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ESTIMATION ALGORITHM OF COMPUTER-INTEGRATED NAVIGATION COMPLEX OF UNMANNED AERIAL VEHICLES

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Using inertial navigation system and Global Positioning System together is preferable to using any of them separately. Derived benefits depend on the level of combining information.

Keywords: inertial navigation system, Global Positioning System, aircraft, integration.

Introduction. Under the influence of high requirements the general tendency of market development is the designers move by way of integration deeping between inertial, satellite and other navigation systems. Thus the International Civil Aviation Organization (ICAO) for air navigation systems offers the obligatory use of satellite navigation systems in combination with inertial navigation systems as a central unit of navigation complex.

For unmanned aerial vehicles (UAV) weighing up to 3,5 – 4 kg there is a vital problem of mass-sized characteristics of navigation complex. Therefore it is suggested to measure the system state, using small-sized strapdown inertial navigation system (SINS) which is the part of aircraft navigation complex. Having triads of micromechanical inertial sensors, barometric altimeter and triaxial magnetometer in the composition and integrating the data of these sensors with data of satellite navigation system, a complex determines all navigation coordinates and orientation angles.

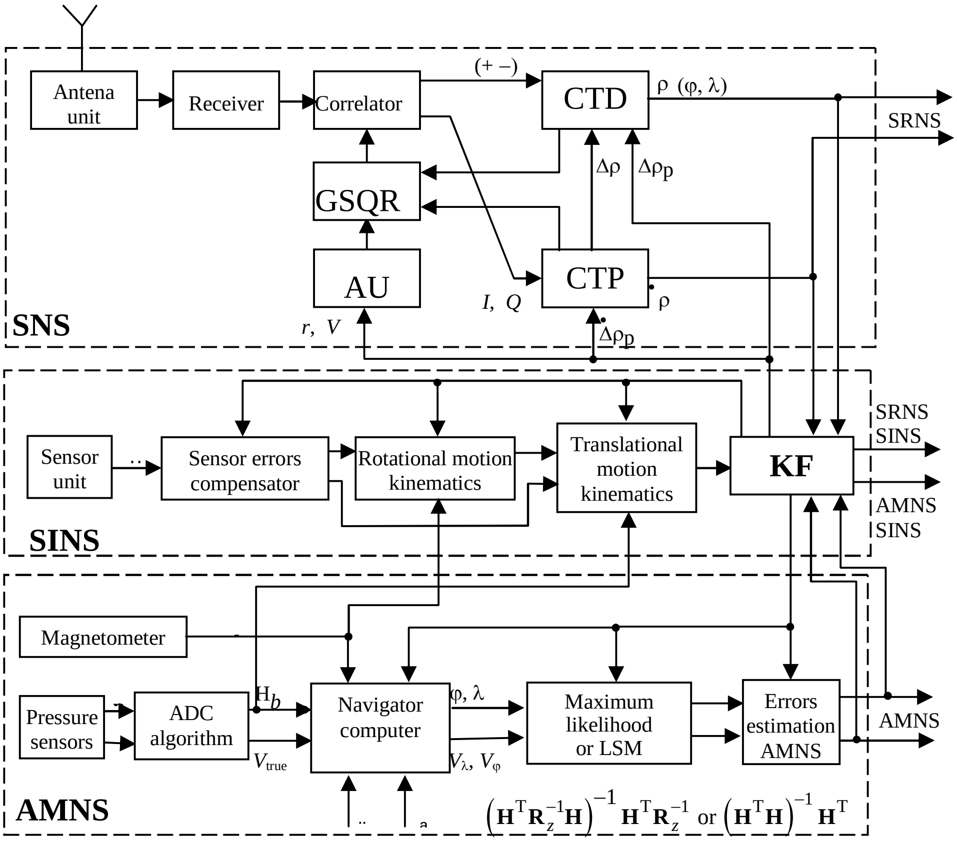
Recent developments in the miniaturization of inertial instruments and GPS receiver hardware have led to the introduction of small, low cost integrated navigation systems such as the Integrated Guidance Systems LLC IGS-200 series and Atlantic Inertial Systems SiNAV products (figure). In applications where GPS remains available, these systems advertise position accuracy of approximately 4 to 10 m [1; 2]. In situations where GPS is denied, compromised (e. g. multipath) or intermittent, position accuracy degrades as error growth from the inertial sensors and dominates the dead reckoning navigation solution. In the construction of computer-integrated complexes a wide spreading was obtained by an approach based on difference measurements where unknown parameters were eliminated. The task of estimating errors of one subsystem on the basis of other subsystem errors is solved with the help of difference measurements.

This approach is often called the method of invariant estimations receipt. Such method is employed in linear models of subsystems errors evolution and in general evolution nonlinear models of unknown navigational parameters themselves, that substantially simplifies construction of algorithms for complex processing of navigation information and gives the possibility to apply the well mastered procedures of Kalman linear filtering.

To use evolution errors linear models (and also linear algorithms of filtration) for SINS, built on rough micromechanical inertial sensors it is necessary not only to correct the output navigation information but also periodical correction of inertial system functioning with help of SINS errors estimations which are obtained at the output of optimal linear filter. In general the principles of such complex navigational system construction are the task, the researches of which is very actual for now.

Problem Statement. The offered computer-integrated navigation complex of UAV (figure) consists of SINS, transceiver of satellite navigational system (SNS) GLONASS/GPS and aeromagnetometer navigational system (AMNS) which consists of a three-component magnetometer and a module of aerometrical sensors.

Basic navigation problems which such navigation complex will solve are the tasks of inertial and satellite navigation, and the basic mode of complex operations is the mode of inertial-satellite navigation.



Computer-integrated navigation complex of UAV: ADC – air data computer system

There are several schemes of possible SNS and SINS complexing. There are several schemes of possible SNS and SINS complexing. The distinguishing feature of the offered ISNS scheme is the use of information about calculated pseudo distance and pseudo distance(or about their increase) by tracking contours after the delay (CTD) and phase (CTP). This information can be formed by Kalman filter (KF). The use of this information allows to substantially improve the stability of tracking and reduce the time of receiver work renewal in case of satellite signals loss.

Aeromagnetometer navigational system is an auxiliary system of the complex, it prevents the divergence of vertical and heading channels of inertial satellite navigation system and also realizes the inertial-heading-aerial method of coordinates reckoning on the period of SNS radio silence.

The problem can be defined as: for computer-integrated navigation complexes on the basis of optimal linear Kalman silteing it is necessary:

– to formulate the complex processing of navigation information algorithms as the solution of errors estimation task of one subsystem on the background of the other subsystem errors;

– to show the possibility of possibility of realization the additional algorithms of redundant navigation data processing from AMNS and application of AMNS for SINS functioning support on the period of SNS radio silence in offered scheme of navigation complex.

Problem solution. The parameters estimation, that characterize the state vector of UAV for basic, inertial-satellite operational mode of navigation complex is realized under the results of the extended Kalman filtering of SINS and SNS signals in KF block. The position and speed corrections of SINS is realized under the results of estimation. It is separately extended the possibility of measuring elements instrumental errors compensation by use of a priori data (for example, for system certificate information) or these errors estimates values. As a result gyros and accelerometers corrected data are transmitted to SINS.

It is suggested to use the procedure of Kalman discrete optimal filter for estimation (filtering) of complex system error measurement state vector $\mathbf{V}_{\mathrm{ISNS},\,k}$, which is formed on the basis of satellite and inertial navigation systems errors $\dot{\mathbf{V}}_{\text{ISNS},k} = \begin{vmatrix} \mathbf{V}_{\text{INS},k} \\ \mathbf{V}_{\text{SNS},k} \end{vmatrix}$. The generalized equation of complex system measurement errors state is expressed as:

$$\dot{\mathbf{V}}_{\text{ISNS},k} = \mathbf{\Phi}_{\text{ISNS},k} \mathbf{V}_{\text{ISNS},k-1} + \xi_{\text{ISNS}}.$$

where $\mathbf{\Phi}_{\text{ISNS},k} = \begin{vmatrix} \mathbf{\Phi}_{\text{INS},k} & 0 \\ 0 & \mathbf{\Phi}_{\text{SNS},k} \end{vmatrix}$ – known matrix of the system which is formed on the basis of matrices $\mathbf{\Phi}_{\text{INS}}, \mathbf{\Phi}_{\text{SNS}}$ of the correlated component errors of satellite and inertial navigation models; $\xi_{\text{ISNS},k} = \begin{vmatrix} \xi_{\text{INS},k} \\ \xi_{\text{SNS},k} \end{vmatrix}$ – Gaussian noise vector with matrix of variance $\mathbf{Q}_{\text{ISNS},k}$, received from components white noise errors of two navigation systems.

The equations for the estimation $\widehat{\mathbf{V}}_{\text{ISNS},k}$, taking into account certain assumptions are derived from general equations of optimal filtering:

$$\begin{aligned} \widehat{\mathbf{V}}_{\text{ISNS},k} &= \tilde{\mathbf{V}}_{\text{ISNS},k|k-1} + \mathbf{K}_{p,k}\left(\mathbf{Z}_{\text{SNS},k} - \widehat{\mathbf{Z}}_{\text{ISNS},k}\right); \\ \widehat{\mathbf{Z}}_{\text{ISNS},k} &= \tilde{\mathbf{V}}_{\text{ISNS},k|k-1} + \mathbf{K}_{p,k}\left(\mathbf{Z}_{\text{SNS},k} - \widehat{\mathbf{Z}}_{\text{ISNS},k}\right); \end{aligned} \tag{1}$$

$$\begin{aligned} \tilde{\mathbf{V}}_{\text{ISNS},k|k-1} &= \mathbf{\Phi}_{\text{ISNS},k} \hat{\mathbf{V}}_{\text{ISNS},k|k-1}; \\ \tilde{\mathbf{V}}_{\text{INS},k|k-1} &= \mathbf{\Phi}_{\text{INS},k} \hat{\mathbf{V}}_{\text{INS},k-1}; \\ \tilde{\mathbf{V}}_{\text{SNS},k|k-1} &= \mathbf{\Phi}_{\text{SNS},k} \hat{\mathbf{V}}_{\text{SNS},k-1}; \end{aligned} \tag{2}$$

$$\begin{aligned} \mathbf{K}_{\text{p},k} &= \mathbf{P}_{k|k-1}\mathbf{H}_k^{\text{T}}(\mathbf{H}_k\mathbf{P}_{k|k-1}\mathbf{H}_k^{\text{T}} + \mathbf{N}_k)^{-1}; \\ \mathbf{P}_{k|k-1} &= \mathbf{\Phi}_{\text{ISNS},k}\mathbf{P}_{k-1}\mathbf{\Phi}^{\text{т}}_{\text{ISNS},k} + \mathbf{Q}_{\text{ISNS},k}; \\ \mathbf{P}_k &= \mathbf{P}_{k|k-1} - \mathbf{K}_{\text{p},k}\mathbf{H}_k\mathbf{P}_{k|k-1}; \\ \mathbf{H}_k &= \frac{\partial}{\partial V_{\text{ISNS},k}}\Big[\mathbf{G}(\mathbf{Z}_{\text{INS},k} - \mathbf{M}_{\text{INS},k}\mathbf{V}_{\text{INS},k}) + \\ &\quad + \mathbf{M}_{\text{SNS},k}\mathbf{V}_{\text{SNS},k}\Big]_{\mathbf{V}_{\text{ISNS},k} = \tilde{\mathbf{V}}_{\text{ISNS},k|k-1}}, \end{aligned} \tag{3}$$

where $\mathbf{Z}_{\text{SNS}}, \mathbf{Z}_{\text{INS}}$ are vectors of observation from outputs of SNS and SINS; $\mathbf{G}$ is known matrix of vector function of $\mathbf{G}(\mathbf{X}_k)$, which connects radionavigation signal with estimated state vector $\mathbf{X}_k$; $\mathbf{M}_{\text{SNS}}, \mathbf{M}_{\text{INS}}$ are known matrices of process disturbances of outputs observations SNS and SINS; $\mathbf{Z}_{\text{ISNS}}$ is estimates of observation vector; $\tilde{\mathbf{V}}_{\text{ISNS}}, \tilde{\mathbf{V}}_{\text{INS}}, \tilde{\mathbf{V}}_{\text{SNS}}$ are complex system errors estimation errors and also errors of SINS and SNS; $\tilde{\mathbf{V}}_{\text{ISNS},k|k-1}$ and $\mathbf{P}_{k|k-1}$ are correspondingly the estimation errors of SINS and SNS and covariance matrix of $\mathbf{P}$ for the moment of k, which are calculated on the basis of the k measurements in previous moments of time of k – 1, k – 2; $\mathbf{H}$ is matrix of measurements for observation vector; $\mathbf{N}$ is correlation matrix.

Received errors estimates of SINS from filter output are used for correction of initial navigation parameters of SINS. The algorithm of coordinates and speed projections estimates correction is expressed as:

$$H^+_i = H^-_i - \Delta\widehat{H}_i; \quad \varphi_i^+ = \varphi^-_i - \frac{\Delta\widehat{R}_{Ni}}{R_e}; \quad \lambda_i^+ = \lambda^-_i - \frac{\Delta\widehat{R}_{Ei}}{R_e}; \quad V^+_{l,i} = V^-_{l,i} - \Delta\widehat{V}_l; \quad l = E, N, H,$$

where the estimations of output navigation parameters before and after correction accordingly are denoted by upper indexes «–» and «+»; $\Delta\widehat{R}_{Ei}, \Delta\widehat{R}_{Ni}, \Delta\widehat{H}_i, \Delta\widehat{V}_E, \Delta\widehat{V}_N, \Delta\widehat{V}_H$ are current errors estimations of SINS (linear coordinates, attitude and three components of speed), obtained at the filter output.

The correction of orientation matrix estimation $\mathbf{B}_i$, performed by SINS is executed with the help of the following procedure:

$$\widehat{\mathbf{B}}_i^{+} = \Delta\mathbf{B}_i \widehat{\mathbf{B}}_i^{-}. \qquad (4)$$

where $\Delta\mathbf{B}_i = \begin{pmatrix} 1 & \widehat{\alpha}_{h,i} & -\widehat{\alpha}_{N,i} \\ -\widehat{\alpha}_{h,i} & 1 & \widehat{\alpha}_{E,i} \\ \widehat{\alpha}_{N,i} & -\widehat{\alpha}_{E,i} & 1 \end{pmatrix}$, here $\widehat{\alpha}_{E,i}, \widehat{\alpha}_{N,i}, \widehat{\alpha}_{h,i}$ are current errors estimations of SINS in determining orientations of geographic coordinate system, obtained at the output of filter.

After performing the operation (4) it is necessary to check up the conditions of matrix $\widehat{B}_i^{+}$ orthogonality and if it is necessary to do the orthogonalizing of direction cosines matrix estimation $\widehat{B}_i^{+}$.

The algorithm (1) – (3) can have different modifications: symmetrical covariance; information; consecutive in time and space of measurements and so on. All these forms are intended for providing the computing stability of algorithms in airborne computers with the limited digit capacity and memory when there are models errors, linearization of nonlinearities, etc. The procedures of estimation (filtration) and correction of SINS are performed simultaneously in the given system.

The period of correction T_{cor} can be derived from the condition:

$$\Delta\alpha(T_{\text{cor}}) = \Delta\alpha_{\text{adm}},$$

where $\Delta\alpha(T_{\text{cor}})$ is maximal geographical system coordinates axes modeling errors estimate of SINS; $\Delta\alpha_{\text{adm}}$ is admissible value of error that ensures the of linearity preservation of SINS errors model evolution.

The analysis shows that the formula for estimation of $\Delta\alpha(T)$ can be used for values T_{cor} satisfying the condition $T_{\text{cor}} \ll T_{\text{Sch}}$ (T_{Sch} = 84,4 min Schuler's pendulum period):

$$\Delta\alpha(T_{\text{cor}}) = \varepsilon T_{\text{cor}} + \Delta\alpha^*(T_{\text{cor}}),$$

where $\alpha^*(T_{\text{cor}}) = \left[\left(\Delta\alpha_0 g + \Delta a\right)\dfrac{T_{\text{cor}}^2}{2} + g\dfrac{\varepsilon T_{\text{cor}}^3}{6} \right] \mathrm{Re}_e^{-1}$; $\Delta\alpha_0$ is maximal error value of SINS initial alignment; $\Delta\alpha_0, \varepsilon$ is maximal error value of SINS inertial sensors.

At the time of SINS correction, the following operations are executed:

– it is carried in the corrections in calculated estimates values of coordinates, speed projections and matrix orientation;

– sensors reduced errors estimates of SINS are renewed by formulas:

$$\begin{aligned} \varepsilon_{i,l}^* &= \varepsilon_{i,l-1}^* + \widehat{\varepsilon}_{i,l}^* \\ \Delta a_{i,l}^* &= \Delta a_{i,l-1}^* + \Delta a_{i,l} \end{aligned} \quad (i = 1, 2, 3),$$

where l is number of correction point (l = 1, 2, ...); $\varepsilon_{i,0}^* = \Delta a_{i,0}^* = 0$, $i = 1, 2, 3$; $\widehat{\varepsilon}_{i,e} = \Delta\widehat{a}_{i,e}$ are estimates of errors in correction point of SINS;

– state vector components X_p $1...15$, corresponding SINS errors are zeroed.

Current estimates of rate gyros and accelerometers reduced errors ε_i^*, Δa_i^* $(i = 1, 2, 3)$ are used in SINS computational algorithms to include corrections in SINS inertial sensors indications:

$$\Delta a_i = \Delta t_s \varepsilon_i^* \text{ and } \Delta v_i = \Delta t_s \Delta a_i^* \ (i = 1, 2, 3),$$

where Δt_s is sampling step of primary information sensors.

In aviation SNS, integrated with SINS, the correlated errors state vector $\mathbf{V_{ISNS}}$, can include: SINS measurements errors, respectively flight latitude, longitude and altitude; SINS measurements errors of velocity components, orientation parameters errors measurements; gyroscopes drifts velocities, errors of time standard and frequency standard deviation, etc. It is assumed the damping of SINS vertical channel with the help of signal H_b from AMNS and complex system heading channel periodic correction from AMNS magnetometer.

Using the information of static pressure p and dynamic barometric pressure p_{dyn} height H_b and true airspeed V_r in AMNS by truncated algorithms for air data computer system are calculated.

$$H_b = \frac{T_0}{\tau_t}\left[1-\left(\frac{p}{p_0}\right)^{\frac{\tau_t R_{sp}}{g_0}}\right] \quad \text{for } H \le 11000 \text{ m};$$

$$V_r = \sqrt{2R_{sp}T\left(\frac{k}{k-1}\right)\left[\left(\frac{p_{dyn}}{p}\right)^{\frac{k-1}{k}}-1\right]}.$$

where τ_t is temperature gradient; R_{sp} is specific gas constant; k is adiabatic index.

For principal navigation complex mode in AMNS computer on the basis of information about estimated components of ground speed $\hat{V}_\lambda, \hat{V}_\varphi$, using the calculated value of true air speed it is calculated and stored the components of wind: U – wind speed, δ – wind direction.

For UAV with a small flight radius the wind parameters can be introduced according to the weather stations data.

Information on wind parameters makes possible to use aeromagnetometer algorithms of navigation parameters calculation:

$$\varphi = \varphi_0 + \int \frac{V_r \cos\psi + U\cos\delta}{R_e} dt;$$

$$\lambda = \lambda_0 + \int \frac{V_r \sin\psi + U\sin\delta}{R_e \cos\varphi} dt$$

where $\varphi, \varphi_0, \lambda, \lambda_0$ are current and initial location geographic coordinates of UAV; $(V_r\cos\psi + U\cos\delta)$, $(V_r\sin\psi + U\sin\delta)$ are ground speed components; R_e is radius of the Earth; ψ is true magnetic heading.

Additional navigation information is permitted to improve significantly the reliability of navigation support and in case of disappearance of SNS signals or presence of noise to continue the further flight mission, realizing inertial-air-head method of coordinates calculation.

The presence of redundant navigation information forces to use the additional data processing algorithms. It is known that if the condition of measurement systems errors spectrum separation in frequency range is not fulfilled, it is expedient to execute the integrated processing of redundant information using the method of maximum likelihood or the least square method.

As estimated parameters it is taken the components of aircraft ground speed:

– obtained with the help of AMNS;

– estimated components of ground speed $\hat{V}_\lambda, \hat{V}_\varphi$, from the KF block (see figure).

When solving the problem of complex processing of information by means of maximum likelihood method the principal task is the determination of weight coefficients, with which are taken parameters estimates.

Algorithm for obtaining estimates for the maximum likelihood method according to [1] is as follows:

$$\hat{\mathbf{X}}_m = (\mathbf{H}^{\mathrm{T}}\mathbf{R}_z^{-1}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{T}}\mathbf{R}_z^{-1}\mathbf{Z}_m,$$

where $\mathbf{H}$ is observation matrix; $\mathbf{R}$ is errors sensors correlation matrix; $\mathbf{Z}_m$ is accumulated observations.

The principal complexity of this process is searching the errors sensors correlation matrix $\mathbf{R}_z$. But the errors sensors correlation matrix can be obtained on basis of separate complex subsystems standard data. In particular it is the variances of ISNS and AMNS, then

$$\mathbf{H} = \begin{vmatrix} 1 \\ 1 \end{vmatrix}; \quad \mathbf{R}_z = \begin{vmatrix} \sigma^2_{\mathrm{ISNS}} & 0 \\ 0 & \sigma^2_{\mathrm{AMNS}} \end{vmatrix}; \quad \mathbf{Z} = \begin{vmatrix} \hat{z}_{\mathrm{ISNS}} \\ z_{\mathrm{AMNS}} \end{vmatrix},$$

$$(\mathbf{H}^{\mathrm{T}}\mathbf{R}_z^{-1}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{T}}\mathbf{R}_z^{-1} = \begin{vmatrix} \dfrac{\sigma^2_{\mathrm{ISNS}}}{\sigma^2_{\mathrm{ISNS}} + \sigma^2_{\mathrm{AMNS}}} & \dfrac{\sigma^2_{\mathrm{AMNS}}}{\sigma^2_{\mathrm{ISNS}} + \sigma^2_{\mathrm{AMNS}}} \end{vmatrix}.$$

The obtained aestimates of navigational parameters are used to determine the current errors of navigation parameters – components of ground speed of aircraft and coordinates, which are formed in AMNS. In case of complex transition in to autonomous mode, for example, when SNS signals disappear, these corrections are taken into account in AMNS indications and in future the corrected navigation parameters of AMNS are replaced by SNS information in the extended Kalman filtration algorithms.

A state vector of complex system measurement errors $\mathbf{V}_{\mathrm{IAMNS},\,k}$ is already formed using AMNS and SINS errors

$$\mathbf{V}_{\mathrm{IAMNS},\,k} = \begin{vmatrix} \mathbf{V}_{\mathrm{INS},\,k} \\ \mathbf{V}_{\mathrm{AMNS},\,k} \end{vmatrix};$$

so the equation of state of complex system measurement errors

$$\dot{\mathbf{V}}_{\mathrm{IAMNS},\,k} = \mathbf{\Phi}_{\mathrm{IAMNS},\,k}\mathbf{V}_{\mathrm{IAMNS},\,k-1} + \xi_{\mathrm{IAMNS}k},$$

changes and some blocks of equations of optimal filtration are the folloming:

$$\hat{\mathbf{V}}_{\mathrm{IAMNS},\,k} = \tilde{\mathbf{V}}_{\mathrm{IAMNS},\,k|k-1} + \mathbf{K}_{\mathrm{f},\,k}(\mathbf{Z}_{\mathrm{AMNS},\,k} - \hat{\mathbf{Z}}_{\mathrm{IAMNS},\,k});$$

$$\hat{\mathbf{Z}}_{\mathrm{IAMNS},\,k} = \mathbf{G}(\mathbf{Z}_{\mathrm{INS},\,k} - \mathbf{M}_{\mathrm{INS},\,k}\tilde{\mathbf{V}}_{\mathrm{INS},\,k|k-1}) + \mathbf{M}_{\mathrm{AMNS},\,k}\tilde{\mathbf{V}}_{\mathrm{AMNS},\,k|k-1};$$

$$\tilde{\mathbf{V}}_{\mathrm{IAMNS},\,k\,|k\text{-}1} = \mathbf{\Phi}_{\mathrm{IAMNS},\,k}\hat{\mathbf{V}}_{\mathrm{IAMNS},\,k\text{-}1};$$

$$\tilde{\mathbf{V}}_{\mathrm{INS},\,k\,|k\text{-}1} = \mathbf{\Phi}_{\mathrm{INS},\,k}\hat{\mathbf{V}}_{\mathrm{INS},\,k\text{-}1};$$

$$\tilde{\mathbf{V}}_{\mathrm{AMNS},\,k\,|k\text{-}1} = \mathbf{\Phi}_{\mathrm{AMNS},\,k}\hat{\mathbf{V}}_{\mathrm{AMNS},\,k\text{-}1};$$

$$\mathbf{K}_{\mathrm{f},\,k} = \mathbf{P}_{k|k-1}\mathbf{H}_k^{\mathrm{T}}(\mathbf{H}_k\mathbf{P}_{k|k-1}\mathbf{H}_k^{\mathrm{T}} + \mathbf{N}_k)^{-1};$$

$$\mathbf{P}_{k|k-1} = \mathbf{\Phi}_{\mathrm{IAMNS},\,k}\mathbf{P}_{k-1}\mathbf{\Phi}^{\mathrm{T}}_{\mathrm{IAMNS},\,k} + \mathbf{Q}_{\mathrm{IAMNS},\,k};$$

$$\mathbf{P}_k = \mathbf{P}_{k|k-1} - \mathbf{K}_{\mathrm{f},\,k}\mathbf{H}_k\mathbf{P}_{k|k-1};$$

$$\mathbf{H}_k = \frac{\partial}{\partial V_{\mathrm{IAMNS},\,k}}[\mathbf{G}(\mathbf{Z}_{\mathrm{INS},\,k} - \mathbf{M}_{\mathrm{INS},\,k}\mathbf{V}_{\mathrm{INS},\,k}) +$$

$$\mathbf{M}_{\mathrm{AMNS},\,k}\mathbf{V}_{\mathrm{AMNS},\,kk} +]_{\mathbf{V}_{\mathrm{IAMNS},\,k} = \tilde{\mathbf{V}}_{\mathrm{IAMNS},\,k|k-1}},$$

With SNS, recovery the complex becomes primary inertial-satellite mode again.

Conclusions. The integrated navigation complex design techniques are based on the principles of the concept of invariant complex information processing using procedures of optimal Kalman linear filtering and additional algorithms for processing redundant navigation information.

The integrated navigation complex consists of micromechanical inertial sensors, a satellite navigation system receiver, a magnetometer and barometrical sensors. Implementation of the proposed methods allows improving the reliability of aircraft navigation support of UAV.

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Алгоритм оцінювання комп’ютерно-інтегрованого навігаційного комплексу безпілотного літального апарата

Обґрунтовано перевагу спільного використання інерціальних навігаційних систем і глобальної системи позиціонування порівняно з будь-якою із них окремо. Переваги спільного використання залежать від ступеня інтеграції.

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Алгоритм оценивания компьютерно-интегрированного навигационного комплекса беспилотного летательного аппарата

Обосновано преимущество совместного использования инерциальных навигационных систем и глобальной системы позиционирования в сравнении с любой из них в отдельности. Преимущества совместного использования зависят от степени интеграции.