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THE PRINCIPLES OF FORMATION OF THE PARAMETRIC COMPONENTS OF THE TERMINATION CONTROL SYSTEM OF THE UNMANNED AERIAL VEHICLE FLIGHT PATH

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Показані принципи формування векторів дальності $\vec{\mathbf{D}}$ *від безпілотного літального апарату до маяка-відповідача ,та його швидкості* $\vec{\mathbf{V}}_k$*, необхідні для обчислення на борту БПЛА параметрів його руху.*

The principles of formation of the vector of distance $\vec{\mathbf{D}}$ *from unmanned aerial vehicle UAV to transponder-beacon, and its velocity* $\vec{\mathbf{V}}_k$*, which are necessary for on board calculation of the UAV motion parameters.*

Introduction

A controlled descent (flight) to the specified area of earth surface (circumterrestrial space) of unmanned aerial vehicle (UAV) with a large lift-drag ratio ($K > 1$) is considered. Such vehicles can significantly change their descent (flight) trajectory as a result of an aerodynamic maneuver in the atmosphere and landing (hovering) in unexpected distance from the specified point of space can happen.

The task of the control is guidance of the vehicle to the point with specified geographical coordinates in presence of random disturbances acting on the UAV during the descent (flight).

Termination control of UAV, based on prediction of coordinates of a point of landing (flight) is proposed for this reason [1]. Because of absence of radio connection on a sizeable part of the starting trajectory the control of UAV is autonomous. Prediction is realized by integration of system of differential equations of motion with initial conditions, determined by autonomous navigation system. Accumulated, as a result of control synthesis during landing (flight), navigation errors lead to appearance of not excluded by control system dispersion of landing (flight) points [2; 3].

To increase accuracy of UAV guidance after radio contact at the final part of landing (flight) a non-autonomous control is reasonable, using information about relative position and motion of aircraft and destination point [1].

In this paper the method of synthesis of the non-autonomous termination dual-channel control of UAV $U = f(\gamma_a, K)$ by a roll angle $\gamma_a(t)$ and lift-drag ratio $K(t)$ under guidance to omnidirectional beacon located in specified point of space. To provide guidance of the vehicle with sufficiently high accuracy method of non-autonomous multistep adaptive termination control in a zone of close-range guidance, starting at the moment of grabbing of a beacon signal by radio equipment of the vehicle [1].

At the moment of grabbing on a board of the UAV an inertial reference frame $Ox_i y_i z_i$ is formed, an origin of the system matches with centre of gravity of the vehicle, Oy_i axis is directed by radius-vector $\vec{\mathbf{r}}$, and vertical plane $Ox_i z_i$ is superposed with radio beacon at a landing point $C(\varphi_c, \lambda_c)$ with geographic latitude φ_c and longitude λ_c. Processing of a data for control synthesis is carried out in this system.

Direction vector of sight line to the beacon $\vec{\mathrm{D}}^0(t)$ and distance to it along the sight line $\mathrm{D}(t)$ are external information. Internal information is a vector of current phase coordinates of the vehicle

$$\mathrm{x}^{\text{н}} = (V_{\text{к}}^{\text{н}}, \theta^{\text{н}}, \psi^{\text{н}}, h^{\text{н}}, \varphi_{\text{ц}}^{\text{н}}, \lambda^{\text{н}})$$

which is determined in autonomous navigation system and includes a ground speed $V_{\text{к}}^{\text{н}}$, a slope angle of the trajectory $\theta^{\text{н}}$, a track angle $\varphi^{\text{н}}$, an altitude $h^{\text{н}}$, geocentric latitude $\varphi_{\text{ц}}^{\text{н}}$ and longitude $\lambda^{\text{н}}$ [4; 5].

For supply of realization of the data processing in the inertial reference frame for the synthesis of the termination control of the UAV trajectory it is necessary to determine the magnitudes of the distance from UAV to the responder beacon $\vec{\mathbf{D}}$ and its speed $\vec{\mathbf{V}}_k$ vectors [6].

Formation of the distance $\vec{\mathbf{D}}$ and velocity $\vec{\mathbf{V}}_k$ vectors of the UAV

The vector of the termination parameters of motion [5] is formed as a result of determination of the final time of the descent [4] $t_{kj} = t_j + T_j$ and the motion parameters V_{ki}, h_i, Θ_i, D_i, ε_i, η_i, α_i in the discrete points τ_j, $i = \overline{1, G}$ of the interval T_j

$$y(t_{kj}) = (V_{KT}, h_T, \Theta_T, D_T, \varepsilon_T, \eta_T, \alpha_T)\,.$$

where V_k is ground speed, Θ is an angle of the trajectory slope, an altitude — h, a distance — D, an angle of sight — ε, a relative course angle — η, a slope angle of the sight line — α.

Taking into account an approximate character of these parameters the predicted point of landing *K* with phase coordinates of the vehicle at it (1) may be situated either in front of the plane of guidance $\left(|\eta_T| \le \frac{\pi}{2}\right)$ or behind it $\left(|\eta_T| > \frac{\pi}{2}\right)$.

In the first case a point of intersection of the plane of guidance and the vector of the final speed and the phase of coordinates of this point *R* and *Φ* are determined (fig. 1).

For this purpose after introduction of the designations of the segments *CF*, *PF*, *PB* and *EF* respectively as $a_П, b_П, l_П, c_П$ and determination of their magnitudes

$$a_n = D_T \cos\alpha_T \sin|\eta_T|,$$
$$b_n = D_T \cos\alpha_T \cos\eta_T,$$
$$l_n = (h_T - h_K)\mathrm{ctg}\Theta_T,$$
$$c_n = \begin{cases} -(h_T - h_K)(\frac{b_n}{l_n} - 1), \text{ при } & h_T \ge h_K \text{ і } l_n < b_n; \\ (l_n - b_n)\mathrm{tg}|\Theta_T|, \text{ при } & h_T \ge h_K \text{ і } l_n \ge b_n; \\ -(b_n + |l_n|)\mathrm{tg}|\Theta_T|, \text{ при } & h_T < h_K, \end{cases}$$

predicted values of distance *R* and angle *Φ* are found from the fig. 1.

$$R = (a_П^2 + c_П^2)^{0,5},\ \Phi = \left(\frac{\pi}{2} - \mathrm{arctg}\frac{c_П}{a_П}\right)\mathrm{sign}\eta_T.$$

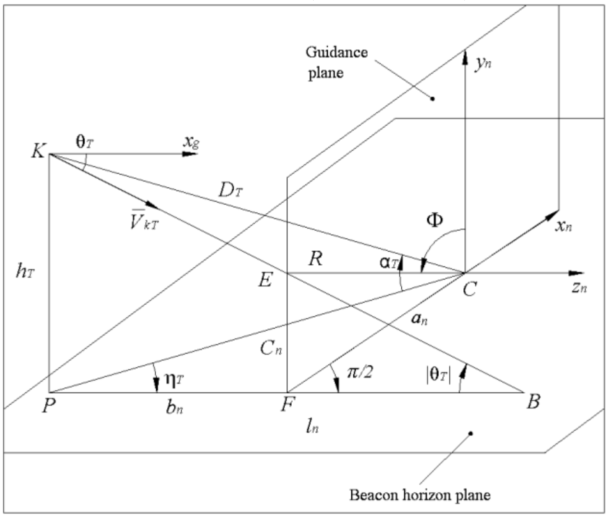

Fig. 1. Determination of the objective function

In the second case the distance *R* and angle *Φ* are determined at the time instant $\tau_j, i = \overline{1, G}$ at the achieving of $\frac{\pi}{2}$ by the course angle $|\eta_i|$

$$R = (a_n^2 + c_n^2)^{0,5},\ \Phi = \left(\frac{\pi}{2} - \mathrm{arctg}\frac{c_n}{a_n}\right)\mathrm{sign}\eta_T.$$

In such way by known phase coordinates of the vehicle $x^H(t_j)$, direction of the sight line $\vec{D}^0(t_j)$ and distance to the beacon $D(t_j)$ for the moment of correction t_j the *termination parameters of motion* $y(t_{kj})$ at the final moment of descent на t_{kj} are predicted and the objective function $R^{(j)}$ on the plane of guidance is determined.

Current phase coordinates of the vehicle

$$x^H(t) = (V_K^H(t), \Theta^H(t), \psi^H(t), h^H(t), \varphi^H(t), \lambda^H(t)) \quad (2)$$

are determined by the navigation system as a result of integration of the system of differential equations of motion in the path reference frame $Ox_K y_K z_K$.

Its origin matches with the centre of gravity of the vehicle, Ox_K axis coincides with the direction of the actual speed vector $\vec{V}_K$, Oy_K axis lies in a vertical plane and Oz_K axis complements the system to a right-hand one (fig. 2). *The angle of trajectory slope* is counted from the plane of a local horizon, which is determined by $Ox_g z_g$ plane of the earth parallel reference frame $Ox_g y_g z_g$ with the origin matched with centre of gravity of the vehicle, Oy_g axis directed along local vertical, Ox_g axis in local vertical plane, passing through the radius-vector $\vec{r}$ and velocity vector $\vec{V}_K$ and Oz_g axis complementing the system to the right-hand one (fig. 2).

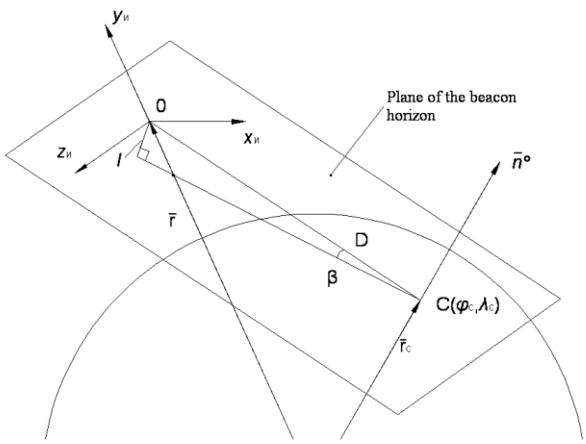

Fig. 2. Reference frames

Parameters of relative position of the vehicle and beacon $\vec{D}^0(t)$ and $D(t)$ are determined by the results of the measurements by radio system of the vehicle and is formed in the inertial reference frame $Ox_n y_n z_n$, which is built at the moment of grabbing of the beacon radio signal.

The moment of grabbing t_0 is registered at getting in direct radio sight of the beacon by the vehicle, located in the landing point $C(\varphi_c, \lambda_c)$ (fig. 3).

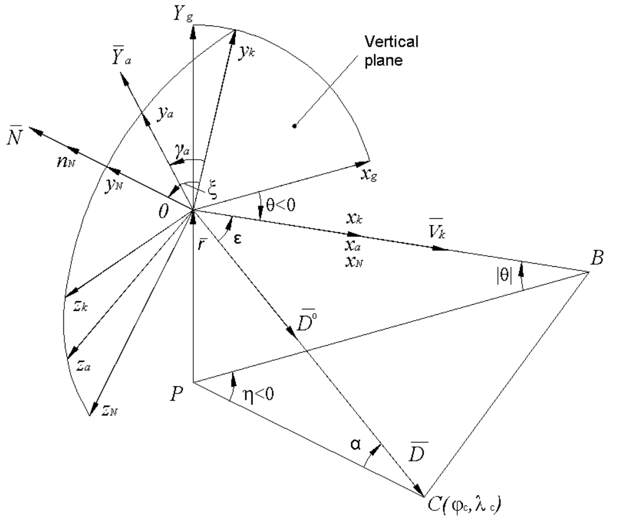

Fig. 3. Radio contact with the beacon

The origin of the reference frame $Ox_i y_i z_i$ is matched with the centre of gravity of the vehicle, Oy_i axis is directed along with radius-vector of the centre of gravity $\vec{\mathbf{r}}(t_0)$, Ox_i axis lies in a vertical plane, passing through the radius vector $\vec{\mathbf{r}}(t_0)$ and the beacon $C(\varphi_c, \lambda_c)$, Oz_i axis complements the system to a right-hand one.

When executing a mathematic simulation to register the moment of grabbing of the beacon t_0 определяется *relative position of the vehicle and the beacon* is determined in the Greenwich moving coordinates $O_G x_G y_G z_G$. Its origin coincides with the centre of gravity of the vehicle, $O_G z_G$ axis is directed along with a vector of angular rate of Earth rotation, $O_G x_G$ axis lies in the plane of Greenwich meridian, $O_G y_G$ axis complements the system to the right-hand one.

To determine the relative position at each step of integration of motion equations of the vehicle after descent lower than the radio contact altitude $h \le h_p$ a radius vector of the centre of gravity of the vehicle $\vec{\mathbf{r}}$ and *the distance vector* $\vec{\mathbf{D}}$ by known phase coordinates of the vehicle (2) are determined.

$$\begin{gathered}\vec{\mathbf{r}} = (r_{xг}, r_{yг}, r_{zг}) \\ r_{xг} = r\cos\varphi_{ц}^{н}\cos\lambda^{н} \\ r_{yг} = r\cos\varphi_{ц}^{н}\sin\lambda^{н} \\ r_{zг} = r\sin\varphi_{ц}^{н} \\ \vec{\mathbf{D}} = (D_{xг}, D_{yг}, D_{zг}) = \vec{\mathbf{r}}_c - \vec{\mathbf{r}} \\ D_{xг} = r_{cxг} - r_{xг} \\ D_{yг} = r_{cyг} - r_{yг} \\ D_{zг} = r_{czг} - r_{zг}\end{gathered} \tag{3}$$

The radius-vector of the landing point $\vec{\mathbf{r}}_c$ is determined by predefined values of its geographical coordinates φ_c, λ_c

$$\vec{\mathbf{r}}_c = (r_{cxг}, r_{cyг}, r_{czг}),\ r_{cxг} = r_c\cos\varphi_{цc}\cos\lambda_c,$$

$$r_{cyг} = r_c\cos\varphi_{цc}\sin\lambda_c,\ r_{czг} = r_c\sin\varphi_{цc}. \tag{4}$$

Geocentric latitude $\varphi_{цc}$ and *values of radii* r_c and r are related to *geographical latitude* φ_c as follows

$$\varphi_{цc} = \arctan\left[\left(1 - 2\alpha - \alpha^2\right)\tan\varphi_c\right],$$

$$r_c = R_e\left(1 - \alpha\sin^2\varphi_{цc}\right) + h_k,$$

$$r = R_e\left(1 - \alpha\sin^2\varphi_{ц}\right) + h^{н}, \tag{5}$$

where α is Earth oblateness, R_e is Earth equator radius.

The moment of grabbing t_0 is defined using condition that an angle of vehicle elevation above the plane of the beacon horizon equals to

$$\beta(t) = \arcsin\frac{l(t)}{D(t)},\ t = \frac{(\vec{\mathbf{r}}\cdot\vec{\mathbf{r}}_c)}{r_c} - r_c,$$

to predefined value of slope $\beta_з$

$$t_0 = \mathrm{arc}\left\{\arcsin\frac{l(t)}{D(t)} - \beta_з = 0\right\},$$

at which a stable radio connection is established in conditions of sight of the beacon by vehicle.

To realize the prediction of the temination parameters of motion $y(t_{kj})$ and objective function $R^{(j)}$, it's necessary to determine values of parameters D_j, ε_j, η_j, α_j at the moment of correction t_j.

The distance to the beacon by the sight line D_j is determined by radio equipment of the vehicle, and when mathematical simulation is computed using the relations (3)—(5)

$$D_j = \left(D_{xгj}^2 + D_{yгj}^2 + D_{zгj}^2\right)^{0,5},$$

$$D_{xгj} = r_{cxг} - r_{xгj},$$

$$D_{yгj} = r_{cyг} - r_{yгj},\ D_{zгj} = r_{czг} - r_{zгj},$$

$$r_{xгj} = r_j\cos\varphi_{цj}^{н}\cos\lambda_j^{н},$$

$$r_{yгj} = r_j\cos\varphi_{цj}^{н}\sin\lambda_j^{н},\ r_{xгj} = r_j\sin\phi_{цj}^{н}.$$

The sight angle ε_j is an angle between the distance vector to the landing point along the sight line $\vec{\mathbf{D}}_j = D_j \cdot \vec{\mathbf{D}}_j^0$ and speed vector $\vec{\mathbf{V}}_{kj}$ (fig. 2).

It is determined using the expression of the modulus of vector product of $\vec{\mathbf{D}}_j$ and $\vec{\mathbf{V}}_{kj}$ vectors

$$\varepsilon_j = \arcsin\left(\frac{\left|\vec{N}_j\right|}{\left|\vec{D}_j\right|\cdot\left|\vec{V}_{kj}\right|}\right),$$

where $\vec{\mathbf{N}}_j = \vec{\mathbf{D}}_j \times \vec{\mathbf{V}}_{kj}$ is a normal vector to a plane of self-guidance, formed by vectors $\vec{\mathbf{D}}_j$ and $\vec{\mathbf{V}}_{kj}$.

The vectors $\vec{\mathbf{D}}_j$, $\vec{\mathbf{V}}_{kj}$ and $\vec{\mathbf{N}}_j$ should be defined in the inertial reference frame $Ox_u y_u z_u$ for calculation of the angle of sight

$$\vec{\mathbf{D}}_j = \left(D_{xuj}, D_{yuj}, D_{zuj}\right),$$

$$\vec{\mathbf{V}}_{kj} = \left(V_{k\,xuj}, V_{k\,yuj}, V_{k\,zuj}\right),$$

$$\vec{\mathbf{N}}_j = \left(N_{xuj}, N_{yuj}, N_{zuj}\right).$$

Conclusions

By the results of onboard measurements the distance vector $\vec{\mathbf{D}}$ is formed in the *inertial reference frame*, and for mathematical simulation in *Greenwich reference frame*. The velocity vector $\vec{\mathbf{V}}_k$ is formed in the *path reference frame* by the navigation system.

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