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The Correction Method of the Astroinertial System of the Aircraft

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***Abstract*—The problem of improving the accuracy of the navigation complex of an unmanned aerial vehicle by the algorithmic method is investigated. The algorithmic correction schemes of navigation systems of modern high-precision unmanned aerial vehicles are considered. A method is proposed for compensating for errors in an inertial navigation system corrected by astrosystem signals. Correction is carried out in the structure of the inertial navigation system using a non-linear Kalman filter and a control algorithm. A nonlinear control algorithm based on the SDC-representation method is used. The proposed method of correction in the AINS structure is easy to implement, but the use of AINS with EA allows obtaining a higher accuracy of the aircraft navigation information.**

Keywords—unmanned aerial vehicle, inertial navigation system, astrosystem, navigation complex, non-linear filter Kalman, error model, regulator, SDC-method

I. INTRODUCTION

Modern high-precision unmanned aerial vehicles (UAV) are equipped with navigation systems and systems that have the highest possible accuracy. The accuracy requirements for UAV navigation systems are steadily increasing. Therefore, to achieve the highest possible accuracy of the navigation definitions of UAVs, navigation systems are combined into complexes (NC) and subjected to their measurement joint processing [1,2,3].

The measuring signals of the systems in the NC have errors due to the design features and operating conditions of the UAV. Improving the accuracy of the NC involves the compensation of errors algorithmically.

The UAV under consideration is equipped with an inertial navigation system (INS), a satellite navigation system (SNS) receiver and an astronautical system (ANS) installed on a gyro-stabilized platform (GSP). NC systems have specific negative features. The errors of a stand-alone INS accumulate over time. Under conditions of active interference, the use of SNS is not always possible [3]. ANSs are subject to passive interference [4,5,6]. Therefore, complex algorithmic processing of signals from these three systems is carried out. Typically, NC correction schemes are used in the output signal [7,9,10,11]. Moreover, INS errors increase with time and with a long UAV flight, the error model used in the NFK becomes inadequate to the real process [3].

The article proposes a correction scheme for NC using a non-linear Kalman filter (NFK) and a non-linear controller, which allows you to compensate for errors INS in the structure of the system. Such correction prevents the growth of INS errors over time and maintain the adequacy of the model adopted by the NFK.

The prospects for further research are related to the search for more universal methods for representing nonlinear models than the SDC method.

A. Astrosystems.

INSs and SNSs have been studied in sufficient detail [3,4], and ANSs are little consecrated in modern literature [6].

The first applications of ANS are associated with guidance of shells [4]. The simplest ANS guidance is shown in fig.1. As sensitive elements of such ANS telescopes were used, aimed at pre-selected celestial bodies. By determining the position of the celestial bodies, the spatial coordinates of the projectile are used to guide the projectile. Usually, several telescopes are used with a direction to fixed stars, which should be at least two.

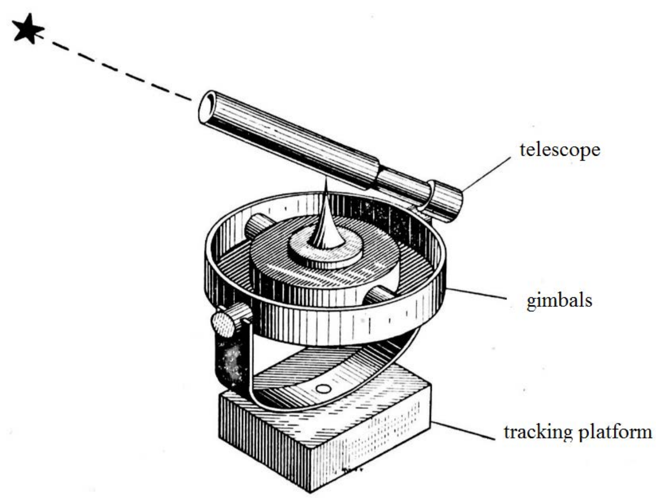

Fig. 1. Tracking telescope.

Tracking telescope systems are very bulky, so their use was limited to large projectiles.

The next step in improving the ANS is a system consisting of an inertial system, continuously adjusted at certain intervals. Consider an inertial automatic orientator with astro correction (IAOAC) and automatic astronavigation (AA).

In IAOAC periodically measures the position of stars to correct the drift of gyroscopes.

One of the possible methods for eliminating the error caused by random drift is to use stars.

An automatic sextant is additionally installed on the platform so that it can change the elevation angle and azimuth.

Motors for changing azimuth and elevation angles are precision torque sensors that are connected to a system that determines the position of the sextant. The system, as shown in fig. 2, receives signals from a tape decoder. Data on the position and velocity of the projectile for the entire duration of the flight is preliminarily applied to the tape.

The data on the azimuth and elevation angles must be decrypted at a certain time when the star is at a given angle to a certain point on the Earth's surface.

The telescope is sent to the star using information taken from the tape, and to track the star, it is programmed in a special way.

The position of the star in the center of the telescope field is determined using a scanning system.

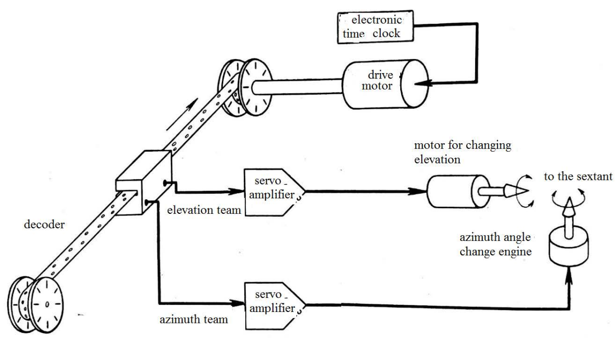

Fig. 2. The system for determining the position of the sextant.

At the present stage of development ANSs are designed on more advanced principles [6]. A modern NC including AINS LN-120G consists of laser gyroscopes, a quartz accelerometer, a SNS receiver, and astrovizir with a mechanical drive [6].

The inclusion of ANS in the NC allows to significantly increase the accuracy of the navigational definitions of UAVs, since the ANS does not depend on its flight range, can be used in polar and equatorial regions. The absence of invariant properties of ANS is successfully compensated by other systems in the composition of the NC.

B. *Non-linear filter Kalman.*

The NC correction scheme involves the use of an estimation algorithm for calculating INS errors and their subsequent compensation in the output signal of the system. The Kalman filter [3] and its various modifications [12], as well as the NFK and its modifications [7 - 14] are often used as an estimation algorithm.

The INS error model has the form [15]:

$$\mathbf{x}_k = \mathbf{\Phi}_k\left(\mathbf{x}_{k-1}\right) + \mathbf{w}_k \tag{1}$$

where $\mathbf{x}_k$ - state vector, $\mathbf{\Phi}_k\left(\mathbf{x}_{k-1}\right)$ - non-linear model vector characterizing the dynamics of the process under study. Part of the state vector is measured using the INS and GPS navigation systems:

$$\mathbf{z}_k = \mathbf{H}_\mathrm{k}\mathbf{x}_k + \mathbf{v}_k \tag{2}$$

where $\mathbf{z}_k$ - measurement vector, $\mathbf{H}_\mathrm{k}$ - measurement matrix, $\mathbf{w}_k$ and $\mathbf{v}_k$ - discrete analogues of Gaussian white noise with zero mathematical expectation and covariance matrices $\mathbf{Q}_k$ and $\mathbf{R}_k$ respectively, uncorrelated with each other.

The NFK equations have the following form [15,16]:

$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_{k,k-1} + \mathbf{K}_k\left(\hat{\mathbf{x}}_{k-1}\right)\left[\mathbf{z}_k - \mathbf{H}_k\hat{\mathbf{x}}_{k,k-1}\right],$$

$$\hat{\mathbf{x}}_{k,k-1} = \mathbf{\Phi}_k\left(\hat{\mathbf{x}}_{k-1}\right)$$

$$\mathbf{K}_k\left(\hat{\mathbf{x}}_{k-1}\right) = \mathbf{P}_{k,k-1}\mathbf{H}_k^T\left[\mathbf{H}_k\mathbf{P}_{k,k-1}\mathbf{H}_k^T + \mathbf{R}_k\right]^{-1} \tag{3}$$

$$\mathbf{P}_{k,k-1} = \frac{\partial\mathbf{\Phi}_k\left(\hat{\mathbf{x}}_{k-1}\right)}{\partial\mathbf{x}_{k-1}^T}\mathbf{P}_{k-1}\left[\frac{\partial\mathbf{\Phi}_k\left(\hat{\mathbf{x}}_{k-1}\right)}{\partial\mathbf{x}_{k-1}^T}\right]^T + \mathbf{Q}_k$$

$$\mathbf{P}_k = \left[\mathbf{I} - \mathbf{K}_k\left(\hat{\mathbf{x}}_{k-1}\right)\mathbf{H}_k\right]\mathbf{P}_{k,k-1}$$

Here $\mathbf{K}_k\left(\hat{\mathbf{x}}_{k-1}\right)$ - gain matrix of the filter Kalman, I - identity matrix, $\mathbf{P}_k$ - covariance matrix of estimation errors.

But this approach is applicable only in the case of the unimodal nature of the posterior density, when the posterior density is multi-extreme, an algorithm is used in which the posterior density is represented by a set of delta functions.

C. *Error estimation AINS.*

In the NC, UAV parameters are calculated based on measurements of the SNS and ANS.

The disadvantage of NFK implementation methods is the high computational complexity.

There is a known approach [15], which consists in the fact that measurements from the ANS are included as a well-known function in the model of INS errors, and not in the measurement equation.

For the most complete compensation of INS errors, various correction schemes using estimation algorithms are used. In fig.3 shows the most common NC correction scheme in the output signal using the estimation algorithm, which uses adaptive filter Kalman or NFK.

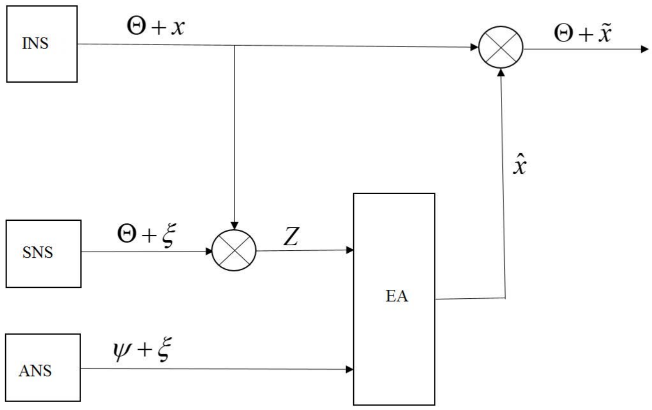

Fig. 3. Correction scheme for the navigation system with an estimation algorithm.

In fig.3 the following notation is introduced: ψ, Θ - true navigation information, ξ - SNS error vector, Z - a mixture of errors INS and SNS.

In the absence of information from the SNS, the AINS correction scheme shown in fig. 4 is used.

The accuracy of the corrected INS also depends on the errors of the algorithm used. In particular, from the adequacy of the mathematical model of INS errors.

With the functioning of the INS for long periods of time without correction, the angles of deviation of the GSP increase. The consequence of this is the inadequacy of the mathematical model to the real process of changing the errors of the INS. In this case, INS correction is applied in the structure of the system by means of control algorithms [3]. The functional diagram of AINS with correction in the structure of INS is presented in fig.4.

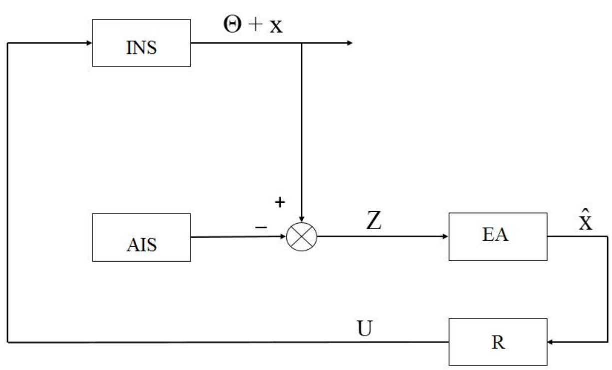

Fig. 4. AINS functional diagram with correction in the INS structure.

As a model of the evaluated process, stationary nonlinear equations of INS errors for horizontal channels were used [12, 16]:

$$\begin{aligned} \delta\dot{V}_N &= g\sin\psi_E + B_N, \\ \delta\dot{V}_E &= -g\cos\psi_E \sin\psi_N + B_E, \\ \dot{\psi}_N &= \frac{\delta V_E}{R} + \varepsilon_N^{\text{др}}, \\ \dot{\psi}_E &= -\frac{\delta V_N}{R}\cos\psi_N + \varepsilon_E^{\text{др}}\cos\psi_N. \end{aligned} \quad 4)$$

Here: δV_N , δV_E - INS errors in determining speed; ψ_N , ψ_E - GSP deviation angles relative to the accompanying trihedron; $\varepsilon_N^{\text{др}}$, $\varepsilon_E^{\text{др}}$ - GSP drift speeds; R - Earth radius; g - acceleration of gravity; B_N , B_E - zero offset of accelerometers.

The GSP drift velocity model for the northern channel has the form

$$\dot{\varepsilon}_N = -\omega\varepsilon_N + A\sqrt{2\omega}w, \quad (5)$$

where ε_N - GSP drift speed; ω - average random drift frequency ($\omega = 10^{-3}\,\text{c}^{-1}$); A - standard deviation of a random drift value; w - white noise. The GSP drift velocity for the eastern channel has a similar form.

Equations (4) and (5), which are an INS error model. Linear models of INS errors have low accuracy, since only the dominant components of the process of changing errors are taken into account. Therefore, to obtain higher accuracy of measuring complexes (MC), it is advisable to use non-linear models of INS errors.

To form control $u(t)$ in the circuit of fig. 4, we represent system (1) in an equivalent form using the SDC - method.

In a particular formulation of the control synthesis problem for a nonlinear system using the SDC - method, a nonlinear algorithm for correcting INS is known [9].

D. *Non-linear algorithm for the correction of INS errors.*

INS error equations are the equations of orientation errors and the error equations of horizontal accelerometers. Model (4), (5) can be simplified, then for one horizontal channel of INS errors the model will take the form [10]:

$$\begin{aligned} \delta\dot{V} &= -g\psi + B, \\ \dot{\psi} &= \frac{\delta V}{R} - \frac{\delta V}{R}\psi + \varepsilon, \\ \dot{\varepsilon} &= -\mu\varepsilon + \eta. \end{aligned} \quad (6)$$

Here δV - error in determining the speed; ψ - the angle of deviation of the gyrostabilized platform (GSP); ε - GSP drift speed; B, η - Markov random processes; R - Earth radius; g - acceleration of gravity; μ - average frequency of random drift changes.

Equations (6) in matrix form have the following form:

$$\dot{x}(t) = f\left(t, x(t)\right) + w(t) \qquad (7)$$

where $x(t) = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} \delta V \\ \psi \\ \varepsilon \end{bmatrix}$; $f\left(t, x\right) = \begin{bmatrix} -gx_2 \\ \frac{x_1}{R} + \frac{x_1 x_2}{R} + x_3 \\ -\mu x_3 \end{bmatrix}$;

$w(t) = \begin{bmatrix} B \\ 0 \\ \eta \end{bmatrix}$.

After converting model (7) by the SDC - method, we obtain:

$$\dot{x}(t) = A\left(t, x\right)x(t) + w(t) \qquad (8)$$

where $A\left(t, x\right)x(t) = \begin{bmatrix} 0 & -g & 0 \\ \frac{1}{R} & \frac{x_1}{R} & 1 \\ 0 & 0 & -\mu \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$.

In a discrete form, model (8) has the form:

$$x_k = Fx_k + w_k, \qquad (9)$$

where $x_k = \begin{bmatrix} \delta V_k \\ \psi_k \\ \varepsilon_k \end{bmatrix}$, $w_k = \begin{bmatrix} B_k \\ 0 \\ \eta_k \end{bmatrix}$,

$F = \begin{bmatrix} 1 & -Tg_k & 0 \\ \frac{T}{R_k} & 1 + \frac{T\delta V_k}{R_k} & T \\ 0 & 0 & 1 - T\mu \end{bmatrix}$, T - discretization step.

Dividing the vector x into two subvectors z_k and y_k. In the vector z_k, we highlight the errors in determining the velocity and the deviation angles of the GSP relative to the accompanied trihedron of the selected coordinate system. The control is based on the z_k subvector by applying signals to the torque sensors and the first integrators of the INS. Then model (9) will take the form:

$$x_k = Fz_{k-1} + Gy_{k-1} + w_{k-1} + u_{k-1} \qquad (10)$$

We introduce the notation

$$w_{k-1} + Gy_{k-1} = \zeta_{k-1} \qquad (11)$$

The quality functional has the form:

$$J = trM\left[x_k x_k^T\right]\min \qquad (12)$$

A minimum of functionality is achieved when

$$K_{k-1} = F$$

E. *Experimental research.*

The results of mathematical modeling have demonstrated the advantage of NC with correction in the structure of INS. Modeling was carried out on an interval of 1 hour and 3 hours. In the first case, the accuracy of the correction is almost the same, and with a longer time interval, the correction in the structure of the INS allows you to get more accurate navigation information. The accuracy assessment of NC correction over an interval of 3 hours using NFK (NC + NFK) and NC with NFK and a regulator (NC + NFK + R) is given in the table.

TABLE I. ACCURACY ASSESSMENT

Algorithms	**Correction accuracy (%)**
NC+NKF	86%
NC+NKF +R	92%

F. *Accuracy evaluation of the INS error correction algorithms*

Accuracy characteristics of a real AINS were determined when it was installed on a fixed base: the output information on the location and speed is the INS errors. The experiment was conducted in Moscow in the daytime for 5.5 hours. Accuracy of AINS with correction in the structure was compared with the accuracy of AINS with EA. The comparison was carried out using the data of a semi-negative experiment with the AINS as part of the INS Ts060K and ANS A-829.

The EA includes a simple linear model of the INS errors, which contains equations of attitude errors and of horizontal accelerometers errors. The model has the form:

$$x_{k+1} = \Phi x_k$$

The model state vector includes the INS path determining errors, velocity determining errors, GSP deviation angles relative to the moving trihedral, and the GSP drift velocity. The measurement vector consists of the difference between the ANS and INS signals, i.e. the first component δx of the state vector Δx_n is measured.The following formula is used to calculate the longitude determining error:

$$\delta\lambda = \frac{\delta x}{R\cos\varphi}$$

where φ, λ – latitude and longitude of the location, R –Earth radius. The AINS longitude determining errors and their estimates obtained with the help of adaptive EA are presented in Fig. 5.

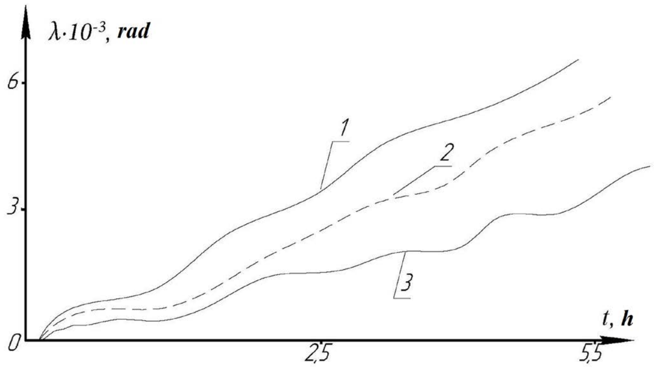

Fig. 5. AINS longitude determining errors and their estimates.

Here: 1 – AINS longitude determining error obtained in the experiment; 2 – the estimates of the AINS longitude determining error calculated using EA; 3 –longitude determining error in the presence of correction in the AINS structure.

The simulation showed that the best results of the correction of AINS longitude determining errors were obtained using adaptive EA. The average longitude determining accuracy for AINS with a correction in its structure is 10^{-4}rad., and for AINS with EA – $5 \cdot 10^{-5}$rad. The values of the AINS errors after the correction are calculated by calculating the standard deviation of the residual error, which is obtained in case of a correction in the system structure, as well as the difference between the INS errors and their estimates obtained using the EA. The figures are obtained on the AINS operation interval within 1 hour.

The proposed method of correction in the AINS structure is easy to implement, but the use of AINS with EA allows obtaining a higher accuracy of the aircraft navigation information.

II. Conclusions

The most accurate navigation information about UAV parameters is determined by combining INS, SNS and ANS. A functional scheme for combining INS and ANS is proposed, which provides for correction in the structure of INS. Using the generated control signals to the moment sensors and the first integrators, it is possible to eliminate the increase in the deviation angles of the GSP INS and maintain the adequacy of the selected model of INS errors in the NFK. When generating INS control signals, the SDC - method was used.

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