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PRINCIPLES OF NAVIGATION SYSTEM DESIGN OF UAV

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Abstract*—It proposed a modified invariant compensation scheme interconnecting an instrument air sensors and on-board equipment of satellite navigation for small unmanned aerial vehicle. The main role of the scheme of complex processing of navigation data assigned to the non-linear digital filter, and regression estimation procedure for amendments to the measurement of the angle of the course and the initial estimate of the horizontal components of wind velocity.*

Index terms—Unmanned aerial vehicle; notation coordinate; course-air sensors; satellite navigation system; non-invariant compensation scheme; the non-linear digital filter; the wind speed.

I. INTRODUCTION

To ensure the accuracy and reliability of operation in noisy environments as onboard systems coordinate notation of unmanned aerial vehicles (UAV) inertial and courses air system are used. Given the tight weight and size restrictions payload certain advantages for small UAV has an instrument air system, for which, unlike inertial system, there is a linear increase of the coordinate notation errors in time. As part of the navigation system (NS) of UAV is used onboard equipment satellite navigation system (SNS), which under normal operation provides highly accurate position-speed correction radix coordinates.

The subject of this work is the new technology of complex processing of navigation data on the course air sensors of the UAV (sensor airspeed, *air altitude sensor*, three-component magnetometer, sensors angles, pitch, roll, slip and attack) and SNS equipment.

II. PROBLEM STATEMENT

There are $\boldsymbol{r}_i$, $i = 1, ..., n$ board navigation systems, which may be included in the navigation system of the UAV. Each of the systems may be described by $\boldsymbol{R}_i$, $i = 1, ..., m$ characteristics. The task is the choice of composition of small UAV navigation system $\boldsymbol{r}_i$, $i = 1,...k$, $k < n$ and improvement scheme of their complexing.

III. PROBLEM SOLUTION

Unlike traditional schemes invariant complex processing of information [1], which involves estimation error of dead reckoning position system by the position-speed information from SNS, in the paper is considered non-invariant scheme, which involves direct estimation of the required navigation parameters [2].

A. Used mathematical models

At the rate of air-reckoning position coordinates of the UAV the following navigation equations with respect to reduced coordinates $R_{\mathrm{N}}(t)$ and $R_{\mathrm{E}}(t)$ can be used:

$$\dot{R}_{\mathrm{N}}(t) = \frac{V_{\mathrm{N}}(t)}{R_1[\varphi(t), h(t)]};\qquad \dot{R}_{\mathrm{E}}(t) = \frac{V_{\mathrm{E}}(t)}{R_2[\varphi(t), h(t)]\cos\varphi(t)}, \tag{1}$$

where $R_{\mathrm{N}}(t) = [\varphi(t) - \varphi_{\mathrm{op}}] R_{\mathrm{Ear}}$; $R_{\mathrm{E}}(t) = [\lambda(t) - \lambda_{\mathrm{op}}] \cdot R_{\mathrm{Ear}}$; $\varphi(t), \lambda(t)$ are geographical latitude and longitude coordinates; $h(t)$ is the altitude above the surface of the earth ellipsoid; $\varphi_{\mathrm{op}}, \lambda_{\mathrm{op}}$ are coordinates of a given point in the area of operations; R_{Ear} is the constant equal to the radius of the Earth's sphere; R_1, R_2 are radii of curvature of the coordinate lines; $V_{\mathrm{N}}(t), V_{\mathrm{E}}(t)$ are projections of the ground speed of the UAV on the horizontal axis of the geographical trihedron.

In view of the results presented in [3], with acceptable accuracy the practical equations (1) can be represented in the form:

$$\dot{R}_{\mathrm{N}}(t) = V_{\mathrm{N}}(t) C_1[\varphi(t), h(t)];\qquad \dot{R}_{\mathrm{E}}(t) = V_{\mathrm{E}}(t) C_2[\varphi(t), h(t)], \tag{2}$$

where $C_1[\varphi, h] = \frac{R_{\mathrm{E}}}{a}[1 + e^2(1 - 1,5\sin^2\varphi(t)) - h(t)/a]$;

$C_2[\varphi, h] = \frac{R_{\mathrm{E}}}{a\cos\varphi(t)}[1 - 0,5e^2\sin^2\varphi(t)) - h(t)/a]$;

a, e^2 is the semi-major axis and eccentricity squared received for navigation terrestrial ellipsoid.

Current ground speed components $V_{\mathrm{N}}(t), V_{\mathrm{E}}(t)$ satisfy the following relations:

$$V_{\mathrm{N}}(t) = V_{\mathrm{AIR\,N}}(t) + V_{\mathrm{Wind\,N}};$$
$$V_{\mathrm{E}}(t) = V_{\mathrm{AIR\,E}}(t) + V_{\mathrm{Wind\,E}}, \quad (3)$$

where $V_{\mathrm{AIR\,N}}(t)$ и $V_{\mathrm{AIR\,E}}(t)$ is the UAV airspeed projection on the axis N and E; $V_{\mathrm{Wind\,N}}$ and $V_{\mathrm{Wind\,E}}$ is the horizontal components of wind speed.

In general, the expression for the horizontal components of the air speed are of the form [4]:

$$V_{\mathrm{AIR\,N}}(t) = V_{\mathrm{AIR}}(t)\{\cos\vartheta(t)\cos\psi_I(t)\cos\alpha(t)\cos\beta(t) + [\sin\psi_I(t)\sin\gamma(t) + \cos\psi_I(t)\cos\gamma(t) \cdot \sin\vartheta(t)]\sin\alpha(t)\cos\beta(t) + [\cos\psi_I(t)\sin\vartheta(t)\sin\gamma(t) - \sin\psi_I(t)\cos\gamma(t)]\sin\beta(t)\};$$
$$V_{\mathrm{AIR\,E}}(t) = V_{AIR}(t)\{\cos\vartheta(t)\sin\psi_I(t)\cos\alpha(t)\cos\beta(t) + [\sin\psi_I(t)\sin\vartheta(t)\cos\gamma(t) - \cos\psi_I(t) \cdot \sin\gamma(t)]\sin\alpha(t)\cos\beta(t) + [\cos\psi_I(t)\cos\gamma(t) + \sin\psi_I(t)\sin\vartheta(t)\sin\gamma(t)]\sin\beta(t)\}, \quad (4)$$

where $V_{\mathrm{AIR}}(t)$ is the current air speed; $\psi_I(t)$, $\vartheta(t)$, $\gamma(t)$ are current angles of the true rate, pitch and roll; $\alpha(t)$, $\beta(t)$ are current angle of attack and slip.

In the case of small absolute angles $\vartheta(t)$, $\gamma(t)$, $\alpha(t)$, $\beta(t)$, from (6) we obtain the following approximate relations:

$$V_{\mathrm{AIR\,N}}(t) \approx V_{\mathrm{AIR}}(t)[\cos\vartheta(t)\cos\psi_I(t) - \sin\psi_I(t)\beta(t)];$$
$$V_{\mathrm{AIR\,E}}(t) \approx V_{\mathrm{AIR}}(t)[\cos\vartheta(t)\sin\psi_I(t) + \cos\psi_I\beta(t)]. \quad (5)$$

Information about the current values of air speed, pitch angles and slip may be obtained by the respective sensors. The current estimate of the angles of the true rate $\psi_I(t)$ is determined by the formula:

$$\psi_I(t) = \psi_{\mathrm{m}}(t) + \delta_{\mathrm{m}}, \quad (6)$$

where $\psi_{\mathrm{m}}(t)$ is the magnetic course; δ_{m} is the magnetic declination.

In its turn, for the calculation of the current magnetic course evaluation formula is used:

$$\psi_{\mathrm{m}}(t) = \mathrm{arctg}(-f_1 / f_2), \quad (7)$$

where $f_1 = H_{Y1}(t)\sin\gamma(t) + H_{Z1}(t)\cos\gamma(t)$;

$$f_2 = H_{X1}(t)\cos\vartheta(t) - H_{Y1}(t)\sin\vartheta(t)\cos\gamma(t) + H_{Z1}(t)\sin\vartheta(t)\sin\gamma(t);$$

$H_{X1}(t)$, $H_{Y1}(t)$, $H_{Z1}(t)$ are current estimates of projections of vector of the Earth's magnetic field on the axis of the UAV related coordinate system derived from three component magnetometer.

B. Basic errors an instrument course air notation coordinate

Errors of an instrument course air notation coordinate UAV depend on the current calculation errors constitute ground speed $V_{\mathrm{N}}(t)$, $V_{\mathrm{E}}(t)$, course readings air sensors and error of numerical integration of the navigation equations (2). In its turn, the current values of the calculation error $V_{\mathrm{N}}(t)$ and $V_{\mathrm{E}}(t)$ depend on instrument air sensors and inaccuracy of estimates of the horizontal components of wind speed.

The analysis shows that the greatest impact on the accuracy of the calculation of the current ground speed components have a systematic error of measurement of the angle of the true rate $\delta\psi_I$ and assignment evaluations of the horizontal components of wind speed $\delta V_{\mathrm{AIR\,N}}$ and $\delta V_{\mathrm{AIR\,E}}$.

C. The non-invariant compensation scheme of complex processing of navigation data

The key role in the non-invariant compensation scheme of complex processing of navigation data from the course-air sensors and SNS, proposed in this paper, as in the scheme considered in [2], [5], plays the nonlinear discrete filtering procedure. However, unlike the scheme [2], [5] filtering procedure is used only for correction and extrapolating estimates given position coordinates of UAV R_{N} and R_{E} using position information from SNS and information from the course-air sensors. Amendments to the measurements of the angle of the true course $\Delta\psi_{IP}$ and to the initial estimates of the horizontal components of wind speed $\Delta V_{\mathrm{AIR\,N}}$ and $\Delta V_{\mathrm{AIR\,E}}$ measured at the initial stage of flight and updated periodically using special procedures on the basis of speed information from SNS.

It is assumed that the update output course-air sensors and the SNS occurs at the same step Δt = 0.1 s. At each step of processing navigation information apart from the first check a condition of normal work of SNS must be satisfied

$$\left|\hat{R}_{\mathrm{N}i} - \tilde{R}^{\mathrm{SNS}}_{\mathrm{N}i}\right| + \left|\hat{R}_{\mathrm{E}i} - \tilde{R}^{\mathrm{SNS}}_{\mathrm{E}i}\right| < \Delta R_{\mathrm{det}}, \quad (8)$$

where $\hat{R}_{\mathrm{N}i}$, $\hat{R}_{\mathrm{E}i}$ are estimates given coordinates extrapolated from the previous step; $\tilde{R}^{\mathrm{SNS}}_{\mathrm{N}i}$, $\tilde{R}^{\mathrm{SNS}}_{\mathrm{E}i}$ are current estimates of coordinates computed by the positional information from the SNS; $\Delta R_{\rm det}$ is the predetermined admission.

The condition (8) is used for correction of current estimates of coordinates and the covariance matrix of estimation errors

$$\hat{\bar{X}}_i^{(+)} = \hat{\bar{X}}_i^{(-)} + K_i\left(\bar{Y}_i - \hat{\bar{X}}_i^{(-)}\right);$$
$$P_i^{(+)} = \left(E_2 - K_i H\right)P_i^{(-)}, \qquad i = 1, 2, ..., \tag{9}$$

where $\hat{\bar{X}}_i = (R_{{\rm N}i}, R_{{\rm E}i})^{\rm T}$; $\bar{Y}_i = (\tilde{R}_{{\rm N}i}^{\rm SNS}, \tilde{R}_{{\rm E}i}^{\rm SNS})^{\rm T} = \bar{X}_i + \bar{\eta}_i$; $\bar{\eta}_i$ is the column vector of random measurement errors with covariance matrix R; $K_i = P_i^{(-)}H^T(HP_i^{(-)}H^T + R)^{\oplus}$ is the filter gain matrix; $H = E_2$ is the identity matrix 2×2; P_i is the covariance matrix of estimation errors; $^{\oplus}$ is the symbol pseudo-matrix method Greville [6]; "–" and "+" are index values "before" and "after" correction.

D. Extrapolation of the coordinates and covariance matrix

At each step of processing, regardless of the fact serviceability SNS operation is performed extrapolating estimates of coordinates and the covariance matrix P. The basis of extrapolation coordinate operation can be put various methods of numerical integration of the equations (2) [7].

Extrapolation by the Euler method is performed in accordance with the formula:

$$\hat{R}_{l\,i+1} = \hat{R}_{l\,i} + f_{l\,i}\Delta t, \quad l = {\rm N,E}, \quad i = 1,2,\ldots, \tag{10}$$

where $f_{{\rm N}i} = \hat{V}_{{\rm N}i}C_1(\hat{\varphi}_i, \tilde{h}_i)$; $f_{{\rm E}i} = \hat{V}_{{\rm E}i}C_2(\hat{\varphi}_i, \tilde{h}_i)$;

$$\hat{\varphi}_i = \varphi_P + \hat{R}_{{\rm N}i}/R_{\rm E}. \tag{11}$$

Current estimates make up ground speed calculated by the formula (3), in which the components of air speed given by equation (5) (where the right of the substituted measurements $\tilde{V}_{{\rm AIR}\,i}$, $\tilde{\beta}_i$, $\tilde{\vartheta}_i$, $\hat{\psi}_{I\,i} = \tilde{\psi}_{I\,i} + \Delta\hat{\psi}_{I\,P}$), and evaluation of the horizontal components of wind speed taken as a

$$\hat{V}_{{\rm Wind}\,l} = \hat{V}_{{\rm Wind}\,l}^{(0)} + \Delta\hat{V}_{{\rm Wind}\,l\,P}, \quad l = {\rm N,E}, \tag{12}$$

where $\hat{V}_{{\rm Wind}\,l}^{(0)}$, $l = {\rm N,E}$ are initial estimates of the speed of the wind; $\Delta\hat{\psi}_{I\,P}$, $\Delta\hat{V}_{{\rm Wind}\,l\,P}$, $l = {\rm N,E}$ are evaluation of the relevant amendments.

Adams method for 4th order [7] on the first three steps extrapolation of coordinates is performed by the formula (10), and each step is divided into two extrapolating substep. In the first substep using Adams extrapolation formula preliminary estimates of coordinates may by calculated

$$\hat{R}_{l\,i+1}^{\rm op} = \hat{R}_{l\,i} + \frac{\Delta t}{24}(55 f_{l\,i} - 59 f_{l\,i-1} + 37 f_{l\,i-2} - 9 f_{l\,i-3}), \qquad l = {\rm N,E}. \tag{13}$$

In the second substep using interpolation formula Adams are the final scores of coordinates

$$\hat{R}_{l\,i+1}^{K} = \hat{R}_{l\,i} + \frac{\Delta t}{24}(9 f_{l\,i+1}^{*} + 19 f_{l\,i} - 5 f_{l\,i-1} + f_{l\,i-2}), \quad l = {\rm N,E}, \tag{14}$$

where $f_{l\,i+1}^{*}, l = {\rm N,E}$ are computed by formulas (11) and the fact that $\hat{R}_{{\rm N}\,i+1} = \hat{R}_{{\rm N}\,i+1}^{P}$.

Extrapolation of the covariance matrix **P** is performed according to the formula:

$$P_{i+1} = \Phi_i P_i \Phi_i^{\rm T} + Q_i, \tag{15}$$

where $\Phi_i = E_2 + \frac{\partial \bar{f}_i}{\partial \bar{X}_i}\Delta t$ is the transition matrix corresponding to the linearized representation of the operation of extrapolation coordinates; Q_i is the covariance matrix of random errors of extrapolation; $\bar{f}_i$ is the vector of the right parts of equations (2).

E. Calculation of the corrections

At the initial stage of flight of the UAV during normal operation is estimated SNS column vector amendments $\bar{\delta}_P = (\Delta\psi_P, \Delta V_{{\rm Wind\,N}\,P}, \Delta V_{{\rm Wind\,E}\,P})^{\rm T}$ using a speed information from SNS:

$$\hat{\bar{\delta}}_P = -G_V^{\oplus}\,\bar{d}_V, \tag{16}$$

where $G_V = \begin{pmatrix} B_1 \\ B_2 \\ \vdots \\ B_{{\rm N}_P} \end{pmatrix}$; $\bar{d}_V = \begin{pmatrix} \tilde{\bar{V}}_1 - \tilde{\bar{V}}_1^{\rm SNS} \\ \tilde{\bar{V}}_2 - \tilde{\bar{V}}_2^{\rm SNS} \\ \vdots \\ \tilde{\bar{V}}_{{\rm N}_P} - \tilde{\bar{V}}_{{\rm N}_P}^{\rm SNS} \end{pmatrix}$;

$\bar{V}_i = (V_{{\rm N}i}, V_{{\rm E}i})^{\rm T}$; $B_i = \begin{pmatrix} -\tilde{V}_{{\rm AIR}\,i}\cos\tilde{\vartheta}_i\sin\tilde{\psi}_{I\,i} & 1 & 0 \\ \tilde{V}_{{\rm AIR}\,i}\cos\tilde{\vartheta}_i\cos\tilde{\psi}_{I\,i} & 0 & 1 \end{pmatrix}$;

$t_{i+1} - t_i = \Delta T_P, i = 1,2,\ldots,{\rm N}_P$.

The current assessment of the components of ground speed $\tilde{V}_{{\rm N}\,i}$ and $\tilde{V}_{{\rm E}\,i}$ is calculated using the formula:

$$\tilde{V}_{l\,i} = \tilde{V}_{\text{AIR}\,i} + \hat{V}^{(0)}_{\text{Wind}\,l}, \quad l = \text{N,E}. \tag{17}$$

In its turn, it is possible to calculate $\tilde{V}_{\text{AIR}\,l\,i}$, $l = \text{N,E}$, using the formula (5), in which the measurements $\tilde{V}_{\text{AIR}\,i}$, $\tilde{\vartheta}_i$, $\tilde{\beta}_i$, $\tilde{\psi}_{I\,i}$ are substituted.

In normal operation, the SNS obtained at the initial stage of flight evaluation of the amendments to the horizontal component of the wind speed periodically clarified by the procedure of the form:

$$\Delta\hat{V}^{(j+1)}_{\text{Wind}\,l\,P} = \Delta\hat{V}^{(j)}_{\text{Wind}\,l\,P} + \delta V^{(j)}_{l\,P}, \quad l = \text{N,E}, \tag{18}$$

$$\delta V^{(j)}_{l\,P} = \frac{1}{N_B}\sum_{i=1}^{N_B}(\tilde{V}_{l\,i} - \tilde{V}^{\text{SNS}}_{l\,i}), \quad l = \text{N,E},$$

where $\tilde{V}_{l\,i}$, $l = \text{N,E}$ are current estimates of the components of ground speed, calculated taking into account the amendments of previous estimates; $t_{i+1} - t_i = \Delta T_B$.

F. Mathematical modeling

The effectiveness of the proposed scheme interconnecting course-air sensors and SNS was assessed using mathematical modeling. In the simulation, set the movement of small UAV at altitudes 0 … 1000 m with speeds 40 … 80 m / s on the trajectories of maneuvers such as “snake” and “circle” and used a simplified model of measurement errors the true course, including systematic and random components. Root mean square values of course-air sensors error are set in the following way: $\sigma_{V\,\text{AIR}} = 1$ m/s; $\sigma_{\psi\,I} = 1$ mrad; $\sigma_h = 1$ m; $\sigma_\vartheta = \sigma_\gamma = \sigma_\beta = 1$ mrad, and displacement sensor readings $\delta h_\delta = \pm 3$ m; $\delta\psi_I = \pm 30$ mrad.

Root mean square value of positional and speed errors SNS adopts the following $\sigma_R = 3$ m; $\sigma_V = 0.03$ m / s.

The actual values of the horizontal component of the stationary wind speed in the vicinity of the fly are ranged within ± 20 m / s, and the error of this initial assess was ± 15 m / s.

Step navigational information processing was assumed to be $\Delta t = 0{,}1$ s, and the parameters of treatments (16) and (18): $\Delta T_P = \Delta T_B = 5$ s; $N_P = N_B = 10$.

Using regression procedure (16) in the first 50 seconds of flight measurement of the angle correction to the estimated error rate is not more than 3 mrad, and the amendments to the initial estimates of the horizontal components of the speed of the stationary wind – with errors less than 0.3 m / s.

The test procedure (18) was simulated with wind amplitudes of ± 15 m / s at predetermined discrete times. Refined amendments to the initial estimate of the speed of the wind after the jump identified errors are not more than 0.2 m / s.

After switching off (failure) SNS the rate of increase error of stand-alone course-air notation of coordinates in time correspond to the level of precision adjustment of amendments (at the rate of ± 3 mrad for and the horizontal component of the stationary wind ± 0.2 m / s).

At processing step $\Delta t = 0.1$ s the rate of increase of computational errors for Euler’s method (10) was not higher than 0.08 m / s, and for the method of Adams (13), (14) – not more than 0.04 m / s.

Computational errors ΔR extrapolation of coordinates for the method of Adams 4th order against time to maneuver the “circle” for different values of the integration step Δt (0,1 s, 0.05 s and 0.01 s) are shown in Fig. 1.

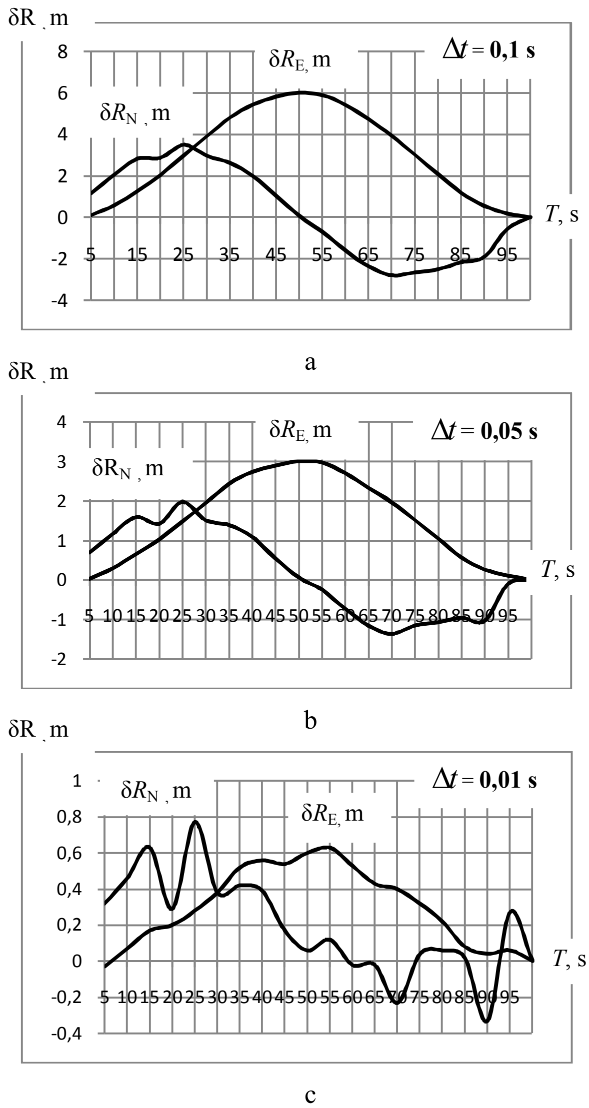

Fig. 1. Graphs of computational errors ΔR extrapolation of coordinates for the method of Adams 4th order a function of time for different steps of integration: (a) $\Delta t = 0{,}1$ s; (b) $\Delta t = 0{,}05$ s; (c) $\Delta t = 0{,}01$ s

The maximum modulo calculation errors notation given coordinates for the Euler method and Adams 4th order for a 100-second interval (UAVs maneuvers such as "circle") as a function of the integration step are shown in Table I.

TABLE I

THE MAXIMUM MODULO CALCULATION ERRORS EXTRAPOLATING COORDINATE FOR 100-SECOND TIME INTERVAL

Method	$\Delta t = 0.1$ s	$\Delta t = 0.05$ s	$\Delta t = 0.01$ s
Euler	8.01	4.00	0.87
Adams	6.00	3.00	0.77

The reduction step is discrete *m* times led to the *m*-fold decrease in the tempo of growth of computational errors in the reckoning given location coordinates UAV.

IV. CONCLUSION

Thus, the simulation results confirmed the performance and sufficiently high efficiency of the proposed modernized non-invariant compensation scheme interconnecting a course-air sensors and SNS for small UAV.

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Ф. М. Захарін, С. О. Пономаренко. Принципи побудови навігаційного комплексу БПЛА

Запропоновано модифіковану неінваріантну компенсаційну схему комплексування курсо-повітряних датчиків і бортової апаратури супутникової навігації для малого безпілотного літального апарату. У даній схемі комплексної обробки навігаційної інформації основна роль відведена нелінійному дискретному фільтру і регресійній процедурі оцінювання поправок до вимірювань кута курсу і початкових оцінок горизонтальних складових швидкості вітру.

Ключові слова: безпілотний літальний апарат; зчислення координат; курсо-повітряний датчик; супутникова навігаційна система; неінваріантна компенсаційна схема; нелінійний дискретний фільтр; швидкість вітру.

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Ф. М. Захарин, С. А. Пономаренко. Принципы построения навигационного комплекса БПЛА

Предложена модифицированная неинвариантная компенсационная схема комплексирования курсо-воздушных датчиков и бортовой аппаратуры спутниковой навигации для малого беспилотного летательного аппарата. В данной схеме комплексной обработки навигационной информации основная роль отведена нелинейному дискретному фильтру и регрессионной процедуре оценивания поправок к измерениям угла курса и начальным оценкам горизонтальных составляющих скорости ветра.

Ключевые слова: беспилотный летательный аппарат; счисление координат; курсо-воздушный датчик; спутниковая навигационная система; неинвариантная компенсационная схема; нелинейный дискретный фильтр; скорость ветра.

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