sciendo
Transactions on Aerospace Research eISSN 2545-2835, VOL. 273, NO. 4/2023, 41-51
DOI: 10.2478/tar-2023-0022

IMPROVING STRAPDOWN INERTIAL NAVIGATION SYSTEM PERFORMANCE BY SELF-COMPENSATION OF INERTIAL SENSOR ERRORS

Mykola Chernyak and **Vadym Kolesnyk***
Institute of Aerospace Technologies, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute," Peremogy av., 37, build. 28, Kyiv, Ukraine

Abstract
Microelectromechanical systems (MEMS)-based strapdown navigation systems offer advantages such as small size, low cost and minimal power consumption. However, MEMS sensors are prone to significant low-frequency noise and poor bias repeatability, which can lead to navigational errors over time. These errors make them unsuitable for autonomous navigation applications, even with frequent recalibration. One way in which to solve this problem is by using the rotation modulation (RM) method. This approach is widely recognised but has only been successful with precise laser and fiber optic gyroscopes equipped with precise rotating platforms. This article focuses on the potential of adapting the RM method for the case of inexpensive MEMS sensors that can significantly improve navigation performance, while maintaining the benefits of microelectromechanical technologies. Potential issues of implementation were discussed, and corresponding requirements were formulated. The proposed optimal computation scheme was verified during static tests of the developed inertial measurement unit (IMU). Further steps in studying the adaptation of the RM method for MEMS sensors have also been outlined.

Keywords: MEMS IMU; autonomous INS; MEMS self-compensation; rotation modulation
Type of the work: research article

1. INTRODUCTION

Satellite navigation systems (SNS) are the primary and most accurate source of navigation information that allows calculating the position and velocity of a receiver object from almost any point on or near the Earth's surface. In the presence of natural (terrain relief) and artificial (electronic interference) obstacles, the SNS signal deteriorates significantly or may even vanish entirely. In such situations, the role of the inertial navigation system, typically a strapdown inertial navigation system (SINS), becomes crucial. The accuracy of the navigation system is directly determined by the accuracy of its primary measurement devices within the inertial measurement unit (IMU): gyroscopes and accelerometers.

It is known that the error of an SINS increases over time quadratically with accelerometer errors and cubically with gyroscope errors [1]. This significantly limits its autonomous operation time, especially when the primary sensors are manufactured using microelectromechanical technology. The undeniable advantages of these sensors, such as small size, low power consumption and, importantly, low cost, are devalued by substantial zero bias errors and low-frequency flicker noises, leading to signal drift in the sensors over time. While overcoming the first problem (zero bias offset) is a relatively straightforward

* Corresponding Author: k.vadim888@gmail.com
ARTICLE HISTORY **Received** 2023-08-01 **Revised** 2023-10-23 **Accepted** 2023-10-26

task that can be addressed during IMU calibration before deployment, mitigating noises within the frequency range coinciding with the valuable signal range is challenging and currently actively researched.

One of the most promising approaches to eliminate low-frequency random errors is the introduction of additional rotational motion for IMU sensors according to a specific law, thereby modulating these errors into periodic signals that can be easily removed from the output signal by averaging them throughout the rotation. This approach, widely known nowadays as rotation modulation (RM), was initially implemented by Geller in 1968 for several submarine navigation systems [2]. A similar technique was repeated in 1980s by Giovanni and Levison [3] using a ring laser strap-down marine gyrocompass, which included using an indexer assembly to rotate the inertial sensor cluster periodically. In 1987, based on this development, Sperry Marine, Inc. and Honeywell Inc. collaborated to create a high-performing marine ring laser inertial navigator (MARLIN) that was both efficient and cost-effective [4]. It confirmed the promise of this approach and, over time, the technique was adapted to apply to INS and Attitude Heading Reference Systems (AHRS) based on fiber-optic gyroscopes (FOG) [5].

This method has proven effective with precise sensors, so the inevitable question that arose was whether it could improve the quality of applications based on cost-effective microelectromechanical systems (MEMS) technology. One of the first studies on this issue by Sun et al. [6] showed that rotating the IMU can modulate the errors of inertial sensors and consequently reduce navigation errors in a static case. Further research was conducted to analyse errors in sensor constant offsets, scale factors and set-up errors as the IMU rotated around the X, Y and Z axes, which was confirmed through real-world rotation tests on a three-axis turntable in a laboratory environment [7].

The possibilities of applying RM in real dynamic conditions were demonstrated using MEMS IMU with a vertical axis of rotation in the land vehicle navigation system [8]. The coordinate determination error was reduced by more than two times, but the rotational platform significantly increased the size and complexity of the overall navigation system, inevitably affecting its cost. It would be advantageous to explore potential solutions for achieving contentment with a simplified turning mechanism or, ideally, obviating it altogether by leveraging an extant rotating object part such as an automobile wheel. The latter has already been partially tested in developing an inertial gyro-based odometer [9]. According to test results, using RM on the IMU attached to a wheel gives more accurate position determination compared with a regular car odometer. However, the maximum allowable angular velocity of wheel rotation is limited by the measurement range of the gyroscopes, which consequently imposes restrictions on the vehicle's top speed. Another limitation is the shape of the road surface, since the accuracy of estimating the wheel phase based on accelerometer readings depends on it. However, despite the many challenges, such implementation of RM for MEMS IMU has enormous potential, which calls for a thorough investigation of the approach.

The purpose of this article is to analyse the implementation of the approach for MEMS IMU with an inexpensive rotating platform as a way to increase the time of the autonomous land vehicle strapdown navigation system, highlight and justify the critical aspects of the technical implementation of the method and solve other nuances related to the rotation scheme and processing of measurement information.

The remainder of this article is structured into five sections. Section 2 formalises the problem of extending an INS autonomous operation duration based on its mathematical model of instrumental errors. Section 3 is dedicated to describing the proposed approach and the essential aspects of its implementation. Section 4 discusses the experiments conducted to validate the proposed method and analyse the results obtained. Finally, we present our conclusions and plans for future research.

2. PROBLEM STATEMENT

The duration of an INS's self-sufficient operation is measured from when an SNS is shut down due to an emergency until the errors in the INS's orientation angles, speed projections and object coordinates reach their maximum acceptable values.

With the assumption that MEMS IMU is insensitive to the Earth rate due to significant gyro noise, the attitude error Eq. (1) can be simplified as follows:

$$\dot{\varepsilon} = C\Delta\omega \tag{1}$$

where ε is the error vector between the estimated and actual orientation, C is the directional cosine matrix describing the estimated orientation and $\Delta\omega$ is the gyroscope triad errors.

Both accelerometer and orientation estimation errors influence the accuracy of estimating the velocity vector:

$$\Delta\dot{V} = [\varepsilon]Ca + C\Delta a \tag{2}$$

where ΔV is the velocity estimation erros, a is the measured acceleration, Δa is accelerometer triad errors and $[\varepsilon]$ is the error vector skew-symmetrical matrix.

Considering the above-mentioned, the velocity and position errors due to the instrumental errors of the IMU gyroscopes are proportional to the square and cube of the INS operation time, respectively. Since the actual values of the INS error depend on the specific conditions of the experiment, as well as on the signs of the error components, which may differ from case to case, to assess the magnitude and nature of the growth of the instrumental error of the INS autonomous operation, we will use the following deviation estimations:

$$\begin{aligned} \varepsilon(t) &= \Delta\omega(t)t; \\ \Delta V(t) &= \Delta a(t)t + \Delta\omega(t)\frac{gt^2}{2}; \\ \Delta S(t) &= \Delta a(t)\frac{t^2}{2} + \Delta\omega(t)\frac{gt^3}{6}; \end{aligned} \tag{3}$$

where $g = 9.81$ m/s^2 is the magnitude of gravitational acceleration.

Therefore, the aim is to enhance the independent operating duration of the autonomous strapdown INS (i.e. to minimise Eq. (3)) via self-mitigating the IMU instrumental errors due to the approach outlined below.

3. METHOD

A MEMS IMU typically consists of an accelerometer and gyroscope orthogonal triads arranged to measure specific force and angular velocity in all three dimensions. The sensor outputs have error components that can be split into additive and scale factor errors. For this discussion, we will consider only the additive errors, which are not influenced by the magnitude of the input signal. Thus, the inertial measurements can be expressed in the sensor (associated with the IMU) frame as:

$$\begin{aligned} \tilde{a}_{IS}^{S} &= C_B^S a_{IB}^B + a_{BS}^S + \Delta a^S; \\ \tilde{\omega}_{IS}^{S} &= C_B^S \omega_{IB}^B + \omega_{BS}^S + \Delta\omega^S, \end{aligned} \tag{4}$$

where $\tilde{a}_{IS}^S$ and $\tilde{\omega}_{IS}^S$ are accelerometers and gyroscopes output, respectively; C_B^S is the matrix of IMU orientation in body (associated with the vehicle) frame; a_{IB}^B and ω_{IB}^B are body acceleration and angular velocity relative to the inertial (associated with the navigation coordinate system) frame in body frame; a_{BS}^S and ω_{BS}^S are acceleration and angular velocity of the IMU relative to the object in sensor frame; and Δa^S and $\Delta\omega^S$ are sensor errors.

Inertial sensor errors mainly consist of constant bias, flicker noise (bias instability) and thermomechanical white noise. Given that the fluctuating error processes in MEMS inertial sensors are difficult to be modelled or estimated but considered quasi-constant on small time intervals, the IMU rotating is an efficient way to compensate them automatically in a couple with constant bias. However, RM does not affect the fast-changing white noise.

Assume the IMU is rotated at a constant rate ω around the Z axis (Fig. 1). The rotary platform is rigidly attached to the body, and the sensor frame initially coincides with the body frame, that is, $a_{BS}^S = (0; 0; 0)^T$ and $\omega_{BS}^S = (0; 0; \omega)^T$. Accordingly, the orientation of the IMU in the body frame after time t is expressed as:

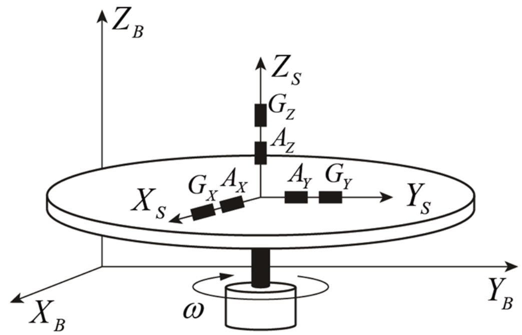

Figure 1. Scheme of the IMU on a rotating platform. $X_BY_BZ_B$ – the body frame; $X_SY_SZ_S$ – the sensor frame. IMU, inertial measurement unit.

$$C_S^B = \begin{pmatrix} \cos\omega t & -\sin\omega t & 0 \\ \sin\omega t & \cos\omega t & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{5}$$

Therefore, the estimation of acceleration $\tilde{a}_{IB}^B$ and angular velocity $\tilde{\omega}_{IB}^B$ has the following form:

$$\begin{aligned} \tilde{a}_{IB}^B &= C_S^B \tilde{a}_{IS}^S - a_{BS}^S = a_{IB}^B + C_S^B \Delta a^S - a_{SB}^B; \\ \tilde{\omega}_{IB}^B &= C_S^B \tilde{\omega}_{IS}^S - \omega_{BS}^S = \omega_{IB}^B + C_S^B \Delta\omega^S - \omega_{SB}^B. \end{aligned} \tag{6}$$

After substitution of (5) and simplification, we get:

$$\tilde{a}_{IB}^B = a_{IB}^B + \begin{pmatrix} \Delta a_x^S \cos\omega t - \Delta a_y^S \sin\omega t \\ \Delta a_x^S \sin\omega t + \Delta a_y^S \cos\omega t \\ \Delta a_z^S \end{pmatrix};$$

$$\tilde{\omega}_{IB}^{B} = \omega_{IB}^{B} + \begin{pmatrix} \Delta\omega_x^S \cos\omega t - \Delta\omega_y^S \sin\omega t \\ \Delta\omega_x^S \sin\omega t + \Delta\omega_y^S \cos\omega t \\ \Delta\omega_z^S \end{pmatrix} - \omega_{BS}^{B}. \tag{7}$$

The integrals of the harmonic components for a full rotation with period T will result in zero. As a result, the estimates for acceleration and angular velocity for one rotation cycle are as follows:

$$\breve{a}_{IB}^{B} = \frac{1}{T}\int_0^T \tilde{a}_{IB}^{B} dt \approx \frac{1}{T}\int_0^T a_{IB}^{B} dt + \begin{pmatrix} 0 \\ 0 \\ \Delta a_z^S \end{pmatrix};$$

$$\breve{\omega}_{IB}^{B} = \frac{1}{T}\int_0^T \tilde{\omega}_{IB}^{B} dt \approx \frac{1}{T}\int_0^T \left(\omega_{IB}^{B} - \omega_{BS}^{B}\right) dt + \begin{pmatrix} 0 \\ 0 \\ \Delta\omega_z^S \end{pmatrix}. \tag{8}$$

4. IMPLEMENTATION

Evidently, the computation of the orientation matrix is the critical process in this approach, and it determines the degree of difficulty in the actual implementation of the method. The naive implementation requires an exact determination of the rotation angle and the reprojection of the output signals to the body frame for each output sample of sensors, which imposes strict requirements on the angle-measuring device. The more suitable choice in this case would be to estimate errors Δa^S and $\Delta\omega^S$ sensor frame by integrating during the complete rotation cycle original IMU output (4):

$$\int_0^T \tilde{a}_{IS}^{S} dt = \int_0^T C_B^S a_{IB}^{B} dt + \int_0^T a_{BS}^{S} dt + \int_0^T \Delta a^S dt \approx \begin{pmatrix} 0 \\ 0 \\ a_{IBz}^S \end{pmatrix} T + \Delta a^S T;$$

$$\int_0^T \tilde{\omega}_{IS}^{S} dt = \int_0^T C_B^S \omega_{IB}^{B} dt + \int_0^T \omega_{BS}^{S} dt + \int_0^T \Delta\omega^S dt \approx \begin{pmatrix} 0 \\ 0 \\ \omega_{IBz}^S + \omega_{BSz}^S \end{pmatrix} T + \Delta\omega^S T. \tag{9}$$

Thus, we reveal the errors of sensors located in the plane of modulating rotation (sensitivity axes are perpendicular to the rotation axis). In this case, it is sufficient to determine the orientation of the IMU only at the point of a complete cycle. Such a decision has its consequence – the frequency of updating output from the IMU f will equal the frequency of the modulating rotation f_{mod}. Obviously, by analogy with the Nyquist–Shannon theorem, this frequency must be at least twice the maximum frequency of object manoeuvre f_{man} to ensure their observability:

$$f_{man} < \frac{1}{2} f. \tag{10}$$

The value f_{man} is known indirectly based on the upper limit of the measurement range of the IMU gyroscope unit, which for the vast majority of MEMS sensors (in particular, the one selected for further experimental verification) equals 2,000°/s, which corresponds to rotation with a frequency 5.6 Hz. So, we must ensure that the condition is fulfilled $f > 11.2$ Hz. The possible solution that may seem obvious is to increase the rotation frequency to the appropriate level. However, this approach can lead to systematic errors due to the potential occurrence of significant centripetal acceleration. On the other hand, it may be impossible to attain such frequency at all. Increasing the number of rotation control points – two or four equidistant points with an angular step of 180° or 90° – would be helpful to improve the situation. As a result, the frequency of updating output from the IMU will be increased multiple times. However, it should be noted that this decision does not cancel the criterion (10), but only partially mitigates possible negative consequences regarding the observability of manoeuvres. This aspect requires detailed experimental research.

Special attention is required for the rotation compensation from the IMU output. When the criterion (10) is fulfilled through increasing rotation frequency beyond the measurement range of the coaxial gyroscope, it is necessary to involve another source of information about the angular velocity along the corresponding axis (e.g. the rotation-isolated uniaxial gyro [10]). Otherwise, when the modulating angular velocity is still available (together with the object's) in the measurement range of the corresponding gyroscope, the ordinary compensation of the modular velocity can be performed based on its indirect estimation of the rotation period and the intervals of the passage through control points.

The last requirement for the listed frequencies – the frequency of the IMU raw output f_{raw} must significantly exceed the output frequency f after modulation:

$$f << f_{raw}. \tag{11}$$

The accuracy of the error calculation will be higher as more measurements from the IMU for a complete revolution are obtained. Therefore, it is desirable to adjust the polling frequency of IMU sensors with excess.

Since the outputs of the MEMS IMU are discrete, in the final version of the algorithm, we will transit from integrals to sums. Let a complete revolution be completed in some time T, while N measurements are accumulated. Then, according to Eq. (9), and having previously excluded from consideration the meters along the axis of rotation, we obtain estimates of the sensor errors:

$$\begin{pmatrix} \Delta\breve{a}_x^S \\ \Delta\breve{a}_y^S \end{pmatrix} = \frac{1}{N}\sum_{i=1}^{N}\begin{pmatrix} \Delta\breve{a}_{ISx}^S(i) \\ \Delta\breve{a}_{ISy}^S(i) \end{pmatrix}; \quad \begin{pmatrix} \Delta\breve{\omega}_x^S \\ \Delta\breve{\omega}_y^S \end{pmatrix} = \frac{1}{N}\sum_{i=1}^{N}\begin{pmatrix} \Delta\breve{\omega}_{ISx}^S(i) \\ \Delta\breve{\omega}_{ISy}^S(i) \end{pmatrix}. \tag{12}$$

The output signals of the equivalent IMU take place with the update of the corrections after each complete revolution according to Eq. (12):

$$\breve{a}_{IB}^B = C_S^B\left(\tilde{a}_{IS}^S - \begin{pmatrix} \Delta\breve{a}_x^S \\ \Delta\breve{a}_y^S \\ 0 \end{pmatrix}\right); \quad \breve{\omega}_{IB}^B = C_S^B\left(\tilde{\omega}_{IS}^S - \begin{pmatrix} \Delta\breve{\omega}_x^S \\ \Delta\breve{\omega}_y^S \\ 0 \end{pmatrix}\right) - \omega_{BS}^B. \tag{13}$$

In the simplest one-point version of the algorithm, the passage through the control point corresponds to the moment when the sensor frame is coaxial with the object frame, that is, $C_B^S = I$, where I is a unit matrix. Accordingly, the determination of meter errors occurs at the end of a complete revolution. For the four-point version, the matrix C_B^S will cyclically take the following values for the corresponding point:

$$C_S^B(1)=\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix};\quad C_S^B(2)=\begin{pmatrix}0&-1&0\\1&0&0\\0&0&1\end{pmatrix};$$
$$C_S^B(3)=\begin{pmatrix}-1&0&0\\0&-1&0\\0&0&1\end{pmatrix};\quad C_S^B(4)=\begin{pmatrix}0&1&0\\-1&0&0\\0&0&1\end{pmatrix}. \tag{14}$$

The two-point variant will involve two matrices Eq. (14): the first and the third.

5. EXPERIMENTS

The effectiveness of the method was primarily verified during static laboratory tests of the IMU prototype built on the Xsens MTI-1 micromechanical module (Table 1). The prototype has a battery to ensure long-term functioning under continuous rotation conditions. Computer control is implemented using a microcontroller from the ESP32 series, which provides wireless data transfer to the main computer using the Bluetooth protocol.

Table 1. Characteristics of IMU Xsens MTI-1 sensors.

	Accelometr block	**Gyroscope block**
Measurement range	±16 g	±2,000°/s
Zero offset instability	0.03 mg	10°/h
Bandwidth (–3 dB)	324 (Z: 262) Hz	255 Hz
Noise density	120μg/√Hz	0.007°/s/√Hz
Non-linearity	0.5%FS	0.1%FS

IMU, inertial measurement unit.

A single-axis rotary stand MPU-1 (Fig. 2A) was used as a modulator, which smooths the angular velocity in the range of 0.03–150°/s. A reed switch and magnets were used to control the rotation angle in a 90° step around the moving platform.

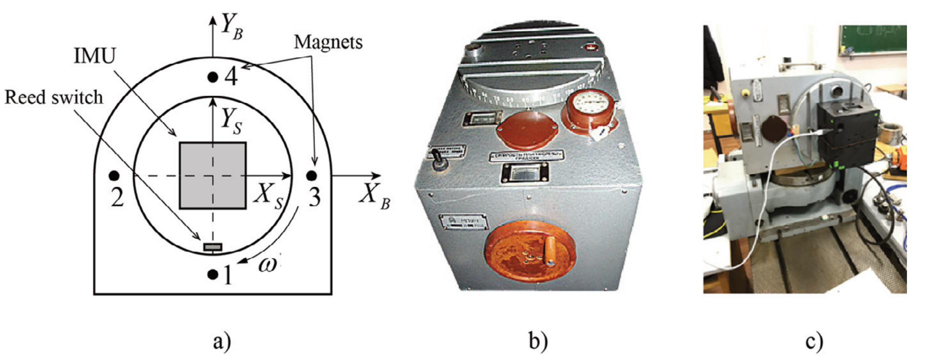

Figure 2. Scheme of the stand of static products (A). uniaxial rotary stand MPU-1 (B) and a test sample, installed on it in a position with a horizontal axis of rotation (C).

Static tests of the modified INS took place with two variants of the orientation of the axis of modulating rotation relative to the gravitational acceleration vector: parallelly (vertical axis case) and orthogonally (horizontal axis case). The modulation rate, according to the maximum capabilities of the available rotary stand, was 150°/s, which means the nominal value of the modulation angular velocity lies within the measurement range of the coaxial gyroscope, which made it possible to evaluate the projection of the angular velocity along the corresponding axis trivially.

The data output frequency of the micromechanical module was 40 Hz, the rotation frequency of the computer (corresponding to a speed of 150°/s) was about 0.4167 Hz for the one-point, 0.8333 Hz for the two-point and 1.6667 Hz for the four-point algorithm, respectively, since the experiment is static (respectively, the frequency of manoeuvres is close to zero), the conditions regarding the ratio of frequencies (10) and (11) are not being violated.

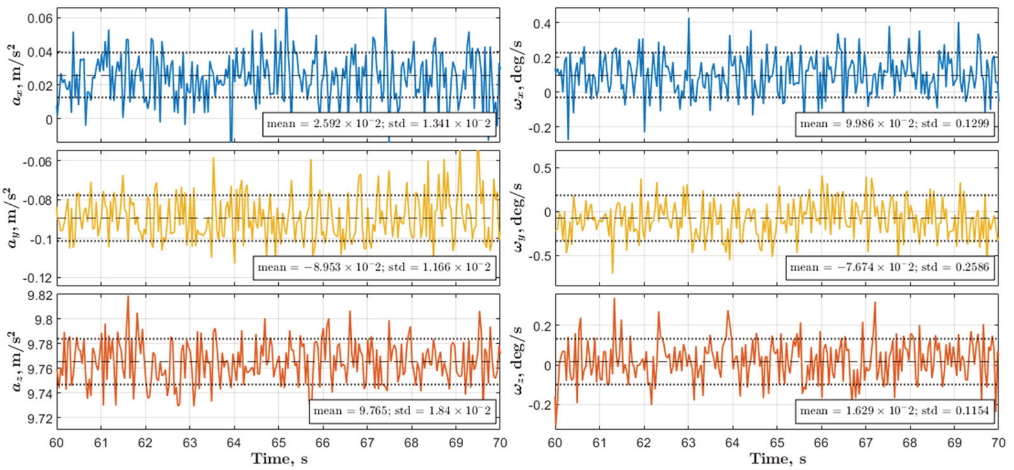

Figure 3. IMU output without modulating rotation. IMU, inertial measurement unit.

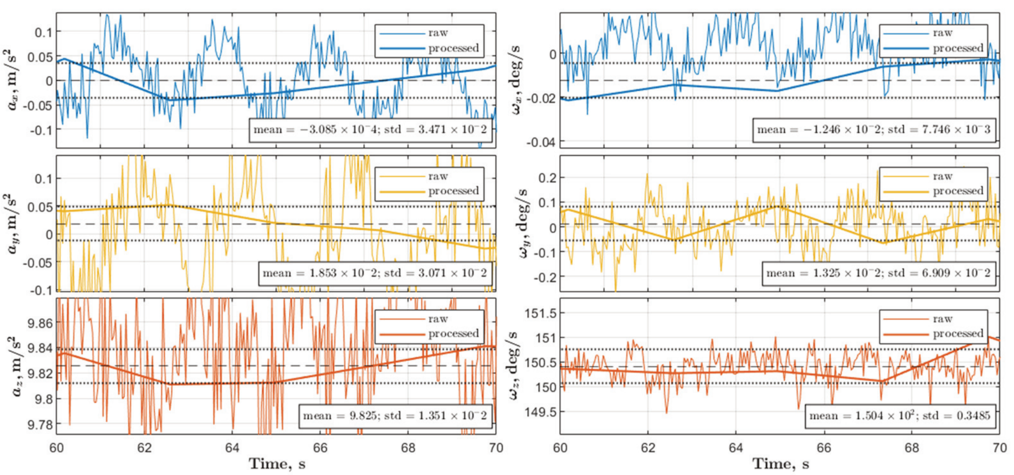

Figure 4. Output signals of rotated IMU with modulating rotation along a vertical axis. IMU, inertial measurement unit.

The duration of each experiment was about 5 min. Figures 3–5 show the graphs of the output signals of the IMU according to three variants of static tests: without modulation and with two variants of the spatial orientation of the axis of modulating rotation.

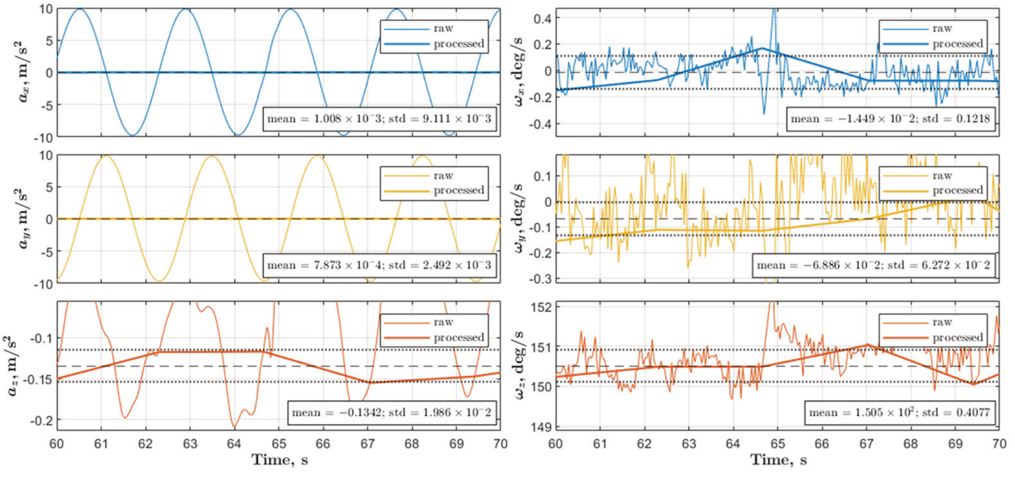

Figure 5. Output signals of rotated IMU with modulating rotation along a horizontal axis. IMU, inertial measurement unit.

Initially, the rotary stand is locked, and the inertial navigation output computes the same way as in a traditional INS. Following a specified duration, the IMU began to rotate. The control position of the algorithm mentioned in Section 4 is the same as the initial position. The magnitude of the modulating rotation, which was subtracted from the output of the axis gyroscope, was estimated indirectly from measurements of the rotation period. Compensation for gravitational acceleration was made based on the estimation obtained at the initial alignment IMU.

Figure 6 shows the accuracy comparisons based on the computed estimations (3). Specific numerical values of the error estimates for tests without rotation and rotation are given in Table 2.

Table 2. Results of static experiments.

		Static	RM (vertical axis)	RM (horizontal axis)
$\varepsilon(t=300\,\mathrm{s}),[\mathrm{deg}]$	X	16.35	–0.95	1.08
	Y	–53.11	0.9	0.86
	Z	5.62	14.07	9.2
$\Delta V(t=300\,\mathrm{s}),[\mathrm{m/s}]$	X	415.37	–33.66	30.83
	Y	–332.5	15.62	32.96
	Z	137.26	95.76	117.3
$\Delta S(t=300\,\mathrm{s}),[\mathrm{km}]$	X	41.46	–3.75	3.3
	Y	–33.29	4.2	6.08
	Z	6.67	8.79	23.16

RM, rotation modulation.

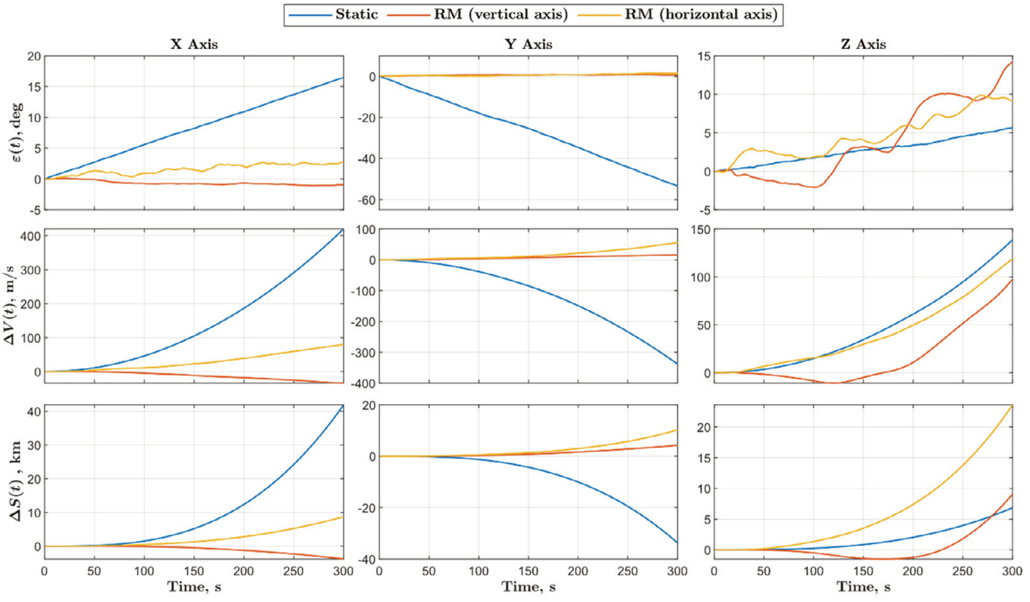

Figure 6. Graphs of the estimations (3) of the RM IMU with vertical and horizontal rotation axis compared with the stationary case. IMU, inertial measurement unit; RM, rotation modulation.

The non-rotational experiment showed that although the IMU was previously calibrated, constant biases still existed due to poor repeatability. The IMU rotation modulates the inertial sensors' constant displacements perpendicular to the rotation axis, and the orientation and velocity errors caused by such displacements are independently eliminated after a complete cycle of rotation. As we can see from the results, the method allows us to reduce the growth rate of errors by an order of magnitude, excluding sensors whose axes were located along the axis of modulating rotation. At the same time, the inertial sensors' constant displacement on the rotation axis cannot be modulated, and the position and speed errors caused by such errors are propagated in the same way as in the classical SINS.

The compensation of the modulating angular velocity along the axial channel based on the mediated data at the intervals of passing the control points showed an acceptable quality, but it still needs to be refined.

5. CONCLUSIONS

The article analyses the rotational modulation method of instrumental errors of IMU and studies this approach's potential for using inexpensive MEMS sensors with a proposed computational scheme that does not require the presence of an accurate rotational mechanism or angle measurement. The rotation of the IMU is capable of harmonically modulating the quasi-static errors of inertial sensors, which are practically eliminated during the navigational algorithm processing estimation, which, in our opinion, paves the way for a significant reduction of its navigation errors and increases its autonomous operation time. However, a substantial limitation of the proposed RIMU computational scheme is that the RIMU's output sample rate is a multiple of the rotation frequency. This frequency must be at least twice the maximum frequency of body manoeuvres to ensure their observability. Furthermore, in the case of an unstable frequency of modulation rotation, the output frequency will also be a variable that must be considered during the navigation algorithm development.

The static tests conducted in laboratory conditions confirmed the research method's high technical potential. It has been shown that the proposed method is effective for various spatial orientations of the rotational modulation axis. Nevertheless, the most significant effect was achieved with the vertical rotation axis, due to less impact of an imperfection of modulation rotation rate compensation from the coaxial gyroscope.

REFERENCES

[1] Savage, Paul. G. "Strapdown Inertial Navigation Integration Algorithm Design Part 2: Velocity and Position Algorithms." *Journal of Guidance, Control and Dynamics* Vol. 21 (1998): pp. 208–221. DOI 10.2514/2.4242.

[2] Edward, S. Geller. "Inertial System Platform Rotation." *IEEE Transactions on Aerospace and Electronic Systems* Vol. AES-4 No. 4 (1968): pp. 557–568. DOI 10.1109/TAES.1968.5409024.

[3] Giovanni, C. San, Jr., and Levinson, E. "Performance of a Ring Laser Strapdown Marine Gyrocompass." *NAVIGATION: Journal of The Institute of Navigation* Vol. 28 No. 4 (1981) pp. 311–341.

[4] Levinson, Emanuel, and Majure, Robert. "Accuracy Enhancement Techniques Applied to the Marine Ring Laser Inertial Navigator (MARLIN)." *NAVIGATION* Vol. 34 No. 1 (1987): pp. 64–86. DOI 10.1002/j.2161-4296.1987.tb01490.x

[5] Feng, Sun, Wei, Sun, Wei, Gao, and Yueyang, Ben. "Research on the Technology of Rotational Motion for FOG Strapdown Inertial Navigation System." *2009 International Conference on Mechatronics and Automation*. Changchun, (2009): pp. 4913–4918. DOI 10.1109/ICMA.2009.5246048.

[6] Sun, Wei, Wang, Daxue, Xu, Longwei, and Xu, Lingling. "MEMS-Based Rotary Strapdown Inertial Navigation System." *Measurement* Vol. 46 No. 8 (2013): pp. 2585–2596. DOI 10.1016/j.measurement.2013.04.035.

[7] Du, Shuang, Sun, Wei, and Gao, Yang. "MEMS IMU Error Mitigation Using Rotation Modulation Technique." *Sensors (Basel)* Vol. 16 No. 12 (2016). DOI 10.3390/s16122017.

[8] Du, Shuang. "A Micro-Electro-Mechanical-System-Based Inertial System with Rotating Accelerometers and Gyroscopes for Land Vehicle Navigation." *International Journal of Distributed Sensor Networks* Vol. 13 (2017): p. 155014771774635. DOI 10.1177/1550147717746351.

[9] Collin, Jussi. "MEMS IMU Carouseling for Ground Vehicles." *IEEE Transactions on Vehicular Technology* Vol. 64 No. 6 (2014): pp. 2242–2251. DOI 10.1109/TVT.2014.2345847

[10] Kohler, Steward, M. "MEMS Inertial Sensors with Integral Rotation Means." Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA (2003). DOI 10.2172/917477