A technique of synthesis of unmanned aircraft control algorithms of a flat-symmetric scheme on the basis of the method of inverse problems of dynamics

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Abstract. The article discusses the development of non-traditional adaptive control systems for such a type of vehicle as an unmanned aerial vehicle based on the concepts of inverse problems of dynamics, adjacent to the class of absolutely stable dynamic systems. The paper proposes to use the idea of dividing spatial motion into isolated longitudinal and lateral motion (horizontal decomposition) to solve the problem of developing mathematical and information support for the trajectory control loop of unmanned aerial vehicles (AC), to synthesize a control algorithm by the method of inverse dynamics problems (OZD) and obtain analytical solution of the reference model. The relatively small tail surfaces of the unmanned aircraft lead to an insignificant mutual influence of the parameters in the longitudinal and lateral channels during the spatial movement of the aircraft, which makes it possible to accept the longitudinal and lateral channels of the aircraft movement as autonomous. The algorithm presented in the work can be considered as the mathematical support of the trajectory control loop of an unmanned aircraft. Based on the formulas given in the work, as well as mathematical dependencies that determine the optimization of the trajectory contour, a functional diagram can be built that determines the architectural appearance of a promising automatic control system for unmanned aircrafts.

1. The choice of a mathematical model of the unmanned aircraft
Relatively small tail surface areas of the unmanned aircraft result in a slight mutual influence of parameters in the longitudinal and lateral channels during the spatial movement of the aircraft. This allows the longitudinal and lateral channels of the aircraft to be considered as autonomous [1, 3].
Figure 1. The coordinate systems used in the basic mathematical model of the movement of the unmanned aircraft in space.

We will specify two main factors justifying the division of the spatial movement of the aircraft into isolated longitudinal and lateral movements [1, 2, 3].

1. With low angular speeds of the aircraft it can be assumed that aerodynamic coefficients related to longitudinal and lateral movements are autonomous:

\[ c_x, c_y, m_z = f_{\text{long}}(\alpha, \omega_z, \delta_{\text{alt}}, \delta_{\text{bg}}), \]

\[ c_z, m_x, m_y = f_{\text{lat}}(\beta, \omega_x, \omega_y, \delta_{\text{alt}}, \delta_{\text{dir}}), \]  

where \( \alpha, \beta \) are the angle of attack and sliding angle respectively, \( \omega_i (i = x, y, z) \) are the angular velocities to body-axis coordinate system \( OXYZ \) [2], \( \delta_i (i = \text{alt, bg, el, dir}) \) are the deviations of steering surfaces to longitudinal and lateral movements. The inertial couplings of movements are dismissively small.

2. The inconsequential influence of kinematic couplings of movements substantiated by the relative turns of different coordinate systems, particularly couplings caused by the wind (Figure 1).

The following coordinate systems are used in the basic mathematical model (BMM) [3].

The normal coordinate system (NCS) is \( OX_s Y_s Z_s \). The \( OY_s \) axis is directed vertically upwards and passes through the center of gravity of the aircraft. The \( OX_s \) axis coincides with the projection of the aircraft symmetry axis on the horizontal plane. The \( OZ_s \) axis complements the coordinate system.
to the right triple of vectors. Coordinates and required aircraft overloads are determined in the normal coordinate system.

The flight path coordinate system is \( OX_kYZ_k \). Its beginning is located in the center of gravity of the aircraft. The \( OX_k \) axis is directed along the vector of its velocity, the \( OY_k \) axis is located in a vertical plane and is directed upwards, the \( OZ_k \) axis complements the coordinate system to the right one.

The wind-axis coordinate system (WACS) is \( OX_aYZ_a \). Its beginning is also located in the center of gravity of the aircraft. The \( OX_a \) axis coincides with the air speed vector of the aircraft. The \( OY_a \) axis coincides with the full vector of the specified transverse overload of \( n_a \), the \( OZ_a \) axis forms the right coordinate system. The wind-axis coordinate system determines the aerodynamic forces acting on the aircraft during the flight.

The body-axis coordinate system is \( OXYZ \). Its beginning is located in the center of gravity of the aircraft. The \( OX \) axis coincides with the longitudinal axis of the aircraft’s body, is directed from the tail surfaces of the aircraft to its fore-body and is in the plane \( OX_aY_a \) of the wind-axis coordinate system. The \( OY \) axis lies in the plane \( OX_aY_a \) of the wind-axis coordinate system, it is perpendicular to the \( OX \) axis and directed upwards. The \( OZ \) axis complements the coordinate system to the right one. The body-axis coordinate system is necessary to determine the current position of the aircraft engine thrust vector and aerodynamic moments on the respective axes.

In the flight path coordinate system, the preset overloads are formed and equations of isolated movements, corresponding to projections of forces acting on the aircraft during the flight, are written down in the simplest technique (Figure 1):

\[
m \frac{dV_k}{dt} = F_{xV} - G \sin \theta + P \cos \alpha,
\]

\[
m V_k \frac{d\theta}{dt} = F_{yV} \cos \gamma_c - G \cos \theta + P \sin \alpha,
\]

\[
m V_k \frac{d\Psi}{dt} \cos \theta = -F_{zV} \sin \gamma_c,
\]

where \( F_{xV}, F_{yV}, F_{zV} \) are the aerodynamic force of the frontal drag, lifting and lateral forces respectively, \( P \) is the thrust of the aircraft aero engine, \( G = mg \) is the force of gravity, \( m \) is the weight of the aircraft, \( g \) is the acceleration of gravity, \( V_k \) is the velocity of the aircraft concerning the Earth’s surface, \( \theta, \Psi \) are the tilt angle of a trajectory and traveling corner respectively, \( \gamma_c \) is the airpath bank angle (the angle of the bank at zero sideslip).

We will write down equations of trajectory movement (2) in the form of Cauchy’s equations, through overload in the wind-axis coordinate system:

\[
\dot{V}_k = \frac{dV_k}{dt} = (n_{xa} - \sin \theta)g + \frac{P}{m} \cos \alpha,
\]

\[
\dot{\theta} = \frac{d\theta}{dt} = \frac{g(n_{xa} \cos \gamma_c - \cos \theta)}{V_k} + \frac{P}{mV_k} \sin \alpha,
\]

\[
\dot{\Psi} = \frac{d\Psi}{dt} = -\frac{n_{xa} g \sin \gamma_c}{V_k \cos \theta},
\]
where \( n_{xa} = \frac{F_{x}}{G} \), \( n_{ya} = \frac{F_{y}}{G} \), \( n_{za} = \frac{F_{z}}{G} \) are the components of the overload vector in the wind-axis coordinate system.

Dynamic equations of the rotational motion are described by equations (4):

\[
\begin{bmatrix}
\dot{\omega}_x \\
\dot{\omega}_y \\
\dot{\omega}_z
\end{bmatrix} = \begin{bmatrix}
\frac{(J_y - J_z)}{J_x} \omega_y \omega_z \\
\frac{(J_z - J_x)}{J_y} \omega_z \omega_x \\
\frac{(J_x - J_y)}{J_z} \omega_x \omega_y
\end{bmatrix} + qS \\ 
\begin{bmatrix}
l_{mx} \\
l_{my} \\
l_{mz}
\end{bmatrix},
\]

where \( J_i (i = x, y, z) \) are the inertia moments in body-axis coordinate system, \( q = \frac{\rho V^2}{2} \) is the high-speed pressure, \( \rho \) is the air density, \( V \) is the air velocity, \( S, l, b_a \) are the area, length and average aerodynamic chord of a wing of the plane.

A peculiar feature of the construction of the aircraft’s basic mathematical model is the fact that the connection between the speed and flight path coordinate systems is determined only by the air-path bank angle \( \gamma \), longitudinal axes of \( OX_a \) and \( OX_k \) coincide and are directed along the vector of the Earth's speed of \( \vec{V}_k \). The vector \( \vec{V}_k \) in the plane of the aircraft's symmetry coincides with the air speed vector \( \vec{V} \).

In the basic mathematical model, instead of kinematic equations in the classical form it is preferable to use kinematic equations in the directional cosines (Poisson's equation) [3]:

\[
\dot{\varepsilon}^T = \Omega \varepsilon^T = \begin{bmatrix}
0 & \omega_z & -\omega_y \\
-\omega_z & 0 & \omega_x \\
\omega_y & -\omega_x & 0
\end{bmatrix} \begin{bmatrix}
\varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\
\varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\
\varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz}
\end{bmatrix},
\]

where \( \varepsilon_{ij} (i = x, y, z; j = x, y, z) \) are the elements of a matrix of the directing cosines. The simulated angular movements have no limitations, and it is possible not to calculate Euler’s angles directly.

Kinematic translational equations, linking changes in the coordinates \( X_g, Y_g, Z_g \) of the center of the aircraft masses with velocities, are described by equations:

\[
\begin{bmatrix}
\dot{X}_g \\
\dot{H}_g \\
\dot{Z}_g
\end{bmatrix} = \varepsilon \begin{bmatrix}
V_{x_k} \\
V_{y_k} \\
V_{z_k}
\end{bmatrix} = \begin{bmatrix}
\varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\
\varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\
\varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz}
\end{bmatrix} \begin{bmatrix}
V_{x_k} \\
V_{y_k} \\
V_{z_k}
\end{bmatrix},
\]

where \( V_{ki} (i = x, y, z) \) are the projections of the Earth’s speed \( \vec{V}_k \) to axes of the body-axis coordinate system.
Calculations (3)-(6) are supplemented by the expression of the definition of the air-path bank angle through projections of longitudinal overloads of the aircraft on the axis of the body-axis coordinate system:

\[
\cos \gamma_c = \frac{n_{ya}}{\sqrt{n_{ya}^2 + n_{ya}^2}}.
\]  

(7)

The aircraft’s basic mathematical model equation system (3)–(7) closes through constraint equations for angular velocities without taking into account the impact of the kinematic couplings of the wind components. This allows one to calculate the current angles of attack, sliding and air-path bank angle without the use of Euler’s angles, which greatly simplifies the mathematical model of the aircraft at the command control level:

\[
\begin{align*}
\alpha &= \omega_z - \Psi (\sin\beta \cos\theta + \sin\gamma_c \cos\beta \cos\theta) - \dot{\theta} \cos\gamma_c \cos\beta, \\
\beta &= \omega_x (\sin\alpha - \tan\gamma_c \cos\alpha \cos\beta) + \omega_y (\cos\alpha + \tan\gamma_c \sin\alpha \sin\beta) + \omega_x \tan\gamma_c \cos\beta - \dot{\theta} \cos\gamma_c \cos\beta, \\
\gamma_c &= \omega_x \cos\alpha \cos\beta - \omega_z \sin\alpha \cos\beta + \omega_z \sin\beta - \dot{\Psi} \sin\theta.
\end{align*}
\]  

(8)

Thus, the aircraft basic mathematical model is fully described by equations (1), (3)-(8), on the basis of which the algorithms of the digital part of the aircraft control system can be developed.

2. Synthesis of the unmanned aircraft control law by the method of inverse problems of dynamics

On the basis of equations (3) of the basic mathematical model, let us perform a synthesis of aircraft overload (aerodynamic forces) control laws providing the optimal trajectory movement of the aircraft. The preset overloads are formed by the method of inverse problems of dynamics using the reference models of the aircraft’s trajectory movement and are the setting actions at the pilot-centered (executive) level of control. The right parts of the reference models take into account the preset movement of the aircraft.

2.1. Formulation of a control synthesis problem

We believe that \( t_0, t_f \) are moments in time that corresponds to the beginning and final of the control process.

For controlled trajectory movement (3) which at the current moment of time \( t \in [t_0, t_f] \) is characterized by the state:

\[
y = (V_x, \theta, \Psi) = (y_1, y_2, y_3).
\]  

(9)

It is necessary to find such overloads \( n_{xa}, n_{ya}, n_{za} \) in which the system (3) moves from the state \( y_i(t_0) \) to the new state of \( y_i(y_i) \). At the same time, it is necessary that the coordinates of the controlled movement with the specified accuracy follow the coordinates:

\[
y^* = (V_x^*, \theta^*, \Psi^*) = (y_1^*, y_2^*, y_3^*),
\]  

(10)

defined by the reference model [4]:

\[
\dot{y}_s + \mathcal{K}_1 \dot{y}_s + \mathcal{K}_0 y_s = \mathcal{K}_0 y_s^0,
\]  

(11)
where $s=1...3, \kappa_{s1}, \kappa_{s0} > 0$ are the adjusting coefficients, $y_0^r = y_0^r(t)$ are the coordinates of the reference trajectory of the aircraft movement.

The degree of approximation of the controlled process $y^r_0(t) \rightarrow y^0_0$ is estimated by the functional:

$$G(n_a) = \frac{1}{2} \sum_{s=1}^{3} [\dot{y}^s_0 - \hat{y}^s_0(t,n_a)]^2,$$  \hspace{1cm} (12)

characterizing the energy of translational acceleration in the vicinity of the phase trajectories of the reference model. Here $n_a = (n_{xa}, n_{ya}, n_{za})$ is the vector of current overloads in the wind-axis coordinate system.

2.2. Formation of preset overloads

Let $n^+_0$ be an overload vector which implements the absolute minimum of functional (12), that is, $G(n^+_0) = 0$ at any $t > 0$.

An effective control algorithm is synthesized from the condition so that the value of $G(n_a)$ at each moment of time $t > 0$ belongs to a small neighborhood of extremum – minimum. The laws of control of $n_{sa}$ by each degree of freedom will be obtained by applying a scheme of gradient hill-climbing technique:

$$\frac{dn_{sa}}{dt}(y) = -\sum_{j=1}^{3} \tilde{r}_{aj} \frac{\partial G(n_a)}{\partial n_{ja}},$$  \hspace{1cm} (13)

where $\tilde{r}_{aj} = const \ \ j = 1, 2, 3 \rightarrow x, 2 \rightarrow y, 3 \rightarrow z$.

Using formulas (3), (12), we will calculate gradients in the equation (13):

$$\frac{\partial G(n_a)}{\partial n_{sa}} = g, \quad \frac{\partial G(n_a)}{\partial n_{ya}} = \frac{g \cos \gamma_c}{V_k}; \quad \frac{\partial G(n_a)}{\partial n_{za}} = \frac{-g \sin \gamma_c}{V_k \cos \theta}.$$ \hspace{1cm} (14)

From the formula (13), taking into account the expressions (14), laws of controlling preset overloads in the wind-axis coordinate system are formed:

$$\dot{n}_{xa}(V_k, \theta, \Psi) = -g \tilde{r}_{11}(V_k - \dot{V}_k) - \frac{g \cos \gamma_c}{V_k} \tilde{r}_{12}(\dot{\theta}^* - \dot{\theta}) + \frac{g \sin \gamma_c}{V_k \cos \theta} \tilde{r}_{13}(\Psi^* - \dot{\Psi}),$$ \hspace{1cm} (15)

$$\dot{n}_{ya}(V_k, \theta, \Psi) = -g \tilde{r}_{21}(V_k - \dot{V}_k) - \frac{g \cos \gamma_c}{V_k} \tilde{r}_{22}(\dot{\theta}^* - \dot{\theta}) + \frac{g \sin \gamma_c}{V_k \cos \theta} \tilde{r}_{23}(\Psi^* - \dot{\Psi}),$$ \hspace{1cm} (16)

$$\dot{n}_{za}(V_k, \theta, \Psi) = -g \tilde{r}_{31}(V_k - \dot{V}_k) - \frac{g \cos \gamma_c}{V_k} \tilde{r}_{32}(\dot{\theta}^* - \dot{\theta}) + \frac{g \sin \gamma_c}{V_k \cos \theta} \tilde{r}_{33}(\Psi^* - \dot{\Psi}).$$ \hspace{1cm} (17)

Since the amount of longitudinal overload, due to the assumptions made for the aircraft's mathematical model, does not depend on the amount of transverse overload $n^r_{za} = \sqrt{n^2_{ya} + n^2_{za}}$, it is possible to accept that the gain factors $\tilde{r}_{12}, \tilde{r}_{13}$ being equal to zero. Then the preset longitudinal overload $n_{sa}$ will be determined from (15) by the expression:
or after integration

\[ n_{sw}(V_k) = -g \tilde{r}_{11}(V_k^* - V_k) \] (18)

In the equations that characterize the transverse overload \( n_{sw}^{\theta} \), the gain factors \( \tilde{r}_{21}, \tilde{r}_{31} \) can also be assumed to be equal to zero. Then formulas (16), (17) will be rewritten as:

\[ \dot{n}_{3y}(V_k, \theta, \Psi) = -\frac{g \cos \gamma^*_c}{V_k} \tilde{r}_{22}(\dot{\theta}^* - \dot{\theta}) + \frac{g \sin \gamma^*_c}{V_k \cos \theta} \tilde{r}_{23}(\Psi^* - \Psi), \] (19)

\[ \dot{n}_{2o}(V_k, \theta, \Psi) = -\frac{g \cos \gamma^*_c}{V_k} \tilde{r}_{32}(\dot{\theta}^* - \dot{\theta}) + \frac{g \sin \gamma^*_c}{V_k \cos \theta} \tilde{r}_{33}(\Psi^* - \Psi). \] (20)

After the integration of equations (18) – (20), we define overloads in the body-axis coordinate system, which are preset for the contour of the trajectory control and are of the form of:

\[ n_{sw}^{\theta} = D_{wa}^{ba} n_{a}^{\theta}, \] (21)

where \( n_{a}^{\theta} = (n_{ax}^{\theta}, n_{ay}^{\theta}, n_{az}^{\theta}) \) are the vectors of angular velocities and overloads in the body-axis coordinate system, \( n_{a}^{\theta} = (n_{ax}^{\theta}, n_{ay}^{\theta}, n_{az}^{\theta}) \) are the overload vectors in the wind-axis coordinate system, calculated according to equations (18)-(20):

\[
D_{wa}^{ba} = \begin{bmatrix}
\cos \alpha \cos \beta & \sin \alpha & -\cos \alpha \sin \beta \\
-\sin \alpha \cos \beta & \cos \alpha & \sin \alpha \sin \beta \\
\sin \beta & 0 & \cos \beta
\end{bmatrix}
\]

is the matrix of the transition from the wind-axis coordinate system to the body-axis coordinate system.

3. Obtaining an analytical solution to the reference model

To implement the control laws of the preset overloads (18 – 20) one needs to choose the parameters of the reference model (11) and obtain its analytical solution.

The reference model of the aircraft’s trajectory movement (11) in detail is of the form:

\[
\begin{align*}
\dot{V}_k^* + \chi_{11}V_k^* + \chi_{10}V_k^0 &= \chi_{10}V_k^0(t), \\
\dot{\theta}_x^* + \chi_{22} \dot{\theta}_x^* + \chi_{20} \theta^* &= \chi_{20} \theta^0(t), \\
\dot{\Psi}_x^* + \chi_{31} \dot{\Psi}_x^* + \chi_{30} \Psi_x^* &= \chi_{30} \Psi_x^0(t),
\end{align*}
\] (22)

where \( V_k^0, \theta^0, \Psi^0 \) are the aircraft’s basic movement coordinates.

The method of obtaining a reference model analytical solution is as follows:

1. Through the definition of the coordinates of the reference trajectory, the right parts of reference model are formed. To do this, the transition from the normal system of coordinates to the trajectory one for the basic trajectory movement is carried out:
\[
\begin{bmatrix}
\dot{x}^0 \\
\dot{y}^0 \\
\dot{z}^0 
\end{bmatrix} = V_k \begin{bmatrix}
\cos \theta^0 \cos \Psi^0 \\
\sin \theta^0 \\
-\cos \theta^0 \sin \Psi^0 
\end{bmatrix}.
\] (23)

By squaring the right and left parts of the formulas (23) and summing them up among themselves, we obtain expressions to describe the basic movement in the trajectory system of coordinates:

\[
V_k^0 = \sqrt{(\dot{x}^0)^2 + (\dot{y}^0)^2 + (\dot{z}^0)^2}, \quad \theta^0 = \arcsin \frac{\dot{y}^0}{V_k^0}, \\
\Psi^0 = \arccos \frac{\dot{z}^0}{V_k^0 \cos \theta^0},
\] (24)

where linear speeds of \( \dot{x}^0, \dot{y}^0, \dot{z}^0 \) take into account the preset (basic) movement of the aircraft.

2. The parameters of the reference model are calculated [5]:

\[
\chi_{11} = 2\xi \frac{1}{T_v}, \quad \chi_{10} = \frac{1}{T_v^2}, \quad \chi_{20} = \frac{1}{T_\theta^2}, \quad \chi_{30} = \frac{1}{T_\psi^2}, \\
T_v = \omega_{v,estab}^{-1}, \quad T_\theta = \omega_{\theta,estab}^{-1}, \quad T_\psi = \omega_{\psi,estab}^{-1},
\] (25)

where the factor of relative damping of the ideal oscillation link is taken as the decrement of damping \( \xi \), constants of time and natural oscillation frequencies of variables \( V_v, \theta, \Psi \) are predetermined by mathematical modeling of the aircraft's spatial movement (2)-(8) by the reaction to single jumps of the rudders \( \delta_{alt}, \delta_{ail}, \delta_{dir} \).

3. The calculated parameters determine the roots of the characteristic polynomial of the reference model. To do this, three similar systems are written out of two algebraic equations:

\[
\chi_{11} = \lambda_1 + \lambda_2, \quad \chi_{10} = \lambda_1 \lambda_2, \\
\chi_{21} = \lambda_{1\theta} + \lambda_{2\theta}, \quad \chi_{20} = \lambda_{1\theta} \lambda_{2\theta}, \\
\chi_{31} = \lambda_{1\psi} + \lambda_{2\psi}, \quad \chi_{30} = \lambda_{1\psi} \lambda_{2\psi},
\] (26)

the solution of which has two roots. For reasons of sustainability of such a solution, its negative roots are chosen:
\[
\lambda_{2V}^{(1,2)} = \frac{\chi_{11} \pm \sqrt{\chi_{11}^2 - 2\chi_{10}}}{2} ; \quad \lambda_{V}^{(1,2)} = \chi_{11} - \lambda_{2V}^{(1,2)},
\]
\[
\lambda_{2\theta}^{(1,2)} = \frac{\chi_{21} \pm \sqrt{\chi_{21}^2 - 2\chi_{20}}}{2} ; \quad \lambda_{\theta}^{(1,2)} = \chi_{21} - \lambda_{2\theta}^{(1,2)},
\]
\[
\lambda_{2\psi}^{(1,2)} = \frac{\chi_{31} \pm \sqrt{\chi_{31}^2 - 2\chi_{30}}}{2} ; \quad \lambda_{\psi}^{(1,2)} = \chi_{31} - \lambda_{2\psi}^{(1,2)},
\]

(27)

4. The analytical solutions of the reference model are written out:

\[
V_e^* (t) = V_e^0 (t) - c_{1V} e^{\lambda_{Vt}} - c_{2V} e^{\lambda_{2Vt}}, \quad \dot{V}_e^* (t) = \dot{V}_e^0 (t) - c_{1V} \lambda_{V} e^{\lambda_{Vt}} - c_{2V} \lambda_{2V} e^{\lambda_{2Vt}},
\]
\[
\theta^* (t) = \theta^0 (t) - c_{1\theta} e^{\lambda_{\theta t}} - c_{2\theta} e^{\lambda_{2\theta t}}, \quad \dot{\theta}^* (t) = \dot{\theta}^0 (t) - c_{1\theta} \lambda_{\theta} e^{\lambda_{\theta t}} - c_{2\theta} \lambda_{2\theta} e^{\lambda_{2\theta t}},
\]
\[
\Psi^* (t) = \Psi^0 (t) - c_{1\psi} e^{\lambda_{\psi t}} - c_{2\psi} e^{\lambda_{2\psi t}}, \quad \dot{\Psi}^* (t) = \dot{\Psi}^0 (t) - c_{1\psi} \lambda_{\psi} e^{\lambda_{\psi t}} - c_{2\psi} \lambda_{2\psi} e^{\lambda_{2\psi t}}.
\]

(28)

Consequently, the movement of the aircraft with the laws of overload control (18) – (20) over time is carried out strictly along the designated basic trajectory.

Formulas (18) – (20), (24) – (28) are implemented in the control unit of the basic mathematical model of the aircraft’s longitudinal and lateral movement.

Thus, the given algorithm can be considered as a mathematical support for the trajectory circuit of the control of the unmanned aircraft. On the basis of the above formulas, as well as mathematical dependencies that determine the optimization of the trajectory circuit, one can build a functional scheme defining the architectural design of the prospective system of automatic control of the unmanned aircraft.

References

[1] Dil V F, Sizykh V N and Daneev A V 2017 Optimization of the control processes of the spatial motion of an aircraft based on the equations of nonlinear dynamics Izvestia of Samara Scientific Center of the Russian Academy of Sciences 19 (1) 195

[2] Dil V F, Sizykh V N, Daneev A V and Tarmaev A A 2017 Methodology for constructing a nonlinear control system on the basis of the optimization of the trajectory contour of an aircraft Izvestia of Samara Scientific Center of the Russian Academy of Sciences 19(6) 130

[3] Krasovskiy A A, Bukov V N and Shendrick V S 1977 Universal algorithms for optimal control of continuous processes (Moscow: Nauka Publ.)

[4] Krutko P D 2004 Inverse problems of dynamics in the theory of automatic control (Moscow: Mashinostroenie Publ.)