Attitude sensors relative angular misalignment estimation in integrated navigation systems

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Abstract. When using modern navigation systems as part of an on-board system, the navigation task can be solved in several ways: using positional, velocity and angular corrections, and systems using measurements of various physical nature—radio, such as short-range and long-range navigation radio systems, GLONASS/GPS satellite global navigation systems, optical—celestial navigation systems—can operate as correctors. The best performance of INS and its sensors (gyroscopes and accelerometers) errors estimation can be obtained when all types of correction are implemented simultaneously. At the same time, it is particularly difficult to implement correction according to attitude parameters due to the fact that the measuring axes of the INS and correctors may not match on board of moving objects. Such a mismatch is commonly called relative angular misalignment. The paper considers a possible approach to the attitude sensors relative angular misalignment estimation in integrated navigation systems (NS), carried out in motion when the NS is in operating mode.

1 Introduction

Most modern and prospective mobile objects navigation and attitude systems are a complex ones, the software and algorithmic support of which carries out complex processing of measuring information from onboard sensors and systems. Depending on the generation and measurements processing approach, the following classification of schemes for algorithms design has now developed [1, 2]: separate, loosely coupled, tightly coupled and deeply integrated. The last three of these approaches pretend the differences generation in the sensors and systems outputs (if necessary, after averaging, setting to a unified coordinate frame and dimensions by initial processing), combined as part of an integrated navigation system (NS), with the subsequent state vector errors estimation, usually using a Kalman filter.

In this case, the errors of the NS subsystems are included in the state vector, which are described by the corresponding mathematical models. In the vast majority of cases, the inertial navigation system (INS) acts as the NS information core, which is highly informative (the ability to calculate a complete list of motion parameters: coordinates, velocities, attitude parameters), autonomy, and a high frequency of data output. In this regard, the remaining NS sensors and systems are commonly referred to as INS correctors. Depending on the type

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of correctors, the following types of INS correction can be considered: positional (by coordinates), by velocity and angular attitude parameters.

The best performance of INS and its sensors (gyroscopes and accelerometers) errors estimation can be obtained when all types of correction are implemented simultaneously. At the same time, it is particularly difficult to implement correction according to attitude parameters due to the fact that the measuring axes of the INS and correctors may not match on board of moving objects. Such a mismatch is commonly called relative angular misalignment. It is possible to minimize angular misalignment by increasing the accuracy of sensors and systems adjustment during their installation on board. However, the adjustment process also has finite accuracy and, in addition, is difficult or impossible in some cases. As examples of the INS correction by angular attitude parameters usage, the following can be mentioned: multi-antenna inertial-satellite navigation systems [3, 4], optical-inertial navigation systems [5–7], astroinertial navigation systems [8], INS initial alignment from the onboard navigation system of the carrier in motion [9–11], etc. The work describes a possible approach to the relative angular misalignment estimation of the NS attitude sensors, carried out in motion when the NS is in operating mode.

2 Mathematical models

The system state equation is presented in the following form:

$$\dot{\bar{X}} = F \cdot \bar{X} + G \cdot \bar{W}, \tag{1}$$

where F is the dynamics matrix, $\bar{X}$ is the system state vector, G is the noise matrix of the system, $\bar{W}$ is the system noise vector.

The state of the system is estimated using the measurement vector $\bar{Z}$:

$$\overline{Z} = H \cdot \overline{X} + \overline{V}, \tag{2}$$

where H is the measurements matrix, $\overline{V}$—the measurement noise vector.

It is proposed to include the following parameters to the state vector [1]:

$$\overline{X} = [X_{INS} \quad \Delta \quad A]^T. \tag{3}$$

Here $\Delta_{INS} = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad \alpha \quad \beta \quad \gamma]$—coordinates, velocity projections and attitude angles errors determining by INS [11]; $\Delta = [\Delta\Omega_1 \quad \Delta\Omega_2 \quad \Delta\Omega_3 \quad \Delta n_1 \quad \Delta n_2 \quad \Delta n_3]$—gyros and accelerometers errors constant components (when extending the model of sensor errors, the state vector can also be extended by corresponding components) $A = [\psi^{ma} \quad \vartheta^{ma} \quad \gamma^{ma}]$—relative angular misalignment parameters between the INS and the attitude angles corrector frames.

The measurement vector in this case will have the following form:

$$\overline{Z} = [\delta\Phi \quad \delta U \quad \delta\Psi], \tag{4}$$

where $\delta\Phi = [\delta\varphi^{INS} - \delta\varphi^{C} \quad \delta\lambda^{INS} - \delta\lambda^{C} \quad \delta h^{INS} - \delta h^{C}]$—the difference in coordinate outputs of the INS and the corrector, $\delta U = [\delta U_E^{INS} - \delta U_E^{C} \quad \delta U_N^{INS} - \delta U_N^{C} \quad \delta U_Z^{INS} - \delta U_Z^{C}]$—the difference in velocities projections outputs of the INS and the corrector $\delta\Psi = [\delta\psi^{INS} - \delta\psi^{C} + \psi^{ma} \quad \delta\vartheta^{INS} - \delta\vartheta^{C} + \vartheta^{ma} \quad \delta\gamma^{INS} - \delta\gamma^{C} + \gamma^{ma}]$—the difference in heading, pitch and roll angles outputs of the INS and the corrector.

The dynamics matrix F is designed on the basis of the INS and its sensitive elements error model [11] and has the following form:

$$F = \begin{bmatrix} 0_{3\times3} & I_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} \\ F_1 & F_2 & F_3 & C_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & 0_{3\times3} & F_4 & 0_{3\times3} & C_{3\times3} \\ & & 0_{6\times18} & & \end{bmatrix}, \tag{5}$$

$$F_1 = \begin{bmatrix} (\Omega_Y^2 + \Omega_Z^2 - \omega_0^2) & \dot{\Omega}_Z + \Omega_X\Omega_Y & -(\dot{\Omega}_Y + \Omega_X\Omega_Z) \\ -(\dot{\Omega}_Z + \Omega_X\Omega_Y) & (\Omega_X^2 + \Omega_Z^2 - \omega_0^2) & \dot{\Omega}_X - \Omega_Y\Omega_Z \\ \dot{\Omega}_Y + \Omega_X\Omega_Z & -(\dot{\Omega}_X - \Omega_Y\Omega_Z) & (\Omega_X^2 + \Omega_Y^2 + 2\omega_0^2) \end{bmatrix},$$

$$F_2 = \begin{bmatrix} 0 & 2\Omega_Z & -2\Omega_Y \\ -2\Omega_Z & 0 & 2\Omega_X \\ 2\Omega_Y & -2\Omega_X & 0 \end{bmatrix}, \quad F_3 = \begin{bmatrix} 0 & n_z & -n_y \\ -n_z & 0 & n_x \\ n_y & -n_x & 0 \end{bmatrix}, \quad F_4 = \begin{bmatrix} 0 & \Omega_Z & -\Omega_Y \\ -\Omega_Z & 0 & \Omega_X \\ \Omega_Y & -\Omega_X & 0 \end{bmatrix},$$

where ω_0—INS errors oscillation natural frequency, Shuler frequency $\omega_0 = 1.25 \cdot 10^{-3}$ s^{-1}, $\Omega_{X,Y,Z}$, $\dot{\Omega}_{X,Y,Z}$—absolute angular velocity vector of the base coordinate frame projections and its derivatives; $n_{X,Y,Z}$—specific force projections vector, $C_{3\times3}$—DCM between the body fixed frame (BFF) and local level frame (LLF). The parameters of relative angular misalignment are assumed to be constant. When forming the matrix H, a certain difficulty is presented by the fact that in the accepted model of the INS errors, attitude errors includes calculating the basic coordinate frame (CF) errors and attitude measurement frame relative to this basic CF errors. To solve this problem, when designing the matrix H, a link matrix between the INS attitude errors according to the model and the errors of the INS in determining heading, pitch and roll angles was formed. The structure of the system noise vector includes random components of the INS sensors errors, and the structure of the measurement noise vector includes random components of the correctors errors.

To estimate the state vector, an option of the discrete optimal Kalman filter is used, written in the Joseph form [10], which provides increased protection against computational divergence.

3 Simulation and car tests results

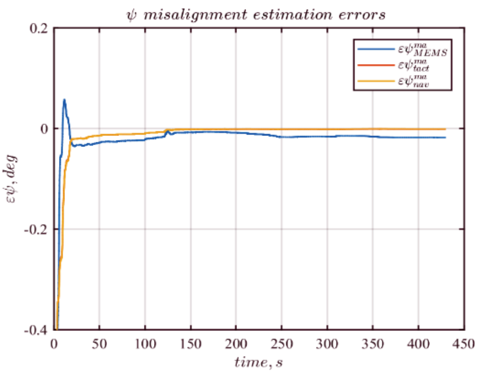
The study of operability and estimation of the proposed approach to determine the relative angular misalignment of attitude sensors achievable performance was carried out using simulation and post-processing of measurement records of a full-scale car test.

As the tested system a multiple antenna inertial-satellite integrated navigation system was used. Simulation scenarios assumed the use of INS sensors of different accuracy grades (from microelectromechanical (MEMS) up to navigation grade), a different number of GLONASS and GPS antennas, with different distances between them as long as the influence of trajectory during the car tests was studied.

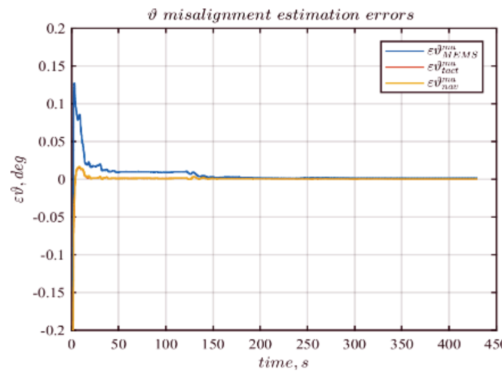
Preliminary simulation results showed the potential possibility of using the proposed approach to estimate the relative angular mismatch of attitude parameters in motion when the system is in operating mode. The section will provide as well as the simulation and the car test results as the most illustrative ones to study the efficiency of a proposed approach to estimate the relative angular mismatch of attitude parameters in motion when the system is in operating mode under selected scenarios and experimental conditions.

As it was mentioned above car test was carried out with the use of NS designed at the department [12]. NS was mounted in the MAI Navigation System Car Testbed inside a car roof rack (figure 1) [13]. Reference attitude parameters were obtained from Novatel SPAN GNSS

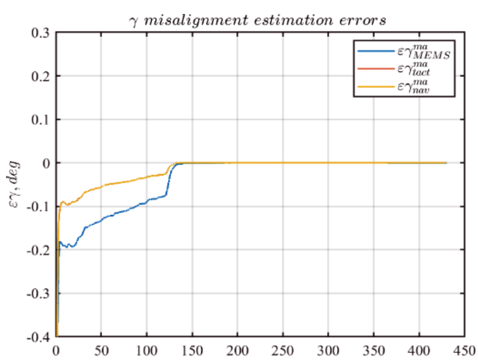
Figure 1. MAI Navigation System Car Testbed



(a)



(b)



(c)

Figure 2. Simulation results (scenario 1)

Inertial Navigation System measurements and geodetic base GNSS receiver measurements postprocessed by NovAtel Inertial Explorer software.

Figures 2–4 show the estimation errors of angular misalignment $\varepsilon\psi^{ma}$, $\varepsilon\vartheta^{ma}$, $\varepsilon\gamma^{ma}$, $\varepsilon\psi^{ma}$, $\varepsilon\vartheta^{ma}$, $\varepsilon\gamma^{ma}$—in heading, pitch and roll angles measurements) in a multiple antenna inertial-satellite integrated navigation system, where in case of simulation an inertial navigation system from its structure was misaligned for a 1 degree to all three angles relative to a multiple antenna satellite navigation system and a multiple antenna inertial-satellite integrated navigation system and NS, designed by the department in case of car tests relatively misaligned the same way physically to a random angles.

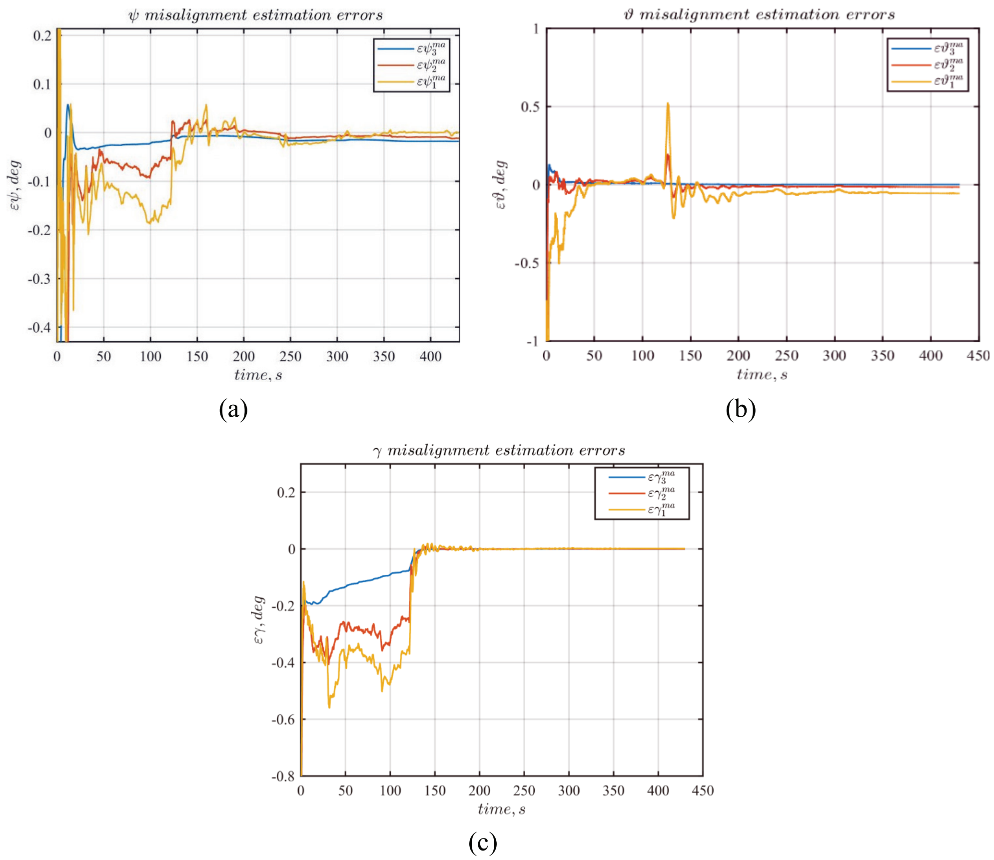


Figure 3. Car tests results (scenario 2)

To study the operability and estimation of the proposed approach to determine the relative angular misalignment of attitude sensors achievable performance three scenarios were designed:

- 1 (simulation)—in this scenario of simulation the output of a multiple antenna inertial-satellite integrated navigation system were generated using mathematical models, presented above. An inertial navigation system from its structure was misaligned for a 1 degree to all three attitude angles relative to a multiple antenna satellite navigation system. The trajectory included low and high maneuverable sections of object movement with different dynamic from a chosen range of navigation parameters—velocities and attitude angles. The feature of this scenario is the INS sensors of different accuracy grades (from micro-electromechanical (MEMS) up to navigation grade) influence study.
- 2 (car tests)—in this scenario of car tests an object—city car with a NS mounted in a roof rack was driving a complex trajectory with as well as low maneuverable with straightforward movement sections and complex maneuverable with S-types movement sections trajectories (in the streets of Moscow city). The feature of this scenario is the difference of base length between onboard antennas influence study, which changed in the range of 1 to 3 meters for a similar trajectories of movement and the same experimental conditions.
- 3 (car tests)—this scenario studies the trajectory type influence on an approach to determine the relative angular misalignment of attitude sensors achievable performance.

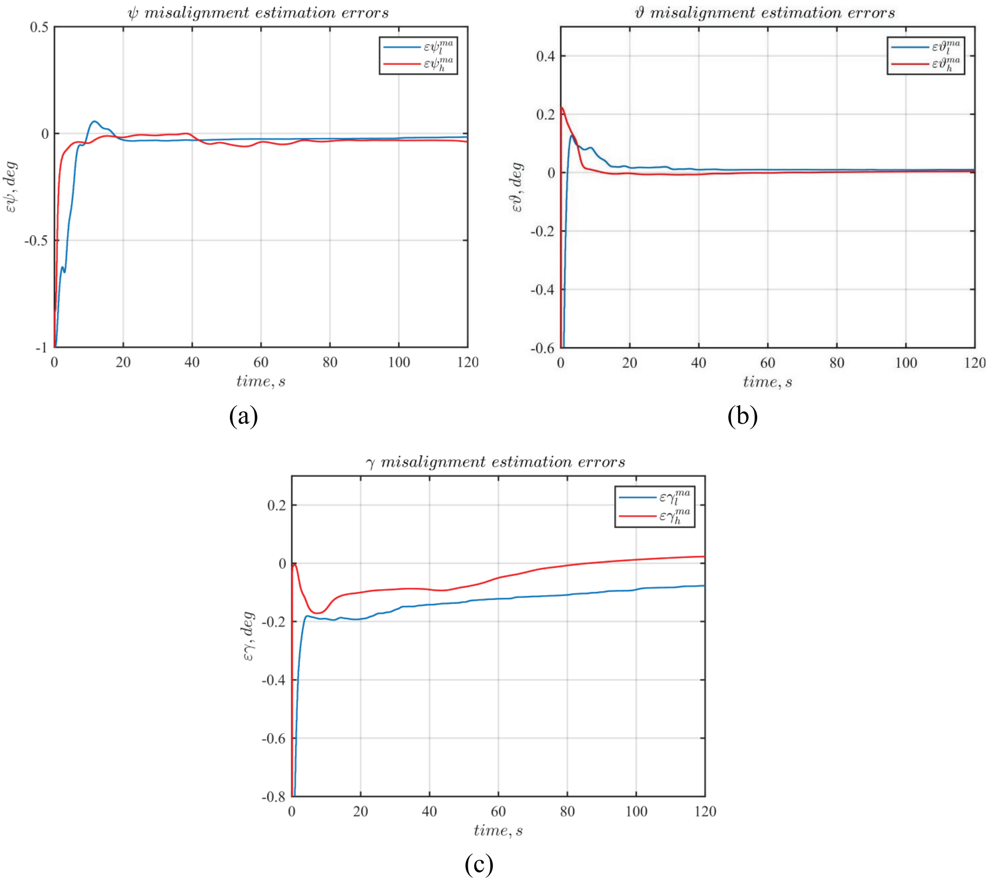


Figure 4. Car tests results (scenario 3)

Table 1 below shows the summary (simulation and car tests) levels of achieved accuracy at the certain timestamps (10, 60 and 160 s respectively), table 2 in the section below shows the summary (car tests) levels of achieved accuracy at the certain timestamps (10, 60 and 120 s respectively) for the scenarios implemented above.

4 Results analysis

The study of different grade IMUs in simulation (scenario 1) shows the absence of its use necessity better than tactical grade. In figure 1 it can be seen red and yellow lines are actually merged into one, and the absolute level of ultimate accuracy differs insignificantly (in the fourth decimal place in heading misalignment and in the fifth decimal place in two other angles).

The study of different base length between the 3 antennas of integrated navigation system (scenario 2) shows its influence on ultimate accuracy of estimation. The most widely spaced antennas relative location (3 meters) changes the qualitive nature of estimation process—more smoothed without sharp outliers during the initial transition process.

It is necessary to note the feature of trajectory influence on a performance of proposed approach to estimate the relative angular mismatch of attitude parameters in motion when

Table 1. Simulation and car test results (scenarios 1 and 2)

Scenario	Time, s	10			60			160		
1	c	*nav*	*tact*	*MEMS*	*nav*	*tact*	*MEMS*	*nav*	*tact*	*MEMS*
	$\varepsilon\psi^{ma}$, deg	0.0185	−0.182	−0.0184	−0.012	−0.012	−0.025	−0.001	−0.001	−0.007
	$\varepsilon\vartheta^{ma}$, deg	0.013	0.014	0.067	0.001	0.009	0.009	0.0009	0.0009	0.002
	$\varepsilon\gamma^{ma}$, deg	−0.09	−0.19	−0.19	−0.04	−0.04	−0.12	−0.0002	−0.0002	−0.008
2	l, m	3	2	1	3	2	1	3	2	1
	$\varepsilon\psi^{ma}$, deg	0.017	−0.72	−0.83	−0.02	−0.06	−0.11	−0.007	0.05	0.02
	$\varepsilon\vartheta^{ma}$, deg	0.06	−0.19	0.07	0.009	0.009	0.02	0.002	−0.003	−0.02
	$\varepsilon\gamma^{ma}$, deg	−0.19	−0.25	−0.28	−0.12	−0.35	−0.27	−0.0008	0.008	−0.0004

Table 2. Car test results (scenario 3)

Trajectory type	Time, s					
	10		60		120	
	low	*high*	*low*	*high*	*low*	*high*
$\varepsilon\psi^{ma}$, deg	0.02	−0.04	−0.025	−0.039	−0.01	−0.038
$\varepsilon\vartheta^{ma}$, deg	0.06	0.006	0.009	−0.001	0.01	0.004
$\varepsilon\gamma^{ma}$, deg	−0.19	−0.15	−0.12	−0.05	−0.07	0.02

the system is in operating mode under selected scenarios and experimental conditions. When comparing the results of simulation and car tests study it can be noted the level of achievable performance can be increased not only by maximizing the time of estimation, but also adding a dynamic maneuver after some time of estimation along low maneuverable movement. Moreover, the estimation accuracy can be increased many times, i.e. up to 10 times in heading misalignment estimation using navigation and tactical grade IMUs (see the results in table 1, scenario 1) and up to 100 times in roll misalignment estimation.

In table 1 “c” corresponds to a inertial measurement unit (IMU) class, where “*nav*” corresponds to a navigation grade (laser gyros, quartz accelerometers), “*tact*” corresponds to a tactical grade (FOG, high-precision silicon accelerometers), “$MEMS$”—microelectromechanical IMU grade respectively, “l” corresponds to a base length between onboard antennas.

Table 2 shows the results of car tests for the scenario which studies the trajectory type influence on an approach to determine the relative angular misalignment of attitude sensors achievable performance at a certain timestamps. The timestamps columns are splitted into two corresponding the types of the trajectory: a "*low*" maneuverable type—mostly with straightforward movement sections, "*high*" corresponds to a complex maneuverable with S-types movement sections trajectories.

5 Conclusions

The results of the study demonstrate the possibility of using the proposed approach to estimate the relative angular mismatch of attitude parameters in motion when the system is in operating mode under selected scenarios and experimental conditions. At the same time, in accordance with theoretical expectations, the angular misalignment is estimated jointly with the INS attitude parameters and the constant components of sensor errors. It is possible to increase the observability and improve the estimation parameters when implementing the movement of an object along a trajectory of a special type.

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