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Analyses of Electronic Inclinometer Data for Tri-axial Accelerometer's Initial Alignment

***Abstract**. This paper deals with the usage of a dual-axis electronic inclinometer EZ-TILT-2000-008 to improve an initial alignment of a tri-axial accelerometer, which forms a part of the inertial measurement unit ADIS16405. There were performed several measurements under various initial conditions with the usage of a precise Rotational-Tilt Platform as a reference. Based on measured data the alignment procedure accuracy, null repeatability, stability of initial null angle, hysteresis, and cross-axis dependence were analyzed and the results of these analyses are presented.*

***Streszczenie.** Zaprezentowano wykorzystanie dwuosiowego inklinometru EZ-TILT-2000-008 do poprawy ustawiania trzyosiowego przyśpieszeniomierza. Przeprowadzono badania dokładności, powtarzalności zera, histerezy i wpływu osi w opracowanym przyśpieszeniomierzu. (**Zastosowanie elektronicznego inklinometru do ustawiania trzyosiowego miernika przyśpieszeń**).*

Keywords: electronic inclinometer, tri-axial accelerometer, initial alignment, cross-axis dependence.
Słowa kluczowe: inklinometr, przyśpieszeniomierz.

Introduction

Recently, a technological improvements in the precision and reliability of Micro-Electro-Mechanical-Systems (MEMS) have enabled the usage of low-cost MEMS inertial sensors in wide range of civil and military applications, such as a car navigation, personal navigation, indoor navigation, navigation of unmanned aerial vehicles, underwater navigation, human motion tracking, etc. [1, 2, 3, 4, 5, 6].

A basic part of common navigation systems, which is an Inertial Measurement Unit (IMU), primarily contains accelerometers (ACCs) and angular rate sensors (ARSs) for providing inertial data, and additionally magnetometers (MAGs). These sensors' data are used for various navigation computations such as attitude, velocity and position estimation, initial alignment, etc. In navigation systems, first of all, it is necessary to determine the initial attitude of the navigation system including the determination of initial Euler angles (the roll, pitch, and yaw). They describe the relationship between the sensor frame (SF) and the local navigation frame (LNF) in which the navigation is performed.

For IMUs with low-cost ARSs the initial attitude cannot be determined by a self-alignment procedure using only ARSs them-selves [7, 8], because aforementioned sensors are not able to sense the Earth rotation, which is usually below the noise level [9]. Therefore, the initial attitude has to be determined using the ACCs and MAGs. The procedure of initial attitude determination is called the coarse alignment and its accuracy depends on the level of imperfections of ACCs and MAGs (scale factor corrections, angles of non-orthogonality, biases, etc.). These can be partially compensated using a sensor error model [3, 10]. After the coarse alignment has been done, the Euler angles are initialized and regular Euler angles estimation process, for details see [11], can take place.

This paper extends the analyses presented in [1] and deals with the usage of an electronic inclinometer (EI) EZ-TILT-2000-008 (Advanced Orientation Systems Inc. [12]). The EI is used to improve the initial levelling done based on tri-axial accelerometer, in our case, contained in the IMU ADIS16405 (Analog Devices [13]). The levelling procedure forms the part of initial attitude determination, in which the pitch and roll angles are estimated. The accuracy of initial attitude determination depends on biases of ACCs which cause non-negligible errors in pitch and roll estimates and vary with each system turning-on. This mentioned imperfection of accelerometers was a motivation for using other system with a different principle of angles estimation. In our case, the EI was used, which enabled the estimation of accelerometer biases. There were performed several measurements under various initial conditions with the usage of the Rotational-Tilt Platform (RoTiP) as the reference. Based on the measured data the accuracy analyses were performed.

Initial Attitude Determination

The initial attitude determination is a procedure, in which Euler angles are estimated. There exist various algorithms for initial attitude determination, e.g. a coarse/fine alignment, static/in-motion alignment, analytic alignment and so on [9]. In this paper, the initial attitude is evaluated using the coarse alignment procedure only. This procedure can be divided into two steps. First one includes the levelling procedure to determine the pitch and roll angles. The following one is named a course alignment and determines the yaw angle [8]. For IMUs consisted of tri-axial MAG as well as ACC and ARS, the yaw angle can be determined easily. In the following part only the levelling procedure is described.

Levelling procedure

A main aim of the levelling is determine the pitch (1) and roll (2) angles according to the gravity vector measured by tri-axial ACC under static conditions [7, 8].

$$(1) \qquad \theta = arctg\left(-f^{by} \Big/ \sqrt{\left(f^{bx}\right)^2 + \left(f^{bz}\right)^2} \right)$$

$$(2) \qquad \phi = arctg\left(f^{bx} \Big/ -f^{bz} \right)$$

where: θ is the pitch angle, ϕ denotes the roll angle, f^{bx}, f^{by}, f^{bz} are measured accelerations in the sensor frame.

The procedures of the levelling and course alignment were described in detail by Soták in [7, 8]. Based on the real tests performed by Soták it can be seen that the estimated values of pitch and roll angles are not identical with the reference ones due to the influence of accelerometer biases. Based on the specifications of ADIS16405 the initial bias error is up to ±50 mg (for 1σ corresponding 68% probability) and thus can cause the error of ±2.9 degree in zero tilt. This error negatively influences the final accuracy of estimated initial attitude as well as the following position evaluation. This imperfection of the process was the motivation for a usage of a different system to measure and correct the pitch and roll angles determined from the accelerometer during the coarse alignment procedure [1].

Applied Systems and Measurement Setup

This section describes basic specifications of applied measurement systems. The performance of the ADIS16405's tri-axial ACC (Analog Devices [13]) is provided in Table 1. In the case of the electronic inclinometer (EI) EZ-TILT-2000-008 (Advanced Orientation Systems Inc. [12]) it is in Table 2.

Table 1. The parameters of the ADIS16405's accelerometer [13]

Accelerometer's parameter	Typical value
Dynamic range	±18 g
Initial sensitivity	3.33 mg/LSB
Initial bias error (± 1σ)	±50 mg
In-run bias error (± 1σ)	0.2 mg
Velocity random walk (± 1σ)	0.2 m/s/√hr
Output noise (no filtering, rms)	9 mg
Noise density (no filtering)	0.5 mg/√Hz

Table 2. The parameters of the EZ-TILT-2000-008 [12]

EI's parameter	Typical value
Range	±8 deg
Analog output	1 to 4 VDC
Power supply	6 to 12 VDC
Resolution of A/D convertor	12 bit
Response (10% - 90%)	40 ms
Repeatability	<0.02 deg
Temperature range	-40 to +60 degC

The EI (Fig. 1a) is an advanced programmable dual-axis linear analog/digital module with CMOS microprocessor which includes a dual-axis polymer based electrolytic tilt sensor (ETS) DX-008. The EI module provides analog, PWM, and RS-232 tilt information in two axes. Full description is specified in [12]. In our case, the viscosity of ETS was about 50% higher than viscosity of standard ETS.

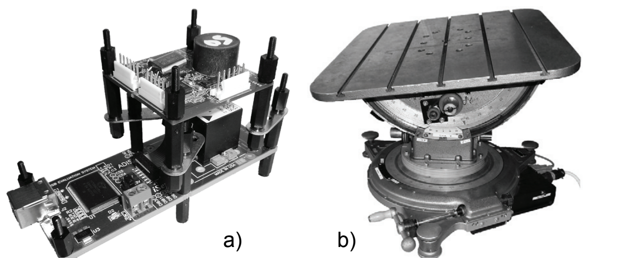

Fig.1. a) ADIS16405 board with EZ-TILT-2000-008 mounted on; b) Rotational-Tilt Platform

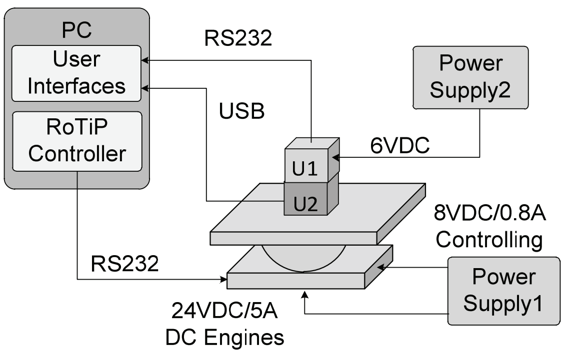

Fig.2. A block scheme of measurement setup; U1 – electronic inclinometer EZ-TILT-2000-008, U2 – IMU ADIS16405

As a reference system for the results comparison and analyses we used the Rotational-Tilt Platform (RoTiP), see Fig. 1b. The RoTiP is capable to set positions with required attitude and speed along three axes. The specification of RoTiP is provided in Table 3.

Table 3. The parameters of Rotational-Tilt Platform

Parameter	Range	Speed of motion	Resolution
Pitch	± 45 deg	± 42 deg/s	0.00033 deg
Roll	± 25 deg	± 60 deg/s	0.00065 deg
Heading	0 to 360 deg	± 310 deg/s	0.00074 deg

A block scheme of measurement setup is shown in Fig. 2. It includes the RoTiP with its power supply, two measurement systems (EI, IMU) powered by other DC power supply and USB, and a PC control station. The PC software controls the RoTiP position via RS232 bus and collects the data from the measurement systems.

Tests and Results

This chapter provides the results of EI and ACCs tests which helped to analyse the measurements system performances from their accuracy point of view. The tests covered the effect of EI correction on the final accuracy, the correction of ACC's transfer characteristics, a null repeatability, the stability of the initial null angle, the hysteresis, and cross-axis dependence.

During all experiments and analyses the data from ADIS16405 were sampled and recorded with the frequency 100 Hz and the data from EZ-TILT-2000-008 with 14 Hz. To eliminate the influence of a noise contained in the data we made a mean value of 100 samples for each channel and each position under steady-state conditions and a resultant averaged value was used as a representative for that particular position and channel.

For a result comparison Root Mean Square Error (RMSE) defined by (3) was used.

$$RMSE(x_1, x_2) = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{1,i} - x_{2,i}\right)^2}{n}} \quad (3)$$

where: $x_{1,i}$ is the vector of reference values, $x_{2,i}$ denotes the vector of measured/estimated values, and n represents the number of measurements.

Transfer Characteristics

The transfer characteristics of both measurement systems were measured using RoTiP platform in the range approximately ±8 deg with the step of 1 deg. The systems were consequently tilted among steady-state positions with angular velocity 2 deg/s. Measured transfer characteristics of EI related to the reference values were then approximated using 2nd order polynomials to get corrections for both pitch (4) and roll (5) angles.

$$\theta_{cor} = 0.001761 \cdot \theta_{nc}^2 + 1.031 \cdot \theta_{nc} + 0.6138 \quad (4)$$

$$\phi_{cor} = 0.001761 \cdot \phi_{nc}^2 + 1.033 \cdot \phi_{nc} + 0.2546 \quad (5)$$

where: θ is the pitch angle, ϕ denotes the roll angle, subscript cor represents the angles after the polynomial correction, subscript nc corresponds to the measured non-corrected angles.

The deviations of EI transfer characteristics from the reference values before and after the correction are shown in Fig. 3. The effect of EI transfer characteristics correction on the precision of ACC biases estimation and consecutive ACC based angles estimation can be seen in Fig. 4. The experiment in each position considered that based on corrected value of EI ACCs were newly initialized, which means that the biases of ACCs were newly estimated and corrected. The RMSE and variance values from Fig. 3 and Fig.4 are listed in Table 4.

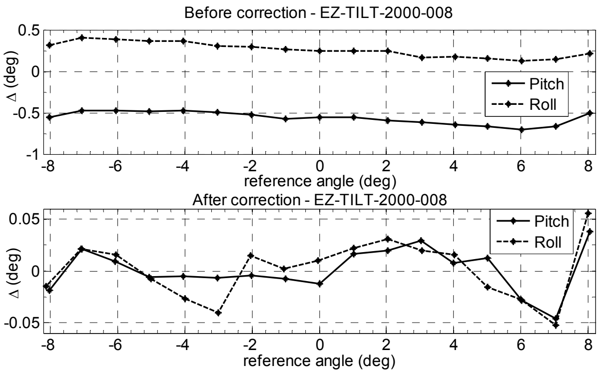

Fig.3. Deviations (Δ) of pitch and roll angles from the reference values before and after corrections using 2[nd] order polynomials – electronic inclinometer EZ-TILT-2000-008

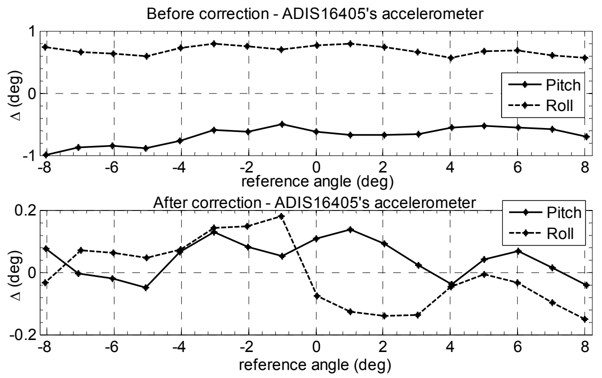

Fig.4. Deviations (Δ) of pitch and roll angles from the reference values before and after bias corrections using corrected data of electronic inclinometer – ACC of IMU ADIS16405

Table 4. The RMSE and variance values before and after correction for EI and ACC (according to Figs. 3-4)

	EI (deg)		ACC (deg)	
	Pitch	Roll	Pitch	Roll
RMSE before correction	0.57	0.27	0.69	0.70
RMSE after correction	0.04	0.05	0.07	0.10
Variance before corr.	0.0057	0.0077	0.0213	0.0053
Variance after corr.	0.0005	0.0005	0.0114	0.0034

Null Repeatability

The repeatability is defined as an angular error calculated from angle deviations when the measurement system is repeatedly placed in the same position and consequently replaced from it. A special angle of importance is the null angle, which is characterized by the null repeatability characteristics [14]. As in the previous case, the RoTiP was used to set the positions and to refer the angles. The ACC and EI were tilted within the range of ±8 deg along combined directions (positive pitch and negative roll and conversely). The angular rate between subsequent positions was kept at the value of 2 deg/s in all cases. For each channel of EI and ACC and steady-state conditions the average of 100 samples was calculated. Fifty times the null angle position was subsequently set up. The performances of EI and ACC are shown in Fig. 5.

Based on obtained data from the null repeatability experiment the RMSE of EI performance was 0.12 deg for the pitch and 0.09 deg for the roll angle. In the case of ACC the RMSE was higher in both cases, i.e. 0.81 deg for the pitch and 0.40 deg for the roll angle. From Fig. 5 it is clear that the null repeatability of ACC is influenced by the initial bias error, which can be compensated using the bias correction obtained from EI.

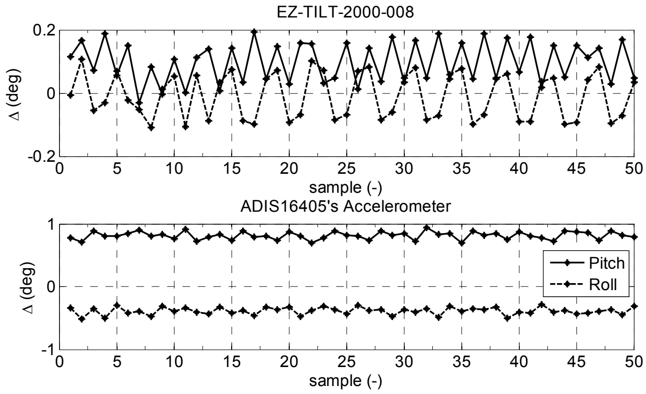

Fig.5. The Null repeatability of pitch and roll angles for the EI and the ACC, where "Δ" means a deviation between measured angle and the reference angle equal in this case to 0 deg

Stability of Initial Null Angle

The stability of an initial null angle, which corresponds to an initial bias error defined by Analog Devices [13], was also observed. For both systems there were performed 20 measurements during 4 days. Each measurement was performed after the power was 60 seconds switched-on to stabilize the system operating conditions. As well as in previous cases in each position and steady-state conditions 100 data samples were averaged to obtain the value we then worked with.

The RMSE for the pitch and roll angles of EI was 0.05 deg in both axes. The RMSE for the pitch and roll of ACC was 0.87 deg and 0.25 deg, respectively. The stability of initial null angle characteristics for both EI and ACC is shown in Fig. 6. From the ACC characteristics it can be seen that the pitch and roll angles were again influenced by an initial bias error, unlike the EI. According to Fig. 6, the initial bias error has smaller influence on EI than on ACC. It proves the EI to be suitable for initial ACC corrections from the null angle stability point of view.

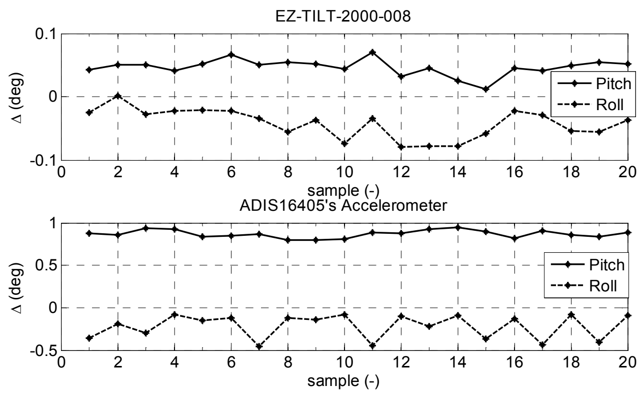

Fig.6. The Stability of an initial null angle for EI and ACC, where "Δ" represents a deviation between a measured angle and a reference angle equal to 0 deg

Hysteresis

The hysteresis characteristics were measured in the range of ±8 deg forward and backward for both angles of tilt. As in previous measurements, the average of 100 samples was taken as a representative value of particular steady-state position. The hysteresis was observed on the sensor data already compensated for the nonlinearity and initial offset. According to tilt angles evaluated based on measured data when the RoTiP was tilted from -8 deg up to +8 deg and back, we evaluated differences between obtained angles of both directions and a particular reference angle of RoTiP. The progresses of those differences for both sensors are presented in Fig. 7. The hysteresis δ_H can be then calculated according to (6).

$$\delta_H = \left(\frac{y_{up} - y_{down}}{y_{max} - y_{min}} \right)_{max} .100\,(\%) \tag{6}$$

where $y_{up,}$ denotes an evaluated value from a forward measurement (tilt being increased), y_{down} corresponds to a backward measurement (tilt being decreased), and y_{min}, y_{max} are the minimal and maximal values of the measurement.

With respect to (6) and measured data the EI hysteresis was 0.51 % for the pitch and 0.43 % for the roll angle. The hysteresis for ACC was 0.71 % for the pitch and 1.19 % for the roll angle.

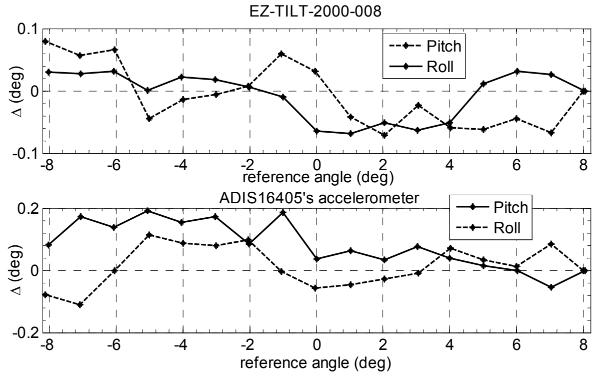

Fig.7. The progress of differences "Δ" defined between tilt angles evaluated from measurements in which the RoTiP was tilted from -8 deg up to +8 deg and in backward direction. The differences correspond to the same reference angle of RoTiP set within a forward and backward direction of the measurement

Cross-axis Dependence

The cross-axis dependence was measured for both systems using the same procedure and the same number of samples to be averaged for representing values as in previous cases. In the cases of the pitch angles being changed, the roll angle deviations were measured. In the other case, the roll angles were changed and pitch angle deviations were measured. The measured data for both systems were analysed. The cross-axis dependencies for ACC are shown in Fig. 8. The RMSE was 0.08 deg for the pitch and 0.06 deg for the roll angle.

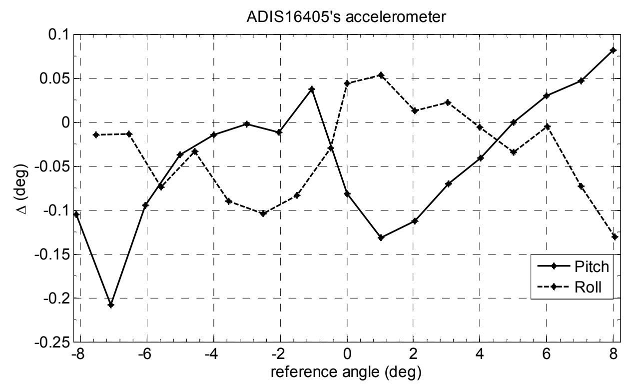

Fig.8. Cross-axis dependence of ACC where "Δ" represents cross-axis deviation

According to measured characteristics of ACC it can be seen that the cross-axis error is negligible with respect to other error sources. Unfortunately, performed analyses of EI showed the strong cross-axis dependence and the additional measurements had to be performed. The cross-axis dependencies for the pitch and roll angles of EI are shown in Fig. 9 and Fig. 10, respectively.

The measured characteristics were analysed and approximated by two-variable polynomials. We analysed different order of polynomials from the computational cost and the accuracy points of view. The RMSEs which were computed from deviations between measured and reference angles before and after cross-axis correction using different order polynomials are shown in Table 5.

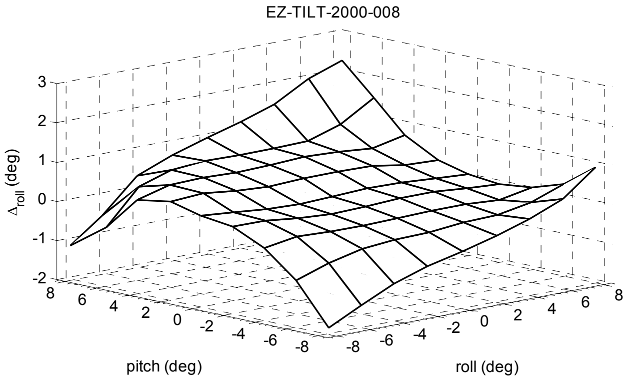

Fig.9. Cross-axis dependence of EI – pitch angle tilted, roll angle deviations observed

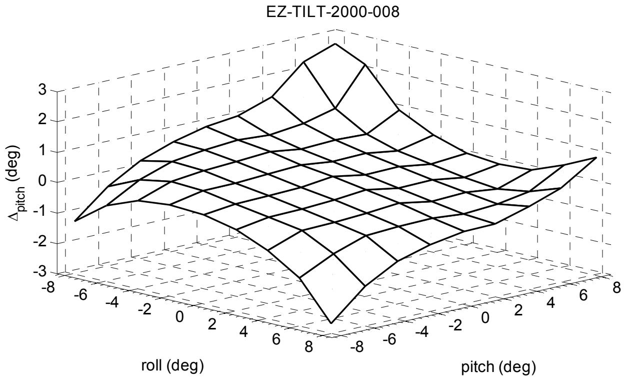

Fig.10. Cross-axis dependence of EI – roll angle tilted, pitch angle deviations observed

Furthermore, we performed the correction using other mathematical algorithm – LOcally WEighted Scatterplot Smoothing (LOWESS), but the application of this algorithm did not lead to well-marked improvement of the accuracy. Finally, we chose 3[rd] order polynomials described by (7) and (8) for pitch and roll correction, respectively.

$$\begin{aligned}\Delta\theta &= 0.093 - 0.081\theta - 0.082\phi - 0.002\theta^2 - 0.003\theta\phi \\ &+ 0.001\theta^3 + 0.003\theta\phi^2 - 0.0001\phi^3\end{aligned} \tag{7}$$

$$\begin{aligned}\Delta\phi &= 0.273 + 0.077\theta - 0.050\phi - 0.001\theta^2 + 0.001\theta\phi \\ &- 0.001\phi^2 + 0.0003\theta^3 + 0.003\theta^2\phi + 0.0005\phi^3\end{aligned} \tag{8}$$

where: $\Delta\theta$, $\Delta\phi$ are the pitch and roll corrections, θ, ϕ are estimated pitch and roll angles.

Table 5. The RMSEs of applied polynomials for EI cross-axis correction

Applied polynomial	RMSE (deg)	
	Pitch	Roll
No correction	0.67	0.77
Correction using 1[st] order polynomial	0.44	0.39
Correction using 2[nd] order polynomial	0.43	0.38
Correction using 3[rd] order polynomial	0.13	0.14
Correction using 4[th] order polynomial	0.12	0.12
Correction using 5[th] order polynomial	0.09	0.10

Conclusion

This paper concerns a levelling procedure of navigation systems using tri-axial accelerometer (ACC) and electronic inclinometer (EI). The levelling forms the part of coarse alignment process which is needed to be performed within the initialization of inertial navigation systems. The levelling is generally done by ACCs; however, ACC biases negatively affect its precision. Due to this reason other system is required and thus we analysed how the precision can be improved by EI utilization and what weak points the system has.

In our case we used ACCs of IMU ADIS16405 and electrolytic tilt sensor of EZ-TILT-2000-008 EI system. Both systems belong to the low-cost category. The main aim was to analyse different effects of their characteristics on the levelling precision. For both systems we analysed the transfer characteristics, null repeatability, stability of initial null angle, hysteresis, and cross-axis dependence. All these characteristics were measured in the range of ±8 deg using a Rotational-Tilt Platform (RoTiP) which provided us with reference values of tilt. These values were related with ACC and EI data and used for analyses.

The RMSEs of performed analyses are summarized in Table 6. From this table, it can been seen that the main error affecting accuracy of the EI was caused by a cross-axis dependence with the RMSE equal to 0.13 deg for the pitch angle and 0.14 deg for the roll angle. These errors can be further reduced by using higher order polynomials or using other correction algorithms, such as aforementioned LOWESS. Nevertheless, with more and more complicated functions applied the computation cost will increase and the accuracy improvement will not change so much.

The measured characteristics of EI were slightly different from values specified by manufacturer. It was probably caused by using an electrolyte with higher viscosity than the one generally used in standard EI systems. However, according to measured data and performed analyses we proved that the corrections based on EI data led to the improvement of the levelling accuracy, which was our main purpose.

Table 6. The results of performed analyses for EI EZ-TILT-2000-008 and ACC ADIS16405's

Performed analyses	EI		ACC	
	Pitch	Roll	Pitch	Roll
No correction: RMSE (deg)	0.57	0.27	0.69	0.70
After correction: RMSE (deg)	0.04	0.05	0.07	0.10
Null repeatability: RMSE (deg)	0.12	0.09	0.81	0.40
Init. null angle stability: RMSE (deg)	0.05	0.05	0.87	0.25
Hysteresis (%)	0.51	0.43	0.71	1.19
Cross-axis dependence: RMSE (deg)	0.13	0.14	0.08	0.06

This research has been partially supported by Czech Science Foundation project 102/09/H082, partially by the research program No. MSM6840770015 "Research of Methods and Systems for Measurement of Physical Quantities and Measured Data Processing" of the CTU in Prague sponsored by the Ministry of Education, Youth and Sports of the Czech Republic and partially by Grant Agency of the Czech Technical University in Prague grant No. SGS10/288/OHK3/3T/13.

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