Accuracy improvement of inertial navigation by special methods of measurements using microelectromechanical systems

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Abstract. The article is devoted to the description of algorithmic mechanism devised for increasing accuracy of inertial navigation based on the use of low-priced (up to 1000 usd) microelectromechanical measuring systems installed on small and mini-aircraft. The proposed algorithms include a series of error model parameters updating operations, which are used to negate inaccuracy occurred upon conducting measurements and their further utilization. It is shown that not only the algorithms proposed by the authors are capable to massively increase accuracy of navigation in comparison with the unprocessed initial navigational information obtained from the measuring devices, but also allow using of low-priced microelectromechanical systems for brief autonomous navigation by integrating aircraft reference motion equations.

1. Introduction
Modern civil and military aircraft are usually equipped with a huge variety of navigation gauges, including inertial measuring devices – optoelectronic gyroscopes and accelerometers, which are considered to be the basis of strapdown inertial navigation system (SINS) [1, 2]. These devices allow high accuracy of measurements whilst maintaining autonomous navigation. However, due to high cost and unavailability to common consumers such equipment is not utilized neither on small and amateur aircraft, nor on modern UAVs. Cheap and small aircraft are usually equipped with inertial measuring devices, produced with high-sensitivity microelectromechanical components [3]. They are featuring low price, variety, relatively simple setup and possibility to integrate with the aircraft software for navigational needs. At the same time there are a number of issues preconditioned by the peculiarities of its utilization, which are: substantial errors, measurement noise, measurement error parameter drift [4], all of which leads to the accumulation of critical navigation errors upon attempting to integrate motion equation and calculating reference trajectory onboard solely by SINS in autonomous mode. All these factors lead to a severe decrease in the possibility of practical utilization of low-priced microelectromechanical systems (MEMS) onboard.

Therefore, cheap MEMS have prospects of them being used on manned aircraft only under the condition of them enjoying higher accuracy and reliability. Without cost increase and necessity to integrate with other onboard measuring devices [5, 6] this goal can only be reached by researching specialized algorithms and software, for example [4, 7], which are capable of conducting intelligent adaptive processing of initial navigation data and updating error models of measuring of a specific device with the considered accumulated statistics. It is obvious that in order to maintain constant increase of navigation measurements accuracy throughout target function – flight – it is necessary for the software
bearing to work simultaneously with the algorithms for navigation measurements analysis above stated functions. In order to create such algorithm it is essential to elaborate the nature of processes, which lead to the deterioration of accuracy of navigation measurements, conducted by inertial MEMS, then draw up adequate models of errors with various nature. It is now necessary to look into the authored thesis through the example of software designed to increase accuracy of navigation solution with accelerometers manufactured by "Analog Devices" company.

2. Methods
Mathematical model of errors occurring in various microelectromechanical measuring devices is formed through the analysis of their operating principles and related documentation by modifying an alternate version presented in [8]:

\[
\Delta a = a_0(t) + a_1(t, a_r) + K_1(a_r) + K_2(a_r) + a_2(u, t) + a_3(t)
\]

being \( t \) – moment of measuring, \( a_1 \) – true value of acceleration (real), \( K_1 \) – nonlinearity factor of accelerometer transfer-function, \( K_2 \) – quotient of accelerometer scale range error consideration, \( a_0 \) – zero shift, \( a_1 \) – random process describing behavior of the device's noise, \( a_2 \) – a set of harmonics characterizing device's noises caused by vibrations and other external fluctuations but not linked to the useful signal \( a_r \), \( u \) – parameter-function to define input control, which amplifies microelectromechanical device measurement errors during flight, \( a_3 \) – a measurement error "outbreak" outside of the area characterized by the density of measuring error distribution. It is necessary to point out, that such model is not complete, as it does not include a number of components, for example, related to non-orthogonality of measuring device sensitive axes etc.

The analysis of the formula (1) allows pointing out several traits of accelerometer measuring errors, which can be represented as a random process or a random value. If they are not eliminated when resolving navigation task, ultimate error becomes rather substantial, and the attempt to integrate motion equation will shortly (up to 5 mins) lead to an exponential divergence of the solution. To avoid such divergence it is necessary to utilize adaptive mechanisms of initial navigation data processing as to eliminate fixed and random measurement errors before the data is integrated and used in the navigation system itself. It is necessary to add, that engine start and initiation of the flight cause such massive disruption of measurements conducted by cheap microelectromechanical gyroscopes and accelerometers, that using such measurements for navigation calculations to integrate vessel trajectory becomes literally senseless. Therefore, software is to be designed and tested statically right before the flight, as well as dynamically after engine start and ascent. The authors are going to look into main calculations, performed by the authors with initial navigation data received upon aircraft's pre-launch activation, in order to evaluate error parameters and models which occur when the engine is already started and therefore accelerometer is receiving substantial vibration interference.

- definition of zero shift \( a_0 \) (1). Zero bias estimate is conducted through the processing of selection of measurements and evaluation of mathematical expectation. Its value is then deducted from the initial navigation data which allows to negate this fixed error [5]. After processing a map of shifts for the aircraft's static and pre-launch activation is drawn up, which as well allows to evaluate zero shift's divergence confidence interval.

- definition of zero drift \( a_1 \) (1) and forming the fixed error trend of measurements. The trend parameters are selected for three variants of approximation: linear, square and cubic, selected on the basis of minimal ultimate dispersion of the initial navigation data drift on specific timeline relating to the chosen model of the trend. The length of the functional timeline is defined experimentally on the basis of the trend's behavior and zero drift evaluation – statically for a specific model of the device. In order to accumulate corresponding statistics it is necessary to test-run the two modes – aircraft static after engine start but before the flight and the flight itself. The drift parameters are evaluated on the basis of Kalman estimator [9] by processing external navigation data, which allows updating parameters of
model (one of three kinds) during flight for their further use when external data is unavailable. The form of approximating function is selected on the basis of minimal error of polynomial extrapolation relating to zero drift values calculated subsequently onboard.

- eliminating gravitational acceleration projections on the axes of measuring devices [8]. This operation is conducted by drawing up a system of equations reflecting connection between calculation in X, Y, Z channel and the angle of high-sensitivity device base (it is considered that the device axes are orthogonal), occurred due to the noncollinearity between gravitational acceleration vector and vertical axle of the accelerometer, that is why the stated error is not included directly in (1), but still exists.

- outbreak evaluation and their elimination upon processing of measurements. "Outbreaks" are calculation errors, which are irrelevant to the realities and exceed certified error values of a specific measuring device defined by the manufacturer. Upon exceeding measurement estimates by K·2·σ (σ being sum of noise error and fixed error standard deviations, K – confidence factor, by default equals 1). Isolated measurements are therefore excluded from the further calculations and processing.

- engine vibration noises filtering a2 (1) is implemented by processing initial navigation data with the use of first-order aperiodic filters, whose cutoff frequency is defined by the type of powerplant installed on the aircraft and spectral density of the noise, caused by the fluctuations of moving parts. Due to the spectral density being both a function of time and of the aircraft parameters during flight (which is predefined by the existence of transition modes in engine operation), a more complex noise filtration a2 is conducted takes into account reference motion model type and control model type. Just as a1, noise parameter update (the type of approximating processes spectral density) during flight is implemented with the specific traits of the aircraft taken into account by accumulating statistics and processing external calculations from other sensors in the onboard algorithm.

All the values of the device errors obtained through the above stated procedure are deducted from the calculations of the accelerometers, which are then transferred to the input of navigation system.

3. Elaborated method efficiency estimation
In order to evaluate the efficiency of the drawn-up algorithms and software a number of experiments were held, centering around consecutive resolution of navigation task in the channel of the aircraft vertical motion (ascend), during which initial navigation data is recorded and processed on every iteration with the use of the above stated algorithms. According to the results, continuous update of the model (1) quotients and parameters allowed substantially increasing the accuracy of the integration to implement aircraft autonomous navigation. The example of algorithms in use is shown in Figure 1. During experiments the authors found out, that altitude evaluation error in vertical channel in static with engines online increased two-fold and reached about 1 cm after 5 mins of the systems operation with the use of cubic polynomial, which approximates accelerometer zero drift, 20 cm without updating device zero drift, and 1 m without any use of the algorithms stipulated in section 2.

The experiment results during flight are given in Figure 2. The figure shows the evolution of the aircraft altitude error during brief autonomous flight featuring multiple low-amplitude ascend and descend. Dash line stands for integrating measurements without use of algorithms. The other two curves show the trajectory with the use of the algorithms stipulated in section 2, whose implementation is characterized either by the use of linear or of polynomial interpolation of zero drift in high-sensitivity devices. The application of these algorithms without interpolating device zero drift never lead to adequate results and is close to behavior of the dash-line relation.
Figure 1. Navigation errors. Without use of algorithms – dash line; using algorithms without polynomial to describe zero drift – dotted line; using all of the algorithms – dot-dash line

Figure 2. Navigation errors. Without use of algorithms – dash line; using all of the algorithms as well as cubic polynomial to describe zero drift – dotted line; using all of the algorithms as well as linear polynomial to describe zero drift – dot-dash line

4. Conclusion
It is shown that the algorithms devised by the authors are capable to substantially (two-fold and higher) increase accuracy of navigational sighting whilst having low-priced inertial measurement devices installed on small aircraft. Therefore, the proposed algorithms and software allow implementing autonomous navigation over 5 mins without any support on behalf of other navigation systems, including satellites, solely basing on the use of cheap inertial devices with high-sensitivity MEMS’ components. Moreover, these algorithms can be subject to various upgrades, including their possible adaptation to particularities of specific hardware installed onboard of a real aircraft. A built-in mechanism of evaluating inherent accuracy and the level of the result probability belief can be viewed as a rational supplement to the above stated algorithms. Another aspect of their future improvement is adaptation to the use in an aircraft's maneuver flight modes.

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