdot \vec{u}_k + \vec{b}_k \; ; \quad k = sensor \;\; type \;\; (g,a,m), \qquad (1)$$

where the index k represents the type of the sensor triplet (g, a or m ; gyro, accelerometer or magnetic field sensor, respectively). The measured physical quantity $\vec{u}_k$, the sensor triplet bias $\vec{b}_k$ and the sensor triplet output voltage $\vec{y}_k$ are arranged in the vectors:

$$\vec{u}_k = \begin{bmatrix} u_{kx} \\ u_{ky} \\ u_{kz} \end{bmatrix}, \quad \vec{y}_k = \begin{bmatrix} y_{kx} \\ y_{ky} \\ y_{kz} \end{bmatrix}, \quad \vec{b}_k = \begin{bmatrix} b_{kx} \\ b_{ky} \\ b_{kz} \end{bmatrix}.$$

On the other hand, the sensors' sensitivities S_k and the mechanical parameters - the orthogonalization T_k and the misalignment R_k - are incorporated in the matrices:

$$S_k = \begin{bmatrix} s_{kx} & 0 & 0 \\ 0 & s_{ky} & 0 \\ 0 & 0 & s_{kz} \end{bmatrix}, \qquad T_k = \begin{bmatrix} 1 & 0 & 0 \\ \cos\alpha_k & 1 & 0 \\ \cos\beta_k & \cos\gamma_k & 1 \end{bmatrix},$$

$$R_k = \begin{bmatrix} r_{k,11} & r_{k,12} & r_{k,13} \\ r_{k,21} & r_{k,22} & r_{k,23} \\ r_{k,31} & r_{k,32} & r_{k,33} \end{bmatrix}.$$

Orthogonalization matrix T_k transforms the vector expressed in the orthogonal sensor reference frame *ko* into the vector expressed in the non-orthogonal sensor reference frame *k* (see Figure 2).

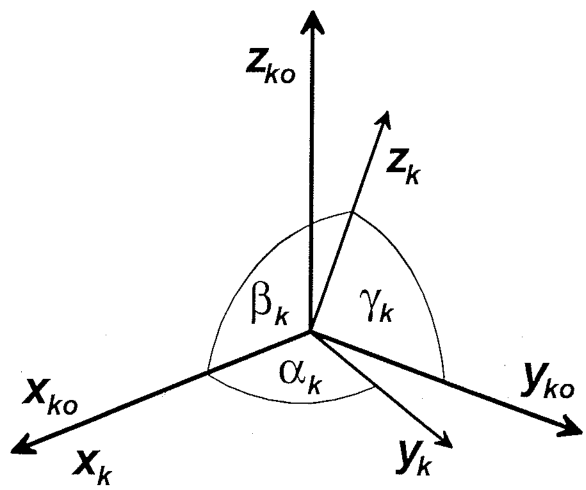

Fig. 2: Orthogonalization of the sensor triplet frame k.

The matrix T_k is constructed using the Gram-Schmidt orthogonalization process /11/. The Gram-Schmidt algorithm takes a finite, linearly independent set of vectors and generates an orthogonal set that spans the same subspace. If the angles α_k, β_k and γ_k are close to 90° (which is usually the case in such systems) some approximations may be made without any significant loss of the accuracy:

$$T_k = \left.\begin{bmatrix} 1 & 0 & 0 \\ \cos\alpha_k & \sin\alpha_k & 0 \\ \cos\beta_k & \cos\gamma_k & \sqrt{1-\cos^2\beta_k-\cos^2\gamma_k} \end{bmatrix}\right|_{\alpha_k,\beta_k,\gamma_k\approx 90^\circ} \approx \begin{bmatrix} 1 & 0 & 0 \\ \cos\alpha_k & 1 & 0 \\ \cos\beta_k & \cos\gamma_k & 1 \end{bmatrix} \quad (2)$$

Misalignment matrix R_k is an Euler angles parameterized rotation matrix, which rotates (aligns) the platform reference frame *p* to the orthogonal sensor reference frame *ko* (see Figure 3):

$$R_k = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_k & \sin\phi_k \\ 0 & -\sin\phi_k & \cos\phi_k \end{bmatrix} \cdot \begin{bmatrix} \cos\vartheta_k & 0 & -\sin\vartheta_k \\ 0 & 1 & 0 \\ \sin\vartheta_k & 0 & \cos\vartheta_k \end{bmatrix} \cdot \begin{bmatrix} \cos\psi_k & \sin\psi_k & 0 \\ -\sin\psi_k & \cos\psi_k & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (3)$$

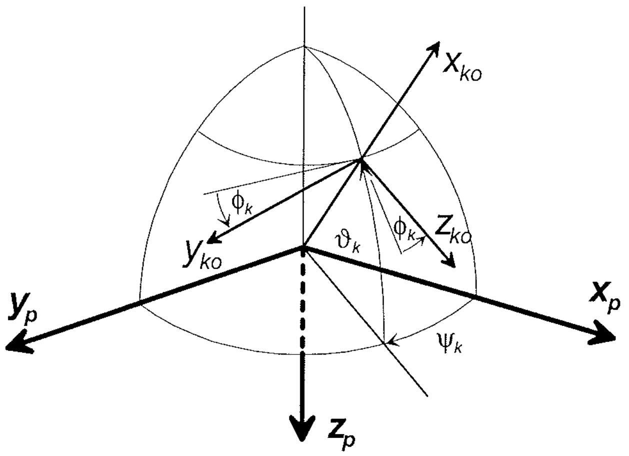

Fig. 3: Misalignment of the sensor triplet frame ko.

This sensor model is used for all sensor triplets used in the MIMU irrespective of the sensor type. When all the 12 parameters (s_{kx}, s_{ky}, s_{kz}; b_{kx}, b_{ky}, b_{kz}; α_k, β_k, γ_k; ψ_k, ϑ_k, ϕ_k) for the each triplet are known, then the estimate $\hat{\vec{u}}_k$ for the observed physical quantity $\vec{u}_k$ is:

$$\hat{\vec{u}}_k = R_k^{-1} \cdot T_k^{-1} \cdot S_k^{-1} \cdot (\vec{y}_k - \vec{b}_k). \quad (4)$$

Mechanical parameters (orthogonalization and misalignment parameters) are assumed to be independent of the temperature and the time during the normal operation (without any excessive shocks and stresses present). Therefore they need to be determined only once, e.g. at the end of their production phase. Electrical parameters, on the other hand, must be reestablished from time to time because they drift with time. The gyro bias has been identified to be the most critical parameter from this point of view and it must be measured at every start up (the maximum drift is ±12% - over the entire operating temperature range). For the outdoor operation, the electrical parameters need to be determined as a function of the temperature.

4. Accelerometer and magnetic sensor calibration

For the calibration of the accelerometer triplet and the magnetic sensor triplet, the scalar field calibration method is applied /12, 13/. This calibration method is based on the local Earth's gravity and the local Earth's magnetic field. It derives benefit from the fact that the magnitude of the measured Earth's gravity acceleration and magnetic field is independent of the measurement system's orientation; the MIMU in our case. The only disadvantage of this method is that the misalignment parameters cannot be estimated as they form the rotation matrix with norm +1, which does not affect the vector magnitude.

The parameters which can be determined with the scalar field calibration are grouped in the calibration parameter vector $\vec{p}_{k\_cal}$:

$$\vec{p}_{k\_cal} = \begin{bmatrix} s_{kx} & s_{ky} & s_{kz} & b_{kx} & b_{ky} & b_{kz} & \alpha_k & \beta_k & \gamma_k \end{bmatrix}^T. \quad (5)$$

The parameter vector $\vec{p}_{k\_cal}$ is established by the minimization of the objective function $O(\vec{p})$. The objective function is defined as the mean square error between the reference value u_{ref} and the corresponding data vector $u_n(\vec{p})$:

$$O(\vec{p}) = \frac{1}{N}\sum_{n=1}^{N}\left(u_{ref} - u_n(\vec{p})\right)^2, \quad (6)$$

where *N* is the number of measured values in the data vector. The reference value is the normalized value of the local gravity acceleration or the Earth's magnetic field ($u_{ref} = 1$ in both cases), and it is compared to the gravity norm estimate ($u_n(\vec{p}) = \|\hat{\vec{a}}_n\|$) or the magnetic field norm estimate ($u_n(\vec{p}) = \|\hat{\vec{m}}_n\|$) for the accelerometer or the magnetic sensor, respectively.

The MIMU must be exposed to at least nine different orientations since nine parameters (Eq. 5) need to be determined and several data points should be acquired at each orientation. The precise knowledge of the orientation is not needed; however it is important that the MIMU is standstill during the data acquisition to minimize the noise in the sensors' outputs. The objective function can be minimized with one of the optimization methods, after the data set has been acquired. In our case the constrained Newton optimization method is applied. The initial values of the parameters and the constraints are set according to the typical values quoted in the sensors' datasheets.

The remaining three parameters, the misalignment angles (Eq. 7) of the accelerometer triplet and electronic compass, are obtained following the approach presented in /14/.

$$\vec{p}_{k\_align} = [\psi_k \quad \vartheta_k \quad \phi_k]^T \qquad (7)$$

If the ideally aligned MIMU rotates about the one of its sensitivity axes, then the data of the corresponding accelerometer and magnetic sensor triplet sensitivity axis should remain constant. But the data are deviated due to the sensor triplet misalignment. The aim of the alignment procedure is to minimize these deviations.

The alignment procedure has two steps. The first step assumes two rotations, one about the roll axis (x-axis) proceeding with the second rotation about the yaw axis (z-axis). In the data processing step the deviation of x-axis data is first minimized by optimizing the heading and elevation misalignment angle (ψ_k, ϑ_k). With these two parameters defined, the z-axis data can be partially aligned. The complete alignment is achieved by the minimization of the partially aligned z-axis data deviation, where the bank misalignment angle (ϕ_k) is optimized. The data deviation is expressed as the mean square error between the acquired data vectors ($u_n(\vec{p}) = \hat{a}_{i,n}$ for the accelerometer triplet or $u_n(\vec{p}) = \hat{m}_{i,n}$ for the magnetic sensor triplet) and their mean values ($u_{ref} = \bar{\hat{a}}_i$ or $u_{ref} = \bar{\hat{m}}_i$, where i stands for the sensitivity axis of interest).

The rotation about the desired axis is performed by putting the MIMU on the flat surface in the way that the axis of interest is normal to the surface. The surface should be placed perpendicularly to the excitation vector (the gravity or the Earth's magnetic field), for the best alignment results. In such position the current sensitivity axis is maximally excited in the cross-axis direction and the acquired data are maximally deviated. Then one revolution about the surface's normal is accomplished and the gravity acceleration and the Earth's magnetic field are acquired in several steady-state points.

5. Rate gyro calibration

The scalar field calibration is inconvenient for the rate gyro triplet calibration, since a rotational platform with known and stable angular rate is required. For this reason the method based on /15/ was developed. The original method was upgraded and modified in such manner that it incorporates the orthogonalization effects as well.

First of all, the gyro triplet bias vector $\vec{b}_g$ is measured. The MIMU is kept in standstill and the bias vector is determined as the mean value of the gyros' data during the data acquisition period.

In order to determine the remaining nine parameters (s_{gx}, s_{gy}, s_{gz}; $\alpha_g, \beta_g, \gamma_g$; $\psi_g, \vartheta_g, \phi_g$) another three measurements must be carried out. Let us assume that we have a rotational platform with known constant angular rate. We carry out three rotations, each about the individual sensitivity axis. The data captured during the rotations are organized in the matrices: the applied angular rates are arranged on the diagonal of the matrix W_g and the bias corrected angular rate estimates $\vec{y}_g - \vec{b}_g$ (Eq. 1) from the gyro triplet are arranged in the matrix v_g, where the element $r_{g,ij}$ represents the i-th gyro's output when the rotation about the j-th axis is accomplished.

$$v_g = S_g \cdot T_g \cdot R_g \cdot W_g \qquad (8)$$

$$v_g = \begin{bmatrix} r_{g,xx} & r_{g,xy} & r_{g,xz} \\ r_{g,yx} & r_{g,yy} & r_{g,yz} \\ r_{g,zx} & r_{g,zy} & r_{g,zz} \end{bmatrix}, \quad W_g = \begin{bmatrix} \omega_x & 0 & 0 \\ 0 & \omega_y & 0 \\ 0 & 0 & \omega_z \end{bmatrix}.$$

The necessity for the rotational platform can be suppressed regarding the fact that the Eq. (8) is linear (the matrices S_g, T_g and R_g are constant). If the Eq. (8) is integrated over the observed period of time then the angular rate matrix W_g is transformed into the angle matrix A_g and the matrix v_g with the bias corrected angular rate estimates is transformed into the angles estimate matrix Y_g.

$$Y_g = S_g \cdot T_g \cdot R_g \cdot A_g \qquad (9)$$

As the result of the integration in the time domain all the operations are made in the angles domain, from now on. Instead of the angular velocity, the angle of rotation must be accurately defined. Indeed, the measurement of the rotation angle is much simpler than the measurement of the angular rate.

The calibration procedure for the rate gyro is therefore as follows. The MIMU is placed on the flat surface and a full revolution about the surface normal axis is made. Then two successive rotations about the remaining axes are completed. The applied angles of rotation are written in the matrix A_g and the angle estimates obtained from the gyro triplet measurements are inserted in the matrix Y_g.

The matrices A_g and Y_g are composed of the measured values, while the matrices S_g, T_g, R_g are determined following the Eq. (10) to Eq. (15), where special facts about the matrices were relevant: (i) the sensitivity matrix S_g is a diagonal matrix (it can be also treated as an upper triangular matrix), (ii) the orthogonalization matrix T_g is a unit lower triangular matrix, and (iii) the misalignment matrix R_g is an orthonormal matrix.

The matrices with the known (measured) data are arranged on the left side meanwhile the matrices composed of the unknown gyro triplet calibration parameters are on the right side of the Eq. (10):

$$Y_g \cdot A_g^{-1} = S_g \cdot T_g \cdot R_g \qquad (10)$$

The symmetrical matrix is constructed by right multiplying each side of the Eq. (10) with its transpose:

$$\left(Y_g \cdot A_g^{-1}\right)\left(Y_g \cdot A_g^{-1}\right)^T = \left(S_g \cdot T_g \cdot R_g\right)\left(S_g \cdot T_g \cdot R_g\right)^T; \qquad (11)$$

then the misalignment matrix R_g is abridged, because of its orthonormality:

$$\left(Y_g \cdot A_g^{-1}\right)\left(Y_g \cdot A_g^{-1}\right)^T = (S_g \cdot T_g)\,(S_g \cdot T_g)^T. \qquad (12)$$

The symmetric positive-definite matrix $\left(Y_g \cdot A_g^{-1}\right)\left(Y_g \cdot A_g^{-1}\right)^T$ is decomposed by the Cholesky decomposition into a lower triangular matrix $S_g \cdot T_g$ and its transpose:

$$S_g \cdot T_g = chol\left[\left(Y_g \cdot A_g^{-1}\right)\left(Y_g \cdot A_g^{-1}\right)^T\right]^T. \qquad (13)$$

The sensitivity and the orthogonalization matrices are retrieved by the LU decomposition of the matrix $S_g \cdot T_g$, where the T_g is a lower and the S_g is an upper triangular matrix:

$$\left[T_g, S_g\right] = LU\left(S_g \cdot T_g\right). \qquad (14)$$

Finally, the misalignment matrix R_g is obtained by the following matrix manipulation:

$$R_g = T_g^{-1} \cdot S_g^{-1} \cdot Y_g \cdot A_g^{-1}. \qquad (15)$$

6. Calibration results

The MIMU was calibrated and aligned at the room temperature according to the presented procedure. The data acquisition was done using the LabVIEW, the optimization algorithm and the matrix calculations are on the other hand performed using the Matlab programming package. The results of the series of five calibration sequences are presented in the Figures 4-6. The y-axis span of the electrical parameters' bar charts corresponds to the parameter span specified in the sensors' datasheets. From the charts it is seen that all determined parameters are within the specified range. The mechanical parameters are also close to the ideal values: 90° for the orthogonalization and 0° for the alignment. The time stability and accuracy of the calibration method was demonstrated by performing several calibration series during a few months period, where all the calibration results manifested minimum scattering of the obtained calibration parameters. The parameters scattering is a consequence of the sensor noise as well as the noise introduced by the analogue to digital conversion.

The calibration was performed at the room temperature; however if the sensors are used in the temperature variable environment, then we would require temperature dependent calibration of the sensors' parameters.

The magnetic sensor triplet calibration should be performed in magnetically clean environment where Earth's magnetic field is undisturbed by the various large scale magnetic disturbances, e.g. major power supply wires, larger electric equipment, etc. However the high frequency magnetic disturbances and noise is effectively rejected by the analogue and digital filtering.

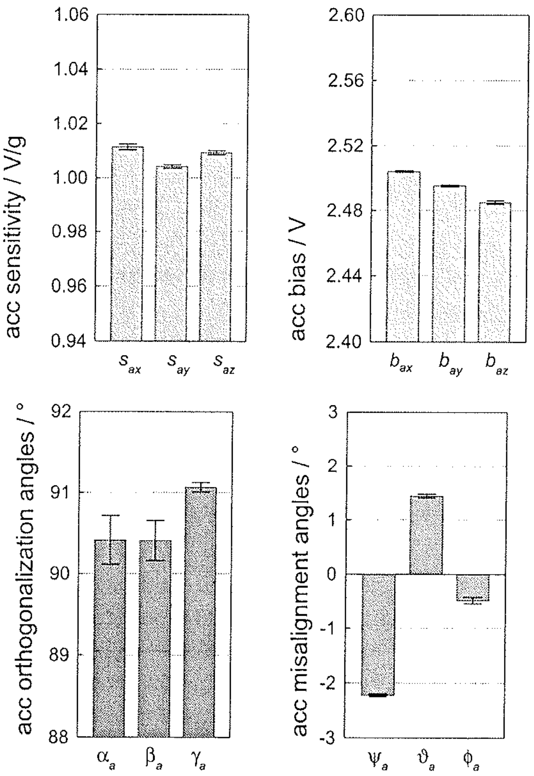

Fig. 4: Determined calibration parameters of the accelerometer triplet.

7. Conclusion

Complete procedure for the in-field calibration and alignment of the accelerometers, magnetic sensors and gyros was developed and successfully applied to the developed modular 6 DOF MIMU. With a view to simplify the sensor description an unified sensor model was used to describe the accelerometer, gyro and magnetic sensors triplets. The model considers the sensors' electrical characteristics as well as the mechanical effects of assembling the sensors into sensor triplets and enclosing them into the MIMU casing. Several calibration series were done at the room tem-

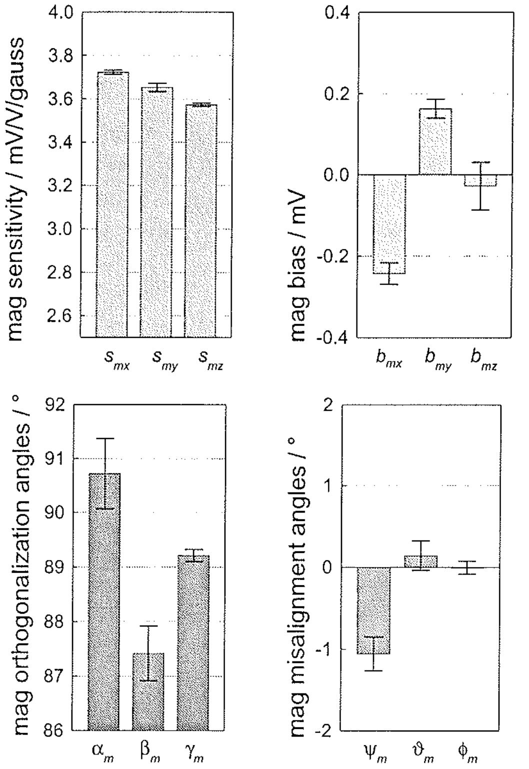

Fig. 5: Determined calibration parameters of the magnetic sensor triplet.

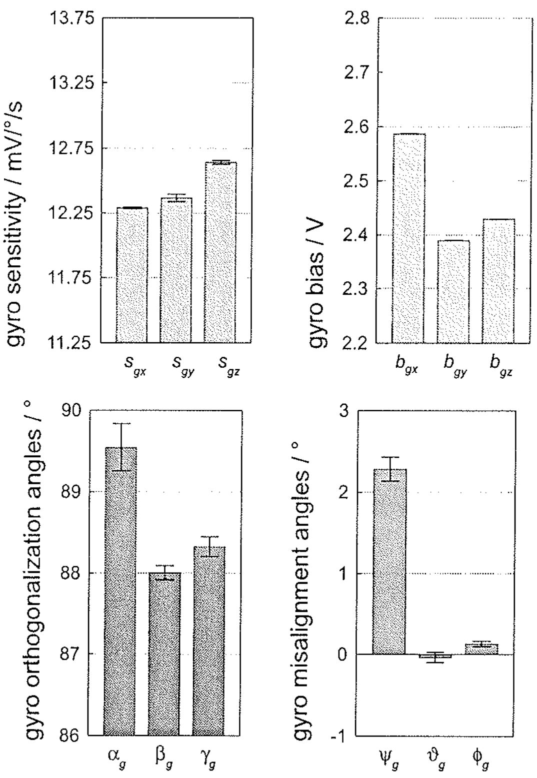

Fig. 6: Determined calibration parameters of the gyro triplet.

perature and they demonstrate the accuracy and stability of the calibration procedure.

8. Acknowledgement

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