

Testing the Coarse Alignment Algorithm Using Rotation Platform

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Abstract: The paper deals with testing the coarse alignment algorithm for the inertial measurement unit ADIS16405 using a rotation platform. The ADIS16405 is the new six-degree of freedom inertial measurement unit which is being produced by Analog Devices. The main goal of the paper is to describe the determination of the initial attitude of the inertial measurement unit with respect to the navigation frame as a referenced frame and to depict appropriate tests using a rotation platform. In this work the attitude is represented by the Euler angles (the roll, pitch and yaw angles). The tests were conducted using the INS/GNSS development kit which had been mounted on the rotation platform. The overall factual results are illustrated and correctness of the algorithm was definitely confirmed.

Keywords: alignment algorithm; attitude; inertial measurement unit; navigation

1 Introduction

The Inertial Measurement Unit (IMU) typically provides an output of a vehicle's accelerations and angular rates, which are then integrated to obtain the vehicle's position, velocity, and attitude. The system providing this information is called an Inertial Navigation System (INS). Over the last decades there has been a remarkable increase in demand for low-cost inertial navigation systems to serve in car navigation, personal navigation, indoor navigation, the navigation of Unmanned Aerial Vehicles (UAVs), etc. Recent technological progress in the precision and reliability of micro-electro-mechanical systems (MEMS) has remarkably affected the area of low-cost INS [13, 14, 15, 16]. The operation of an inertial navigation system follows the laws of classical mechanics as formulated by Newton. The ability to measure specific forces using accelerometers allows for calculating changes in velocity and position by performing successive integration of the acceleration with respect to time [4]. To function properly, the INS must be initialized when turned on by an initialization procedure containing an alignment

procedure which determines the initial attitude [3, 17]. The initial attitude is understood as setting up the initial Euler angles (the roll, pitch and yaw angles) which express the relationship between the navigation frame as the reference frame and the body frame as the frame where the inertial measurement unit is mounted. Low-cost inertial measurement units contain three-axis accelerometers, three-axis gyroscopes and three-axis magnetometers. The reason for the implementation of magnetometers into this configuration is that the low quality of gyroscopes in the low-cost inertial measurement units does not allow for the performance of the so-called self-alignment. Self-alignment stands for the capability to determine the initial attitude without external sources.

2 Transformation Matrix and Euler Angles

The relationship between vectors in the navigation frame (as a reference frame) and the body frame are completely described by the transformation matrix C_n^b [3, 5, 6, 8]. The C_n^b is defined by the sequence of three rotations of the planes $[\phi]_1, [\theta]_2, [\psi]_3$, comprising Euler angles ϕ, θ, ψ and can be calculated

$$C_n^b = [\phi]_1 \cdot [\theta]_2 \cdot [\psi]_3, \quad (1)$$

where

$$[\phi]_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & \sin \phi \\ 0 & -\sin \phi & \cos \phi \end{bmatrix}, \quad (2)$$

$$[\theta]_2 = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix}, \quad (3)$$

$$[\psi]_3 = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (4)$$

where ϕ, θ and ψ represent the roll, pitch and yaw angles. Substituting equations (2), (3) and (4) in the equation (1) can be expressed as the transformation matrix C_n^b in the following way

$$\mathbf{C}_n^b = \begin{bmatrix} \cos \psi \cos \theta & \sin \psi \cos \theta & -\sin \theta \\ \begin{pmatrix} \cos \psi \sin \theta \sin \phi \\ -\sin \psi \cos \phi \end{pmatrix} & \begin{pmatrix} \sin \psi \sin \theta \sin \phi \\ +\cos \psi \cos \phi \end{pmatrix} & \cos \theta \sin \phi \\ \begin{pmatrix} \cos \psi \sin \theta \cos \phi \\ +\sin \psi \sin \phi \end{pmatrix} & \begin{pmatrix} \sin \psi \sin \theta \cos \phi \\ -\cos \psi \sin \phi \end{pmatrix} & \cos \theta \cos \phi \end{bmatrix}. \quad (5)$$

Due to the fact that transformation matrix is orthogonal [3, 4, 7, 9], an inverse transformation from the body frame to navigation frame can be calculated as following

$$\mathbf{C}_b^n = [\mathbf{C}_n^b]^T = [\psi]_3^T \cdot [\theta]_2^T \cdot [\phi]_1^T. \quad (6)$$

3 Coarse Alignment Algorithm

As mentioned above, the goal of the alignment procedure is to determine the initial attitude of the inertial navigation system. Due to the fact that the IMU ADIS16405 consists of three-axis accelerometers, three-axis gyroscopes and three-axis magnetometers, the self-alignment can be achieved easily. Therefore, it isn't necessary to use any information from other systems to determine the initial attitude. The coarse alignment algorithm can be split into two parts. The first step of the coarse alignment algorithm is called leveling and the second step is called course alignment.

3.1 Leveling

The goal of leveling is to determine the roll angle ϕ and the pitch angle θ between the navigation frame and the body frame. Typically, the orientation of the navigation frame is defined as x -axis towards north, y -axis towards to the east and z -axis towards down [3, 6, 11]. Therefore, this notification is denoted as a NED (North, East, Down) direction and the axes of navigation frame are denoted as $[x_{\text{NED}}^n, y_{\text{NED}}^n, z_{\text{NED}}^n]$ and the vectors of accelerations are expressed in the navigation frame as $\mathbf{a}_{\text{NED}}^n = [a_{\text{NED}}^{nx}, a_{\text{NED}}^{ny}, a_{\text{NED}}^{nz}]^T$. The measured outputs of accelerometers represent the specific forces, expressed in the body frame as the components of vector $\mathbf{f}_{\text{ADIS}}^b = [f_{\text{ADIS}}^{bx}, f_{\text{ADIS}}^{by}, f_{\text{ADIS}}^{bz}]^T$. In the Fig. 3 the ADIS16405 sensor is illustrated with the sensors axes orientation defined. It is clear that the accelerometers axes are in the opposite direction of the axes of magnetometers and

the axes of gyroscopes. Therefore, it is suitable to transform the outputs of the accelerometers to the opposite direction. Typically in navigation for the reference frame it is preferable to express the sensor outputs in the same direction as in the navigation frame axes direction (under the condition that the roll, pitch and yaw angles are equal to zero; it means the navigation frame is coincident with the body frame). It can be done by the transformation matrix $\mathbf{C}_{ADIS}^{ADISinNAV}$.

The mentioned transformation can be written as

$$\mathbf{f}_{ADISinNAV}^b = \mathbf{C}_{ADIS}^{ADISinNAV} \cdot (-\mathbf{f}_{ADIS}^b), \quad (7)$$

or

$$\begin{bmatrix} \mathbf{f}_{ADISinNAV}^{bx} \\ \mathbf{f}_{ADISinNAV}^{by} \\ \mathbf{f}_{ADISinNAV}^{bz} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} -\mathbf{f}_{ADIS}^{bx} \\ -\mathbf{f}_{ADIS}^{by} \\ -\mathbf{f}_{ADIS}^{bz} \end{bmatrix}. \quad (8)$$

In general, the specific force vector is defined as

$$\mathbf{f}_{ADISinNAV}^b = \mathbf{a}_{ADISinNAV}^b - \mathbf{g}^b, \quad (9)$$

where vector $\mathbf{a}_{ADISinNAV}^b$ is represented as an acceleration of the body frame relative to the inertial frame. Assuming the alignment procedure of the ADIS16405 is stationary, the $\mathbf{a}_{ADISinNAV}^b = 0$ so equation (3) can be rewritten

$$\mathbf{f}_{ADISinNAV}^b = -\mathbf{g}^b. \quad (10)$$

Let \mathbf{g}^b be the gravity vector in the body frame, and taken that the sensor position on the Earth is known, according to this, the gravity in the navigation frame can be computed [6] as

$$\mathbf{g}^n = \begin{bmatrix} 0 \\ 0 \\ 9.7803267715 \frac{1+0.001931851353 \sin^2(\varphi)}{\sqrt{1-0.0066943800299 \sin^2(\varphi)}} \end{bmatrix}, \quad (11)$$

where φ is the latitude.

If the sensor position is unknown, then

$$\mathbf{g}^n = \begin{bmatrix} 0 \\ 0 \\ \mathbf{g}_c \end{bmatrix}, \quad (12)$$

where $g_e = 9.80665 \text{ m}\cdot\text{s}^{-2}$ is the Earth gravity constant. The relationship between the gravity vector in the body frame and navigation frame can be expressed as

$$\mathbf{g}^b = \mathbf{C}_n^b \cdot \mathbf{g}^n, \quad (13)$$

or

$$\mathbf{g}^b = \begin{bmatrix} -\sin \theta \\ \cos \theta \sin \phi \\ \cos \theta \cos \phi \end{bmatrix} \cdot g_e. \quad (14)$$

Substituting equation (14) into equation (10) can be rewritten as

$$\begin{bmatrix} f_{\text{ADISinNAV}}^{\text{bx}} \\ f_{\text{ADISinNAV}}^{\text{by}} \\ f_{\text{ADISinNAV}}^{\text{bz}} \end{bmatrix} = - \begin{bmatrix} -\sin \theta \\ \cos \theta \sin \phi \\ \cos \theta \cos \phi \end{bmatrix} \cdot g_e. \quad (15)$$

In the Fig. 1, the determination of roll angle ϕ is illustrated. The outputs of x and z accelerometers are $f_{\text{ADIS}}^{\text{bx}} = 0.31g$, $f_{\text{ADIS}}^{\text{bz}} = -0.95g$ or, applying the equation (7), they are $f_{\text{ADISinNAV}}^{\text{by}} = -0.31g$ and $f_{\text{ADISinNAV}}^{\text{bz}} = -0.95g$. It is depicted in the upper part of Fig. 1 which is denoted as “ADIS16405 in x - z plane”. From the equation (15), the roll angle can be computed as

$$\phi = \text{atan} 2 \left(-f_{\text{ADISinNAV}}^{\text{by}}, -f_{\text{ADISinNAV}}^{\text{bz}} \right), \quad (16)$$

So the values of specific forces can be substituted as following

$$\phi = \text{atan} 2 \left(-(-0.31g), -(-0.95g) \right) = 18^\circ. \quad (17)$$

Using direct outputs from the accelerometers

$$\phi = \text{atan} 2 \left(f_{\text{ADIS}}^{\text{bx}}, -f_{\text{ADIS}}^{\text{bz}} \right). \quad (18)$$

When the measured values of specific forces are substituted we can get following

$$\phi = \text{atan} 2 \left(0.31g, -(-0.95g) \right) = 18^\circ. \quad (19)$$

For the roll angle determination in all four quadrants it is necessary to use the *atan2* function. Due to the correct determination of roll in all four quadrants, the correct expression of the parameters is very important. Therefore, in the bottom part of Fig. 1, which is denoted as “function *atan2* in plane”, the transformation of accelerometers outputs in ADIS16405 x - z plane to the x - y plane for *atan2* function is illustrated.

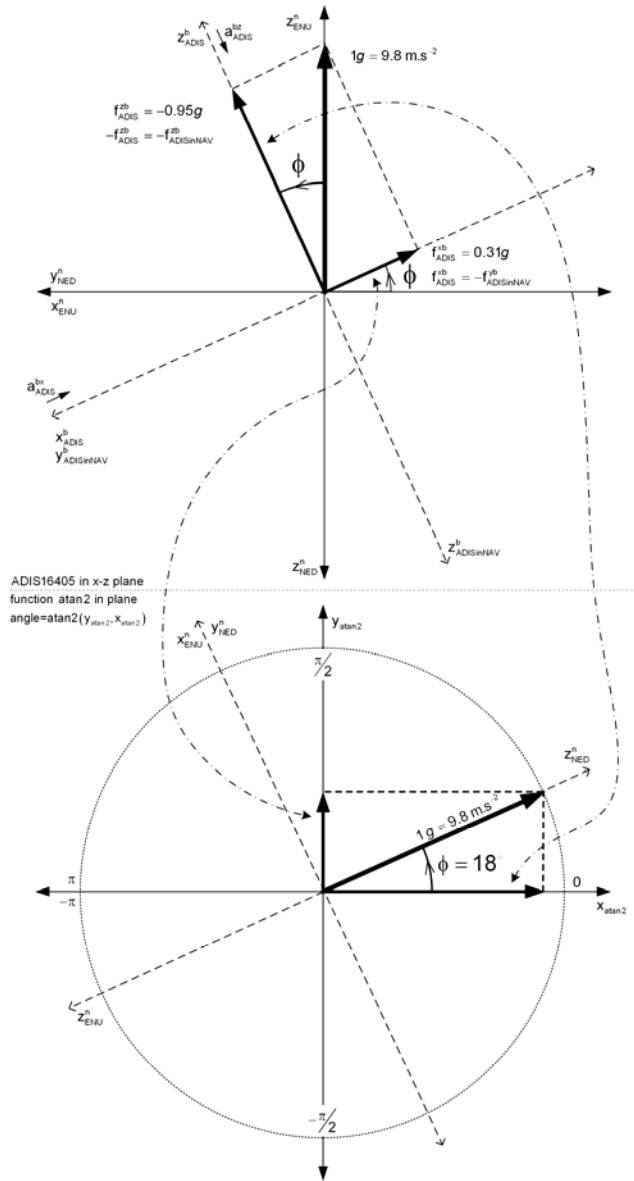


Figure 1
The determination of roll angle ϕ

Likewise, the pitch θ angle can be determined as

$$\theta = \text{atan2} \left(f_{ADISinNAV}^{bx}, \sqrt{\left(f_{ADISinNAV}^{by} \right)^2 + \left(f_{ADISinNAV}^{bz} \right)^2} \right), \quad (20)$$

or, using of the accelerometers output measurements

$$\theta = \operatorname{atan} 2 \left(-f_{\text{ADIS}}^{\text{by}}, \sqrt{\left(f_{\text{ADIS}}^{\text{bx}}\right)^2 + \left(f_{\text{ADIS}}^{\text{bz}}\right)^2} \right). \quad (21)$$

The output of y accelerometer is $f_{\text{ADIS}}^{\text{by}} = 0.08g$ or applying the equation (7) it is $f_{\text{ADISinNAV}}^{\text{bx}} = -0.08g$, so the values of specific forces can be substituted to equation (20) as following

$$\theta = \operatorname{atan} 2 \left((-0.08g), \sqrt{(-0.31g)^2 + (-0.95g)^2} \right) = -4.57^\circ. \quad (22)$$

When the measured values of specific forces are substituted to equation (21) we can get following

$$\theta = \operatorname{atan} 2 \left(-(0.08g), \sqrt{(0.31g)^2 + (-0.95g)^2} \right) = -4.57^\circ. \quad (23)$$

3.2 Course Alignment

The goal of the course alignment is to determine the yaw angle ψ between the navigation frame and the body frame. For the low-cost sensors, where low quality gyroscopes are used (it means the errors of the gyroscopes are greater than angular rate of Earth), the yaw can be determined by the magnetometers [6, 10].

Using the World Magnetic Model [2], the geomagnetic field vector, $\mathbf{b}_{\text{Earth}}$, can be described by 7 elements. These are the northerly intensity $b_{\text{Earth}}^{\text{nx}}$, the easterly intensity $b_{\text{Earth}}^{\text{ny}}$, the vertical intensity $b_{\text{Earth}}^{\text{nz}}$ (positive downwards) and the following quantities derived from $b_{\text{Earth}}^{\text{nx}}$, $b_{\text{Earth}}^{\text{ny}}$, and $b_{\text{Earth}}^{\text{nz}}$ - i.e. the total intensity $\|\mathbf{b}_{\text{Earth}}\|$, the horizontal intensity $b_{\text{Earth}}^{\text{horizontal}}$, the inclination angle $\gamma_{\text{inclination}}$, (also called the dip angle and measured from the horizontal plane to the field vector, positive downwards), and the declination angle $\alpha_{\text{declination}}$ (also called the magnetic variation and measured clockwise from true north to the horizontal component of the field vector). In the descriptions of $b_{\text{Earth}}^{\text{nx}}$, $b_{\text{Earth}}^{\text{ny}}$, $b_{\text{Earth}}^{\text{nz}}$, $\|\mathbf{b}_{\text{Earth}}\|$, $b_{\text{Earth}}^{\text{horizontal}}$, $\gamma_{\text{inclination}}$ and $\alpha_{\text{declination}}$ above, the vertical direction is perpendicular to the WGS-84 ellipsoid model of the Earth, the horizontal plane is perpendicular to the vertical direction, and the rotational directions clockwise and counter-clockwise are determined by a view from above (see Fig. 2). The Earth's geomagnetic field points from the magnetic north pole to the magnetic south pole through the Earth, taking the opposite path through the upper atmosphere. The field is thus vertical at the magnetic poles and horizontal near the equator.

The magnetic field is measured by the three magnetometers of ADIS16405 and the vector of magnetic field can be denoted as $\mathbf{m}_{ADIS}^b = [m_{ADIS}^{bx}, m_{ADIS}^{by}, m_{ADIS}^{bz}]^T$. Due to same reason as mentioned for the accelerometers, it should be transformed by the following

$$\mathbf{m}_{ADISinNAV}^b = \mathbf{C}_{ADIS}^{ADISinNAV} \cdot \mathbf{m}_{ADIS}^b \quad (24)$$

The relationship between the magnetic vector in the body frame and the navigation frame can be expressed by

$$\mathbf{m}^n = \mathbf{C}_b^n \cdot \mathbf{m}_{ADISinNAV}^b \quad (25)$$

Using equation (4), equation (21) can be rewritten as

$$\mathbf{m}^n = [\psi]_3^T \cdot [\theta]_2^T \cdot [\phi]_1^T \cdot \mathbf{m}_{ADISinNAV}^b \quad (26)$$

multiplying both sides by the rotation matrix $[\psi]_3$ we get

$$[\psi]_3 \cdot \mathbf{m}^n = [\theta]_2^T \cdot [\phi]_1^T \cdot \mathbf{m}_{ADISinNAV}^b \quad (27)$$

and

$$[\theta]_2^T \cdot [\phi]_1^T \cdot \mathbf{m}_{ADISinNAV}^b = [\psi]_3 \cdot \mathbf{m}^n \quad (28)$$

Expressing $[\theta]_2^T \cdot [\phi]_1^T$, equation (28) can be rewritten

$$\begin{bmatrix} \cos \theta & \sin \theta \sin \phi & \sin \theta \cos \phi \\ 0 & \cos \phi & -\sin \phi \\ -\sin \theta & \cos \theta \sin \phi & \cos \theta \cos \phi \end{bmatrix} \cdot \mathbf{m}_{ADISinNAV}^b = [\psi]_3 \cdot \mathbf{m}^n \quad (29)$$

The roll and pitch angles are determined by equations (16), (20) and the vector $\mathbf{m}_{ADISinNAV}^b$ is known from equation (24) respective from the magnetometers measurements. Therefore, the left side can be substituted by the new vector $\mathbf{m}_{ADISinNAV}^{\theta\phi}$,

where

$$\mathbf{m}_{ADISinNAV}^{\theta\phi} = \begin{bmatrix} \cos \theta & \sin \theta \sin \phi & \sin \theta \cos \phi \\ 0 & \cos \phi & -\sin \phi \\ -\sin \theta & \cos \theta \sin \phi & \cos \theta \cos \phi \end{bmatrix} \cdot \mathbf{m}_{ADISinNAV}^b \quad (30)$$

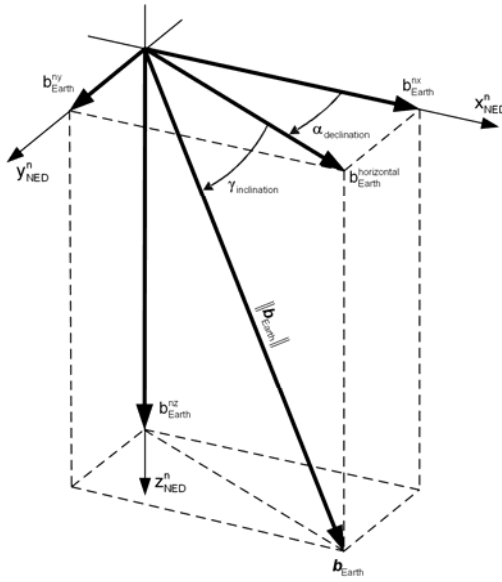


Figure 2

The geomagnetic field vector in the navigation frame

The right side of the equation (29) consists of the unknown variable yaw ψ and the magnetic field vector \mathbf{m}^n expressed in the navigation frame, which represents the geomagnetic field vector $\mathbf{b}_{\text{Earth}}$. The geomagnetic field vector $\mathbf{b}_{\text{Earth}}^n$ in the navigation frame can be calculated as

$$\mathbf{m}^n = \mathbf{b}_{\text{Earth}}^n = \mathbf{C}_{\text{GMF}}^n \cdot \begin{bmatrix} \|\mathbf{b}_{\text{Earth}}\| \\ 0 \\ 0 \end{bmatrix}, \quad (31)$$

where $\mathbf{C}_{\text{GMF}}^n$ is the transformation matrix from the geomagnetic frame to the navigation frame, and is determined according to equation (6) with the declination and the inclination angles

$$\mathbf{C}_{\text{GMF}}^n = [\alpha_{\text{declination}}]_3^T \cdot [-\gamma_{\text{inclination}}]_2^T \cdot [0]_1^T, \quad (32)$$

where

$$[-\gamma_{\text{inclination}}]_2 = \begin{bmatrix} \cos(-\gamma_{\text{inclination}}) & 0 & \sin(-\gamma_{\text{inclination}}) \\ 0 & 1 & 0 \\ -\sin(-\gamma_{\text{inclination}}) & 0 & \cos(-\gamma_{\text{inclination}}) \end{bmatrix}, \quad (33)$$

$$\left[\alpha_{\text{declination}} \right]_3 = \begin{bmatrix} \cos \alpha_{\text{declination}} & \sin \alpha_{\text{declination}} & 0 \\ -\sin \alpha_{\text{declination}} & \cos \alpha_{\text{declination}} & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (34)$$

Applying equations (30) and (31), equation (29) can be rewritten as

$$\mathbf{m}_{\text{ADISinNAV}}^{\theta\phi} = [\Psi]_3 \cdot \mathbf{C}_{\text{GMF}}^n \cdot \begin{bmatrix} \|\mathbf{b}_{\text{Earth}}\| \\ 0 \\ 0 \end{bmatrix}, \quad (35)$$

or

$$\mathbf{m}_{\text{ADISinNAV}}^{\theta\phi} = [\Psi]_3 \cdot \left[\alpha_{\text{declination}} \right]_3^T \cdot \left[-\gamma_{\text{inclination}} \right]_2^T \cdot \begin{bmatrix} \|\mathbf{b}_{\text{Earth}}\| \\ 0 \\ 0 \end{bmatrix}, \quad (36)$$

and after multiplying the right side

$$\mathbf{m}_{\text{ADISinNAV}}^{\theta\phi} = [\Psi]_3 \cdot \begin{bmatrix} \cos \alpha_{\text{declination}} \cdot \cos \gamma_{\text{inclination}} \\ \sin \alpha_{\text{declination}} \cdot \cos \gamma_{\text{inclination}} \\ \sin \gamma_{\text{inclination}} \end{bmatrix} \cdot \|\mathbf{b}_{\text{Earth}}\|, \quad (37)$$

where $\alpha_{\text{declination}}$, $\gamma_{\text{inclination}}$ and $\|\mathbf{b}_{\text{Earth}}\|$ can be determined by the World Magnetic Model [2]. The angle between the magnetic north pole and the x axis of the body frame can determine the magnetic heading

$$\Psi_m = \Psi - \alpha_{\text{declination}}. \quad (38)$$

The low-cost systems assume the magnetometers measurements are either isolated or compensated from the vehicle magnetic field [6]. Also, there are the assumptions that the local magnetic field deviation and inclination are compensated. Taking these assumptions into consideration, equation (31) and equation (35) can be rewritten

$$\mathbf{m}^n = \left[\|\mathbf{b}_{\text{Earth}}\| \quad 0 \quad 0 \right]^T, \quad (39)$$

$$\mathbf{m}_{\text{ADISinNAV}}^{\theta\phi} = [\Psi]_3 \cdot \begin{bmatrix} \|\mathbf{b}_{\text{Earth}}\| \\ 0 \\ 0 \end{bmatrix}, \quad (40)$$

or

$$\mathbf{m}_{\text{ADISinNAV}}^{\theta\phi} = \begin{bmatrix} \cos \psi \\ -\sin \psi \\ 0 \end{bmatrix} \cdot \|\mathbf{b}_{\text{Earth}}\|. \quad (41)$$

From equation (41), the yaw can be computed as

$$\psi = \text{atan } 2\left(-\mathbf{m}_{\text{ADISinNAV}}^{\theta\phi y}, \mathbf{m}_{\text{ADISinNAV}}^{\theta\phi x}\right), \quad (42)$$

where $\mathbf{m}_{\text{ADISinNAV}}^{\theta\phi x}, \mathbf{m}_{\text{ADISinNAV}}^{\theta\phi y}$ are transformed measured values from magnetometers.

The magnetometers are measuring the following values $\mathbf{m}_{\text{ADIS}}^b = [86.0, 233.5, -361.0]^T$ mG and therefore the values of roll and pitch from equations (17) and (22) can be substituted to equation (30) as following

$$\mathbf{m}_{\text{ADISinNAV}}^{\theta\phi} = \begin{bmatrix} 0.99 & -0.02 & -0.07 \\ 0 & 0.95 & -0.30 \\ 0.07 & 0.30 & 0.94 \end{bmatrix} \cdot \underbrace{\mathbf{C}_{\text{ADIS}}^{\text{ADISinNAV}}}_{\mathbf{m}_{\text{ADISinNAV}}^b} \cdot \begin{bmatrix} 86.0 \\ 233.5 \\ -361.0 \end{bmatrix} = \begin{bmatrix} 203.2 \\ -29.7 \\ 387.3 \end{bmatrix} \text{ mG}. \quad (43)$$

Substituting $\mathbf{m}_{\text{ADISinNAV}}^{\theta\phi x}, \mathbf{m}_{\text{ADISinNAV}}^{\theta\phi y}$ from equation (43) into equation (42) the value of yaw angle is the following

$$\psi = \text{atan } 2\left(-(-29.7), 203.2\right) = 8.3^\circ. \quad (44)$$

4 The Sensor ADIS16405

The ADIS16405 iSensor is a complete inertial system that consists of triaxial gyroscope, triaxial accelerometer, and triaxial magnetometer sensors [1]. Each sensor in the ADIS16405 combines industry-leading iMEMS technology with signal conditioning optimizing dynamic performances. The factory calibration characterizes each sensor for sensitivity, bias, alignment, and linear acceleration (gyro bias). As a result, each sensor has its own dynamic compensation formulas that provide accurate sensor measurements over a temperature range of -40°C to $+85^\circ\text{C}$. The magnetometers employ a self-correction function to provide accurate bias performance over temperature as well. The ADIS16405 provides a simple, cost-effective method for integrating accurate, multi-axis, inertial sensing into industrial systems, especially when compared with the complexity and investment associated with discrete designs. All necessary motion testing and calibration are part of the production process at the factory, greatly reducing system integration

time. Tight orthogonal alignment simplifies inertial frame alignment in navigation systems. An improved SPI interface and register structure provide faster data collection and configuration control. This compact module is approximately 23 mm × 23 mm × 23 mm and provides a flexible connector interface, which enables multiple mounting orientation options, see Fig. 3. The functional block diagram of ADIS16405 is illustrated in Fig. 4.

BASIC SPECIFICATIONS OF ADIS16405

GYROSCOPES

Dynamic Range	±300°/sec
or	±150°/sec
or	±75°/sec
Initial Sensitivity	
for range ±300°/sec	0.05 °/sec/LSB
for range ±150°/sec	0.025 °/sec/LSB
for range ±75°/sec	0.0125 °/sec/LSB
Initial Bias Error ($\pm 1\sigma$)	±3 °/sec
In-Run Bias Stability (1σ)	0.007 °/sec
Angular Random Walk (1σ)	2.0 °/√hr
Output Noise ±300°/sec range, no filtering, rms	0.9 °/sec
Rate Noise Density (±300°/sec, no filtering, rms)	0.05 °/sec/√Hz

ACCELEROMETERS

Dynamic Range	±18g
Initial Sensitivity	3.33 mg/LSB
Initial Bias Error ($\pm 1\sigma$)	±50 mg
In-Run Bias Stability (1σ)	0.2 mg
Velocity Random Walk (1σ)	0.2 m/sec/√hr
Output Noise (no filtering, rms)	9 mg
Noise Density (no filtering, rms)	0.5 mg/√Hz

MAGNETOMETERS

Dynamic Range	±3.5gauss
Initial Sensitivity	0.5 mgauss/LSB
Initial Bias Error ($\pm 1\sigma$)	±4 mgauss
Output Noise (no filtering, rms)	1.25 mgauss
Noise Density (no filtering, rms)	0.066 mgauss/√Hz

POWER SUPPLY

Operating voltage range, VCC	5.0 V
Power Supply Current (max)	70 mA

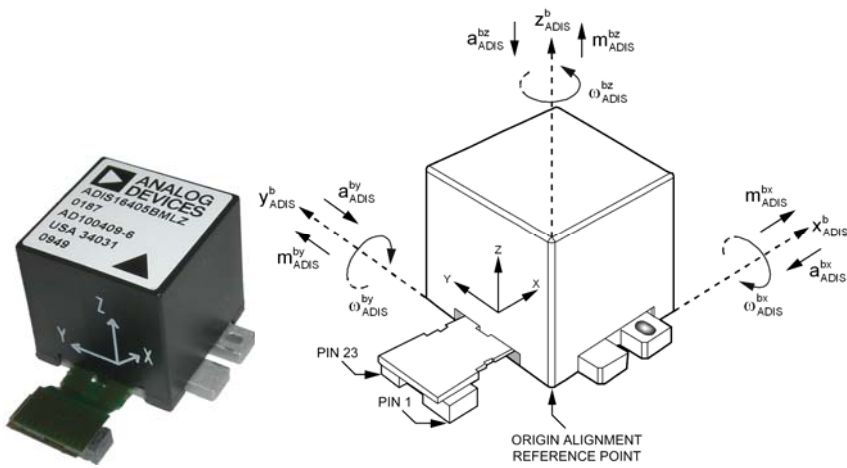


Figure 3
The sensor ADIS16405BMLZ

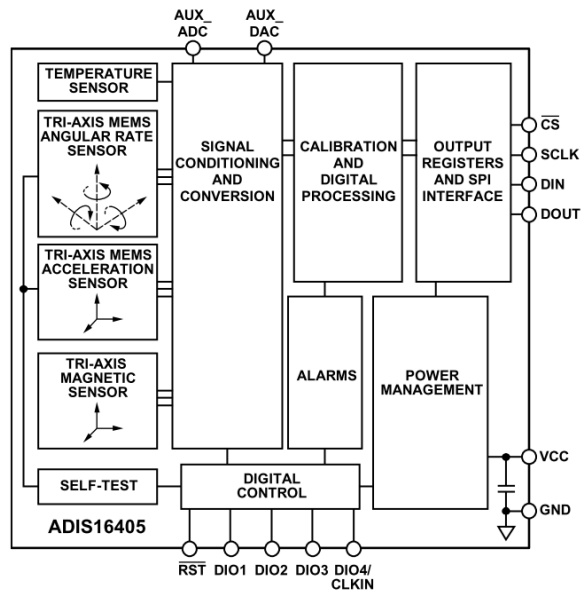


Figure 4
Functional Block Diagram of ADIS16405 [1]

5 Tests & Results

All tests were conducted using the INS/GNSS development kit. The INS/GNSS development kit is shown in Fig. 5 and consists of the inertial measurement unit ADIS16405, the GNSS receiver LEA-5T, pressure sensors and a WIFI module. All sensors and systems are controlled by the processor. These tests have been conducted using the ADIS16405 and the WIFI module only. The data from ADIS16405 were processed and then transferred by WIFI module to a personal computer for further processing.



Figure 5

The rotation platform with INS/GNSS development kit placed on it

The IMU was externally synchronized by the processor and the data sampling rate was 100 Hz. For testing, the INS/GNSS development kit was mounted on the rotation platform. The varied attitudes of ADIS16405 within the known quadrants were set and the data from sensors were collected and processed. For every adjusted attitude, an average of 100 measured samples was computed. In other words, according to the equations (45) and (46), the mean for each sensor was calculated.

$$f_{\text{ADIS}}^b = \frac{\sum_{k=1}^{100} f_{\text{ADIS}}^b(k)}{100} \quad (45)$$

$$m_{ADIS}^b = \frac{\sum_{k=1}^{100} m_{ADIS}^b(k)}{100} \quad (46)$$

The roll, pitch and yaw angles were calculated from average values.

Three tests were conducted. During the first test the roll angle was changed within an interval $\pm 30^\circ$. The results for this test are depicted in Fig. 9. The large crosses represent the manually set roll angles of the platform. The small crosses represent the values of the roll angles calculated from the measured data. During the second test, the pitch angle varied within an interval $\pm 60^\circ$. The test results are illustrated in Fig. 10. During the last test, the yaw angle varied from 0° to 360° and the results are shown in Fig. 11. The raw measured data from sensors, for all three tests, are depicted in Fig. 6, Fig. 7 and Fig. 8. The equations (16), (20) and (42) were used to calculate the values of the Euler angles.

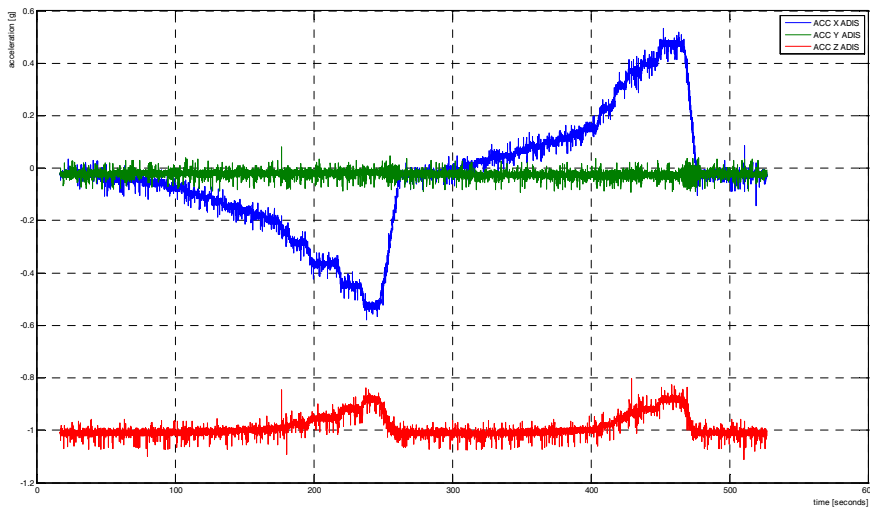


Figure 6

Test 1 - measured data for the roll angle

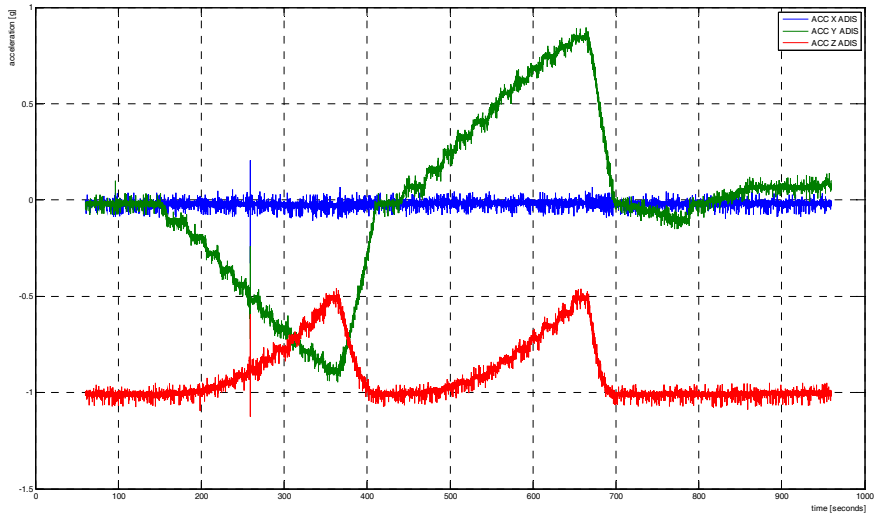


Figure 7
Test 2 - measured data for the pitch angle

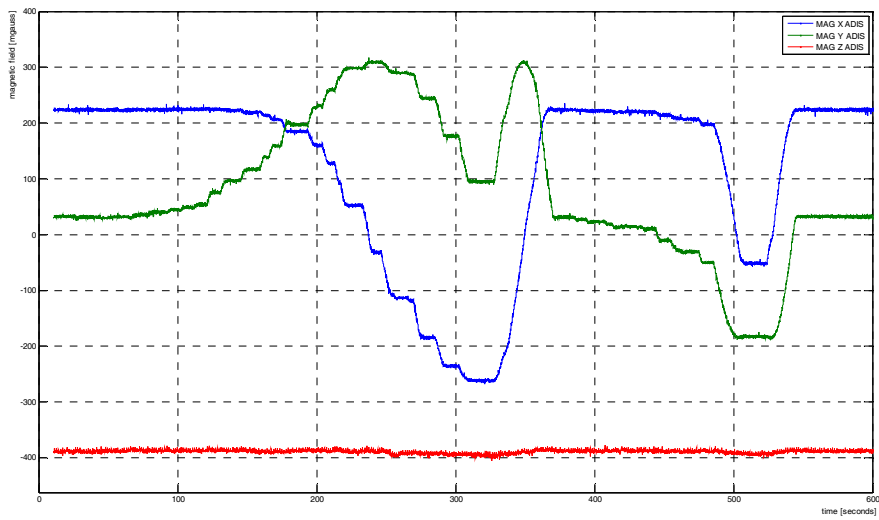


Figure 8
Test 3 - measured data for the yaw angle



Figure 9
Test 1 - the roll angle measurement

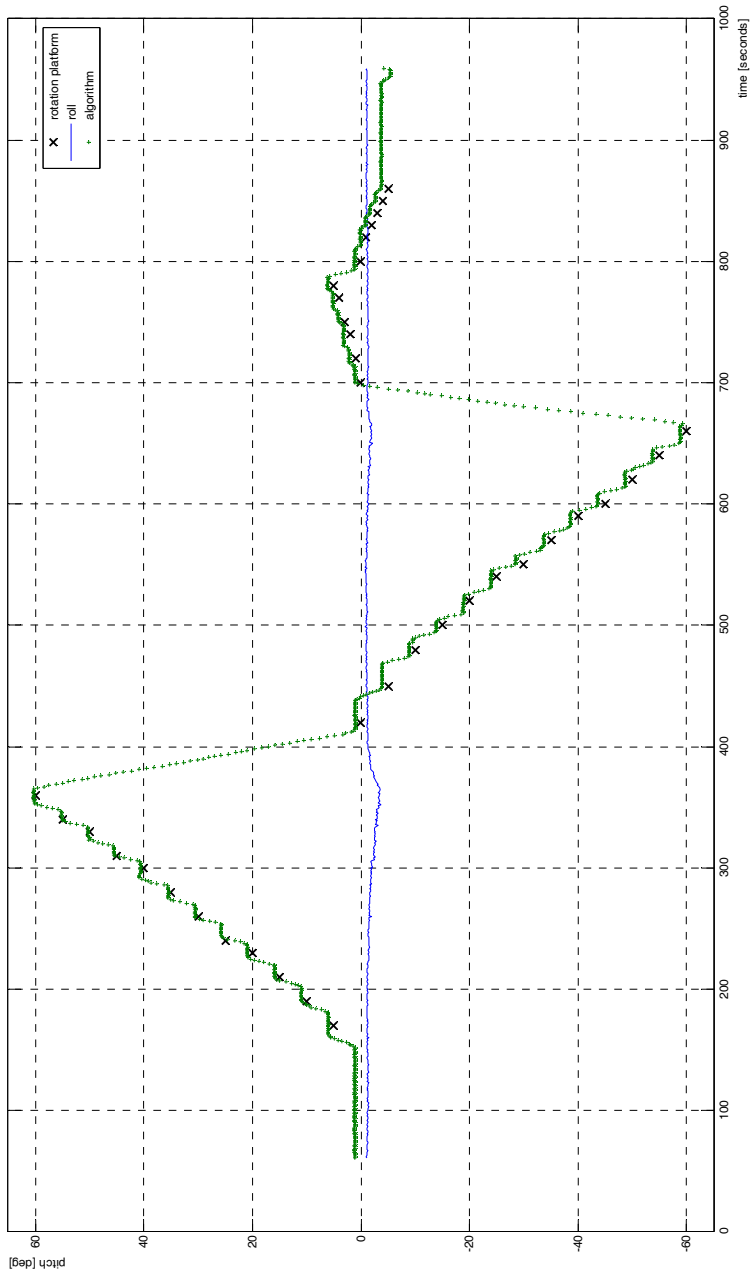


Figure 10
Test 2 - the pitch angle measurement

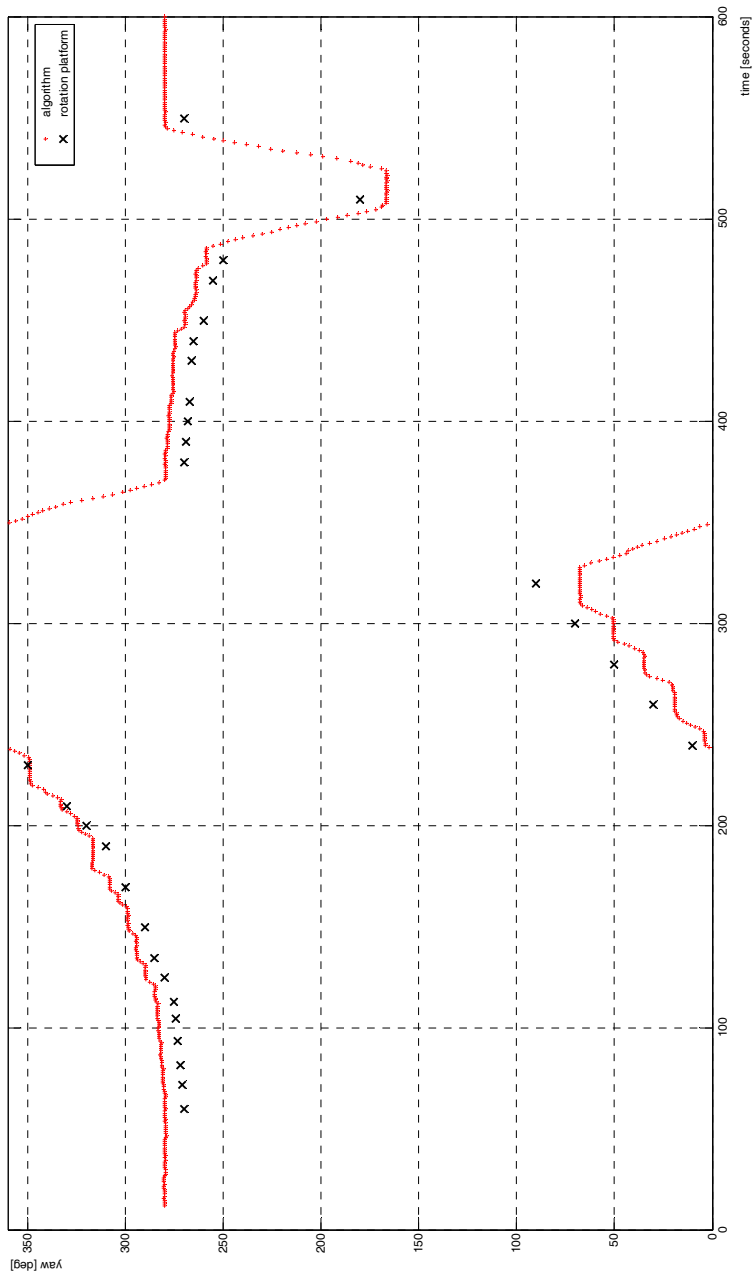


Figure 11
Test 3 - the yaw angle measurement

Conclusion

The paper describes the testing of the coarse alignment algorithm for the inertial measurement unit ADIS16405 using a rotation platform. The main part of the paper deals with the coarse alignment algorithm for the inertial measurement unit. The attitudes (the roll, pitch and yaw angles) are defined by equations (16), (20) and (42). The results of the tests are depicted. It is clear that the calculated values of the roll and pitch angles are not identical to values set by the rotation platform. The reason for the difference is a bias of accelerometers. Each milli-g of sensor bias contributes to the attitude estimate by 1 mrad of the error. The error in yaw angle determination is caused by magnetometer and accelerometer bias as well as by rough determination of the initial direction of rotation platform with respect to the north magnetic pole. The tests were conducted using the INS/GNSS development kit which was mounted on the rotation platform. The results confirm the validity of the coarse alignment algorithm for ADIS16405. The main contribution of this research is the coarse alignment algorithm for the ADIS16405 which was evaluated and applied for real sensor data. This coarse alignment algorithm is implemented in the real-time integrated navigation systems developed nowadays.

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References

- [1] Datasheet of ADIS16405: High Precision Tri-Axis Gyroscope, Accelerometer, Magnetometer http://www.analog.com/static/imported-files/data_sheets/ADIS16400_16405.pdf
- [2] Maus, S., Macmillan S., McLean S., Hamilton B., Thomson A., Nair M., and Rollins C.: The US/UK World Magnetic Model for 2010-2015, NOAA Technical Report NESDIS/NGDC
- [3] Sotak, M., Sopata, M., Breda, R., Rohac, J., Vaci, L.: Navigation System Integration. Monograph: 1. ed., printed by Robert Breda, Kosice, the Slovak Republic, 2006, ISBN 80-969619-9-3 (in Slovak)
- [4] Reinstein, M., Sipos, M., Rohac, J. Error Analyses of Attitude and Heading Reference Systems. In Przegląd Elektrotechniczny, ISSN 0033-2097, Vol. 85, No. 8, pp. 114-118, 2009
- [5] Farrell, J. A., M. Barth.: The Global Positioning System and Inertial Navigation: Theory and Practice. McGraw-Hill 1999. ISBN-0-07-022045-X
- [6] Farrell, J. A.: Aided Navigation: GPS with High Rate Sensors. McGraw-Hill 2008, ISBN: 978-0-07-149329-8

-
- [7] Berezny, S. [et al.]: Another Mathematical Optimization Models Based on Assignment Problem. In: Acta Montanistica Slovaca, ISSN 1335-1788, Vol. 12, No. 4, pp. 356-360, 2007
- [8] Orejas, M. E., Vaci, L., Sopata M.: Multiple Sensor Integration for Autonomous Vehicle Navigation. In: MOSATT 2009: proceedings of the International scientific Conference: Zlata Idka, September 22-24, 2009, Košice: printed by Robert Breda, pp. 272-277, ISBN 978-80-970202-1-7, 2009
- [9] Groves, Paul D.: Principles of GNSS, Inertial, and Multi-Sensor Integrated Navigation Systems. Artech House Publishers, 2007, ISBN: 978-1580532556
- [10] Kuffova, M., Kralik, V.: Indoor Navigation and Mapping Robot System. In: ICMT '09: International Conference on Military Technologies 2009, May 5-6, 2009, Brno: University of Defence, ISBN 978-80-7231-648-9, pp. 499-502, 2009
- [11] Breda, R.: Computation of Navigational Equation in the Inertial Coordinate System. In: Acta Avionica, ISSN 1335-9479, Vol. 11, No. 17, pp. 71-73, 2009
- [12] Necas, P.: Simulation Systems and the Slovak Digitalized Terrain Environment. In: ITEC 2001, 12th International Conference and Exhibition for Training, Education and Simulation, April 24-26, 2001, Lille, France, Warminster, 2001, ISBN 0953-4215-4-4
- [13] Labun J., Adamcik F., Pila J., et al.: Effect of the Measured Pulses Count on the Methodical Error of the Air Radio Altimeter, In: Acta Polytechnica Hungarica, Vol. 7, Issue: 1, pp. 41-49, 2010, ISSN 1785-8860
- [14] Kelemen, M.: Progressive Technologies in Military Aviation Education and Training: The Part of Navigation in Support of Human Activity on the SEA, 14th International Scientific and Technical Conference Proceedings, Naval University of Gdynia Gdynia, November 18-19, 2004
- [15] Kurnaz S., Cetin O.: Autonomous Navigation and Landing Tasks for Fixed Wing Small Unmanned Aerial Vehicles, In: Acta Polytechnica Hungarica, Vol. 7, Issue 1, pp. 87-102, 2010, ISSN 1785-8860
- [16] Ochodnický, J.: Multisensor Networks. Data Association and Target Tracking Principles. Military Academy, Liptovský Mikuláš, ISBN 80-8040-157-8, 2001 (in Slovak)
- [17] Cizmar, J., Skvarek, J., Jalovecký, R.: An Inertial Reference Unit - Development and Testing, 2nd International Scientific Conference, Bratislava, April 29, 2008, ISBN: 978-80-8075-324-5