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Efficiency of MEMS Inertial Sensors Used in Low-dynamics Application

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ABSTRACT: The analysis presents the performance of navigation application driven with MEMS and FOG inertial sensors. The inertial sensors were working under conditions simulating a potential robotic mission, which reduce accuracy of some of the navigation applications. Empirical results of the test confirm degradation of the navigation system performance in the presented demanding mission. Influence of the testing conditions and of the inertial sensor technology is presented and discussed in the paper.

1 INTRODUCTION

1.1 *Study motivation*

The test presented in here is a part of a study heading towards a design of an autonomous navigation system for an ice-probe. Destination of the ice-probe is ice exploration on Enceladus, one of the Saturn's moon. There is a will, driven by astrobiology scientific community, to explore the icy shell of the moon and to reach the under-ice water source. To cater for this will, the German Aerospace Centre, (DLR), took an initiative of assessing the feasibility of an Enceladus exploration mission. The first phase of the project, which concluded in 2015, resulted in a design of a demonstrator of an ice-probe. The probe characterizes with length of around 2 meters, weight of around 60 kg and power consumption at the level of 2 kW. The probe's main designed features were the maneuverability in the ice, precise location and navigation in the ice without usage of the GNSS system nor optical instruments, targeting the water reservoir and self-decontamination ability in order to not to contaminate the recovered under-ice water samples. The final test mission was a scientific field survey in Antarctica, where the under-ice iron-rich hypersaline water samples, which supply the outflowing Blood Falls, ware successfully collected.

The navigation system design of the probe was based on following technologies: inertial rotation and acceleration measurements for attitude determination; magnetometry for heading estimation; ultrasounds in positioning as well as reconnaissance subsystem. All subsystems were integrated into a position and attitude navigation system with trajectory planning.

The Institute of Space Technology and Space Applications, (ISTA), contributed to the navigation system design with attitude determination system. Having the availability of the space and sufficient power supply within the ice-probe, the Northrop Grumman LN-200, tactical grade Inertial Measurement Unit (IMU) with Fiber Optic Gyroscopes (FOG), was used. Attitude determination was of high accuracy, although the environmental conditions were not trivial. The key factors playing the significant role in the overall performance of the attitude determination system-only were: very low ice-probe dynamics (velocity at the level of 1 m/hour), axial rotation rate of the ice-probe during the run at the level of the Earth rotation rate, testing at high latitudes, and very long, over 24 hours, test duration time.

1.2 *Requirements of the experiment*

Currently, the development of the attitude determination system based on the inertial measurement technology continues with new requirements. The study focuses strongly on miniaturization and energy consumption optimization. Neither of these belongs to the characteristics of previously used LN-200 in view of the studied exploration mission. In order to meet the requirements, Microelectromechanical systems (MEMS) IMU takes part of the tested system. For this purpose the LITEF µIMU has been chosen as one of the best performing MEMS-based inertial sensor commercially available.

Another important focus of the current study is the environment of the studied mission destination, Enceladus. From the inertial measurements point of view, the inertia and gravity of Enceladus are much smaller than the ones of the Earth, and at the same time not so well and accurate known. The most influential on the inertial subsystem Enceladus characteristics are small moon gravity field of about 0.01 g on the surface and small rotation period of around 1.37 days.

Both, the less performant IMU and the characteristics of Enceladus are set to be requirements of the executed inertial attitude determination test.

2 TESTING SCENARIO

2.1 *Gyrocompassing*

The purpose of the test was assessing the effectiveness of the attitude determination system during the Enceladus ice exploration mission. The mission characteristics results with a very long exploration time, even several weeks long. During long navigation time the inertial subsystem require multiple realignments. Realignment, as well as the initial alignment, requires a certain time, when the probe, together with an inertial sensor inside, stays still. The only movement, which should at that time be detected by the inertial sensor, is the movement of the moon. In such situation it is possible to determine two characteristic to the moon vectors: rotation of the moon and gravity.

Considering a local frame, defined here as North-East-Down, as the one used in the navigation of the probe, the moon gravity and rotation vectors may almost directly define that frame. Three equations (1) are considered for derivation of the NED frame from the measured vectors.

$$\begin{aligned} \vec{D} &= |\vec{g}|\vec{n}_g \\ \vec{E} &= \vec{D} \otimes |\vec{\omega}|\vec{n}_\omega \\ \vec{N} &= \vec{E} \otimes \vec{D} \end{aligned} \tag{1}$$

where N, E, D = unity base vectors of the NED frame; g = gravity vector; ω = moon rotation vector n_g = unity vector of the gravity vector g; n_ω = unity vector of the rotation vector ω. This way of finding the North direction may be also named as gyrocompassing. The realization of the equations (1) in formation of the NED frame in the first Enceladus Explorer project are described in (Niedermeier et al. 2014).

Measure of the gravity and rotation vectors is not error free, especially when the measured values are small enough to be comparable with noise generated by the sensor. In the described application the gravity measured on the surface of Enceladus is expected to be equal to 0.114 m/s^2 and the average rotation rate is equal to 5.3e^{-5} rad/s (3e^{-3} °/s). As can be seen in the equations (1) accuracy of the g and ω vectors determine accuracy of the NED frame derivation. The gravity vector is usually leading to a very little error providing the down-angle estimation on accuracy of several mrads level or better. Even for such reduced gravity available on Enceladus it shouldn't implicate in significant leveling error. The situation is different when using measures of the rotation rate ω. As for an example, consumer grade gyroscopes are not able to measure effectively the rotation of the Earth. Eventually in this case, the North and East directions cannot be found. Therefore, this aspect of the inertial sensing is the most sensitive in the navigation systems. It becomes a focus of the test to check the influences of the rotation rate vector on the North finding. The IMU were rotated w.r.t. the inertial frame with the angular velocity expected being observed on Enceladus. In order to simulate such condition, the sensors have been rotated on a turn table with an angular velocity equal to 0.00112 °/s in the opposite direction to the Earth rotation. Attitude determination was performed using the measurement recording. The results were juxtaposed with the counterpart calculations for the Earth conditions. In this case the sensors stood still sensing Earth rotation only. A detailed description of Enceladus on the inertial measurement are presented in (Szumski et al. 2016).

2.2 *IMU performance*

Accuracy of the rotation and gravity vector estimation depends as much on the strength of the vector mentioned above as on the noise coming from the sensor. Estimation of the inertial sensor noise is not straight forward to be obtained since it depends on many different aspects. One of the most convenient way of the inertial sensor noise estimation is to measure it using the Allan Variance methodology. Observing the outcome signal for a long enough time one obtain, with a quite good reliability, a dependence of the sensor noise on the samples averaging time. The dependency is not linear and therefore must be performed for many different integration times, which usually is time consuming. In a reward, the obtained variance is easy to interpret. Choosing an optimal averaging time leads to minimization of the sensor noise. The following equation (2) (Hove et al. 1981) was used.

$$\sigma(t)=\sqrt{\frac{1}{2\tau^2(N-2)}\sum_{k=1}^{N-2}\left(\theta_{k+2}-2\theta_{k+1}+\theta_k\right)^2} \qquad (2)$$

where σ = Allan standard deviation τ = time of the integration cluster; N = number of clusters; θ = increments of angle / velocity during integration time. This analysis was done for each of the sensors separately. Assuming that there is no restriction in the alignment procedure duration, for each sensor there has been chosen an optimum averaging time according to the minimum gyroscope noise.

3 EXPERIMENT IMPLEMENTATION

3.1 *Sensors platform*

In total three sensors have been used in the testing. Aforementioned LN-200E IMU from Northrop Grumman played in the test the role of reference IMU. The FOGs of this IMU characterizes with bias stability of 1 °/hr, random walk of 0.08 °/√hr and scale factor of 100 ppm. This sensor has a robust housing of a volume of around 0.7 l and weights 700 g.

Another sensor is built entirely in MEMS technology. The µIMU from LITEF contains gyroscopes with bias stability of 6 °/hr, random walk of 0.3 °/√hr and scale factor of 1400 ppm. As a MEMS technology sensor, its characteristics are gravity dependent. It is important to mention it because making the same test in 10 mg gravity of Enceladus would probably give slightly different output. The µIMU is not much smaller than the LN-200E IMU. It does not define the miniaturization. It was, however, chosen for the test as one of the best representative of the IMUs made in MEMS technology.

Exclusively for the comparison purpose also the Xsens MTi-G710 has been tested. This sensor belongs to group of consumer grade sensors and haven't been considered to be used in such demanding application as the ice-probe navigation. Its gyroscopes have bias stability of 10 °/hr.

All sensors were connected to a common data logging platform build on a programmable board myRIO-1900 from National Instruments. This board runs on a Linux on ARM system and contains an FPGA chip. The sensors were read and controlled in a deterministic way. They were also referred to a common clock assuring that the measurements are comparable. The recorded samples were available for post-processing.

3.2 *Testing environment*

Realization of a very precise rotation of the sensors was possible with a precise two-axis rate table build by Contraves Goery Corporation. The rate table characterizes with position accuracy better than 5 arcsec, position resolution of 0.36 arcsec, rotation range starting from 0.0001 °/s.

Setup of this rate table played a crucial role in simulating rotation of the Enceladus. The outer axis of the rate table was set during the measurement in such a position, that the inner axis of the table was parallel to the rotation axis of the Earth. The inner axis of the table was rotating the sensors with a mentioned rate of 0.00112 °/s in the opposite direction to the Earth rotation. The cumulative, absolute rotation of the sensors measured with respect to the inertial frame was 0.003 °/s (revolution period equal to 33 hours). A special care was taken on the correct weight distribution and balancing in order to avoid a jitter of the rate table motor which are balancing the given attitude.

The static, no movement test was realized with the sensors attached to the foundation and at the same time being completely isolated from the building structure.

4 TESTING RESULTS

4.1 *IMU performance*

The analysis of the test results begins with the comment on the Alan variance analysis. The plots presented in the paper shows recalculated into Allan standard deviation relation to the averaging time. Two plots for each sensor are given, one with the accelerometers' standard deviation and one with the gyroscopes'.

Beginning with our reference sensor, LN-200E IMU, its standard deviation of the accelerometers' noise reaches minimum after 20 seconds of averaging (see Figure 1.). Until the integration time of 1 second the dominant noise source is the quantization noise. This is quite a long dominance and the reason for that is that the LN-200E IMU uses 16-bit representation of the values preserving broad operating range of 20 g. This noise is easy to be filtered out, especially in the presented application, where longer averaging times are allowed to be used.

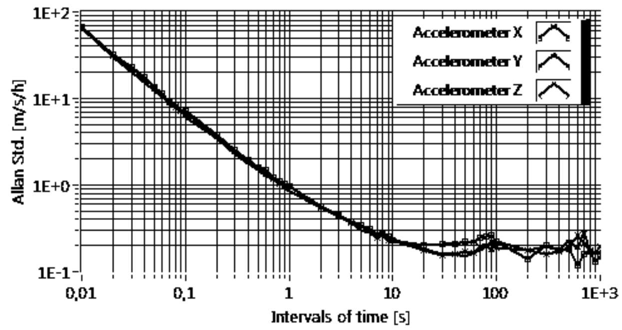

Figure 1. Allan standard deviation of the accelerometers measured in the LN-200 IMU.

Velocity random walk of the accelerometers dominates for only 2 to 20 s of averaging time. This shows that the accelerometer are of the good class. At the 20 s averaging it can be filtered out down to σ = 0.2 m/s/hr. The accelerometer bias instability and correlated noise defines the minimum variance in a wide range of 20 to over 1000 s averaging time.

The gyroscopes of the LN-200E IMU, as presented in a Figure 2., are very well performing. In a difference to the behavior of the accelerometers the quantization noise is to be well observed until 30 ms of integration. Very quickly, the angle random walk contributes to the deviation of the measurement. This may be problematic for some applications, because filtering the random walk noise out takes ten times longer as filtering the quantization noise out. It takes 300 s of measurement to observe reduced noise down to σ = 0.15 °/hr.

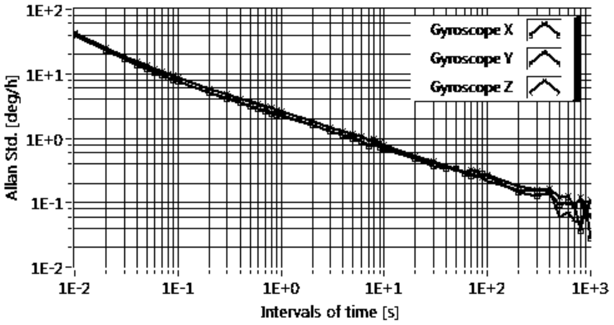

Figure 2. Allan standard deviation of the gyroscopes measured in the LN-200 IMU.

The μIMU from LITEF has both, accelerometers and gyroscopes; implemented in MEMS technology. The quantization noise in the accelerometers is dominant for only approximately 20 ms, what is probably a result of longer, 32-bit representation of samples. The minimum noise at the level of σ = 0.3 m/s/hr is obtained for a 100 s measurement representation. After that time, the correlated noise and bias instability are more powerful than the noise caused by velocity random walk. (see Figure 3.)

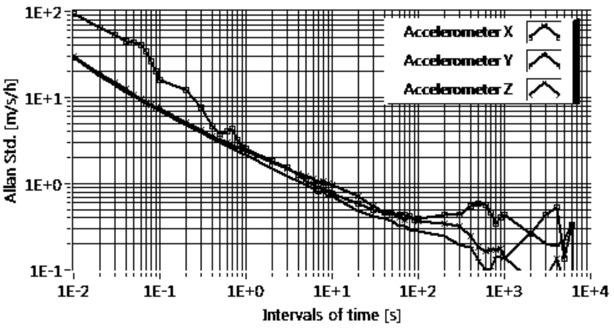

Figure 3. Allan standard deviation of the accelerometers measured in the LITEF μIMU.

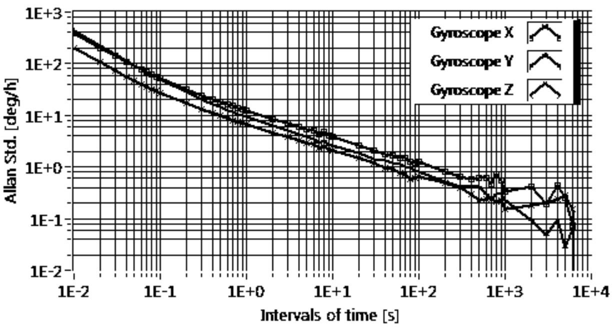

Figure 4. Allan standard deviation of the gyroscopes measured in the LITEF μIMU.

The plots of the Allan standard deviation of the gyroscopes in μIMU presented in Figure 4 show that these MEMS sensors are very well performing. Dominant quantization noise is observed until approximately 70 ms of integration. Further integration until 400 s reduces the noise down to σ = 0.4 °/hr. This level of noise is very small as for the MEMS gyroscope. It is obtained however after a long integration time.

The Xsens MTi-G710 is a very small factor integrated inertial navigation system. The noise characteristics of accelerometers and the gyroscopes of this system were tested and presented respectively in Figures 5. and 6.

In general, in the Xsens gyroscopes and accelerometers, the quantization noise is not observable at any time. The measured values are represented in 64-bit floating-point numbers, which gives a sufficient margin for representing a very wide dynamics of the measurement. The integration of the accelerometers' measurement makes it profitable only until 1 s. After that time the velocity random walk is buried in the electronic noise, interpreted as bias instabilty. At 1 s integration the accelerometer's Allan standard deviation is reduced to σ = 6 m/s/hr.

Very quickly, after 10 seconds of integration, the acceleration random walk becomes a dominating component in the sensor noise characteristics.

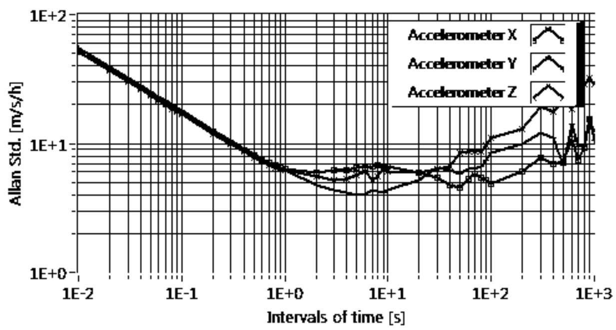

Figure 5. Allan standard deviation of the accelerometers measured in the Xsens MTi-G710.

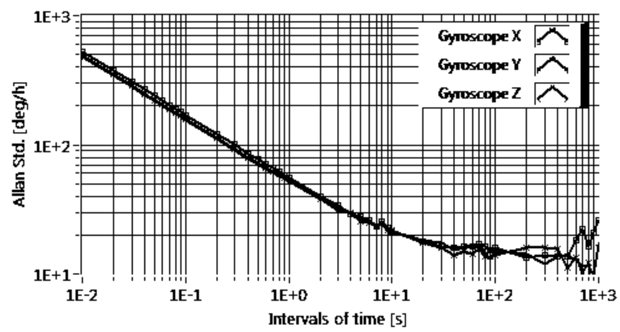

Figure 6. Allan standard deviation of the gyroscopes measured in the Xsens MTi-G710.

The optimum integration time for the Xsens gyroscopes is 30 s, according to the measurements. At that time the most contributing angle random walk drops to σ = 17 °/hr.

The final comparison of the minimum standard deviation of the tested accelerometers is shown in Table 1.

Table 1. Accelerometers' minimum Allan standard deviation

Sensor	Minimum σ(τ) m/s/hr	Integration time s
LN-200E IMU	0.2	20
μIMU	0.3	100
MTi-G710	6	10

The accelerometers of the LN-200E IMU are most stable within the set of the tested sensors. Their velocity random walk may be observed only until the 20th second of integration. It also operates with the smallest, among the tested sensors, noise level. Not much less performant are accelerometers of the μIMU. They generated at tiny bit more of velocity random walk, but it was observed not until 100th second of averaging time. The optimum observation time for the MTi-G710 accelerometers was the shortest, i.e. only 10 s, but after that time the significant, in comparison, 6 m/s/hr standard deviation is observed.

The performance of all tested gyroscopes are once more presented in the Table 2.

Table 2. Gyroscopes' minimum Allan standard deviation

Sensor time	Minimum σ(τ) °/hr	Integration s
LN-200E IMU	0.15	300
μIMU	0.4	400
MTi-G710	17	30

As it was expected from the FOG, it outperforms the MEMS gyroscopes. The best minimum $\sigma(\tau)$ is obtained after relatively short time, when comparing to the μIMU. The LITEF sensor is also measuring with slight pollution of the measurements. The minimum $\sigma(\tau)$ is obtained after much longer time but it is important to underline, this was achieved with a MEMS technology gyroscope. Representing the consumer grade IMU MTi-G710 generates the minimum noise at the level of $\sigma(\tau)$ = 17 °/hr and is not capable to compete with the other two sensors. In fact this value is greater than the Earth rotation rate = 15 °/hr.

It is important to inform here that the authors did not compare the results with the factories product specification due to lack of complete information and different for each product testing procedure. That was also a reason of performing the relative comparison of the units, what complements the sensors specifications

4.2 *Gyrocompassing*

The following test aimed an estimation of the attitude determination of the sensor with respect to the local frame. As described in a previous chapter, the vulnerable are the rotation measurements, because the measured values are on the level of the sensors inaccuracies. Therefore, in order to get the best gyroscope measurements, each sensor's best integration time of the samples presented in the Table 2., was used in this part of testing.

The identical test procedure of attitude determination was performed for two scenarios: non-rotating sensors for the attitude determination in the Earth conditions; rotating sensors what simulated Enceladus environment.

The results of that testing part are gathered in the Table 3. The values in the table are representing the standard deviation from the actual attitude of the sensors. $\sigma_{leveling}$ is depends on the accelerometer measurements and they are the same for every test run, since only nominal 1 g gravity acceleration was available to be measured. σ_{North} articulates the standard deviation of the North finding. It is different for the Earth and simulated Enceladus conditions.

The presented errors of north estimation have their origin in the bias instability and correlated noise of the gyroscopes. A bias or scale factor of the sensors have had negligible influence on the accuracy presented in the table. This was also a purpose of the test to expose the errors, which cannot be corrected in a stand-alone inertial attitude determination system and can be modelled only with statistics.

Table 3. Attitude estimation error: comparison between North-finding on the Earth and on Enceladus and leveling accuracy.

Sensor	$\sigma_{leveling}$ deg	$\sigma_{NorthEarth}$ deg	$\sigma_{NorthEnceladus}$ deg
LN-200E IMU	$3.24e^{-3}$	0.18	0.26
μIMU	$4.71e^{-3}$	0.42	0.77
MTi-G710	$27.2e^{-3}$	n/a	n/a

The leveling error caused by the accelerometer noise is on the similar level, tens of arc seconds, in the LN-200E and μIMU. The same error caused by the MTi-G is almost ten times bigger. North finding is more challenging for all sensors. This is the result of a small rotation measurement. The FOG was best performing among the tested gyroscopes. The North finding uncertainty cause by the gyroscope noise was almost 0.2 ° for the Earth conditions and increased 44 % in case of rotation of Enceladus.

The μIMU was over twice worse comparing to the tested FOG. This happened after a longer by 100 s integration time. The degradation of North finding in the Enceladus condition almost doubled.

The MTi-G710 was not reasonably close to the real North pointing.

5 CONCLUSIONS

The test answered to two questions of the study. The first was if it is possible to estimate the attitude of the inertial sensors on Enceladus, and if yes, what degradation of such estimation should be expected. The obtained degradation w.r.t. the previous generation of the attitude determination system for an iceprobe, that is performance of the μIMU tested in Enceladus conditions w.r.t. the LN-200 tested in the Earth conditions, has been measured to be around 430 %. This test concentrated on random behavior of the gyroscopes and constant error, like misalignment and bias repeatability were not in the test considered. The obtained result may be interpreted as the minimum for course alignment algorithms. The drop of accuracy is significant but not critical for the presented, higher demanding application.

This study haven't answer yet the question what is the minimum accuracy of the attitude estimation in the subpolar regions, which is one of the mission assumptions. It seems however that yet, there is a justified presumption that the more demanding, low-dynamic application may be realized with MEMS technology inertial sensors in the nearest future. This may drive significant costs reduction in the navigation systems implementation. This is an advantage which may be taken in the exploration applications, space or terrestrial, as well as in the maritime application, which characterizes with very low frequencies movements.

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