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MEMS TECHNOLOGY QUALITY REQUIREMENTS AS APPLIED TO MULTIBEAM ECHOSOUNDER

Krzysztof Bikonis
Jerzy Demkowicz
Gdansk university of Technology, Poland

ABSTRACT

Small, lightweight, power-efficient and low-cost microelectromechanical system (MEMS) inertial sensors and microcontrollers available in the market today help reduce the instability of Multibeam Sonars. Current MEMS inertial measurement units (IMUs) come in many shapes, sizes, and costs — depending on the application and performance required. Although MEMS inertial sensors offer affordable and appropriately scaled units, they are not currently capable of meeting all requirements for accurate and precise attitudes, due to their inherent measurement noise. The article presents the comparison of different MEMS technologies and their parameters regarding to the main application, namely Multibeam Echo Sounders (MBES). The quality of MEMS parameters is crucial for further MBES record-processing. The article presents the results of undertaken researches in that area, and these results are relatively positive for low-cost MEMS. The paper undertakes some vital aspect of using MEMS in the attitude and heading reference system (AHRS) context. The article presents a few aspects of MEMS gyro errors and their estimation process in the context of INS processing flow, as well as points out the main difficulties behind the INS when using a few top MEMS technologies.

Keywords: Inertial Measurements Unit, Multibeam Echo Sounder, Attitude and Heading Reference System, Motion Reference Unit

INTRODUCTION

The main target of the paper is evaluating a low-cost microelectromechanical system (MEMS) in a very demanding application context, i.e. Multibeam Echo Sounders, using a Kalman estimator. Low-cost MEMS inertial sensors and microcontrollers available in the market today help reduce the instability of Multibeam Sonar measurements. Over the past decades, MEMS researchers have demonstrated a number of microsensors for almost every possible sensing modality, including attitudes. Today, MEMS-based gyros challenge the 'prone to wear' mechanical gyro solutions, as well as gyros based on fibre optic (FOG) technology. MEMS sensors have proved and demonstrated performances exceeding those of their macroscale counterpart sensors [9]. Obviously, the quality of MEMS parameters is crucial for further MBES record-processing, especially in the context of attitudes, which is the main motivation for the author to present the results of researches undertaken in that area.

The measurement methodology follows the Seatex MRU Calibration Certificate methodology applied for vessels equipped with MBES and operating at sea, at highly challenging activity, by its very nature. So the methodology of roll and pitch accuracy tests carried out during the research consist of static accuracy and dynamic accuracy tests [17], and is compared to the available Kongsberg Motion Rotation Unit (MRU) which obtained the certificate. The static accuracy is measured by sampling at 4 Hz for 30 minutes, when the IMU is stationary. The dynamic accuracy is measured in a rate table test with simultaneous sinusoidal excitation in two axes for 10 minutes. The standard uncertainty error of static roll and pitch test requirements is expected to be less than 0.10 deg. The standard uncertainty error dynamic requirement should be less than 0.15 deg [17].

The rate gyro accuracy test consists in measuring the angular rate sensor noise level and the rate gyro scale factor error. The angular rate sensor noise level is measured by sampling at 4 Hz for 30 minutes when the IMU is stationary. The rate gyro scale factor error is tested by single-axis rotation on a rate table at ±30 deg/s and at ±50 deg/s.

The accelerometer accuracy test consists in mmeasuring the acceleration sensor noise level and the accelerometer scale factor. The accelerometer sensor noise lever is measured by sampling at 4 Hz for 30 minutes when the IMU is stationary, while the accelerometer scale factor is measured by tilting the IMU in steps of 90 deg around a circle [17].

HIGH PRECISION IMU REQUIREMENTS

High precision IMU requirements, as applied to MBES, are very demanding. Fig. 1a presents the MBES scanning acquisition process, and 3D data visualization of 0.1 m resolution (Fig. 1b). High resolution accuracy depends on IMU resolution and stability. At 10 meters of depth, the angular error of 0.1 degree results in a near 0.02 m linear horizontal error at the bottom; and of course, at 100 meters of depth, that error gives a 0.2 m error, which is unacceptable in many current applications [18].

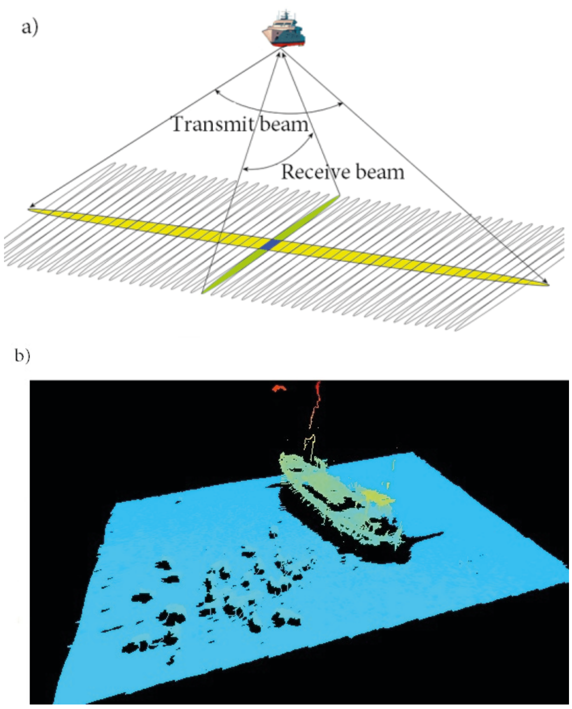

Fig. 1. Multibeam sonar system a) data acquisition b) data visualization

Fig. 2 presents the overall context of IMU applications. The most important are accelerometer and gyroscope sensors. In a wider perspective, Inertial Navigational Systems utilize them, and it is well-known what a challenge it is [7, 8]. But even in this narrowed IMU context, these sensor errors are still a serious issue, see Tab. 1 as a reference where the bias error possesses the most important impact. A motion reference unit (MRU) from Kongsberg was chosen for the experiment, along with IMU systems with parameters similar to those of the MRU. The most important parameters in the context of attitudes of selected systems are shown in Tab. 2, where *g* is the acceleration due to gravity (assumed to be 9,80665 m/s²). Tab. 1 and Tab. 2 can be treated as the budget error calculation start point of the tested MEMS unit.

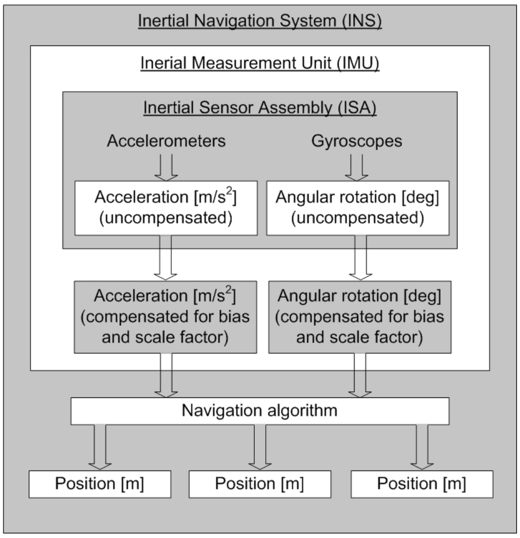

Fig. 2. Classification of inertial systems

To mitigate the accuracy problem, the Kalman estimator usually reads in the sensor data, and in turn outputs the Euler angles and the bias of the gyros as presented in Fig. 3.

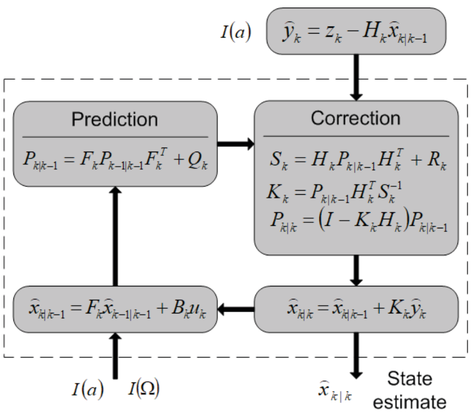

Fig. 3. Kalman filtering algorithm

The Kalman filter uses the knowledge of deterministic and statistical properties of system parameters and measurements to obtain estimates which are optimal. It is an example of the Bayesian estimation technique. The estimation process is supplied with initial estimates, usually a one- dimensional matrix, and then operates recursively updating the working estimates with the optimal weighted average of their previous values and new values derived from the innovation measurement. In Fig. 3, $\hat{x}_\kappa$ stands for matrix state estimation, which consists of linear acceleration from accelerometers $I(\alpha)$, angular velocities from gyroscopes $I(\Omega)$, and attitudes. P_κ stands for process covariance, y_κ – innovation, z_κ –current measurement, K_κ – Kalman gain, H_κ – measurement matrix, R_κ – measurement error variance, Q_κ – model variance, and F_κ – stands for process model. B_κ may be interpreted as the control matrix; however, it was not used in the model.

Tab. 1. Gyroscope error sources

Error type	Description	Results of integration
Bias	Constant bias $\in$	Steadily growing angular error $\theta(t) = \in \cdot t$
White noise	White noise with some standard deviation σ	Angular random walk, whose standard deviation $\sigma_\theta(t) = \sigma \cdot \sqrt{\delta t \cdot t}$ grows with the square root of time
Temperature effects	Temperature dependent residual bias	Any residual bias is integrated into the orientation, causing an orientation error which grows linearly with time
Calibrations	Deterministic errors in scale factors, alignments and gyro linearity	Orientation drift proportional to the rate and duration of motion
Bias instability	Bias fluctuations, usually modeled as a bias random walk	Second-order random walk

Tab. 2. Comparison of selected IMU parameters

	MRU EM3002	3DM-GX3-25	MTi-G700	MTi-G
Static accuracy				
Roll and Pitch	0.04 deg	0.5 deg	0.2 deg	0.5 deg
Dynamic accuracy				
Roll and Pitch	0.05 deg	2 deg	0.3 deg	1 deg
Gyroscope				
Full scale	±100 deg	±300 deg	±450 deg	±300 deg
Bias	0.1 deg/s	0.25 deg/s	0.2 deg/s	1 deg/s
In-run bias stability	–	18 deg/h	10 deg/h	20 deg/h
Non-linearity (% of full scale)	0.2	0.1	0.01	0.1
Accelerometer				
Full scale	±3 g	±5 g	±5 g	±5 g
Bias	0.001 g	0.002 g	0.003 g	0.01 g
In-run bias stability	0.2 mg	0.04mg	0.04 mg	2 mg
Non-linearity (% of full scale)	0.02	0.03	0.03	0.2

CURRENT MEMS GYRO CAPABILITIES. OPERATIONAL TESTS AND RESULTS

Operational measurements for the following IMU devices were carried out simultaneously, as presented in Fig. 4. The MRU from Kongsberg is specially designed for high precision motion measurements in marine applications, and for users requiring high accuracy roll, pitch, and heave measurements. The MRU provides high performance motion data for various marine applications, ranging from small underwater vehicles to large ship motion control systems. Very high reliability is achieved by using solid state sensors, with no moving parts and with proven MRU electrical and mechanical construction.

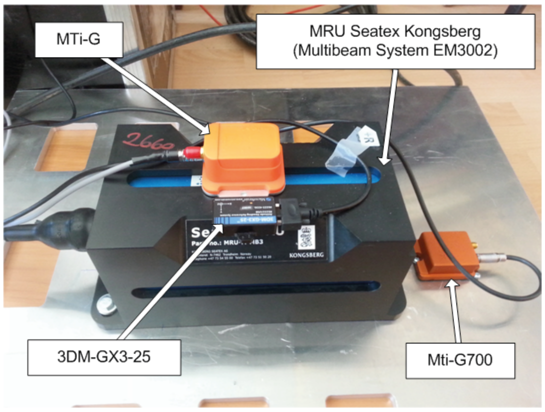

Fig. 4. Operational measurements carried out simultaneously for various devices

3DM-GX3-25 is a high-performance, miniature Attitude Heading Reference System (AHRS), utilizing MEMS sensor technology. It combines a triaxial accelerometer, triaxial gyro, triaxial magnetometer, temperature sensors, and an on-board processor running a Kalman sensor fusion algorithm to provide static and dynamic orientation and inertial measurements.

MTi-G is an integrated GPS and MEMS Inertial Measurement Unit with a Navigation and Attitude and Heading Reference System processor. The internal low-power signal processor runs a real time Xsens Kalman Filter (XKF), providing inertial enhanced 3D position and velocity estimates. The MTi-G also provides drift-free and GPS enhanced 3D orientation estimates, as well as calibrated data of 3D acceleration, 3D rate of turn, 3D earth - magnetic field, and static pressure (barometer). In theory, the MTi-G is a measurement unit for navigation and control of vehicles and other objects.

Results of static tests are presented in Fig. 5, for static Roll measurements. These measurements were also performed for Roll at other attitudes and for various IMU units, but the recorded results were similar and are omitted in the article. Fig. 6 summarizes some of the obtained results.

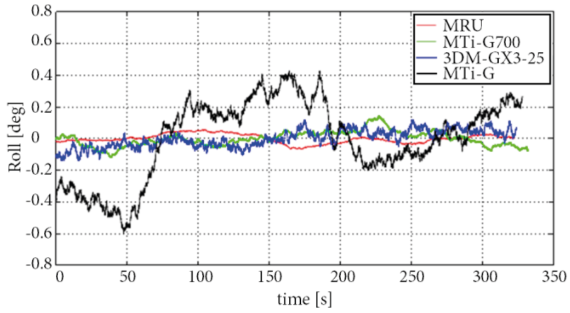

Fig. 5. Measurement results for static Roll tests

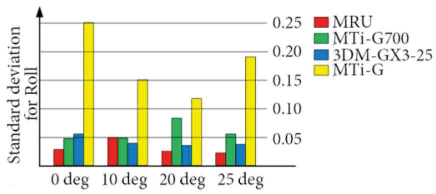

Fig. 6. Standard deviation for static Roll measurements

It can be seen clearly from Fig. 6 that the MRU is distinctly the best IMU. However, the results of dynamic tests reveal a rather opposite tendency in some situations. In the latter case, significant differences can be observed between new generation MTi-G700, 3DM-GX3-25, and MTi-G, but the MTi-G satisfies the requirements. That all is true for dynamic measurement frequencies under 1Hz see Fig. 7.

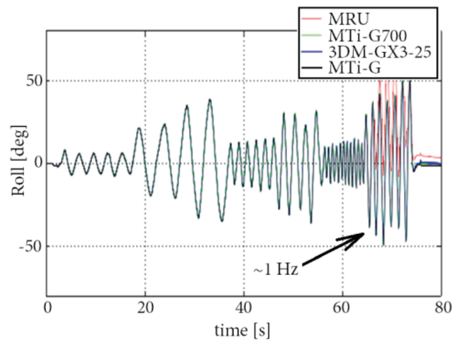

Fig. 7. Dynamic IMU tests for all IMU units

For frequencies close to 1 Hz and higher, the MRU is very unstable and returns to a stable state after over 16 minutes. The records for MTi-G700, 3DM-GX3-25, and MTi-G are much better, and the stable state return period lasts only over 10 seconds. Figs. 8 and 9 present some details of dynamic IMU tests carried for all devices out simultaneously. The highest precision MRU features very long time constant and low sampling time (see Fig. 9).

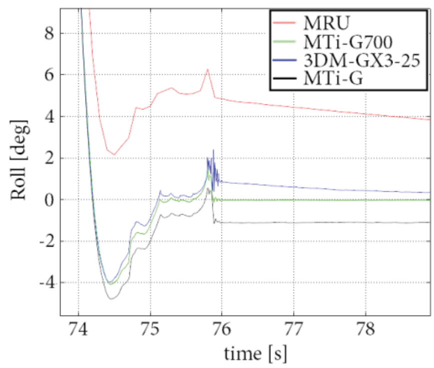

Fig. 8. Dynamic IMU measurements, enlarged for some seconds

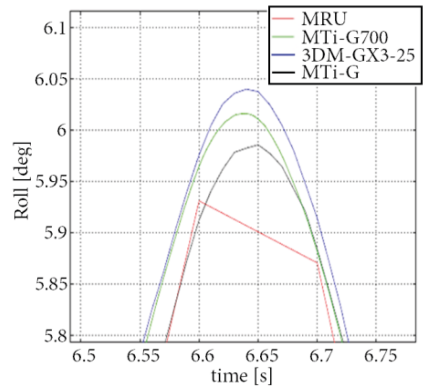

Fig. 9. Dynamic IMU tests for all IMU units, enlarged for some seconds

It should be mentioned that IMU gyros are typically of higher quality, but burden with a bias, as integrating over the time yields a drift. The drift over time results in unreliable input for further processing in the INS system and some compensation is required. So another sensor is used to provide a second tilt or orientation measurement to remove the drift and improve real orientation of the system. Here, an accelerometer or magnetic sensor is a typical choice. However, the magnetic sensor is subject to the influence of physical environment and cannot measure a pitch, but only roll and yaw, and is not always reliable again, therefore the accelerometer sensor is the only choice in practice.

Figs. 7,8,9 present the results of AR integration for the examined IMU technologies, after bias removal. These figures prove high quality of the MEMS gyro and present real roll as a result of the Kalman fusion algorithm process. The AR integration of the gyros as presented in the figures proves their high quality, because the obtained results are comparable to those recorded for the tested Kongsberg MRU device (see Fig. 5). E.g. the standard deviation equals 0.022579 for MRU, 0.076428 for MTi-G700, 0.034849 for 3DM-GX3-25, and 0.15256 for MTi-G. The standard deviation and the variance error obtained from operational tests as presented in Fig. 6.

SUMMARY

The paper presents a unique opportunity of performance comparison of the Seatex MRU Calibration Certificated device to other low cost IMUs. The Seatex MRU is used in high end MBES EM3000. Different MEMS technologies were presented above in very demanding context, where the 10cm resolution required at 100m proofs that even in the narrowed AHRS (Attitude and Heading Reference System) applications, the presented sensor's errors are still a serious problem.

Operational tests were carried out for Kongsberg MRU-M-MB3 – certified device, Xsens MTi-G700, Xsens MTi-G-28A53G3, and MicroStrain 3DM-GX3-25. The tests carried out according to [17] consisted of static operational test comparisons, and dynamic tests for frequencies < 1Hz and higher. They have proved that dynamic tests above 1Hz are a very demanding case for all tested IMUs, but especially for the Kongsberg MRU. In that last case, the test procedure was carried out very carefully and repeated. The results of the dynamic tests above 1Hz resemble a low pass filter answer with long time constant, and that is the case of the Kongsberg MRU.

Other MEMS inertial sensors, which are not certified (see Fig.4), offer affordable and appropriately scaled units that are currently capable of meeting all requirements for accurate and precise attitude evaluation. While the MRU offers the best standard variance of 0.01 deg for the Roll and Pitch, the new generation MTi-G700 offers comparable performance with low noise.

The last question is if these technologies can be used in INS. In author's opinion, they can, perhaps in non-shocking, close to stable conditions. Low cost MEMS gyros are still proving their high quality, but they are not as perfect as other sensors and introduce small errors in each measurement. The gyro sensors currently present quite good quality only for AVHR applications, and progress in this area is still observed.

It is noteworthy that the results of the researches presented in the paper, namely comparative researches and especially the Kalman fusion algorithm, are important issues of marine drone vertical stability estimation. Marine drones possess distinctive dynamic parameters, and that area of investigation has been undertaken as a continuation of current author's investigations.

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CONTACT WITH THE AUTHORS

Krzysztof Bikonis
e-mail: binio@eti.pg.edu.pl
Gdansk University of Technology
Narutowicza 11/12
80-233 Gdansk
Poland

I**Jerzy Demkowicz**
e-mail: demjot@eti.pg.edu.pl
Gdansk University of Technology
Narutowicza 11/12
80-233 Gdansk
Poland