COMPUTER-AIDED DESIGN SYSTEMS

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UNMANNED AERIAL VEHICLE INTEGRATED NAVIGATION COMPLEX

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Abstract—*The proposed scheme of construction of an integrated navigation complex of an unmanned aerial vehicle, the basis of which are two subsystems – inertial and course-air. For each subsystem, implementation of algorithms for the complex processing of navigation information from the corresponding navigation sensors and onboard equipment of the Global Positioning System on the basis of a non-invariant compensation circuit is envisaged. The logic of using navigation measurements from both subsystems reflects the adaptation of the navigation complex to the flight conditions of the aircraft. The adaptive navigational complex unmanned aerial vehicle will improve the accuracy of the determination of navigational parameters of the flight, reliability and noise immunity of the aircraft during the flight task.*

Index Terms—Integrated navigation complex; adaptive tuning unmanned aerial vehicle; notation coordinates; accelerometer; angular velocity sensors; course-air sensors; GPS-corrector; noninvariant compensation scheme; procedure of discrete filter.

I. INTRODUCTION

The current trend and the basic principle of the construction of navigation complexes of aircraft is the algorithmic integration of various on-board navigation devices. Integrated navigation complexes provide the necessary level of accuracy and reliability of navigation equipment for unmanned aerial vehicles (UAV) in difficult operating conditions. The basis of such complexes is the course-air and inertial systems for notation coordinates, as well as the on-board equipment of the Global Positioning System (GPS), which, under the condition of normal functioning, provides high-precision position-velocity correction of the systems of calculating coordinates.

The main advantage of both of these systems for notation coordinate is their autonomy and noise immunity. In this case, additional advantages for the course-air system are the linear nature of the increase of errors in the notation coordinates in time and low cost, and for the inertial system – the ability to operate in conditions of high dynamics of flight UAV. The disadvantages of these systems include: for the course-air system – dependence on the wind situation, and for the inertial system – nonlinear character of the increase of errors in the calculation of coordinates in time. For both systems of notation coordinates, a great positive effect is their integration with GPS-corrector. Algorithmic and hardware issues of such integration are thoroughly studied and reflected in the literature, for example in [1] – [5], and others. However, the reserve for improving the accuracy, reliability and noise immunity of the integrated navigation complex of the UAV is its adaptive tuning, depending on the flight conditions of the aircraft. That is why the topic of the article is relevant and timely.

II. PROBLEM STATEMENT

Creation of integrated navigation complex UAV on the basis of navigational meters of different principle of action: inertial, course-air, etc. has its own peculiarities. These features include: the feasibility of separating the vertical and horizontal channels of navigation calculations; the need to determine the conditions and logic of switching inertial and course-air subsystems of the complex; a special procedure for the correction and extrapolation operations of the non-invariant compensation scheme of integration and the existence of a procedure for identifying the parameters of the systematic errors of sensors.

This article is devoted to the disclosure of these features of the integrated navigation complex of UAV with adaptive tuning on a qualitative level.

III. INTEGRATED NAVIGATION COMPLEX

The scheme of complex processing of navigation information in the integrated navigation complex of UAV with adaptive tuning is shown in Fig. 1.

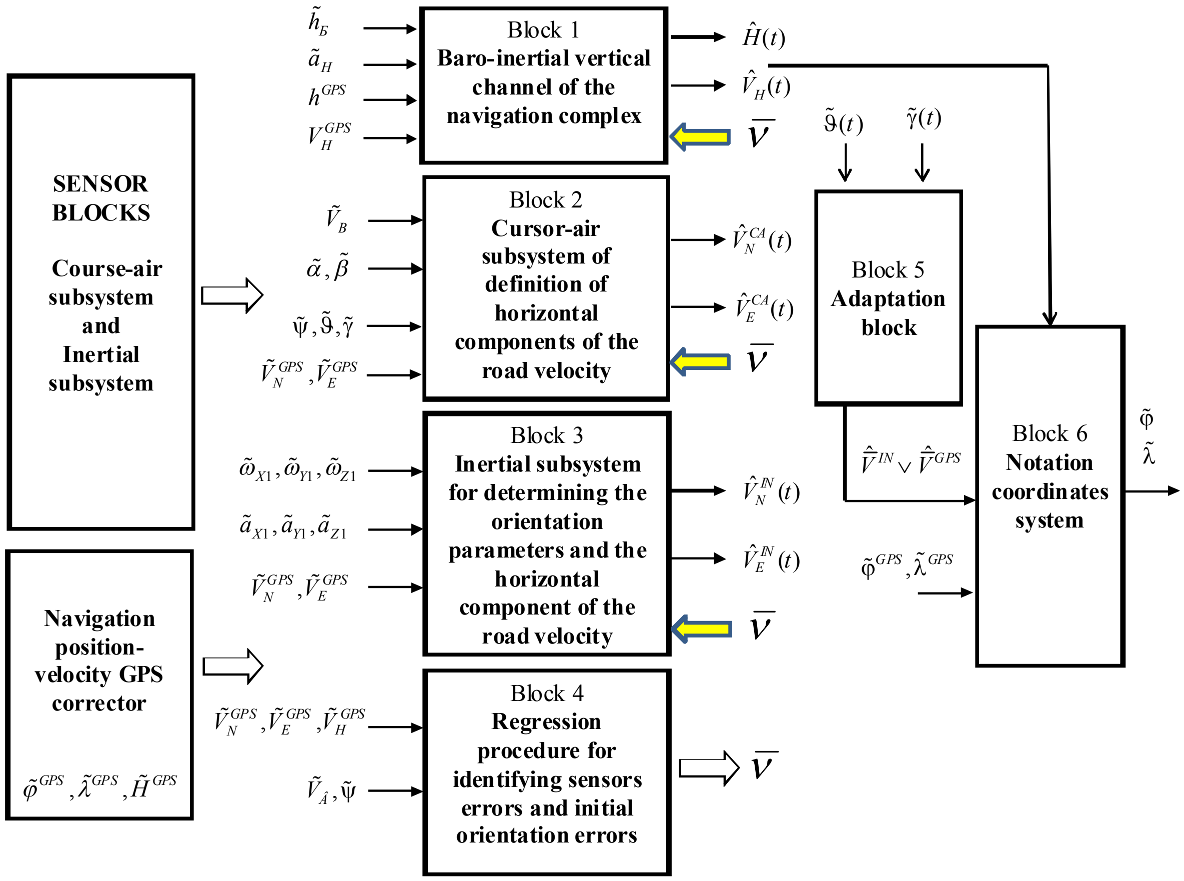

Fig. 1. Scheme of complex processing of navigation information in the integrated navigation complex with adaptive tuning for UAV

A. Composition of the integrated navigation complex

The structure of the course-air subsystem includes sensors of air velocity, angles of attack, sliding, vertical angles and a three-component magnetometer. An inertial subsystem is constructed using accelerometers and gyroscopes (angular-rate sensors). In computational algorithms, the following navigation measurements are used (Fig. 1): $\tilde{h}_B$ is the barometric altitude of the flight; $\tilde{a}_I$ is the vertical component of imaginary acceleration from accelerometer; $h^{\mathrm{GPS}}, V_H^{\mathrm{GPS}}$ are the values of the height and vertical flight velocity of the UAV from the receiver of the GPS; $\tilde{\alpha}, \tilde{\beta}$ are the angles of attack and slip; $\tilde{\psi}, \tilde{\vartheta}, \tilde{\gamma}$ are the angles of course, pitch and roll; $\tilde{V}_N^{\mathrm{GPS}}, \tilde{V}_E^{\mathrm{GPS}}, \tilde{V}_H^{\mathrm{GPS}}$ is the northern, eastern and vertical velocity components from the GPS; $\tilde{\omega}_{X1}, \tilde{\omega}_{Y1}, \tilde{\omega}_{Z1}$, $\tilde{a}_{X1}, \tilde{a}_{Y1}, \tilde{a}_{Z1}$ are the components of the absolute angular velocity and imaginary acceleration on the axes of the instrument coordinate system; $\tilde{V}_{\mathrm{WIND}}, \tilde{\psi}$ is the velocity and angle of the stationary wind direction; $\tilde{\varphi}, \tilde{\lambda}, \tilde{H}$ and $\tilde{\varphi}^{\mathrm{GPS}}$, $\tilde{\lambda}^{\mathrm{GPS}}, \tilde{H}^{\mathrm{GPS}}$ are geographical coordinates (longitude, latitude, height) in the Earth's coordinate system and their estimates for information from the GPS-corrector, respectively.

B. Particularity of the functioning of the integrated navigation complex

The first particularity of the functioning of the integrated navigation complex is that its algorithms can be divided into six different groups (six blocks in Fig. 1).

The second particularity is the two levels of the navigational calculations.

Level 1. The current horizontal components of the road velocity are calculated either on the basis of the course-air principle in block 2, or on the basis of the inertial principle in block 3.

Level 2. The calculation of the coordinates of the location is performed in block 6.

A third particularity is the use of a non-invariant compensation schemes in the form of a non-linear discrete filters. This filter is implemented in the baro-inertial vertical channel in block 1; in the inertial subsystem of determination of orientation parameters and horizontal components of the road velocity in block 2; and in the subsystem for calculating the coordinates of the UAV location in block 6.

In general terms, the mathematical models of these subsystems have the following form:

$$\bar{X}_{i+1} = f_i(\bar{X}_i) + \bar{\xi}_i, \quad \bar{Y}_i = h_i(\bar{X}_i) + \bar{\eta}_i, \quad i = 1, 2, 3, \tag{1}$$

where $\bar{X}_i$ is the n-dimension vector of the system state; $\bar{Y}_i$ is the m-dimension vector of observation; $\bar{\xi}_i$, $\bar{\eta}_i$ are gaussian vectors of random perturbations of the subsystem and observations with covariance matrices Q_i and R_i respectively; f and h are known in the general case nonlinear vector functions that determine the dynamic properties of the subsystem and the measurement process, the dimensions n and m, respectively.

The fourth particularity is that for each of the non-linear discrete filters, at each step of the calculation, the following basic operations are implemented: the operation of correction of the state vector on the information from the navigator corrector, and the operation of extrapolating the state vector using the information from the sensors (or information about the assessment of the horizontal components of the road velocity for block 6).

The correction operation implements the estimation of the state vector and the covariance matrix of error estimates using the information from the navigator corrector.

This operation is realized using known procedures [2], [7]:

$$\begin{aligned} &\hat{\bar{X}}_i^{(+)} = \hat{\bar{X}}_i^{(-)} + K_i\left(\bar{Y}_i - h_i(\hat{\bar{X}}_i)\right), \\ &P_i^{(+)} = (E_2 - K_i\, H)P_i^{(-)}, \end{aligned} \qquad i = 1, 2, \dots, \tag{2}$$

where $K_i = P_i^{(-)}H^{\mathrm{T}}(HP_i^{(-)}H^{\mathrm{T}} + R)^{\oplus}$ is the matrix coefficient of filter amplification; E_n is the unit matrix; P_i is the covariance matrix of estimation errors; $\oplus$ is the symbol of the pseudo-rotation of the matrix by the Greville method; “–” and “+” are the indexes of the values “ before ” and “ after ” the correction.

The fifth particularity is the use of a linear regression procedure to identify the errors of primary information sensors and initial orientation errors in block 4. In this case, for the course-air subsystem, horizontal components of the wind stationary velocity and displacement of the readings of the course angle sensor are identified, and for the inertial subsystem, the displacement of the readings of the inertial sensors and the error of the initial alignment are identified.

C. Algorithmic realization of the functions of the integrated navigation complex

Block 1 – baro-inertial vertical channel of the navigation complex

The vertical and horizontal channels of navigation complex of the UAV are, to a large extent, independent, therefore, in algorithmic implementation, it is advisable to ensure separation of calculations on these channels. In addition, this separation will reduce the dimensionality of the subsystem models and, accordingly, reduce the computational cost of implementing discrete filters.

The height value should be calculated by the complex processing of the readings of the barometric altimeter, the vertical component of the imaginary acceleration from the accelerometers, and the estimates of H and V from the GPS-corrector on the non-invariant compensation scheme. In this case, for the nonlinear discrete filter (1), the vector of the system $\bar{X}_{Bi}$ and observation $\bar{Y}_{Bi}$ (n = 2, m = 3) will have the following form:

$$\bar{X}_{Bi} = (h_i, V_{hi})^{\mathrm{T}}, \qquad \bar{Y}_{Bi} = \left(h_{\hat{A}i}, h_i^{\mathrm{GPS}}, V_{hi}^{\mathrm{GPS}}\right). \tag{3}$$

The baro inertial vertical channel (*block 1*) operates throughout the all flight of the UAV (autonomously or in combination with a navigational correction).

The definition of the horizontal components of the road velocity occurs separately for the course-air subsystem (*block 2*) and the inertial subsystem (*block 3*).

Block 2 – course-air subsystem of definition of horizontal components of the road speed

Current components of the road velocity for the course-air system $V_N(t), V_E(t)$ satisfy the following ratio:

$$\begin{aligned} V_N(t) &= V_{\mathrm{air}\,N}(t) + V_{\mathrm{wind}\,N}, \\ V_E(t) &= V_{\mathrm{air}\,E}(t) + V_{\mathrm{wind}\,E}, \end{aligned} \tag{4}$$

where $V_{\mathrm{AIR}\,N}(t)$ and $V_{\mathrm{AIR}\,E}(t)$ are the projections of the airspeed speed of the UAV on the axis N and E, calculated on the basis of current information from air velocity sensors, angles of attack, sliding, pitch, roll and course; $V_{\mathrm{wind}\,N}$ and $V_{\mathrm{wind}\,E}$ is the horizontal components of the stationary wind velocity.

In the general case, the equation for the horizontal components of the air velocity is as follows:

$$
\begin{aligned}
V_{\text{air}\,N}(t) = V_{\text{air}}(t)\{&\cos\vartheta(t)\cos\psi_{\text{tr}}(t)\cos\alpha(t)\cdot\cos\beta(t) + [\sin\psi_{\text{tr}}(t)\sin\gamma(t) + \cos\psi_{\text{tr}}(t)\cos\gamma(t) \\
&\cdot\sin\vartheta(t)]\sin\alpha(t)\cos\beta(t) + [\cos\psi_{\text{tr}}(t)\sin\vartheta(t)\cdot\sin\gamma(t) - \sin\psi_{\text{tr}}(t)\cos\lambda(t)]\sin\beta(t)\}, \\
V_{\text{air}\,E}(t) = V_{\text{air}}(t)\{&\cos\vartheta(t)\sin\psi_{\text{tr}}(t)\cos\alpha(t)\cdot\frac{1}{2}\cos\beta(t) + [\sin\psi_{\text{tr}}(t)\sin\vartheta(t)\cos\gamma(t) - \cos\psi_{\text{tr}}(t) \\
&\cdot\sin\gamma(t)]\sin\alpha(t)\cos\beta(t) + [\cos\psi_{\text{tr}}(t)\sin\gamma(t) + \sin\psi_{\text{tr}}(t)\sin\vartheta(t)\sin\gamma(t)]\sin\beta(t)\},
\end{aligned}
\tag{5}
$$

where $V_{\text{air}}(t)$ is the current air velocity; $\psi_{\text{tr}}(t)$, $\vartheta(t)$, $\gamma(t)$ are current angles of the true course, pitch and roll; $\alpha(t)$, $\beta(t)$ are current angles of attack and slip.

For the course-air in block 2, instead of the filter, the procedure for determining the weighted estimations of the components of the road velocity $\hat{V}_{Ni}$ and $\hat{V}_{Ei}$. In this case, the vectors of the state of the system $\bar{X}_{Ki}$ and the observation $\bar{Y}_{Ki}$ (n = 2, m = 4) will have the following form:

$$
\begin{aligned}
&\bar{X}_{Ki} = (V_{Ni}, V_{Ei})^{\text{T}}, \\
&\bar{Y}_{Ki} = (V_{Ni}^{CA}, V_{Ei}^{CA}, V_{Ni}^{GPS}, V_{Ei}^{GPS})^{\text{T}}.
\end{aligned}
\tag{6}
$$

Block 3 – an inertial subsystem of determining the orientation parameters and horizontal components of the road velocity

Algorithms of the inertial subsystem are the most complex and here the linear nonlinear discrete filter (1) is used to calculate the horizontal components of the road velocity, in which the vector-column of the system $\bar{X}_{Ii}$ and the observation $\bar{Y}_{Ii}$ (n = 6, m = 2) will have the following form:

$$
\begin{aligned}
&\bar{X}_{Ii} = (V_{Ni}, V_{Ei}, \lambda_0, \lambda_1, \lambda_2, \lambda_3)^{\text{T}}, \\
&\bar{Y}_{Ii} = (V_{Ni}^{\text{GPS}}, V_{\hat{A}i}^{\text{GPS}})^{\text{T}},
\end{aligned}
\tag{7}
$$

where $\lambda_0, \lambda_1, \lambda_2, \lambda_3$ are the elements of the quaternion orientation of the instrumental coordinate system relative to the reference coordinate system.

In order to ensure the required accuracy of the inertial subsystem, the reading of the inertial sensors (accelerometers and gyroscopes) is performed at high frequency, and, as a rule, multi-step algorithms of high order of accuracy are used for extrapolation of the required navigational parameters [8, 9, 10].

The analysis shows that the algorithms for extrapolating navigational parameters from the primary navigation information from the inertial sensors of the navigation accuracy class (integrating accelerometers and angular velocity meters) can be classified into two groups:

– high-frequency, as a rule, multi-step algorithms for calculating the orientation parameters of the instrument dipole and the increase of the imaginary speed;

– mid-frequency algorithms for numerical integration of navigation equations with respect to component speeds.

In the synthesis of high-precision algorithms for extrapolation of the orientation parameters of the instrument triangular relative to the reference coordinate system, the fact that the primary information from inertial sensors is obtained in the form of quantized in time and in terms of increments of quasi-coordinates is taken into account:

$$
\begin{aligned}
&\bar{P}_{k+1} = \bar{b}_{k+1} = \begin{pmatrix} b_{x1,k+1} \\ b_{y1,k+1} \\ b_{z1,k+1} \end{pmatrix} = \int_{t_k}^{t_{k+h}} \bar{a}(t)\,dt; \\
&\bar{b}_{k+1} = \begin{pmatrix} b_{x1,k+1} \\ b_{y1,k+1} \\ b_{z1,k+1} \end{pmatrix} = \int_{t_k}^{t_{k+h}} \bar{a}(t)\,dt; \quad k = 0,1...,
\end{aligned}
\tag{8}
$$

where $\bar{\omega}(t) = (\omega_{x1}(t), \omega_{y1}(t), \omega_{z1}(t))^{\text{T}}$ and $\bar{a}(t) = (a_{x1}(t), a_{y1}(t), a_{z1}(t))^{\text{T}}$ are vectors-columns of components of absolute angular velocity and the apparent acceleration of the beginning of the device triangular.

When calculating the desired current orientation parameters, for example, Rodrigueh–Hamilton parameters, as intermediate parameters, as a rule, use increments of the so-called vector of orientation [9].

The compact representation of a high-precision four-step algorithm for calculating the growth of the vector of orientation has the following form [8]:

$$
\begin{aligned}
\Delta\bar{\varphi}_{k+4} &= \bar{P}_{\Sigma} - \frac{2}{9}(P_1 + P_2)(\bar{P}_3 + \bar{P}_4) \\
&+ \frac{32}{15}(P_1\bar{P}_3 + P_2\bar{P}_4) + \frac{32}{45}\big[(\bar{P}_1\cdot\bar{P}_4)\bar{P}_2 - (\bar{P}_1\cdot\bar{P}_2)\bar{P}_4 \\
&- (\bar{P}_4\cdot\bar{P}_3)\bar{P}_1 + (\bar{P}_4\cdot\bar{P}_1)\bar{P}_3\big] - \frac{64}{45}\big(1 - (\bar{P}_2\cdot\bar{P}_3)\big)P_2\bar{P}_3,
\end{aligned}
\tag{9}
$$

where $(\bar{P}_1\cdot\bar{P}_4)$ is the denoting the scalar product of the column vectors $\bar{P}_1$ and $\bar{P}_4$.

The algorithm (9) has the sixth order of accuracy. Growth of the Rodriguez–Hamilton parameters in four steps of the survey of angular velocity sensors are calculated according to the following equations:

$$\Delta\lambda_i = \frac{1}{2}\left(1 - \frac{1}{24}\left|\Delta\overline{\varphi}_{k+4}\right|^2\right)\Delta\varphi_{k+4,i},\; i = 1,2,3,$$
$$\Delta\lambda_0 = 1 - \frac{1}{8}\left|\Delta\overline{\varphi}_{k+4}\right|^2 + \frac{1}{384}\left|\Delta\overline{\varphi}_{k+4}\right|^4, \tag{10}$$

where $\Delta\overline{\lambda} = \left(\Delta\lambda_0, \Delta\lambda_1, \Delta\lambda_2, \Delta\lambda_3\right)^{\mathrm{T}}$ is the increase of quaternion.

Calculation of quaternion estimates $\overline{\lambda}^{+} = \overline{\lambda}(t_{k+4\Delta t})$ is performed according to the following equations:

$$\begin{aligned}
\lambda_0^{+} &= \lambda_0^{-}\Delta\lambda_0 - \lambda_1^{-}\Delta\lambda_1 - \lambda_2^{-}\Delta\lambda_2 - \lambda_3^{-}\Delta\lambda_3,\\
\lambda_1^{+} &= \lambda_0^{-}\Delta\lambda_1 + \Delta\lambda_0\lambda_1^{-} + \lambda_3^{-}\Delta\lambda_2 - \lambda_2^{-}\Delta\lambda_3,\\
\lambda_2^{+} &= \lambda_0^{-}\Delta\lambda_2 + \Delta\lambda_0\lambda_2^{-} - \lambda_3^{-}\Delta\lambda_1 + \lambda_1^{-}\Delta\lambda_3,\\
\lambda_3^{+} &= \lambda_0^{-}\Delta\lambda_3 + \Delta\lambda_0\lambda_3^{-} + \lambda_2^{-}\Delta\lambda_1 - \lambda_1^{-}\Delta\lambda_2,
\end{aligned} \tag{11}$$

where $\overline{\lambda}^{(-)} = \overline{\lambda}(t_k)$.

Quaternion $\overline{\lambda}$ characterizes the motion of a connected (instrumental) triangular relative to the initial position of the reference geographic basis of *NHE* at the time $t = 0$.

To calculate the growth of the imaginary velocity vector in a bound basis, a four-stage algorithm of the sixth order accuracy of this kind can be used:

$$\Delta\overline{W}_{bb}(t_k + 4\Delta t) = 2\left\{\Delta\lambda_0\begin{pmatrix}\Delta\mu_1\\ \Delta\mu_2\\ \Delta\mu_3\end{pmatrix} - \Delta\mu_0\begin{pmatrix}\Delta\lambda_1\\ \Delta\lambda_2\\ \Delta\lambda_3\end{pmatrix} - \begin{pmatrix}\Delta\lambda_2\Delta\mu_3 - \Delta\lambda_3\Delta\mu_2\\ \Delta\lambda_3\Delta\mu_1 - \Delta\lambda_1\Delta\mu_3\\ \Delta\lambda_1\Delta\mu_2 - \Delta\lambda_2\Delta\mu_1\end{pmatrix}\right\}, \tag{12}$$

where $(\mu_0, \Delta\mu_1, \Delta\mu_2, \Delta\mu_3)^{\mathrm{T}} = \Delta\overline{\mu}$ is the growth of the so-called dual quaternion; $(\Delta\lambda_0, \Delta\lambda_1, \Delta\lambda_2, \Delta\lambda_3)^{\mathrm{T}} = \Delta\overline{\lambda}$.

In turn, the following algorithm is used to calculate the growth of a dual quaternion $\Delta\overline{\mu}$:

$$\Delta\mu_0 = -\frac{1}{2}\frac{\sin\frac{\Delta\varphi}{2}}{\Delta\varphi}\left(\Delta\overline{\varphi}\cdot\Delta\overline{\varphi}^0\right),$$
$$\Delta\mu_i = \frac{\sin\frac{\Delta\varphi}{2}}{\Delta\varphi}\Delta\varphi_i^0 - \frac{\Delta\varphi_i}{\Delta\varphi^2}\cdot\left[\frac{1}{2}\cos\frac{\Delta\varphi}{2} - \frac{\sin\frac{\Delta\varphi}{2}}{\Delta\varphi}\right](\Delta\overline{\varphi}\cdot\Delta\overline{\varphi}^0); \qquad i = 1,2,3. \tag{13}$$

In equation (13) $\Delta\overline{\varphi}^0$ is the so-called dual orientation vector: $\Delta\overline{\varphi}^0 = (\Delta\varphi_1^0, \Delta\varphi_2^0, \Delta\varphi_3^0)^{\mathrm{T}}$, for the calculation of which uses the following four step algorithm:

$$\begin{aligned}
\Delta\overline{\varphi}^0 = \overline{b}_\Sigma &- \frac{2}{9}\left[(B_1 + B_2)(\overline{P}_3 + \overline{P}_4) + (P_1 + P_2)(\overline{b}_3 + \overline{b}_4)\right] + \frac{32}{15}\left(B_1\overline{P}_3 + P_1\overline{b}_3 + B_2\overline{P}_4 + P_2\overline{b}_4\right)\\
&+ \frac{32}{45}\left[\overline{b}_1\cdot\overline{P}_4)\overline{P}_2 - (\overline{b}_1\cdot\overline{P}_2)\overline{P}_4 - (\overline{b}_4\cdot\overline{P}_3)\overline{P}_1 + (\overline{b}_4\cdot\overline{P}_1)\overline{P}_3 + +(\overline{b}_2\cdot\overline{P}_1)\overline{P}_4 - (\overline{P}_4\cdot\overline{P}_1)\overline{P}_2\right.\\
&\left.+ (\overline{P}_2\cdot\overline{P}_1)\overline{b}_4 - (\overline{b}_4\cdot\overline{P}_1)\overline{P}_2 - (\overline{b}_1\cdot\overline{P}_4)\overline{P}_3 + (\overline{P}_3\cdot\overline{P}_4)\overline{b}_1 - (\overline{P}_1\cdot\overline{P}_4)\overline{b}_3 + (\overline{b}_3\cdot\overline{P}_4)\overline{P}_1\right]\\
&- \frac{64}{45}\left\{\left[1 - (\overline{P}_2\cdot\overline{P}_3)\right](B_2\overline{P}_3 + P_2\overline{b}_3) - \left[(\overline{P}_2\cdot\overline{b}_3) + (\overline{b}_2\cdot\overline{P}_3)\right]P_2\overline{P}_3\right\}.
\end{aligned} \tag{14}$$

The algorithm (14) is a dual version of the algorithm (9) for calculating the increment of the usual orientation vector obtained on the basis of the well-known principle of the transfer of Kotelnikov–Studi [10], [12].

Block 4 – regression procedure for identification of the sensor errors and initial orientation errors

In order to improve the accuracy of the determination of the navigational parameters of the UAV in blocks 1, 2, 3, 6, it is proposed to implement a regression procedure for identifying the parameters of the systematic errors of the primary information sensors and the initial alignment errors. To construct the identification procedure it is recommended to use the apparatus of the theory of sensitivity.

For the course-air subsystem, horizontal components of the velocity of the stationary wind and the displacement of the readings of the sensor of the course are identified.

At the initial stage of the flight of the BPPL at the normal operation of the GPS, the vector column of corrections $\overline{\delta}_{edit} = (\Delta\psi_{\text{edit}}, \Delta V_{\text{wind}\,N\,\text{edit}}, \Delta V_{\text{wind}\,E\,\text{edit}})^{\text{Ò}}$ using the high-speed information from the on-board equipment of GPS is estimated:

$$\hat{\overline{\delta}}_{\text{edit}} = -G_V^{\oplus}\,\overline{d}_V\,, \quad (15)$$

where $G_V = \begin{pmatrix} B_1 \\ B_2 \\ \vdots \\ B_{N\,\text{edit}} \end{pmatrix}, \quad \overline{d}_V = \begin{pmatrix} \tilde{\overline{V}}_1 - \tilde{\overline{V}}_1^{\text{GPS}} \\ \tilde{\overline{V}}_2 - \tilde{\overline{V}}_2^{\text{GPS}} \\ \vdots \\ \tilde{\overline{V}}_{N\,\text{edit}} - \tilde{\overline{V}}_{N\,\text{edit}}^{\text{GPS}} \end{pmatrix},$

$\overline{V}_i = (V_{Ni}, V_{Ei})^{\text{T}}, \; B_i = \begin{pmatrix} -\tilde{V}_{\text{air}\,i}\cos\tilde{\vartheta}_i \sin\tilde{\psi}_{\text{tr}\,i} & 1 & 0 \\ \tilde{V}_{\text{air}\,i}\cos\tilde{\vartheta}_i \cos\tilde{\psi}_{\text{tr}\,i} & 0 & 1 \end{pmatrix},$

$t_{i+1} - t_i = \Delta T_{\text{edit}}\,, i = 1, 2, \ldots N_{\text{edit}}.$

In this case, the current estimates of the components of the road velocity $\tilde{V}_{N\,i}$ and $\tilde{V}_{E\,i}$ calculated by the equation

$$\tilde{V}_{l\,i} = \tilde{V}_{\text{air}\,i} + \hat{V}^{(0)}_{\text{wind}\,l}\,, \; l = N, E. \quad (16)$$

In turn, for the calculation $\tilde{V}_{\text{air}\,li}$, $l = N, E$ we use equations (5), in which the results of measurements $\tilde{V}_{\text{air}\,i}$, $\tilde{\gamma}_i$, $\tilde{\alpha}_i$, $\tilde{\vartheta}_i$, $\tilde{\beta}_i$, $\tilde{\psi}_{\text{tr}\,i}$.

Under normal operation of the on-board equipment of GPS, obtained at the initial stage of the flight, the evaluation of the corrections to the horizontal component of the wind speed periodically specified by the next procedure:

$$\Delta\hat{V}^{(j+1)}_{\text{wind}\,l\,\text{edit}} = \Delta\hat{V}^{(j)}_{\text{wind}l\,\text{edit}} + \delta V^{(j)}_{l\,\text{edit}}\,, \quad l = N, E, \quad (17)$$

where $\delta V^{(j)}_{l\,\text{edit}} = \dfrac{1}{N_W}\sum_{i=1}^{N_W}(\tilde{V}_{li} - \tilde{V}^{\text{GPS}}_{li}), l = N, E;$

$\tilde{V}_{li}, l = N, E$ are current estimates of the components of the road velocity, derived from the preliminary estimates of the amendments; $t_{i+1} - t_i = \Delta T_W$.

The identification of the errors of setting the horizontal components of the speed of the stationary wind and the systematic error of the definition of the angle of the course is recommended when performing the UAV maneuver in a horizontal plane of the type "circle".

For the inertial subsystem, the displacement of the readings of the inertial sensors and the initial alignment errors are identified by the nonlinear regression procedure.

The equation of the errors of the inertial system is as follows:

$$\Delta\dot{\overline{X}} = F\left(\overline{X}(t)\right)\Delta\overline{X}(t) + \mathrm{B}\left(\overline{X}(t)\right)\overline{\mu}, \quad (18)$$

where $\Delta\overline{\mathrm{X}} = \left(\Delta\overline{V}^{\text{T}}, \Delta\overline{R}^{\text{T}}, \Delta\overline{\theta}^{\text{T}}\right)^{\text{T}}$;

$\Delta\overline{V} = (\Delta V_N, \Delta V_h, \Delta V_E)^{\text{T}}$; $\Delta\overline{R} = (\Delta R_N, \Delta h, \Delta R_E)^{\text{T}}$; $\Delta\overline{\theta} = (\alpha_N, \alpha_h, \alpha_E)^{\text{T}}$ are NHE baseline modeling errors; $R_N = (\varphi - \varphi_0)R_{\text{Earth}}$, $R_E = (\lambda - \lambda_0)R_{\text{Earth}}\cos\varphi_0$; φ_0 is the local geographic coordinates of the location are given; $\overline{\mu} = (\Delta\overline{\omega}^{\text{T}}, \Delta\overline{a}^{\text{T}})^{\text{T}}$ is the displacement of indications of primary information sensors of the inertial navigation system.

The linear regression model has the form:

$$G_\Sigma\overline{\delta} = \Delta\overline{Y}_\Sigma, \quad (19)$$

where $\overline{\delta} = (\overline{\mu}^{\text{T}}, \Delta\overline{\theta}_0^{\text{T}})^{\text{T}}$ is the vector of identifiable parameters; $G_\Sigma = \begin{pmatrix} G(t_1) \\ G(t_2) \\ \ldots \\ G(t_N) \end{pmatrix}$ is the regression matrix;

$G(t_j) = (U^*(t_j) \vdots L^*(t_{j_0} t_0)$; $U^*(t_j)$ is the matrix 6×6, created by the first six lines of the matrix of sensory functions of estimates of navigational parameters at the moment t_j of displacement of indications of inertial sensors $U(t_j) = \dfrac{\partial\Delta\overline{X}(t_j)}{\partial\overline{\mu}}$;

$L^*(t_j, t_0)$ is the matrix 6×3, created by the last three columns of the first six lines of the transition matrix $L\,(t_j, t_0)$; $\overline{Y}_\Sigma = \begin{pmatrix} \overline{Y}(t_1) \\ \overline{Y}(t_2) \\ \ldots \\ \overline{Y}(t_N) \end{pmatrix}$ is the vector of variation of navigational parameters; $\Delta\overline{Y}(\overline{Z}(t_j) = = \overline{Z}^M(t_j) - \overline{Z}^{\text{GPS}}(t_j)$; $\overline{Z}(t_j) = \left(\overline{V}^{\text{T}}(t_j), \overline{R}^{\text{T}}(t_j)\right)^{\text{T}}$.

The matrix of sensitivity functions $U(t)$ is calculated by numerically integrating the equation of the form:

$$\dot{U}(t) = F\left(\overline{X}(t)\right)U(t) + B\left(\overline{X}(t)\right), \quad (20)$$

at zero initial condition $U(t_0) = 0$.

The transition matrix $L(t_j, t_0)$ is a matrix function of the influence of the variation of the initial values of navigation parameters on their current value:

$$\Delta\overline{X}(t_j) = L(t_J, t_0)\Delta\overline{X}(t_0) \quad (21)$$

The values of the elements of the transition matrix for moments $t(j=1,2,...,N)$ are calculated by numerically integrating the equation $\dot{L}(t,t_0)= = F(\bar{X}(t))L(t,t_0)$ at the initial condition in the form of a single diagonal matrix $L(t_0,t_c)=E_9$.

Estimation of the parameter vector $\bar{\delta}$ corresponding to the regression model (19) is determined by the following algorithm:

$$\hat{\bar{\delta}} = G_{\Sigma}^{\oplus}\Delta\bar{Y}_Z. \tag{22}$$

When implementing the regression procedure for identifying the systematic errors of the inertial system, positional and velocity correction of navigational parameters estimates using information from the navigator corrector is performed only at the initial time. Estimates of displacement of sensor readings and the initial alignment errors, obtained by means of a regression procedure, are used to make corrections to the values of the navigational parameters estimates at the time of the end of the error identification stage.

In order to provide the conditions for observation of estimations of parameters of the navigation system, which are calculated, the accumulation of information for a regression model is recommended during the performance of the UAV combined maneuver of the type "snake" in the horizontal plane and the "slide" with the set of altitudes and descent in the vertical plane.

Block 5 – block of adaptation

In this block, the adaptive tuning of the integrated navigation complex of the UAV is realized by connecting various subsystems to determine the horizontal components of the road velocity (block 2 or 3). It is performed automatically, depending on the nature of the flight path of the UAV, namely the values of the angles of the roll and pitch. If these angles are in absolute value less than 30°, then the readings of the course-air subsystem are used, at values of angles larger than 30° – the indications of the inertial subsystem are used.

Block 6 – a system for notation the coordinates of the location

In this block, based on the horizontal components of the road velocity and height, estimates of the coordinates of the location of the UAV $R_N(t)$ and $R_E(t)$ are calculated.

The operation of correction of coordinates of location is performed using current positional information from the navigator corrector.

In this case, in the nonlinear discrete filter, the vectors-columns of the system $\bar{X}_{Li}$ and the observation $\bar{Y}_{Li}$ (n = 2, m = 2) have the following form:

$$\bar{X}_{Li} = (R_{Ni}, R_{Ei})^{\mathrm{T}},$$
$$\bar{Y}_{Li} = (R_{Ni}^{\mathrm{GPS}}, R_{Ei}^{\mathrm{GPS}})^{\mathrm{T}}, \tag{23}$$

where $R_N = (\varphi-\varphi_0)R_{\mathrm{Earth}}$ and $R_E = (\lambda-\lambda_0)R_{\mathrm{Earth}}\cos\varphi_0$.

The operation of coordinate extrapolation is realized using information on the current estimates of the components of the road velocity. Taking into account the results presented in [8], the equations for the reduced geographic coordinates can be represented as follows [4]:

$$\dot{R}_N(t) = V_N(t)C_1[\varphi(t),h(t)],$$
$$\dot{R}_E(t) = V_E(t)C_2[\varphi(t),h(t)], \tag{24}$$

where

$$C_1[\varphi,h] = \frac{R_{\mathrm{Earth}}}{a}\left[1+e^2\left(1-1.5\sin^2\varphi(t)\right)-h(t)/a\right],$$
$$C_2[\varphi,h] = \frac{R_{\mathrm{Earth}}}{a\cos\varphi(t)}\left[1-0.5e^2\sin^2\varphi(t)-h(t)/a\right],$$

$\varphi(t),\lambda(t)$ is the geographic latitude and longitude; $h(t)$ is the flight height above the surface of the earth's ellipsoid; R_{Earth} is the constant, accepted equal to the radius of the Earth's sphere; $V_N(t), V_E(t)$ are projections of the velocity of the UAV on the horizontal axis of the geographic triangular; a, e^2 is the large half-axis and the square of the eccentricity taken to navigate the Earth's ellipsoid.

IV. Conclusions

Creation of an integrated navigation complex of the UAV with adaptive tuning will allow to improve the accuracy of the determination of navigational parameters of the flight, the reliability and noise immunity of the UAV in the performance of the flight task.

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Ф. М. Захарін, С. О. Пономаренко. Інтегрований навігаційний комплекс для безпілотних літальних апаратів

Запропоновано схему побудови інтегрованого навігаційного комплексу безпілотного літального апарату, основу якої складають дві підсистеми – інерціальна та курсо-повітряна. Для кожної підсистеми передбачено реалізацію алгоритмів комплексної обробки навігаційної інформації від відповідних навігаційних датчиків та бортової апаратури супутникової навігаційної системи на основі неінваріантної компенсаційної схеми. Логіка використання навігаційних вимірювань від обох підсистем відображає адаптацію навігаційного комплексу до умов польоту літального апарату. Адаптивний навігаційний комплекс безпілотного літального апарату дозволить підвищити точність визначення навігаційних параметрів польоту, надійність і завадозахищеність безпілотного літального апарату при виконанні польотного завдання.

Ключові слова: акселерометр; датчик кутової швидкості; бортовий навігаційний коректор; процедура нелінійної дискретної фільтрації; лінійна регресійна процедура; матриця функцій чутливості; псевдообернена матриця.

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Ф. М. Захарин, С. А. Пономаренко. Интегрированный навигационный комплекс для беспилотных летательных аппаратов

Предложена схема построения интегрированного навигационного комплекса беспилотного летательного аппарата, основу которой составляют две подсистемы – инерциальная и курсо-воздушная. Для каждой подсистемы предусмотрена реализация алгоритмов комплексной обработки навигационной информации от соответствующих навигационных датчиков и бортовой аппаратуры спутниковой навигационной системы на основе неинвариантной компенсационной схемы. Логика использования навигационных измерений от обеих подсистем отражает адаптацию навигационного комплекса к условиям полета летательного аппарата. Адаптивный навигационный комплекс беспилотного летательного аппарата позволит повысить точность определения навигационных параметров полета, надежность и помехозащищенность беспилотного летательного аппарата при выполнении полетного задания.

Ключевые слова: акселерометр; датчик угловой скорости; бортовой навигационный корректор; процедура нелинейной дискретной фильтрации; линейная регрессионная процедура; матрица функций чувствительности; псевдообратная матрица.

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