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Acceleration Data Correction of an Inertial Navigation Unit Using Turntable Test Bed

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Abstract -This study aims to increase the accuracy of the acceleration data of an inertial measurement unit (IMU) mainly used for navigation. This is performed by using a turntable as reference. The angular motion of a turntable is modeled precisely and the acceleration data of the IMU placed on the turntable is calibrated accordingly. Following this procedure an artificial neural network (ANN) is trained to correct future data to be received from the sensor. The comparison of the ANN performance with several system identification models puts forth that the ANN submits superior characteristics than its counterparts. A satisfactory value of around 67% is achieved for the goodness of fit which gives high motivation for further study on the proposed method to calibrate a IMU.

Keywords**:** Inertial measurement unit, acceleration data, calibration, turntable, artificial neural network

1. Introduction

Inertial measurement units (IMU) are widely used in unmanned navigation systems. These units mainly contain three accelerometers to determine the acceleration in each of the three axes. The main reason to measure the accelerations is to define the position which is performed by integrating the acceleration data twice. This procedure in fact results in accumulation of error if the measured time prolongs significantly and no additional precaution is taken. Here the global positioning system (GPS) is a good assistant for land/air applications, but for underwater use GPS cannot be a remedy since radio frequency signals cannot reach far in water (Bennamoun M. et al., 1996). Thus, for long term underwater operation we need to enhance the accuracy of the IMU data. There are several studies intended for this purpose (Ishibashi S., 2007, Kamer Y., 2013, Fong W. et al., 2008, Skog I., 2006). In another study of us we have focused on calibrating the system with optical mouse data (Ikizoglu S., 2014). In this study we investigate the utility of a turntable as a calibrator of the IMU accelerometers.

2. Description of the System

2 .1. The Inertial Measurement Unit (IMU)

The IMU tested is the orientation sensor Microstrain 3DM-GX1 that combines three angular rate gyros with three orthogonal DC accelerometers, three orthogonal magnetometers, multiplexer, 16 bit A/D converter, and embedded microcontroller to output its orientation in dynamic and static environments (Web-1) (Fig. 1). The characteristics of its accelerometers are given as: Range: ±5g, Resolution: $2 \cdot 10^{-4}$g, Nonlinearity: 0.2%, Bias stability: 0.01g.

2 .2. The Turntable

We've used a record player as the turntable. Since there isn't any speed feedback on the turntable, the need arises to calibrate the angular velocity which has been performed via a stroboscobic disc (Fig. 2). The disc has two bar strings each of which corresponds to 33.3 rev/min and 45 rev/min angular velocity respectively. The disc is placed on the turntable and when rotating, the light of a lamp supplied by 50Hz mains voltage will be reflected on it. If we observe a ‘standing bar’, the corresponding velocity is said to be that of the disc. In our study the angular velocity is adjusted to 33.3 rev/min (rpm).

Fig. 1. The IMU 3DM-GX1

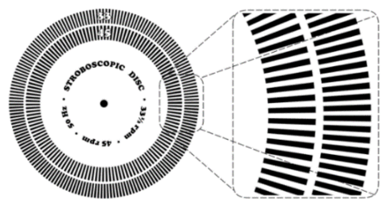

Fig. 2. Structure of the stroboscobic disc

2 .2. 1. Dynamics of the Turntable

The 3DM-GX1 IMU placed at the distance r from the rotation axis will measure the linear accelerations. Since the linear speed is held constant, a zero linear acceleration is expected. Similarly, the centripetal acceleration should be effective on the perpendicular direction to the axis and towards the axis. The equations for the angular acceleration a_m and the linear speed v related with the rotation are as follows:

$$
\begin{aligned}
a_m &= v^2/r \\
v &= \omega r \\
a_m &= \omega^2 r
\end{aligned}
\qquad (1)
$$

where r stands for the radius of the rotation. Thus, the angular speed of a turntable with 33.3 rpm will be

$$\omega = \frac{33.3x2\pi}{60} = 3.49\, rad/sec$$

Fig. 3 displays the change of the centripetal acceleration a_m with respect to r on a turntable of the radius 15cm.

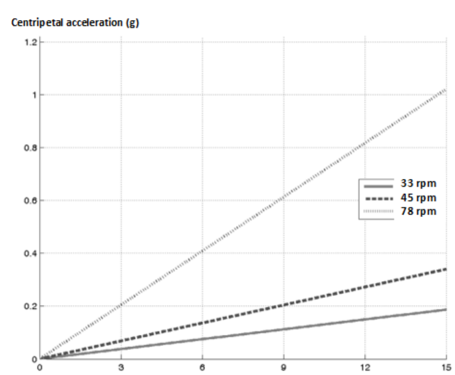

Fig. 3. The change of the centripetal acceleration with respect to r

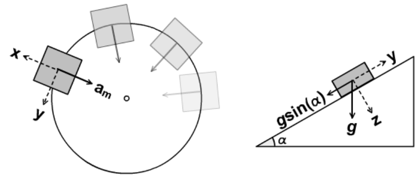

Fig. 4. a) Rotational movement b) Inclined plane

2. 2. 2. Effect of the Skewness of the Turntable Axis

On a completely flat plane with zero inclination the sensor is submitted to centripetal acceleration only (Fig. 4a). But our measurements have put forth sinusoidal accelerations tangential to the rotation axis. This fact is obviously due to the inclination of the turntable. For an accelerometer placed on a plane having an inclination angle of α we will measure an acceleration of $g \cdot \sin(\alpha)$ (Fig. 4b).

Fig. 5 shows the accelerations that the accelerometer will be submitted to on an inclined plane at various stages of the rotational movement. Hence, if the IMU is placed on the turntable such that its x-axis will show outwards from the rotation axis and the y-axis is tangential to the rotation axis, at the position I the acceleration component due to the inclination ($g \cdot \sin(\alpha)$) will be at the same direction as the centripetal acceleration. Since these accelerations are directed towards the center, negative values will be measured for the x-axis acceleration while no acceleration will be effective on the y-axis. At position II, the component $g \cdot \sin(\alpha)$ will effect the y-axis acceleration with positive sign, while on the x-axis only the negative valued centripetal acceleration a_m is effective.

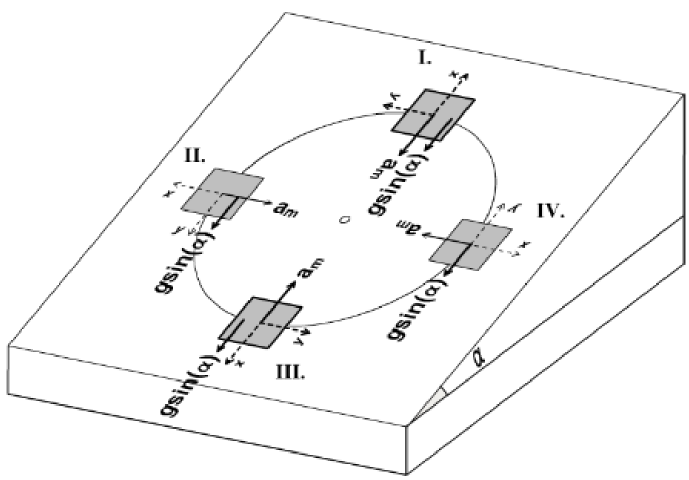

Fig. 5. Acceleration components during the rotation on an inclined plane

At any point of the rotational movement the resultant accelerations on each axis are given as

$$
\begin{aligned}
a_y &= g\sin(\alpha)\cos(\omega t) \\
a_x &= g\sin(\alpha)\sin(\omega t) + \omega^2 r
\end{aligned}
\tag{2}
$$

Thus, the y-component of the acceleration is a sine wave having a zero mean value. The x-component on the other side has a mean value of $\omega^2 r$ and its alternating component is lagging the y-acceleration by 90^0.

In order to estimate the acceleration components correctly, the system parameters as: the distance of the center of the sensor to the rotation axis (r), the angular frequency of the turntable (ω) and the angle of the plane with respect to the horizontal position (α) are to be determined with high accuracy. In order to investigate the effect of the measurement errors of all these parameters on the accelerations, we've calculated the accelerations each time considering a deviation of 15% in any parameter while the others are assumed to remain unchanged. The results are listed in Table 1. Fig. 6 pictures the changes in accelerations when investigating the effect of α.

In addition to the parameters listed in Table 1 the angle β due to the misalignment of the x-axis is also effective on the acceleration measurements along the sensor axis (Fig. 7). Considering even this fact, the equations (2) should be revised as

$$\begin{aligned} a_m &= \omega^2 r \\ a_y &= a_m \sin(\beta) + g\sin(\alpha)\cos(\omega t - \beta) \\ a_x &= a_m \cos(\beta) + g\sin(\alpha)\sin(\omega t - \beta) \end{aligned} \tag{3}$$

Table. 1. Effect of parameter changes on the acceleration components.

Investigated parameter	**Other parameter values**	**Resulting effect**
Distance r (10 cm ± 15%)	$\alpha = 5^o$; $\omega = 33.3$ rpm	a_y varies sinusoidally with an amplitude of 0.087 g. An increase in the distance r increases the mean of the centripetal acceleration a_x from 0.1056 g to 0.1428 g.
Slope angle α (5^0± 15%)	r = 10 cm; ω = 33.3 rpm	An increase in the slope of α causes an increase in the amplitude of a_y and a_x from 0.074 g to 0.01 g. The mean value of a_x remains unchanged at 0.124 g.
Angular frequency ω (33.3 rpm ± 15%);	r = 10 cm; $\alpha = 5^0$	An increase in ω causes an increase in the mean value of a_x from 0.09 g to 0.164 g. The amplitudes of the alternating components of both a_y and a_x remain unchanged at 0.087 g.

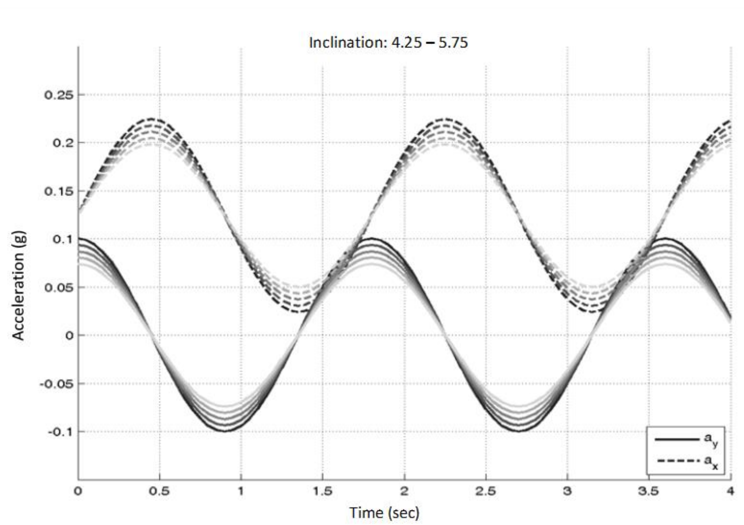

Fig. 6. Effect of the change in α on a_y and a_x.

3. Parameter Estimation Concerning the Turntable Dynamics

The estimations of the acceleration components can be obtained via the equations (3) in case the introduced parameters can be determined precisely. For this purpose an optimization procedure is realized using the Matlab function *fminsearchbnd* (Web-2) that is similar to the function *fminsearch* with the difference that bounds are applied to the variables. For each parameter we've defined an uncertainty interval and created an objective function which calculates the squared error between the modelled and the measured accelerations at any point of the parameter space. The parameter vector to minimize this objective function is obtained via *fminsearchbnd*.

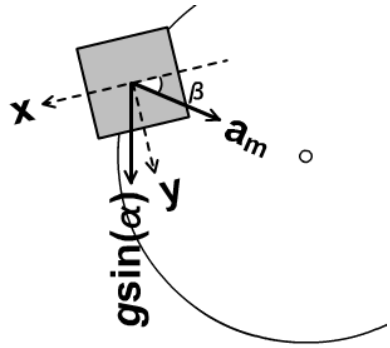

Fig. 7. Effect of the angle β

Since the angular speed of the turntable is not expected to change during the measurements, its value is considered to be taken constant for all experiments. This angular speed is calculated as 33.5 rpm from the oscillations of the acceleration components for each axis.

The measurements have pictured a drift of 0.05g in the y-axis acceleration while changing from positive to negative values. Hence, for the data where the drift is recognized, the objective function is arranged as to take the squared errors in the x-axis into consideration only. The effect of this modification on the parameter estimation is shown in Fig. 8.

Fig. 9 submits some of the results of the models constructed by means of the parameter estimation based on the collected data in different experiment conditions. The signals point out that for small valued accelerations (0.025g peak to peak) noise is effective on measurements which results in reduction of the goodness of fit.

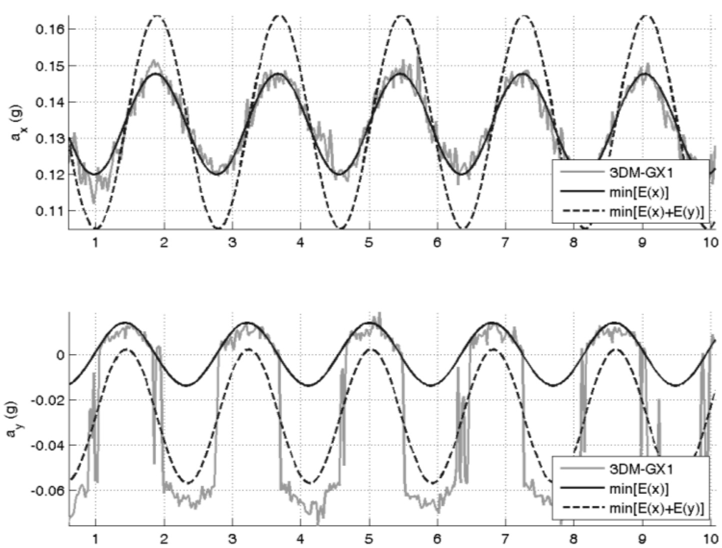

Fig. 8. Effect of different objective functions on the parameter estimation

4. Correcting the Data from the IMU

4 . 1. The Artificial Neural Network (ANN)

For the artificial neural network we have determined the size of the training set as 60%, the sizes of the verifying and the test sets as 20% each. The clustering of the turntable data according to the given sizes is shown in Fig. 10.

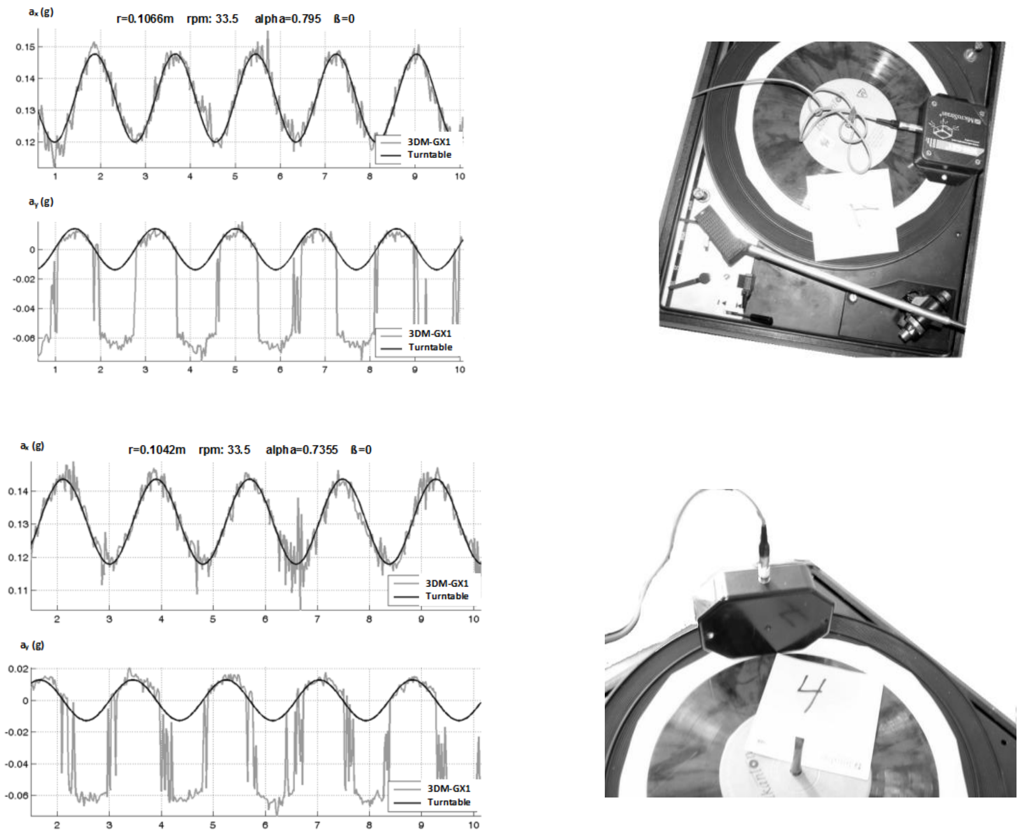

Fig. 9. Acceleration signals obtained from the model and received from the sensor

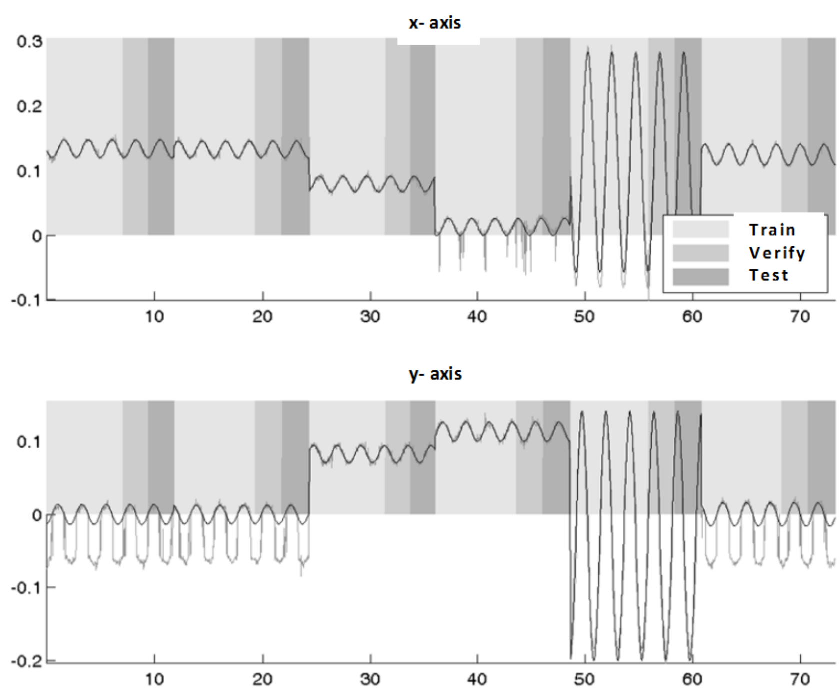

Fig. 10. Data clusters of the turntable data

Both the SISO (single input-single output) (Fig. 11) and the MIMO (multi input-multi output) structures are inspected for the ANN. In our case, the SISO architecture models the single-axis sensor data as the input to the ANN trying to follow the corresponding turntable acceleration data whereas the MIMO represents the case of training both axes data in parallel. Various methods are examined for the ANN implementation and the Levenberg – Marquardt method is decided to be used as it has shown one of the highest performances (Kılıç K. et al., 2009). In this method, the error at the output will be back-propagated along the structure in accordance with the weights of the cells in the layers and new weights will be calculated for the cells to reduce the error. In order to search for an optimal solution, a minimum on the whole error surface is tried to be reached moving to the opposite direction of the error gradient on the surface (Web-3).

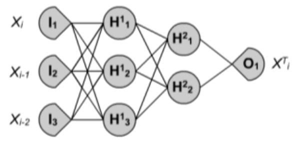

Fig. 11. SISO architecture of ANN

Two different error characters can be investigated when training the ANN. These are the 'synchronous serial error' and the 'successive serial error'. The first one calculates the difference between each output element and its corresponding target value where the latter takes the difference of the whole strings at the output and the true data into consideration. Hence, the overall training time is shorter for the second case since the total error for the whole string is back-propagated once only.

4 .2. Training Results

In our experiments we stopped the training period when the decrease rate in the training set fell below 1 ppm or the error for the verifying set did not drop for the last 15 steps. The squared error of the verifying set is taken as the measure of the performance. In order to take the effect of the initial weights of the cells into account, we have repeated the trainings 10 times for the same input & ANN-structure conditions. After all, the best result is taken as the valid one.

The conformity of the output data with the reference is calculated via

$$R(x, x_{ref}) = 100\left(\frac{1-|x-x_{ref}|}{|x_{ref}-\bar{x}_{ref}|}\right) \tag{4}$$

Fig. 12 pictures the results of the successive serial error calculations for a MIMO structure. Regarding these results only, the best performance is obtained for 2 hidden layers with 10 and 6 neurons respectively. The goodness of fit for this structure is approx. 67%.

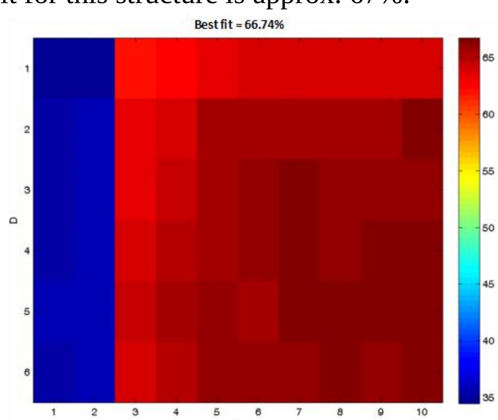

Fig. 12. Results of the successive serial error calculations for a MIMO structure

4. 3. ANN vs System Identification Methods

In order to have an expressive idea about the performance of the ANN, we need to compare its results with other methods. In this manner a performance comparison is executed between the ANN and various system identification methods. The parameters related with the models are acquired via Matlab System Identification Toolbox 7.2.1 to meet the best goodness of fit with the training set (Web-4). Some of the results are listed in Table 2. We recognize that with a 67% goodness of fit the ANN shows better performance than most of the identification models.

Table. 2. Training results of several system identification models.

Model	Model Structure	Goodness of fit of the training set (%)	Goodness of fit of the test set (%)
ARX	[na(6) nb(8) nk(1)], $A(q)y(t)=B(q)u(t-nk)+e(t)$	51.81	48.29
BJ (Box-Jenkins)	[nb(4) nf(4) nc(4) nd(4) nk(1)] $y(t)=\frac{B(q)}{F(q)}u(t-nk)+\frac{C(q)}{D(q)}e(t)$	66.66	60.18
Nonlinear ARX	[na(2) nb(2) nk(1)] $A(q)y(t)=B(q)u(t-nk)+e(t)$ Nonlinear regressors $y(t-1), y(t-2), u(t-1), u(t-2)$	61.09	54.70
Hammerstein-Wiener	[nb(2) nf(3) nk(1)] $y(t)=\frac{B(q)}{F(q)}u(t-nk)+e(t)$ Nonlinear estimator	67.17	59.66

5. Conclusion

In this study we have focused on correction of the IMU acceleration data via turntable test bed. The need for this study we felt when we worked on tracking/controlling an autonomous underwater vehicle (AUV). Since the GPS is not directly effective in the underwater, a method is needed to increase the accuracy of the collected data from the IMU. In this manner an ANN based training is searched using the data from a turntable.

We have obtained satisfactory results as around 67% for the goodness of fit. So far, this study encourages us for further research on the applied method. An improvement in determining the parameters of the turntable will definitely result in increase of the success.

References

Bennamoun, M., Boashash, B., Faruqi, F., & Dunbar, M. (1996). The Development of an Integrated GPS/INS/Sonar Navigation System for Autonomous Underwater Vehicle Navigation. *Proceedings of the Symposium on Autonomous Underwater Vehicle Technology*, 256–261.

Fong, W., Ong, S., & Nee, A. (2008). Methods for In-Field User Calibration of an Inertial Measurement Unit Without External Equipment. *Measurement Science and Technology*, 19, 1–11.

Ikizoglu, S., & Kamer, Y. (2014). Optical Computer Mouse Referenced Calibration of an Inertial Measurement Unit for Use in Unmanned Underwater Vehicles. *Proc. of ICEMA 2014*, Dubai.

Ishibashi, S. (2007). The Improvement of the Precision of an Inertial Navigation System for AUV Based on the Neural Network. *IEEE OCEANS -Asia Pacific*, 1–6.

Kamer, Y., & Ikizoglu, S. (2013). Effective Accelerometer Test Beds for Output Enhancement of an Inertial Navigation System. *Measurement*, 46, 1641–1649.

Kılıç, K., Baş, D., & Boyacı, H.I. (2009). An Easy Approach for the Selection of Optimal Neural Network. *GIDA*, 34.

Skog, I., Hndel, P. (2006). Calibration of a Mems Inertial Measurement Unit. *Proc. of XVII IMEKO WORLD CONGRESS*.

Web sites:
Web-1: http://www.microstrain.com/pdf/3DMGX1% 20Datasheet%20Rev%201.pdf.
Web-2: www.mathworks.com/products/matlab/
Web-3: en.wikipedia.org/.../Levenberg–Marquardt_algorithm
Web-4: www.mathworks.com/help/pdf.../ident_gs.pdf