Optimal calibration plan for inertial measurement unit based on microelectromechanical system

A A Krylov
Department 305 “Automated complexes of orientation and navigation systems”, Moscow Aviation Institute (National Research University), 4 Volokolamskoe shosse, Moscow, 125993, Russian Federation
E-mail: AAKrylov@mai.education

Abstract. This paper is about the composition of scientifically substantiated calibration plan from the specific requirements for inertial measurement unit on microelectromechanical sensors. It is proposed to decompose the common problem into three tasks – converting implicit requirements to the explicit requirements with error components, determining of requirements by indirect parameters and finding direct parameter values, time limited calibration that have limits for full time. All these tasks may be presented as multi-criteria optimizations and be solved by numerical methods with some semi-analytical substitutions. Suggested methods are useful for composing an optimal calibration plan in conditions of ambiguous requirements, to estimate reaching accuracy, test volume and total calibration time. This approach offers the researcher a new look at the problem of balance between calibration accuracy and optimal use of resources.

1. Introduction
A significant part of the cost of unmanned aerial vehicles is the cost of the control system, including the navigation system. In the context of integrated systems, it is not always advantageous to use the most accurate inertial navigation system as possible. One of the ways to reduce the cost of a navigation system is to optimize its calibration technology that is to ensure the required accuracy with minimal time and labor costs. The characteristics of strapdown inertial navigation system (SINS) are largely determined by the characteristics of the primary information sensors - gyroscopes and accelerometers.

Construction SINS based on microelectromechanical (MEMS) sensors is a difficult task, in processing which it is necessary to take into account such properties of MEMS sensors as run-to-run instability [1] and the deviation of characteristics from storage time [2, 3]. The ultimate capabilities of such SINS largely depend on the quality of the primary information sensor calibration. It is most justified to carry out such calibration with direct information outputs of navigation information - angular velocities and linear accelerations. That is, in the form of an inertial measurement unit (IMU) containing three mutually orthogonal angular velocity and linear acceleration sensors.

The main errors of MEMS sensors are zero drift and scale factor error. These coefficients have a fairly significant dispersion, depending on different conditions, which determines the end roughness of these sensors. For example, zero drift has a large component caused by the run-to-run instability [4], instability in time during one run [5], temperature instability [6], as well as instability depending on the storage time [7]. Good calibration requires algorithms that accurately take into account all conditions, as well as statistically reliable determination of systematic coefficients. Performing a sufficient amount of calibration tests, as well as ensuring their independence and reliability, can be time-consuming.
In case of inertial measurement unit serial production this issue becomes especially acute and requires a scientifically based approach. The compliance of the calibrated unit with the requirements of the technical task will remain as the key parameter. It may be not necessary to complete full calibration to meet the requirements, but it is important to save time if the limit for a full batch calibration exists. This prompts to formalize the calibration plan, compose a reasonable model of calibrated errors, determine statistical indicators and optimize the entire process taking them into account by using mathematical models.

A lot of literature [8] is devoted to the optimal finding of certain calibration parameters of units in terms of accuracy and time, a number of them contain an integrated approach that tries to observe all errors using the minimal number of movements [9]. There are works devoted to the multi-parameter optimization of the internal sensor tuning (finding the optimal ratio of parameters [10] or more accurate use of the available measurement information [11]). Some works touch on the general calibration plan [12] or optimized calibration of large batch of units [13], but they do not take into account the peculiarities of the MEMS sensor errors. This work aims to describe the construction of a calibration plan taking into account the structure of the MEMS sensor errors, but without going into the technological details of each error finding.

2. Inertial measurement unit, its characteristics and calibration principles

The investigated IMU (its characteristics are in table 1) includes three MEMS gyroscopes and MEMS accelerometers (their characteristics are in table 2) of the linear-linear (LL) type (one gyroscope and one accelerometer in one MEMS case), as well as a microcontroller that allows to correct sensor readings taking calculated systematic errors into account.

| Characteristic | Value |
|----------------|-------|
| IMU Mass       | 140g  |
| IMU sizes      | 80x43x34mm |

Table 2. The declared characteristics of the sensors.

| Characteristic | Value               |
|----------------|---------------------|
| Frequency of data output | 1000 Hz          |
| Dynamic Range of gyroscope  | ±500°/s          |
| Dynamic Range of accelerometer | ±100g          |
| Zero bias run-to-run stability of gyroscope | 0.02°/s     |
| Zero bias run-to-run stability of accelerometer | 0.02g         |
| Scale factor run-to-run stability of gyroscope | 0.15%      |
| Scale factor run-to-run stability of accelerometer | 0.15%      |
| Zero signal noise of gyroscope | 0.006 °/s/√Hz |
| Zero signal noise of accelerometer | 0.002 g/√Hz   |

Proposed error models for gyroscopes and accelerometers are listed below. Gyroscope error model for any considered axis (sensor) is:

\[
\omega_m = S_{fg}(\omega_a + \delta \omega),
\]

where \(\omega_m\) – the measured value by the gyroscope, \(\omega_a\) – the adjusted by the rotary bench angular velocity value, \(\delta \omega\) – the total error of the gyroscope.

\[
\delta \omega = v_{\omega a} \omega_{a x} + v_{\omega a} \omega_{a y} + v_{\omega a} \omega_{a z} + \omega_a K \omega_a + \Delta \omega_{\alpha} + \epsilon \omega
\]
where \( \nu_g, \nu_g, \nu_g \) – non-orthogonal angle coefficients of gyroscope relatively to instrument axes; 
\( K_\omega \) – scale factor error coefficient of gyroscope; 
\( \Delta \omega \) – zero drift of gyroscope; 
\( \sigma_w \) – gyroscope noise (random process with zero mean).

Accelerometer error model for any considered axis is:

\[
a_m = Sfa(a_a + \delta a),
\]

where \( a_m \) – the measured value by the accelerometer, \( a_a \) – the linear acceleration value set by the bench, 
\( \delta a \) – the total error of the accelerometer.

\[
\delta a = \nu_{ax}a_{ax} + \nu_{ay}a_{ay} + \nu_{az}a_{az} + a_nKa_n + \Delta a_n + \varepsilon a,
\]

where \( \nu_{ax}, \nu_{ay}, \nu_{az} \) – non-orthogonal angle coefficients of accelerometer relatively to instrument axes; 
\( K_a \) – scale factor error coefficient of accelerometer; 
\( \Delta a_n \) – zero drift of accelerometer; 
\( \varepsilon a \) – accelerometer noise (random process with zero mean).

General principle of calibration is setting up calibration tests for sequential search for each parameter [14]. There are may be different approaches to determine each error and to divide them into components, however, we consider the non-orthogonality of the sensor installation in relation to the instrument axis to be constant for all tests and runs, also we consider noise as conditionally white with a zero mean.

3. The problem of constructing an optimal calibration plan

The IMU calibration system based on MEMS sensors is a scientifically sound volume of calibration tests, sufficient for the most accurate compensation of errors (finding the calibration parameters) defined by the technical task. The required error values of gyroscopes and accelerometers can be presented in the terms of reference in several ways:

1) Specific requirements for sensors such as maximum allowable values of drifts, scale factor errors, skews, or their components under certain conditions.

2) Not quite specific requirements for sensors, i.e. requirements described under item 1, but allowing different interpretation under different conditions or test methods.

3) Requirements for a product on sensors (IMU, SINS) i.e. presentation of the maximum allowable roll error, linear velocity of the object in direction, final coordinate, etc.

In the above paragraphs, the complexity of the approach to a reasonable interpretation of technical specifications as well as the creation of calibration and test procedures increase with each paragraph. Item 1 is quite simple, item 2 can be reduced to item 1 by using additional information related to the operating conditions of the product, limitations on calibration capabilities, etc. Item 3 allows for a broad interpretation, since the achievement of meeting the requirements is possible in different ways. The factor of limiting the time admissible for calibration tests can also be important. In this study, an attempt to formalize the problem of a reasonable calibration test plan and present it as a multi-criteria optimization problem was made, the criteria of this task is the error accuracy and the time of calibration. The solution of the problem is offered through the sequential solution of three problems - optimization of implicit requirements, determination of requirements for indirect parameters and calibration with limited time.

4. Optimization of implicit requirements

The first stage is the formalization of the calibration problem under implicit requirements. Implicitness can be expressed in the absence of information regarding the decomposed parameters. For example, the modes of the product operation at a number of specific temperatures are indicated, but there is no information about the permissible behavior under other conditions.
From the general formula for the errors $\delta$, of particular interest to us are the zero drifts $\Delta \omega_d$, $\Delta \omega_l$, and also the errors of the scale factor $K\omega_n$ and $Ka_{sl}$. Therefore, we try to decompose each of these errors into its components. The formula of gyroscope zero drift is:

$$\Delta \omega_d = \Delta \omega_{d,t} + \Delta \omega_{l,t} + \Delta \omega_{t} + \Delta \omega_{run,instab}$$

(5)

where $\Delta \omega_d$ – systematic component, depending on time from switching on (figure 1); $\Delta \omega_{d,t}$ – the change of the systematic component from the storage time (figure 2); $\Delta \omega_{t,sys}$ – systematic component depending on temperature (figure 3); $\Delta \omega_{run,instab}$ – run-to-run instability (figure 4).

The proposed models do not take into account the drift of abruptly changing conditions, heating and cooling, under which the phenomenon of hysteresis is observed in MEMS sensors [15, 16]. To simplify the situation, we will focus on relatively permanent external conditions.

Similarly, the scale factor error is decomposed as:

$$K\omega_n = K\omega_{n,t} + K\omega_{l,t} + K\omega_{t} + K\omega_{run,instab}$$

(6)
where $K_{oT,syst}$ – systematic component depending on temperature; $K_{ot}$ – the change of the systematic component from the storage time; $K_{ot}$ – systematic component, depending on time from switching on; $K_{ot,run,instab}$ – run-to-run instability.

It is assumed that the composite parameters in formulas 5 and 6 are independent, but for specific sensors this may be incorrect and requires additional research. For example, many sensors have bigger $\Delta o_{t}$ value on the temperature at the edges of the range than under normal climatic conditions.

It can be seen from the above formulas that under an ideal calibration, the total drift or scale factor error will be reduced to run-to-run instability, provided that the rest of the systematic parameters are calibrated so accurately that they can be neglected. If we do not have the opportunity to calibrate each component as reliably as possible, then we need to know the importance of each of them for use in the final object, the weight of each in the total error, as well as the required number of tests to achieve the required reliability. The number of repetitions of the systematic drift under normal conditions is determined by the confidence interval formula [17]:

$$n \geq \left( \frac{t_{kp} s}{d} \right)^2$$

(7)

where $n$ – number of repetitions; $t_{kp}$ – Laplace function value; $d$ – confidence interval; $s$ – estimated standard deviation of selected values.

At the same time when we using this formula, it is necessary to know approximately the spread of the parameter, as well as the required reliability, which will be provided by the given confidence probability. The number of repetitions for the remaining components of the error is calculated in a similar way. The calculated values of the number of repetitions for a confidence level of 99% are shown in tables 3 and 4.

**Table 3.** Approximate values of uncalibrated error components.

| Error value                      | Gyroscope drift, °/s | Gyroscope SF error, % | Accelerometer drift, g | Accelerometer SF error, % |
|----------------------------------|----------------------|-----------------------|------------------------|--------------------------|
| Run-to-run instability           | 0.02                 | 0.02                  | 0.02                   | 0.02                     |
| Instability during one run       | 0.01                 | 0.01                  | 0.01                   | 0.01                     |
| Temperature instability          | 0.05                 | 0.5                   | 0.03                   | 0.5                      |
| Instability of the average value from storage time | 0.02 | 0.2 | 0.02 | 0.2 |

**Table 4.** Number of repetitions for 99% confidence.

| Number of measurements            | Gyroscope drift | Gyroscope SF error | Accelerometer drift | Accelerometer SF error |
|-----------------------------------|-----------------|-------------------|---------------------|------------------------|
| Run-to-run instability, number of runs | 25              | 10                | 20                  | 10                     |
| Instability during one run, duration*frequency | 300*1000       | 20*1000           | 120*1000            | 20*1000                |
| Temperature instability, discretization by 2 °C | 60              | 10                | 30                  | 10                     |
| Instability of the average value from storage time | 24 (every 2 weeks during a year) |                     |                     |                        |
For simplicity, we assume that the distribution of the inclusion error is normal, the 99% confidence level is sufficient for reliability, and the scale factor error is the same over the entire range (although the study [18] shows that this is not the case). Instability from storage time makes sense for a periodic calibration plan where it is possible [19]. For a single calibration plan, it makes sense to consider the remaining parameters. The optimization problem, which is to minimize the drift, looks like this:

\[
\Delta \omega_d = f(\Delta \omega_{r,syst}, \Delta \omega_s, \Delta \omega_t, \Delta \omega_{run,instab}) - > \min
\]

and given that we consider \( \Delta \omega_{run,instab} \) as a constant unchanging parameter that cannot be calibrated, and that we consider one calibration, we get:

\[
f(\Delta \omega_{r,syst}, \Delta \omega_t) - > \min
\]

Here and below, \( f \) is a generalized optimization function with an unknown structure and character.

This problem can be solved numerically. Analytical replacement of one parameter through another can be made. So, according to table 3, the weight of the temperature component is 2.5 times greater than the instability with one run, but at 7 temperatures it becomes approximately equal. Solving a problem in this form is useful for understanding the main sources of error, but in practice, calibration time is important. A similar task will be discussed in the section 6. Estimating time in real conditions is complicated by the configuration of test equipment.

5. Determination of requirements by indirect parameters

There are many possible options for the transition from indirect to direct parameters, the most common is the transition from orientation errors, linear velocity and coordinates to sensor errors. In this case, there are two options for determining errors - determining the range of permissible values by simulation and semi-natural modeling by means of specifying the expected trajectory at the stand. It is more rational to use the first option.

In example the maximum error of a given trajectory of a short-range missile should not exceed total coordinate error \( S \). Suppose that we have 4 basic errors - total zero drifts (as in formula 5) and total scale factor errors (as in formula 6) of gyroscopes and accelerometers.

\[
S = f(\Delta \omega_d, \Delta a_d, K \omega_d, K a_d) - > \min ,
\]

where \( S \) is the total coordinate error. Using this formula, it should be accepted that we take the errors depending on storage as 0, and after one or two month it may not be so.

To solve such a problem, it is necessary to understand the real trajectory of the moving sensor unit, which can be mathematically modeled. That is, it is necessary to simulate the algorithm of the strapdown inertial navigation system and set the trajectory to the input of the sensors of the primary information, at the same time simulating the random and systematic values of these errors. The result of the calculations will be \( S \), having received which one can try to evaluate its dependence on each of the parameters. If such dependence can be represented by polynomials of low degrees, then the simplified problem can be solved numerically by using various methods, from simple enumeration to the use of genetic algorithms [20].

6. Time-limited calibration

The problem from the previous paragraph can be solved in case of the limit time. In this case, the problem is decomposed into two:

\[
S = f(\Delta \omega_d, \Delta a_d, K \omega_d, K a_d) - > \min ,
\]

\[
t = f(t_{\omega_d}, t_{a_d}, t_{K \omega_d}, t_{K a_d}) - > \min ,
\]

where \( S \) – total coordinate error, and \( t \) – total calibration time.
Herewith:

\[ t_{a\omega_{a}} = f(\Delta \omega_{a}) \] (13)

\[ t_{a\omega_{d}} = f(\Delta \omega_{d}) \] (14)

\[ t_{K\omega_{a}} = f(K\omega_{a}) \] (15)

\[ t_{K\omega_{d}} = f(K\omega_{d}) \] (16)

Generally, \( t_{a\omega_{a}} \) и \( t_{a\omega_{d}} \) can be measured together in a stationary position.

With minimal \( S \) and \( t \) first given, the first problem is solved and the Pareto set of admissible values is found for \( S \). Then, from the surface representing the given set, a set of extreme values corresponding to a given \( S \) is chosen. For it the task with finding parameters for an admissible \( t \) is solved. That is, if we accept the maximum permissible calibration time limit, then the solution to this problem will be a part of the set from the previous problem that meets the time requirements.

7. Experiments and mathematical modeling

The problem of achieving the maximum systematic zero drift of gyroscopes of 0.01 °/s is presented below. The solution to the problem will be the Pareto set \((k1, k2)\), when

\[ k1 \cdot \Delta \omega_{T, sys} + k2 \cdot \Delta \omega_{t} = 0.01 \] (17)

where \( k1 \) and \( k2 \) are conditional coefficients of decreasing the systematic value. Table 5 shows extreme ways to achieve the parameter:

| Error value | Instability during one run, duration, °/s (repetitions*time once, s) | Temperature instability, (repetitions*time once, s) | Total error (total time, min) |
|-------------|---------------------------------------------------------------|-------------------------------------------------|-----------------------------|
| Variant 1   | 0.01 (5*600)                                                  | 0 (60*600)                                      | 0.01 (650)                  |
| Variant 2   | 0 (25*600)                                                    | 0.01 (15*600)                                  | 0.01 (400)                  |

If you choose from a set \((k1, k2)\) according to outside criteria, it is necessary to take into account that the time spent on temperature instability with the same contribution is longer, that is, from the point of view of such an additional criterion, the second option is optimal.

We consider the problem of reaching the coordinate error of 300m. By mathematical modeling of the SINS algorithms operation [21] along the trajectory shown in figures 5 and 6, the values given in table 6 were obtained. Figure 5 shows the change of coordinate during the flight. Figure 6 shows change of angular velocity during the flight.

| Error value | Gyroscope zero drift °/s | Gyroscope SF error, % | Accelerometer zero drift, g | Accelerometer SF error, % |
|-------------|--------------------------|-----------------------|-----------------------------|---------------------------|
| Maximum permissible error at other zero | 0.018 | 0.15 | 0.02 | 0.18 |
Figure 5. The specified trajectory by the coordinates of the horizontal (a) and vertical (b) channels.

Figure 6. Specified trajectory based on measurements of vertical (a) and horizontal (b) gyroscopes.

Mathematical modeling along a certain trajectory of the aircraft showed that the contribution of variables to the total error of the coordinate is independent and has an approximately linear dependence on the magnitude of the error. Knowing these parameters, you can choose the most appropriate calibration option, taking into account the total time, labor intensity, and parameter instability. Figure 7 shows the Pareto set for the case when the errors of the accelerometer are equal to zero and the maximum possible errors of the gyroscopes are investigated.

3) Let us examine optimal quantitative-time calibration parameters for solving the problem from the previous paragraph. Let us introduce the restriction of \( t \leq 1700 \) min – total calibration time – we can make up inequality:

\[
t = N_1 \cdot t_{\Delta a_{ap}} + N_2 \cdot t_{K_{ap}} + N_3 \cdot t_{K_{Ap}} \leq 1700
\]

Let \( t_{\Delta a_{ap}} = 60 \) min, \( t_{K_{ap}} = t_{K_{Ap}} = 90 \) min. It is necessary to find the number of repetitions \( N_1, N_2 \) and \( N_3 \) for each parameter with values from the area defined in the previous step. Pareto set \( N_1, N_2 \) and \( N_3 \) for drift and nonlinearity will be the solution to the problem.

Taking into account the peculiarities of the MEMS sensors, the values given in table 7 were numerically determined.
Figure 7. The Pareto set of admissible errors of gyroscopes for zero errors of accelerometers.

Table 7. Example of calibration parameters for a set of selected maximum error values.

| Error value             | Gyroscope zero drift | Gyroscope SF error | Accelerometer zero drift | Accelerometer SF error |
|-------------------------|----------------------|--------------------|--------------------------|------------------------|
| Number of repetitions   | 10                   | 10                 | 10                       | 2                      |
| (time)                  | (600 min)            | (900 min)          | (600 min)                | (180 min)              |
| Residual value of systematic error (coordinate error component) | 0.002 °/s | 0.05 % | 0.002 g | 0.06 % |
|                         | (32.1 m)             | (87.9 m)           | (35.2 m)                 | (106.1 m)              |

Total time \( t = 1680 \) min. Achievable residual systematic error for which the calculation time was carried out \( S = 261.3 \) m. These calculations estimate only systematic error and do not take into account run-to-run instability and that i.e., after two months the calibration may be partially lost. Run-to-run instability may add \( \pm 300 \) m from gyroscope instability and \( \pm 300 \) m from accelerometer instability. Storage instability may add similar values. The value of sum coordinate instability \( \pm 1200 \) m for one minute flight we can call the finitely attainable accuracy, which exceeds the residual systematic \( (261.3 \) m) by \( \sim 5 \) times. It means that SINS based on MEMS sensors of such type cannot be improved without recalibration or external correction.

8. Discussion

Based on the above experimental data, it can notice that the main task of calibration is the optimal reduction of time and temperature variability in some parameters (third and fourth line in tables 3 and 4). The options for reducing one error due to the components are shown in table 5. The contribution of different errors to the distance error of the final SINS is shown in table 6 and figure 6. An example of choosing the least costly in terms of time errors from those indicated is given in table 7. Other variants are also possible — the given components may be unknown and unobservable, then their total value will have to be taken into account, nevertheless, the division indicated in formulas 5 and 6 will be useful for this. Calculation of each error contribution to the total deviation of the trajectory of the final SINS is labour-intensive (also computationally), but it fully justifies itself in serial production. The calculation of the time spent on the calibration of each error is conditional and in case
of serial production it should be used with considering the calculation of labor costs, taking into account the features of the equipment, its occupancy, etc.

Repetitive measurements of parameters such as zero drift and scaling factor are important for MEMS sensors as they have run-to-run instability (second line in tables 3 and 4) and that parameter will mean the least error in conditions of the best calibration.

Since MEMS sensors have the property of parameter drift from storage time (fifth line in tables 3 and 4), the proposed approaches can be useful for determining and finding the recalibration parameters. A feature of recalibration is the necessity to redefine only the systematic parameters, which does not require a new full calibration.

The proposed approach is a universal tool for estimating the calibration parameters of inertial measurement units on MEMS sensors. Ideally, it should be combined with some optimal method for estimating errors suitable for a particular type of problem [22]. Compared to works [9] and [12], a more general and formalized approach to achieving calibration parameters is proposed, which can be reasonably edited and controlled in terms of time and accuracy, if necessary. It is also worth noting that most of the works, including [9] and [12], do not take into account the peculiarities of the functioning of MEMS sensors, such as instability from turn on to turn on and instability from storage time. The proposed method offers a more plausible assessment of the accuracy of the calibrated gyro-inertial unit. Also, the proposed error model forces one to approach more carefully the mathematical methods for assessing errors. The use of optimal filters in the case of MEMS sensors gives only the optimal estimate of any parameter for a particular record. Since several time-spaced records are needed to estimate some parameters, post-processing techniques will be required.

9. Conclusion

The article discusses an approach that allows you to move from the requirements for a ready-to-use calibrated inertial measurement unit and known sensor errors to mathematically grounded calibration plan. The problem is divided into three typical problems, the sequential execution of which solves the general problem, and for a specific case of requirements, the problem can have an independent solution. These stages are: finding the parameters of explicitly specified requirements, finding implicitly specified requirements (e.g. indirectly specified requirements for permissible errors of the final object) and finding the optimal variant for calibration with limited time. Every stage may be represented as a multicriteria optimization task with a certain Pareto set as a solution.

The above methods are suitable for working with blocks on MEMS sensors, since they take into account their specific features. The considered examples can be useful for the cases of calibrating a batch of blocks used in unmanned aerial vehicles, since they clearly demonstrate a step-by-step transition from the errors of uncalibrated sensors and the permissible coordinate error of the navigation system on a specified trajectory to a calibration plan with estimated time and accuracy. The proposed approach also notes the change in the parameters of MEMS sensors during storage, which can be useful for finding the expiration date and need of recalibration.

References
[1] Alper S E and Akin T 2005 A single-crystal silicon symmetrical and decoupled MEMS gyroscope on an insulating substrate. J. Microelectromech. S. 14 (4) 707 doi: 10.1109/JMEMS.2005.845400
[2] Kaajakari V, Kiiham’aki J, Oja A, Sepp’a H, Pietik’ainen S, Kokkala V and Kuisma H 2006 Stability of wafer level vacuum encapsulated single-crystal silicon resonators. Sensors and Actuators A: Physical 130 42 doi: 10.1016/j.sna.2005.10.034
[3] Zotov S A, Simon B R, Sharma G, Trusov A A and Shkel A M 2014 Utilization of mechanical quadrature in silicon MEMS vibratory gyroscope to increase and expand the long term in-run bias stability. Proc. Int. Symp. on Inertial Sensors and Systems (ISISS) (Laguna Beach: IEEE) p 1-4 doi: 10.1109/ISISS.2014.6782536
[4] Junlong B, Wenjie Ch and Tao C 2013 Compensation for MEMS gyroscope zero bias stability. Proc. 2013 Chinese Automation Congress (Changsha: IEEE) p 744 doi: 10.1109/CAC.2013.677583

[5] Zaman M F, Sharma A, Hao Zh and Ayazi F 2008 A mode-matched silicon-yaw tuning-fork gyroscope with subdegree-per-hour Allan deviation bias instability. J. Microelectromech. S. 17(6) 1526 doi: 10.1109/JMEMS.2008.2004794

[6] Prikhodko I P, Nadig S, Gregory J A, Clark W A and Judy M W 2017 Half-A-month stable 0.2 Degree-per-hour mode-matched MEMS gyroscope. Proc. IEEE International Symposium on Inertial Sensors and Systems (INERTIAL) (Kauai, HI, USA: IEEE) p 15 doi: 10.1109/ISISS.2017.7935679

[7] Krylov A A and Veremeenko K K 2020 Comparative analysis of calibration variants for inertial measurement unit based on microelectromechanical system. IOP Conf. Ser.-Mat. Sci. 868 012037 doi: 10.1088/1757-899X/868/1/012037

[8] Panahandeh Fv G, Skog I and Jansson M 2010 Calibration of the accelerometer triad of an inertial measurement unit, maximum likelihood estimation and Cramér-Rao bound. Proc. 2010 Int. Conf. on Indoor Positioning And Indoor Navigation (Zurich: IEEE) doi: 10.1109/IPIN.2010.5646832

[9] Fang B, Chou Wu and Ding Li 2014 An optimal calibration method for a MEMS inertial measurement unit. International Journal of Advanced Robotic Systems 11 (2) 1 doi: 10.5772/57516

[10] Gu H, Su W, Zhao B, Zhou H and Liu Xi 2020 A Design methodology of digital control system for MEMS gyroscope based on multi-objective parameter optimization. Micromachines 11 (1) 1 doi: 10.3390/mi11010075

[11] Kupper S, Fiebelkorn R, Gedat, E Wagner Ph, Rothe F and Bodrova A 2020 Optimization of MEMS-gyroscope calibration using properties of sums of random variables Proc. 2020 IEEE Int. Symp. on Inertial Sensors and Systems (INERTIAL) (Hiroshima: IEEE) doi: 10.1109/INERTIAL48129.2020.9090077

[12] Yang H, Zhou B, Wang Li, Xing H and Zhang R 2018 A Novel Tri-Axial MEMS Gyroscope Calibration Method over a Full Temperature Range. Sensors 18 (9) 3004 doi: 10.3390/s18093004

[13] Prato A, Schiavi A, Mazzoleni F, Touré A, Genta G and Galetto M 2020 A reliable sampling method to reduce large sets of measurements: a case study on the calibration of digital 3-axis MEMS accelerometers. Proc. 2020 IEEE Int. Workshop on Metrology for Industry 4.0 & IoT (Rome: IEEE) doi: 10.1109/MetroInd4.0IoT48571.2020.9138293

[14] Joo J W and Choa S H 2007 Deformation behaviour of MEMS gyroscope sensor package subjected to temperature change. IEEE Transactions on Components and Packaging Technologies 30 (2) 346 doi: 10.1109/TCAPT.2007.897948

[15] Gulmammadov F 2009 Analysis, modeling and compensation of bias drift in MEMS inertial sensors. Proc. 4th Int. Conf. on Recent Advances in Space Technologies (Instanbul: IEEE) p 591 doi: 10.1109/RAST.2009.5158260

[16] Nagel C, Ante F, Putnik M, Classen J and Mehnerg J 2016 Characterization of temperature gradients on MEMS acceleration sensors. Procedia Engineer. 168 888 doi: 10.1016/j.proeng.2016.11.298

[17] Kirkko-Jaakkola M, Collin J and Takala J 2012 Bias prediction for MEMS gyroscopes IEEE Sensors Journal 12 (6) 2157 doi: 10.1109/JSEN.2012.2185692

[18] Trusov A A, Prikhodko I P, Rozelle D M, Meyer A D and Shkel A M 2013 PPM precision self-calibration of scale factor in MEMS Coriolis vibratory gyroscopes. Proc. 17th In. Conf. on Solid-State Sensors, Actuators and Microsystems (Transducers & Eurosensors XXVII) (Barcelona: IEEE) p 2531 doi: 10.1109/Transducers.2013.6627321
[19] Antonov D A, Veremeenko K K, Zharkov M V, Zimin R Yu, Kuznetsov I M and Pron'kin A N 2016 Test complex for the onboard navigation system of an airport ground vehicle J. Comput. Sys. Sc. Int.55 832 doi: 10.1134/S106423071604002X

[20] Deb K, Agrawal S, Pratap A and Meyarivan T A 2000 Fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II International Conference on Parallel Problem Solving from Nature PPSN VI (Paris: Springer) p 849

[21] Veremeenko K K and Savel’ev V M 2013 In-flight alignment of a strapdown inertial navigation system of an unmanned aerial vehicle J. Comput. Sys. Sc. Int. 52 106 doi: 10.1134/S1064230712060147

[22] Nemec D, Janota A, Hruboš M and Šimák V 2016 Intelligent real-time MEMS sensor fusion and calibration IEEE Sensors Journal 16 (19) 7150 doi: 10.1109/JSEN.2016.2597292