**Calibration of an inertial measurement unit at changing temperature with simultaneous estimation of temperature variation coefficients:   
a case study on BINS-RT**

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**Abstract**

**Keywords**: calibration, BINS-RT, changing temperature

*The work aims to present the results of the application of previously developed calibration technique that allows conducting calibration experiments at changing temperature with simultaneous estimation of temperature variation coefficients, to an inertial measurement unit of navigation grade, namely BINS-RT of JSC "Inertial Technologies of Technocomplex". The whole dataset obtained from the inertial sensors in calibration experiment is processed by a single estimation algorithm, i.e. Kalman filter, there is no requirement for some strict sequence of operations to be carried out during the calibration experiment, and the estimates for calibration accuracy are computed along with calibration parameters. The absence of stringent requirements on the experiment makes the method easy to transfer between different manufacturers, IMU designs and bench equipment configurations. The experiment must simply provide some static period for the conventional initial alignment of the IMU, followed by some rotation around each instrumental axis set nearly to the horizon without a special rotation profile, but with the magnitude of the angular rate close to a real IMU application. Simultaneous changing of temperature strong enough for the temperature variations of inertial sensor errors to manifest itself is also expected in the experiment, with no wait for the thermal equilibrium inside the IMU. A case study on BINS-RT shows that calibration experiments can go under the continuous changing of temperature inside the desired temperature range, to halve the time required for the whole calibration process compared to traditional temperature profile.*

**Introduction**

The traditional approach to calibrate temperature variations of inertial measurement unit (IMU) instrumental error parameters implies a series of experiments conducted under the constant temperature at different temperatures. After the desired parameters are estimated for each temperature value, one approximates the temperature variations using some analytic function, e.g. by piecewise linear one or cubic polynomial. For the aviation type IMU, including BINS-RT designed by JSC "Inertial Technologies of Technocomplex" (ITT), the accuracy requirements make the condition of constant temperature to be crucial: the temperature of inertial sensors in calibration experiment should not change by more than fraction of a degree. At the same time, the operational temperature range of IMUs of this kind is rather wide. This means that one should perform the calibration in the same range, i.e. at many temperatures.

Inertial measurement units for aviation applications are complex instruments, which include vacuum chambers containing inertial sensing elements and mechanical decoupling of sensor array from the housing by snubbers. Due to the above factors, heat exchange processes inside the IMU are relatively slow. As a result, the temperature usually requires hours to set constant. Only after that, the actual calibration operations begin. Thus, nearly a half of the whole calibration time consists of thermal transitions, which still can be used for test purposes, but not for the calibration itself.

In this work we present a case study of using the calibration technique previously tested for low-grade IMUs under changing temperature [1], complemented by measurements from the turntable, which had been before analyzed for effect on calibration performance in simulation [2], this time on BINS-RT calibration performed on a two-axis Accutronic motion simulator in ITT. The basis of the method lies in the fact that when a motion of the IMU is limited to rotation only, we can obtain its attitude using several sources of information, namely using accelerometer measurements, gyro outputs and rotation table readings. Under the very general conditions on the rotation profile, every systematic term in IMU sensor errors manifests itself into attitude error in a unique way, allowing to distinguish them from each other and to estimate their magnitude. Apart from having less stringent requirement on the calibration experiment, the other advantage of the method lies in using the single uniform estimation algorithm (i.e. Kalman filter) for the whole measurement dataset. The algorithm does not require any change or adjustment upon changing the profile of experiment or upon the transition from one of its phase to another. This advantage permits to transfer the calibration technology easily between different IMU designs (within the same accuracy grade) and different testing equipment, engaging additional facilities when needed, even if they do not allow performing exactly the same experiments. In addition, the ability to carry out calibration at changing temperature nearly halves the duration of the whole experiment as compared to the traditional approach assuming the calibration itself only after a wait for the thermal equilibrium inside the IMU.

**Mathematical models of calibration problem**

The detailed description of mathematical formulation for calibration problem one can find in [1]. We introduce the state vector of a nonautonomous linear dynamical system with measurements, which includes the following components:

* small errors of IMU attitude determination using gyro measurements;
* constant terms of gyro null drift;
* temperature coefficients of gyro null drift;
* constant terms of accelerometer null bias;
* temperature coefficients of accelerometer null bias;
* constant terms of accelerometer scaling error;
* temperature coefficients of accelerometer scaling error;
* small angular misalignments of accelerometer sensitive axes respect to instrumental frame;
* constant terms of gyro scaling error;
* temperature coefficients of gyro scaling error;
* small angular misalignments of gyro sensitive axes respect to instrumental frame;
* small angular misalignments between instrumental frame and the faceplate of the rotation table;
* coordinates of the center of rotation in the instrumental frame, if unknown or not accurate enough;
* time lags between measurements from inertial sensors and the rotation table, if unknown;
* stiffness parameters of sensor array damping system, if relevant.

All state vector components, except orientation errors, are assumed constant within every single experiment. The linearized model mechanization equation for the state vectorhas the form:

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| --- | --- |
|  | (1) |

wherestands for stochastic perturbations considered as independent gaussian white noises having known order of magnitude for intensity, andis a system matrix, having most of the elements equal to zero.

The difference between the true reaction force in the local-level frame and its computed value obtained from accelerometer readings and gyro-derived orientation serves as system measurements:

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|  | (2) |

where  denotes the 3-dimensional measurement vector,  stands for gyro-derived attitude matrix,  represents accelerometer output and  implies the magnitude of local gravity acceleration. Measurements from the rotation table usually come less frequently than inertial data and sometimes appear to be unreliable due to data synchronization issues. In case they are present and credible, we compose additional set of measurements describing the difference between gyro-derived attitude matrix and orientation based on the turntable encoders:

|  |  |
| --- | --- |
|  | (3) |

with  for the set of three new measurements and  for the attitude matrix computed using the output of turntable axes encoders. Both measurement combinations relate linearly to the state vector, with small terms of the second and higher order ignored:

|  |  |
| --- | --- |
|  | (4) |

where ,  are appropriate matrices and ,  standing for stochastic error components which are treated as independent gaussian white noises similarly to  above. To estimate the state vector of the system introduced by equations (1–4), we use conventional Kalman filter implemented in the covariance square root form, which is a standard technique traditionally used for problems of this kind.

The calibration experiment itself starts with initial alignment for obtaining initial attitude matrix, followed by a sequence of rotations for several hours. Rotation rate should reach the magnitude of that in a real IMU application. When rotating around a specific instrumental axis, the last is preferred to be nearly horizontal. Simultaneously, the temperature in a thermal chamber changes, causing the temperature of inertial sensors inside the IMU to alter by 5–10 degrees Celsius. After the rotation and temperature change cycle completes, the calibration proceeds immediately to the new temperature interval, where the process repeats. Reference [3] and practical experience indicate that in an experiment of this kind, the introduced linear dynamical system becomes observable, and all state vector component estimates attain the desired accuracy.

**Calibration results for BINS-RT at changing temperature**

The specific rotation and temperature changing profile shown below is accepted for IMU calibration in ITT. Fig. 1 demonstrates angular rate measurements and temperature sensor outputs from BINS-RT in a typical calibration experiment.

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| Fig. 1. Rotation profile and temperature variation inside BINS-RT in calibration experiment. |

Apart from the actual rotations around the horizontal axis, every calibration cycle contains several short static positions with different orientations. Due to data transfer hardware issues and synchronization concerns, the measurements from the rotation table appear to be valid only within these stationary intervals.

Temperature variation of gyro parameters in BINS-RT turned out to be close to zero and the most significant effect the temperature exerts on inertial sensors manifests in accelerometer measurements. Fig. 2 shows the calibration results for BINS-RT accelerometer parameters. Temperature variations predicted in each experiment shown by dotted lines meet well the true temperature variations obtained from the whole calibration sequence. We also see that temperature intervals between the consecutive experiments satisfy the assumption of linear temperature variations within each single experiment. Further testing of the IMU indicate that average measurement errors after calibration do not exceed 0.01 deg/hour for ring laser gyroscopes and 2∙10−4 m/sec2 for accelerometers, matching the typical values for the considered accuracy grade of navigation system.

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| Fig. 2. Calibration results for accelerometer parameters obtained from experiments at changing temperature in six temperature subranges. Dotted lines show predicted temperature variations for temperature coefficient estimates in each experiment along with 1-intervals. |

**Conclusions**

The results of BINS-RT calibration using the method under consideration [1–2] prove its feasibility for aviation grade inertial navigation systems in experiments with temperature changing. It is expedient to divide the operational temperature range into several intervals of 5–10 degrees Celsius each. On the one hand, this size of interval allows the temperature variations to manifest itself to a considerable extent; and on the other hand, it keeps these variations close to linear.

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