Moving object SINS transfer alignment time synchronization parameters estimation

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Abstract. The main unmanned aerial vehicles launched from a carrier aircraft onboard navigation system, usually, is a strapdown inertial navigation system. The paper considers the influence of the time synchronization error in the strapdown inertial navigation system transfer alignment on a moving base task. The influence of the time synchronization error, as well as the technique of its estimation, is directly the subject of this study. SINS mathematical models are considered on the basis of error equations, the state vector, including errors of coordinates, linear velocities projections, attitude angular errors of the measuring coordinate system relative to the calculated one, accelerometers and gyro systematic errors components are extended by the angles of misalignment of two systems – unmanned aerial vehicle strapdown inertial navigation system and carrier aircraft navigation system and time delay component. The measurement vector includes the difference of the corresponding output parameters of two systems – carrier aircraft strapdown inertial navigation system or its navigation system and unmanned aerial vehicle strapdown inertial navigation system. A simulation was performed, and state vector estimates were obtained.

1. Introduction

For now, the main onboard unmanned aerial vehicles (UAVs) launched from the carrier aircraft (CA) navigation device, as a rule, is a strapdown inertial navigation system (SINS), which is a source of such object navigation parameters as coordinates, velocities and attitude angles autonomous determination. These parameters are determined based on information received from sensors that are structurally the part of SINS – accelerometers and angular velocity sensors (gyros).

For the correct SINS algorithm operation, it is required to know the initial conditions with a given accuracy. Setting the initial conditions (IC) requires the implementation of a special procedure called the SINS initial alignment.

It is known that in the UAV immobility conditions, the SINS attitude in the autonomous operation mode is determined based on the gravity acceleration vector projections measurements using accelerometers and the angular velocity vector of the Earth's rotation using gyros [1]. An alignment like this usually takes quite a long time. When an object moves relatively to the ground, these measurements are distorted, so in practice it is used the involvement of information from the CA navigation system (NS) to align the system. Such SINS alignment on a movable base techniques are called transfer alignment [2], belong to the ones considered in this article, and allow to perform a SINS alignment during the flight, immediately before the UAV launch [3].
To perform a transfer alignment, the values of the navigation and attitude parameters are being copied from the CA NS to the UAV SINS, taking into account coarse information about the relative location of both systems. This information contains static and dynamic errors that limit the alignment achievable accuracy. Static errors occur as a result of manufacturing tolerances and inaccurate onboard navigation systems installation. Dynamic errors can be associated with vibrations or deformations of the aircraft structure, for example, as a result of aerodynamic loading [3].

One of the easiest ways to align a UAV SINS in flight is to instantly copy location data, linear velocity projections, and angular attitude from the CA's own navigation system. This technique is called “one-shot” alignment.

The figure 1 shows a block diagram of the initial alignment instant process.

![Diagram](image)

**Figure 1.** Instant initial alignment block diagram.

The disadvantage of this technique is the fact that the navigation parameters transmitted values do not correspond to the actual values for the SINS being aligned. It is caused by the angular misalignment between the reference frames of the two systems due to production tolerances, vibrations, and deformations of the aircraft construction during the flight. Thus, the described SINS alignment technique can only be used to perform a coarse and fast alignment.

Since the angular misalignment between the CA NS and the SINS being aligned are unknown in advance, the task of its estimation and compensation arises in the process of getting the navigation solution.

The techniques based on the measured and calculated values matching of the CA NS and the UAV SINS allow to perform a more accurate alignment. These techniques are based on the principle of comparing these values and obtaining corrections that analytically compensate for angular misalignment between the master and slave systems [3]. The algorithm of the SINS initial alignment by matching the specific force acceleration vector is known.

The matching is performed by comparing the measurements of the UAV overload vector components in the body fixed frame obtained from accelerometers and projected using the direct cosine matrix (DCM) to the local level frame (LLF) with the calculated CA overload vector in the LLF. The difference of these vectors determines the rotation angle between the UAV and CA frames.

The alignment algorithm is intended to refine the transition matrix estimation from the UAV body fixed frame to the local level frame. As a result of the complex processing of incoming information, the rotation matrix is being formed and multiplied by the transition matrix from the UAV body fixed frame to the local level frame. When the certain accuracy is reached, the alignment algorithm terminates its work. When designing the SINS alignment algorithm, it is assumed that the angular velocity and the CA overload are constant at the interval of updating the initial information.

Such an alignment requires an input information for the algorithm:
- Heading, pitch and roll angles of the carrier relative to the base navigation frame;
- The turn angle about UAV roll relatively to the CA;
- The specific force acceleration vector components, measured by CA NS and UAV SINS.

Based on the information about the CA NS angular position, the DCM between the local level frame and the UAV body fixed frame is calculated. With this matrix, a coarse alignment is carried out.

This algorithm is quite simple to implement, but it has a significant drawback. Due to the fact that measurements of the specific force are obtained by the inertial sensors, as already was mentioned above, these measurements are affected by various vibrations and deformations, which leads to the dramatically decreasing of the initial alignment accuracy.

Obtaining more accurate values of the IC parameters is possible when implementing complex information processing based on the optimal Kalman filter (OKF) from two systems – CA inertial navigation system (INS)/NS and UAV SINS.

Due to the considered transfer alignment technique features, one of the key tasks is to analyze the time synchronization error occurring when the parameters from CA SINS/NS to UAV SINS transfer in the absence of hardware synching implementation due to the fact that the signal coming from the CA NS, as a rule, transfers through some switching and computing CA and UAV units. That leads to a time delay of this signal relatively to system UAV SINS time scale. Such errors can be both constant and variable in nature and manifest themselves in different ways not only in the problem of initial alignment by the transfer technique, but also in the complex information received from the subsystems of the navigation complex processing [4-7]. There are known techniques of hardware synchronization that allow to avoid additional errors arising due to the time delay when performing the SINS alignment [8,9], which require a priori hardware implementation. However, in real operating conditions, generally, the problem of UAV SINS and CA NS system timescales synchronization absence is more common and the problem of systems time syncing onboard is quite critical. Many techniques of delay estimation are known, i.e. a combined parameter-state estimator [10], multiple-model adaptive estimation [11], the technique of posterior distribution and point estimators for a linear Gaussian smoothing formulation [12] etc. In this regard, the purpose of this article is to show an approach based on technical task for estimate the impact of the time synchronization error of a certain systems, including a description of its technique, as well as an analysis of the results obtained during simulation.

2. Methodology
The method is based on the principles of integration the SINS output information with the information from aiding systems using the OKF. As a source of such information, it is proposed to use the CA NS.

To solve the problem of the UAV SINS UAV alignment based on navigation information from the CA NS using optimal filtering, it is advisable to design the structure of an integrated system, according to which the UAV SINS and CA NS form independent solutions. The solution of the UAV SINS initial alignment problem based on the proposed method is performed in two stages.

At the beginning, the UAV SINS UAV algorithm initializes approximate initial values of coordinates, velocity projections, and the DCM from the CA NS, taking into account the separate mounting of the CA NS and the UAV SINS (figure 2).

**Figure 2. Transfer alignment block diagram.**
The UAV SINS is a three-channel system, consisting of three accelerometers and three angular rate sensors. CA NS is designed on the basis of INS, additionally aided from alternative navigation information sources onboard the CA.

The approximate initial value of the UAV SINS DCM determines the relative position of the measurement basis of the UAV SINS inertial measurement unit and the basic navigation frame. The calculation accuracy of DCM depends not only on the errors of the measuring sensors used, but also on a number of other factors.

In the second phase in the OKF processing block (figure 2) based on the reference navigation data from CA NS, using as the measurement information the difference between independently computed UAV SINS and CA NS navigation parameters, generates an estimate of the state vector and the correction data received from the UAV SINS – refined the DCM value, i.e. estimate the angular misalignments between the UAV SINS and CA NS, then it is being compensated, obtaining the estimation of sensor parameters and time delay. The advantage of such an approach is the high reliability of the integrated system, and the disadvantage is the possible correlation of processes being entered to the input of the Kalman filter, which requires white Gaussian noise in the classical formulation, and the need to synchronize the received measurements from both sides to the input of the complex solution performing unit.

The OKF structure is based on the representation of the UAV SINS dynamics model in the form of a linear differential equations describing the SINS errors system. To implement such an initial alignment algorithm, it is necessary to have a mathematical model of SINS errors, as well as to know a priori statistical information about the interference and disturbances are presented in the system.

Optimal navigation information processing based on the Kalman filter technique in order to improve the alignment accuracy is proposed to be applied in this case due to the fact that the actual movement of the object under the influence of external factors, as well as the errors of the inertial system measuring elements, generally, are unknown and only their probabilistic characteristics can be specified.

The system mathematical model obtained by the article authors based on [13] is represented in the form of linear dynamic errors model and measurement equations. The SINS errors dynamics equation has the following form:

$$\dot{\mathbf{X}} = F\mathbf{X} + G\mathbf{W},$$

where $F$ is the dynamics matrix; $G$ is the noise matrix of the system; $\mathbf{W}$ is the system noise vector.

In this work, the state vector $\mathbf{X}$ represented in [13] is extended by the parameters of the relative angular misalignment between the two frames: measuring SINS and CA NS $\Delta A = [\psi^{\text{ms}}, \phi^{\text{ms}}, \gamma^{\text{ms}}]$ and the data transmission from CA NS to UAV SINS UAV time delay component $\Delta \tau$ and has the form:

$$\mathbf{X}_{\text{ext}} = \begin{bmatrix} \mathbf{X} & \Delta A & \Delta \tau \end{bmatrix}.$$

Such extension is caused by the problem of angular misalignment between the CA NS and the SINS being aligned. It is generally unknown in advance, because of the technological issues of its installation onboard of the object. So the task of its estimation and compensation arises in the process of getting the navigation solution and affects directly on its absolute accuracy.

The dynamics matrix has the following form:

$$F = \begin{bmatrix}
0_{3 \times 3} & I_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} \\
F_1 & F_2 & F_3 & 0_{3 \times 3} \\
0_{3 \times 3} & 0_{3 \times 3} & F_4 & 0_{3 \times 3} \\
0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} \\
0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3}
\end{bmatrix},$$

where $I_{3 \times 3}$ is the identity matrix.
where $F_i = \begin{bmatrix} (\Omega_i^2 + \Omega_i^2 - \omega_0^2) & (\dot{\Omega}_i - \Omega_i \Omega_i) & - (\dot{\Omega}_i + \Omega_i \Omega_i) \\ - (\Omega_i + \Omega_i \Omega_i) & (\Omega_i^2 + \Omega_i^2 - \omega_0^2) & (\dot{\Omega}_i - \Omega_i \Omega_i) \\ (\Omega_i - \Omega_i \Omega_i) & - (\dot{\Omega}_i + \Omega_i \Omega_i) & (\dot{\Omega}_i + \Omega_i \Omega_i) \end{bmatrix}$;

$F_j = \begin{bmatrix} 0 & 2\Omega_z & -2\Omega_y \\ -2\Omega_z & 0 & 2\Omega_x \\ 2\Omega_y & -2\Omega_x & 0 \end{bmatrix}$; $F_k = \begin{bmatrix} 0 & \Omega_z & -\Omega_y \\ -\Omega_z & 0 & \Omega_x \\ \Omega_y & -\Omega_x & 0 \end{bmatrix}$.

$\omega_0$ - SINS errors oscillation natural frequency, Shuler frequency ($\omega_0 = 1.25 \times 10^3 \, s^{-1}$); $\Omega_{X,Y,Z}$ - absolute angular velocity vector of the base coordinate frame projections and its derivatives; $n_{x,y,z}$ - specific force projections vector, $C_{3x3}$ - DCM between the body fixed frame (BFF) and LLF.

The vector and the system noise matrix has the form similar to [13]. The measurement equation:

$\bar{Z}(t) = H(t) \bar{X}_{est}(t) + \bar{V}(t)$,

where $\bar{Z}$ is the measurements vector; $\bar{X}_{est}$ - extended state vector; $H$ is the measurements matrix; $\bar{V}$ – the measurement noise vector.

So the measurement noise vector is formed as follows:

$Z(t) = [C^S - C^C \ V^S - V^C \ A^S - A^C]^T = [\delta C^S - \delta C^C \ \delta V^S - \delta V^C \ \delta A^S - \delta A^C]^T$,

where $C^S = [\psi^S \ \lambda^S \ h^S]^T$, $C^C = [\phi^C \ \lambda^C \ h^C]^T$, $\phi^S$, $\lambda^S$, $h^S$, $\phi^C$, $\lambda^C$, $h^C$ - location geographical latitude, longitude and altitude according to the UAV SINS and CA SN output; $\delta C^S = [\delta \phi^S \ \delta \lambda^S \ \delta h^S]^T$, $\delta C^C = [\delta \phi^C \ \delta \lambda^C \ \delta h^C]^T$, $\delta \phi^S$, $\delta \lambda^S$, $\delta h^S$, $\delta \phi^C$, $\delta \lambda^C$, $\delta h^C$ - errors in determining the corresponding values; $V^S = [V_E^S \ V_N^S \ V_Z^S]^T$, $V^C = [V_E^C \ V_N^C \ V_Z^C]^T$, $V_E^S$, $V_N^S$, $V_Z^S$, $V_E^C$, $V_N^C$, $V_Z^C$ - the relative flight speed according to the UAV SINS and CA NS on the LLF axes projections; $\delta V^S = [\delta V_E^S \ \delta V_N^S \ \delta V_Z^S]^T$, $\delta V^C = [\delta V_E^C \ \delta V_N^C \ \delta V_Z^C]^T$, $\delta V_E^S$, $\delta V_N^S$, $\delta V_Z^S$, $\delta V_E^C$, $\delta V_N^C$, $\delta V_Z^C$ - errors in calculating the corresponding velocity projections; $A^S = [\psi^S \ \theta^S \ \gamma^S]^T$, $A^C = [\psi^C \ \theta^C \ \gamma^C]^T$, $\psi^S$, $\theta^S$, $\gamma^S$, $\psi^C$, $\theta^C$, $\gamma^C$ - angles of heading, pitch and roll according to the UAV SINS and the CA NS output; $\delta A^S = [\delta \psi^S \ \delta \theta^S \ \delta \gamma^S]^T$, $\delta A^C = [\delta \psi^C + \psi_{ma} \ \delta \theta^C + \theta_{ma} \ \delta \gamma^C + \gamma_{ma}]^T$, $\delta \psi^S$, $\delta \theta^S$, $\delta \gamma^S$, $\delta \psi^C$, $\delta \theta^C$, $\delta \gamma^C$ - errors in calculating the corresponding angles; $\psi_{ma}$, $\theta_{ma}$, $\gamma_{ma}$ - angular misalignment between the measuring UAV SINS and the CA NS frames.

The measurement noise vector has the form:

$V(t) = [\delta \phi^C \ \delta \lambda^C \ \delta h^C \ \delta V_E^C \ \delta V_N^C \ \delta V_Z^C \ \delta \psi^C \ \delta \theta^C \ \delta \gamma^C]^T$

and represents errors in determining the parameters of the CA NS in the form of “white noise”.

Then, taking into account the SINS error model, the measurement matrix will take the form:

$H = \begin{bmatrix} H_1 & 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} \\ H_2 & I_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & H_5 \\ H_3 & 0_{3x3} & H_4 & 0_{3x3} & 0_{3x3} & I_{3x3} \end{bmatrix}$. 

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As part of the simulation, in order to verify the operability of the developed algorithm, a set of studies based on the created software package, which includes units for simulating trajectories of spacecraft motion on a single horizontal channel and got the simulation results. The analytical analysis of observability was made taking into account the fact that it is difficult to analyze the observability of systems with such an order (of 19 component state vector), so the system was decomposed to a single horizontal channel and got the seventh order. For a simplified trajectory it could be shown, that the rank of the observability matrix equals 4, which means the existence of simultaneous observed components of the attitude, misalignment angles and constant accelerometer errors. Thus, the derivatives of dynamic matrix of increasingly higher orders will also be nonzero, so the rank of observability matrix will also grow.

3. Simulation results

As part of the simulation, in order to verify the operability of the developed algorithm, a set of studies were carried out based on the created software package, which includes units for simulating trajectories...
specific to the selected object type, modeling the inertial measurement unit of the UAV SINS based on a given mathematical model, the UAV SINS algorithm, complex information processing based on the OKF, implementing the transfer alignment algorithm, analysis and comparison of data obtained during the simulation.

In order to analyze the influence of the trajectory type on the transfer alignment accuracy, when performing the simulation, the whole range of scenarios was used – from the simplest (for example, uniform horizontal flight) up to trajectories with sections of dynamic change of all flight and navigation parameters.

The SINS mathematical models are considered based on the errors equations, the state vector, including errors of coordinates, projections of linear velocities, the measuring frame relative to calculated one, angular attitude errors, accelerometers and gyros biases, is extended by the time delay component, and the measurement vector includes the difference of the corresponding output parameters of two systems – SINS/CA NS and the UAV SINS. A full-fledged simulation was carried out, and estimations of time synchronization errors were obtained.

The CA NS errors specified in the simulation were presented in the form of discrete random sequences corresponding to random processes of the “white noise” type with zero mathematical expectation. In this case, the following standard deviations (RMS) of these sequences were taken: the coordinates – 12 m, the velocity projections – 0.15 m/s, the attitude angles – 0.1°.

The errors of the SINS IMU were presented as the sum of the bias and random components. Gyro bias – 5 °/h, random drift – 1 °/h (1 RMS). Bias and random errors (1 RMS) of accelerometers – 0.01 m/s². The angular misalignment between CA NS and UAV SINS UAV is 0.5° for all three angles. The time delay of data transmission from the CA NS to the UAV SINS varied in the range from 100 to 750 ms.

The simulation results were obtained using the created software package and one of the simulation scenarios (the most complex trajectory and the worst option in terms of accuracy). Figures 3-6 show the estimation errors of the transfer alignment main parameters – angular misalignment between the CA NS and the UAV SINS, IMU errors in the absence of a time delay in data transmission from the CA NS to the UAV SINS. Figure 5 shows that the accuracy of the gyro bias estimation increases during the time evaluation, so for two horizontal gyros $\Delta \Omega_1$ and $\Delta \Omega_2$ at the time of 60 seconds, it is about 0.15 °/h and for the vertical one is 0.07 °/h, and at the 120th second – 0.1 °/h and 5·10⁻³ °/h, respectively. Figure 4 shows that the accuracy of estimating the vertical accelerometer bias which begins to converge to a steady value of 1·10⁻⁴ m/s² after the 125th second. Similarly, the definition of angular misalignment by the angle of roll evaluation behaves. This behavior is caused by the joint observability of these two parameters, and their more intense onset of convergence at this point in time is associated with the appearance of a relatively dynamic change in the roll angle in the range from 3 to 5 degrees.

The numerical values of the obtained accuracy estimates for different time points are summarized in the table 1 for clarity. It can be seen that the estimates converge to the steady-state value in an acceptable time.

Figures 7-11 show the effect of having different levels of time delay ($\Delta \tau = 0.1, 0.2, 0.3, 0.5, 0.75$ seconds respectively) on the alignment parameters estimation accuracy. IMU parameters are presented for sensors only of the 1st measuring horizontal axis, the behavior of errors on the remaining two axes is largely similar to them. It can be seen that with an increase in the time delay, in particular, depending on the presence of an active change in the moment of trajectory parameters, the error of the estimated values increases many times, but nevertheless, over time, it converges more and more to the steady values.
Figure 3. Misalignment estimation errors using transfer alignment algorithm.

Figure 4. Accelerometers bias estimation errors using transfer alignment algorithm.

Figure 5. Gyros bias estimation errors using transfer alignment algorithm.

Figure 6. Time delay estimation errors using transfer alignment algorithm.

Table 1. Transfer alignment estimation error parameters.

| Parameter | 10 s | 20 s | 60 s | 120 s |
|-----------|------|------|------|-------|
| $\Delta n_1$, m/s² | -0.01 | -1·10⁻³ | 1.2·10⁻⁵ | 9.8·10⁻⁶ |
| $\Delta n_2$, m/s² | 0.01 | 0.013 | 9·10⁻³ | 6·10⁻³ |
| $\Delta n_3$, m/s² | 2·10⁻³ | 1·10⁻³ | 6·10⁻⁴ | 3·10⁻⁴ |
| $\Delta \Omega_1$, °/h | 2.37 | 0.56 | 0.18 | 0.101 |
| $\Delta \Omega_2$, °/h | 2.16 | 0.63 | 0.16 | 0.08 |
| $\Delta \Omega_3$, °/h | 2.51 | 0.36 | 0.075 | 3·10⁻³ |
| $\Delta \psi$, ' | -13.74 | 0.7 | 0.65 | 0.47 |
| $\Delta \theta$, ' | 7 | 1 | -0.05 | -0.05 |
| $\Delta \gamma$, ' | 4 | 4.9 | 3.57 | 2.17 |
| $\Delta \tau = 100$ ms², ms | 7 | 3 | 1 | 1 |
| $\Delta \tau = 200$ ms², ms | 14 | 8 | 2 | 3 |
| $\Delta \tau = 300$ ms², ms | 20 | 12 | 4 | 3.5 |
| $\Delta \tau = 500$ ms², ms | 33 | 23 | 19 | 18.8 |
| $\Delta \tau = 750$ ms², ms | 102 | 66 | 61.6 | 62.8 |

*The nominal value of the estimation error at given time delay*
Figure 7. Different $\Delta \tau$ value influence on $\Delta \psi$ estimation.

Figure 8. Different $\Delta \tau$ value influence on $\Delta \theta$ estimation.

Figure 9. Different $\Delta \tau$ value influence on $\Delta \gamma$ estimation.

Figure 10. Different $\Delta \tau$ value influence on $\Delta n_1$ estimation.

Figure 11. Different $\Delta \tau$ value influence on $\Delta \Omega_1$ estimation.
For ease of perception, the steady-state values of estimation errors for various values of the time delay for the expected moments of the alignment procedure completion (at 60/120th seconds) are summarized in a table 2.

| Time delay value, ms | \( \Delta n_1, m/s^2 \) | \( \Delta \Omega_1, ^\circ/h \) | \( \Delta \gamma, ^\circ \) | \( \Delta \varphi, ^\circ \) | \( \Delta \psi, ^\circ \) |
|----------------------|-----------------|----------------|--------|--------|--------|
| 100                  | \(-3 \cdot 10^{-3} / 2 \cdot 10^{-4}\) | \(-1.6 \cdot 10^{-2} / 1.8 \cdot 10^{-2}\) | \(-0.22 / -0.1\) | \(0.019 / 0.074\) | \(0.006 / 0.018\) |
| 200                  | \(-2 \cdot 10^{-3} / 4 \cdot 10^{-5}\) | \(9.7 \cdot 10^{-3} / 7.2 \cdot 10^{-3}\) | \(-0.37 / -0.36\) | \(0.04 / 0.021\) | \(-0.07 / -0.066\) |
| 300                  | \(1.2 \cdot 10^{-3} / 4.6 \cdot 10^{-4}\) | \(8.7 \cdot 10^{-2} / 7.1 \cdot 10^{-2}\) | \(-0.24 / -0.67\) | \(0.09 / -0.11\) | \(-0.07 / -0.121\) |
| 500                  | \(1.9 \cdot 10^{-4} / 2.4 \cdot 10^{-3}\) | \(0.39 / 0.323\) | \(0.43 / -1.39\) | \(0.15 / -0.76\) | \(0.16 / 0.83\) |
| 750                  | \(4.5 \cdot 10^{-4} / 5.7 \cdot 10^{-3}\) | \(0.96 / 0.741\) | \(3.65 / -0.756\) | \(-0.1 / -1.97\) | \(2.22 / 1.956\) |

*The value at 60/120th second of estimation respectively.*

It should be noted that the implementation of extended OKF (EKF) of the proposed form and structure enables the time delay parameter estimation with a certain accuracy at the time of alignment procedure completion (figure 6), which values are also summarized in table 1 and shows that the estimation error of this parameter grows with the time delay value at all. In order to estimate the values of estimated parameters additional errors to the levels that are reflected in Table 1, additional simulation was performed, which revealed that for the case of the two largest considered in this article values of time delay (500 and 750 ms), and corresponding values of of their estimate errors (20 and 60 ms respectively) the amount of the contribution to the total error depending on the parameter is at the level of 1.4 - 3.3% of the nominal value of estimations of the considered parameters errors, which is an acceptable value in view of the achievable levels of accuracy for estimates of these parameters.

4. Conclusions
The transfer alignment algorithm proposed in [13] and supplemented in this article, taking into account the errors of the relative angular misalignment of the systems mounting and the time delay when transmitting information from the CA NS to the UAV SINS, showed the operability and acceptable levels of achievable alignment accuracy depending on its time and various values of the time delay parameter. Based on the results of the simulation, it can be concluded that the algorithm demonstrates fundamental operability, the convergence of parameter estimates takes from tens to hundreds of seconds at acceptable levels of alignment residual error. The algorithm can be adopted for various scenarios. The developed software package and the results obtained are planned to be used in further research, including HIL simulation techniques.

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