Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Position-Trajectory Control System for Unmanned Robotic Airship

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Abstract: This paper considers design of the control system for prototype of stratospheric airship, that is distinctive for its hybrid shape, leading to essential aerodynamic moments in flight. Mathematical model of the airship is presented. Control system implements remotely controlled by pilot flight and autonomous flight. Algorithm of automatic distribution of controlling forces and moments in actuators is presented. Adaptation of control system is provided with robust estimator of disturbances as indirect robust control. Control system is experimentally tested with hardware and software complex for HIL-simulation and pilots training.

1. INTRODUCTION

Research and design of various lighter-than-air vehicles are very topical at present time (Elfes et al., 1998, Ramos et al., 2001, Pshikhopov et al., 2009 a, Pshikhopov et al., 2010, Pshikhopov et al., 2011). Peculiarities of airships require development of design methods for navigation and control of airships (Pshikhopov et al., 2011, Mueller at al., 2004, Vucinic at al., 2013, Azinheira at al., 2009).

Airship is distinctive for its small ratio of main propulsion drives power to airship weight. This is main advantage of airship in comparison with planes and helicopters. Meanwhile, small amount of energy brings to the fact that airship is controllable in small area of state variables. Besides small airship velocity in values is close to wind velocity, and it makes inadequate separation of motion into lateral and longitudinal components. In (Pshikhopov et al., 2013) it is shown that for airships interrelated forces and moments reach up to 80% of full forces and moments, that makes design of interrelated control system topical. In this regard, appliance of classical approaches of design of control systems, based on separation of lateral and longitudinal motions (Krutjko, 1997), is difficult for airships. In this work method of position-trajectory control is applied for control of autonomous robotized airship (Pshikhopov, 2009 b).

2. MATHEMATICAL MODEL OF THE AIRSHIP

Prototype of stratospheric airship, similar to Lockheed-Martin P-791 is considered. It is shown in Fig. 1. Main parameters of airship: length 38 m, width 17 m, height 10 m, envelope volume 4 100 m^3, weight (with empty ballonets) 3 300 kg, one ballonet volume 900 m3. Coordinates of gravity center in reference to volume center (0 m, -1.5 m, 0 m). Main propulsion engines generate thrust of 4 000 N each. Engines are rotated in vertical plane in range from -180º up to +180º. Coordinates of main engines gravity centers are (0 m, 0 m, ±9 m). Tail steering motors generates up to 200 N each. They rotate in range from -90º up to +90º both in horizontal and vertical planes. They are located in tail part of airship and have coordinates (–20 m; 0 m; ±3.5 m).

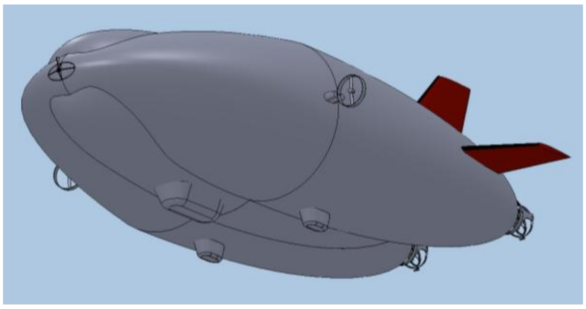

Fig. 1. Hybrid airship

Kinematics equations of airship are

$$\begin{bmatrix} \dot{r}_0 \\ \dot{\Theta} \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & A_\omega \end{bmatrix} \begin{bmatrix} V \\ \omega \end{bmatrix}, \qquad (1)$$

where $r_0 = [x_0, y_0, z_0]^T$ is linear position of airship in ground coordinate system; $\Theta = [\psi, \vartheta, \gamma]^T$ is vector of Euler angles; $V = [V_x \; V_y \; V_z]^T$ is airship linear velocities in body coordinate system; $\omega = [\omega_x \; \omega_y \; \omega_z]^T$ is angular speed vector; A, A_ω are the matrices of kinematic transformations (Pshikhopov et al., 2011).

Dynamic equations of airship with constant mass are

$$\begin{bmatrix} \dot{V} \\ \omega \end{bmatrix} = M^{-1} \begin{bmatrix} F \\ N \end{bmatrix}, \qquad (2)$$

where F, N are resulting vectors of forces and torques, acting on airship;

$$M=\begin{bmatrix} m+\lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & mz_{\text{т}}+\lambda_{15} & -my_{\text{т}}+\lambda_{16} \\ \lambda_{12} & m+\lambda_{22} & \lambda_{23} & -mz_{\text{т}}+\lambda_{24} & \lambda_{13} & mx_{\text{т}}+\lambda_{26} \\ \lambda_{13} & \lambda_{23} & m+\lambda_{33} & my_{\text{т}}+\lambda_{34} & mz_{\text{т}}+\lambda_{15} & \lambda_{36} \\ \lambda_{14} & -mz_{\text{т}}+\lambda_{24} & my_{\text{т}}+\lambda_{34} & J_x+\lambda_{44} & -J_{xy}+\lambda_{45} & -J_{xz}+\lambda_{46} \\ mz_{\text{т}}+\lambda_{15} & \lambda_{25} & -mx_{\text{т}}+\lambda_{35} & -J_{xy}+\lambda_{45} & J_y+\lambda_{55} & -J_{yz}+\lambda_{56} \\ -my_{\text{т}}+\lambda_{16} & mx_{\text{т}}+\lambda_{26} & \lambda_{36} & -J_{xz}+\lambda_{46} & -J_{yz}+\lambda_{56} & J_z+\lambda_{66} \end{bmatrix} \quad (3)$$

m is airship mass; λ_{ij} are added masses; J_x, J_y, J_z, J_{xy}, J_{xz}, J_{yz} are inertia moments; x_T, y_T, z_T are coordinates of gravity center in reference to volume center of airship.

Forces vectors F, N can be broken down as follows:

$$F = F_{\text{т}} + F_{\text{a}} + F_{\text{u}} + R_{\text{a}}\,, \quad (4)$$

$$N = N_{\text{т}} + N_{\text{u}} + N_{\text{a}}\,, \quad (5)$$

where $F_{\text{т}}$ and $N_{\text{т}}$ are vector of force and force torque of gravity force; F_{a} is buoyant force; F_{u} and N_{u} are vector of force and torque of propulsion thrust; R_{a} and N_{a} are vector of aerodynamic force and torque, acting on airship.

Gravity force vector $F_{\text{т}}$ in body coordinate system is

$$F_{\text{т}} = \begin{bmatrix} F_{\text{т}}^x \\ F_{\text{т}}^y \\ F_{\text{т}}^z \end{bmatrix} = mg\begin{bmatrix} -\sin\vartheta \\ -\cos\vartheta\cos\gamma \\ \cos\vartheta\sin\gamma \end{bmatrix}, \quad (6)$$

where ϑ, γ are pitch and roll angles; g is gravitational acceleration; $F_{\text{т}}^x, F_{\text{т}}^y, F_{\text{т}}^z$ – are projections of gravity force to the axis of body coordinate system.

Moments generated by gravity force in reference to airship axes are:

$$\begin{aligned} N_{\text{т}}^x &= y_{\text{т}}F_{\text{т}}^z - z_{\text{т}}F_{\text{т}}^y, \\ N_{\text{т}}^y &= z_{\text{т}}F_{\text{т}}^x - x_{\text{т}}F_{\text{т}}^z, , \\ N_{\text{т}}^z &= x_{\text{т}}F_{\text{т}}^y - y_{\text{т}}F_{\text{т}}^x, \end{aligned} \quad (7)$$

where $N_{\text{т}}^x, N_{\text{т}}^y, N_{\text{т}}^z$ are projections of gravity force moments to body coordinate system.

Components of buoyant force F_{a} in body coordinate system are

$$\begin{aligned} F_{\text{a}}^x &= \rho g U \sin\vartheta, \\ F_{\text{a}}^y &= \rho g U \cos\vartheta\cos\gamma, \\ F_{\text{a}}^z &= -\rho g U \cos\vartheta\sin\gamma \end{aligned} \quad (8)$$

Projections of vector R_{a} and moment N_{a} of dynamic forces to body axes are calculated as follows

$$\begin{aligned} R_{\text{a}}^x &= m\left(V_y\omega_z - \omega_y V_z - y_T\omega_x\omega_y - z_T\omega_x\omega_z + x_T\left(\omega_y^2+\omega_z^2\right)\right) - \\ &-\sum_{k=1}^{6} q_k(\lambda_{3k}\omega_y - \lambda_{2k}\omega_z) - 0,5c_x S\rho V^2 \end{aligned} \quad (9)$$

$$\begin{aligned} R_{\text{a}}^y &= m\left(V_z\omega_x - \omega_z V_x - x_T\omega_x\omega_y - y_T\left(\omega_x^2+\omega_z^2\right) - z_T\omega_y\omega_z\right) - \\ &-\sum_{k=1}^{6} q_k(\lambda_{1k}\omega_z - \lambda_{3k}\omega_x) + 0,5c_y S\rho V^2 \end{aligned} \quad (10)$$

$$\begin{aligned} R_{\text{a}}^z &= m\left(V_x\omega_y - \omega_x V_y - x_T\omega_x\omega_z - y_T\omega_y\omega_z + z_T\left(\omega_x^2+\omega_y^2\right)\right) - \\ &-\sum_{k=1}^{6} q_k(\lambda_{2k}\omega_x - \lambda_{1k}\omega_y) + 0,5c_z S\rho V^2 \end{aligned} \quad (11)$$

$$\begin{aligned} N_{\text{a}}^x &= \omega_x\left(J_{xz}\omega_y - J_{xy}\omega_z\right) + J_{yz}\left(\omega_y^2 - \omega_z^2\right) + \left(J_y - J_z\right)\omega_y\omega_z - \\ &-m\left(-y_T V_x\omega_y + y_T V_y\omega_x - z_T V_x\omega_z + z_T V_z\omega_x\right) - \\ &-\sum_{k=1}^{6} q_k(\lambda_{6k}\omega_y - \lambda_{5k}\omega_z) + 0,5m_x U\rho V^2 \end{aligned} \quad (12)$$

$$\begin{aligned} N_{\text{a}}^y &= \omega_y\left(J_{xy}\omega_z - J_{yz}\omega_x\right) + J_{xz}\left(\omega_z^2 - \omega_x^2\right) + \left(J_z - J_x\right)\omega_x\omega_z - \\ &-m\left(x_T V_x\omega_y - x_T V_y\omega_x - z_T V_y\omega_z + z_T V_z\omega_y\right) - \\ &-\sum_{k=1}^{6} q_k(\lambda_{4k}\omega_z - \lambda_{6k}\omega_x) + 0,5m_y U\rho V^2 \end{aligned} \quad (13)$$

$$\begin{aligned} N_{\text{a}}^z &= \omega_z\left(J_{yz}\omega_x - J_{xz}\omega_y\right) + J_{xy}\left(\omega_x^2 - \omega_y^2\right) + \left(J_x - J_y\right)\omega_x\omega_y - \\ &-m\left(x_T V_x\omega_z - x_T V_z\omega_x + y_T V_y\omega_z + y_T V_z\omega_y\right) - \\ &-\sum_{k=1}^{6} q_k(\lambda_{5k}\omega_x - \lambda_{4k}\omega_y) + 0,5m_z U\rho V^2 \end{aligned} \quad (14)$$

where $q_1 = V_x$, $q_2 = V_y$, $q_3 = V_z$, $q_4 = \omega_x$, $q_5 = \omega_y$, $q_6 = \omega_z$ are projections of linear and angular velocities of airship to body coordinate system; $S = U^{2/3}$ is characteristic area of airship; U is volume of envelope; $c_x, c_y, c_z, m_x, m_y, m_z$ are aerodynamic coefficients;.

Dynamics of actuators is

$$\dot{\delta} + T_{\text{ac}}\delta = K_{\text{ac}}U \quad (15)$$

where $\delta = \begin{bmatrix} P_1 & \alpha_1 & P_2 & \alpha_2 & P_3 & \alpha_3 & \beta_3 & P_4 & \alpha_4 & \beta_4 \end{bmatrix}$ – is a vector of thrusts and orientation angles; U is control; $T_{\text{ac}} = diag\left(T_{P1}, 0, T_{P2}, 0, T_{P3}, 0, 0, T_{P4}, 0, 0\right)$ – diagonal matrix of time constants; K_{ac} – diagonal matrix of transfer coefficient. Angular speed for tilting of propellers is up to ±60 grad/s.

Equations (1), (2), (15) are mathematical model of airship.

3. INVESTIGATION OF THE MATHEMATICAL MODEL

We define requirements to controlling forces and torques in steady-state motion. For airships straightforward flight and flight along circle are typical.

We consider straightforward flight of airship at altitude of 2 000 m with 10 m/s velocity with angle of -30° to OX_0 axis of ground coordinate system, that is shown in Fig. 2

Required steady-state flight of airship in ground coordinate system is described by equations

$$x_0^0 = 10t\cos\left(-30^\circ\right) = 8,66t\,,\ z_0^0 = -10t\sin\left(-30^\circ\right) = 5t\,,$$

$$y_0^0 = 2000\,,\ \psi^0 = -30^\circ,\ \vartheta^0 = Const\,,\ \gamma^0 = 0\,.$$

Required velocities of airship in ground coordinates are

$$\begin{bmatrix} V_x^0 & V_y^0 & V_z^0 & \omega_x^0 & \omega_y^0 & \omega_z^0 \end{bmatrix} = \begin{bmatrix} 8,66 & 0 & 5 & 0 & 0 & 0 \end{bmatrix}$$

On the basis of equations (2) we define numerical values of control forces and moments, generated by propulsion drives, that is presented in Table 1.

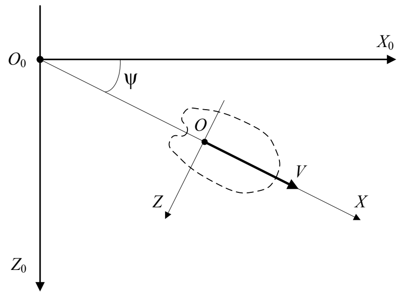

Fig. 2. Straightforward flight

Table 1. Control forces and torques

Forces	Straightforward flight			
	5 m/s	10 m/s	15 m/s	20 m/s
F_{ux}	158	601	1150	2760
F_{uy}	1280	1060	970	840
F_{uz}	0	0	0	0
N_{ux}	0	0	0	0
N_{uy}	0	0	0	0
N_{uz}	5600	8000	11000	17500
	Flight along circle			
N_{uy}	1520	3200	5000	9400

Now we consider steady-state flight of airship along circle of 500 m radius at the altitude of 2 000 m with velocity of 10 m/s. Trajectory, shown in Fig. 3, is described as follows.

$$x_0^0 = 500 + 500\sin\left(-\frac{\pi}{2} + 0,02t\right),\ \psi^0 = -\frac{\pi}{2} + 0,02t\ ,\ \gamma^0 = 0$$

$$z_0^0 = 500\cos\left(-\frac{\pi}{2} + 0,02t\right),\ y_0^0 = 2000\ ,\ \vartheta^0 = Const\ .$$

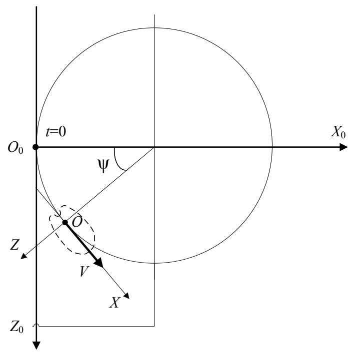

Fig. 3. Flight along circle trajectory

Velocities vector of airship in ground coordinate system is:

$$\begin{bmatrix} V_x^0 & V_y^0 & V_z^0 & \omega_x^0 & \omega_y^0 & \omega_z^0 \end{bmatrix} = \begin{bmatrix} 10 & 0 & 0 & 0 & 0,02 & 0 \end{bmatrix}.$$

On the basis of equation (2) we define numerical values of controlling forces and torques, generated by propulsion drives for flight along circle, that are presented in Table 1. The control forces and torques are the same as for straight line flight, except torque N_{uy}.

On the basis of content of Table 1 one can check feasibility of certain flight trajectories. On the basis of investigations of the mathematical model of airship following conclusions were made:
– location of gravity center of airship is a bit high, therefore airship has quite low statical stability;
– in transient flight required pitch moment can reach tens of thousands of Nm, therefore loss of pitch stability appears;
– loss of stability may occur because of high yaw rates.
Detailed mathematical model of airship with consideration of ballonets, aerodynamic research and parameters identification is presented in (Pshikhopov et al., 2013).

4. CONTROL SYSTEM DESIGN

Certain peculiarities of an airship should be considered for control system design, particularly:
– regarding the fact, that wind speed can excess own speed of airship, ground speed of an airship should be limited relatively to wind speed in control algorithm;
– as far as propellers of airship are unable to generate forces along OZ axis, than control algorithms should provide flight along required trajectories with sideslip angle, defined by direction and speed of wind;
– pitch angle and yaw rate should be limited in airship flight for the prevention of loss of stability;
– most optimal attack angle should be selected for minimization of energy cost of flight.
We note, that loss of stability here is excess of external forces under control forces.
Control algorithms design is occurred with method of position-trajectory control of vehicles (Pshikhopov, 2009 b). Engines has time constant of 1 s. It allows us not to include equation of engines in main control loop of flight control, and control system is designed with equations (1), (2):

$$F_u = -M_1^{-1}\left(M_2\left(F_d + \hat{F}\right) + \psi_\Sigma\right) \tag{16}$$

where M_1 is matrix M^{-1} with erased 3-rd column and 3-rd row; M_2 is matrix M^{-1} with erased 3-rd row; $F_d = \left[F,\ N\right]^T$ is the vector вектор of dynamic and external forces and moments, acting on airship; $\hat{F}$ is the vector of disturbing forces and moments;

$$\Psi_\Sigma = \begin{bmatrix} A_4 & 0_{3\times2} \\ A_1 A & A_2 A_\omega \end{bmatrix}^{-1} \begin{bmatrix} T_3\psi_V \\ A_1\dot{A}V + A_2\dot{A}_\omega\omega + T_2\Psi_{TR} + T_1\dot{\Psi}_{TR} \end{bmatrix},$$

$$\Psi_{TR} = A_1 r_0 + A_2\Theta + A_3,\ \ \psi_V = A_4 V + A_5,$$

A_1, A_2, A_3, A_4, A_5 – matrices of the given path and speed of the airships.
Consider airship flight along straight line at given altitude:

$$A_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & 0 \end{bmatrix}, A_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, A_3 = \begin{bmatrix} -\psi^0 \\ k_y y^0 - \alpha^0 \\ -\gamma^0 \end{bmatrix},$$

$$A_4 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, A_5 = \begin{bmatrix} -V_x^0 \\ -V_y^0 \end{bmatrix},\ \dot{\psi}_{TR} = A_1 A V + A_2 A_\omega \omega,$$

k_y is controller gain; ψ^0 is yaw angle reference; γ^0 is angle of roll reference; y^0 is height reference; α^0 is angle of attack reference; V_x^0 is X component speed reference; V_y^0 is Y component speed reference; T_1, T_2, T_3 are matrixes of constant coefficients.
The solution found is converted into thrusts and orientation angles of drives with expressions:

$$P_3 = P_{34}^{\max},\ P_4 = P_3,\ \beta_3 = 0,\ \beta_4 = \beta_3 \tag{17}$$

$$P_1 = \sqrt{P_{1x}^2 + P_{1y}^2},\ \alpha_1 = \arctan(P_{1y} / P_{1x}), \tag{18}$$

$$P_2 = \sqrt{P_{2x}^2 + P_{2y}^2},\ \alpha_2 = \arctan(P_{2y} / P_{2x}), \tag{19}$$

$$\alpha_3 = \arctan\left(P_{3y} / P_{3x}\right),\ \alpha_4 = \alpha_3. \tag{20}$$

If calculated thrust values exceed maximum values, defined by:

$$P_{34}^{\max} = 200\left(1 - 0.0000667 y_0\right), \tag{21}$$

$$P_{12}^{\max} = 4000\left(1 - 0.000121 y_0\right), \tag{22}$$

than they are become automatically limited.
Trajectory error provides control of pitch angle for reaching of required altitude and change of yaw angle for flight along defined line. At the same time pitch angle is limited in maximum value, depending on airspeed of airship. At the same time heading of airship is perpendicular to goal trajectory if distance towards it exceeds r_0. Also this expressions provides sidesliping of airship with side wind. Sideslip flight is required due to the absence of control force, acting on OZ axes of airship. Trajectory error is defined in similar way for the flight along circular trajectory

5. ESTIMATOR DESIGN

The most significant uncertainties present in the dynamic equation (2). It is required to estimate a disturbances resulting from inaccurate definition of the aerodynamic coefficients and coefficients of added mass. Method of design of disturbance estimator is based on the results presented in (Pshikhopov et al., 2010). We represent the dynamic equation (2) of the airship in the form:

$$\begin{bmatrix} \dot{V} \\ \dot{\omega} \end{bmatrix} = M^{-1} \begin{bmatrix} F + F_{es} \\ N + N_{es} \end{bmatrix},\quad \begin{bmatrix} \dot{F}_{es} \\ \dot{N}_{es} \end{bmatrix} = \begin{bmatrix} g_1\left(F_{es}\right) \\ g_2\left(N_{es}\right) \end{bmatrix}, \tag{23}$$

where $g_1\left(F_{es}\right), g_2\left(N_{es}\right)$ are functions, approximating model of immeasurable disturbances F_{es}, N_{es}, acting on the object.
We denote estimations of immeasurable vectors F_{es}, N_{es} by $\hat{F}_{es}, \hat{N}_{es}$. We introduce vector of estimation errors:

$$\psi = \begin{bmatrix} F_{es} \\ N_{es} \end{bmatrix} - \begin{bmatrix} \hat{F}_{es} \\ \hat{N}_{es} \end{bmatrix}, \tag{24}$$

We require error ψ (24) to be in solution of equation

$$\dot{\psi} + L\left(V, \omega\right)\psi = 0, \tag{25}$$

where $L\left(V, \omega\right)$ is matrix, providing specified properties of equation (25).
We introduce substitution of variables:

$$\begin{bmatrix} \hat{F}_{es} \\ \hat{N}_{es} \end{bmatrix} = s\left(V, \omega\right) + \hat{z}, \tag{26}$$

where $\hat{z}$ is the vector of new variables, $s\left(V, \omega\right)$ – vector-function to be defined in process of design of estimator.
Differentiation of (24) with consideration of model (2) from (23) with substitution (26) we obtain estimator equation, distinctive for usage of vector functions $g_1\left(F_{es}\right), g_2\left(N_{es}\right)$, approximating equations of disturbances. We select functions $g_1\left(F_{es}\right), g_2\left(N_{es}\right)$ in form of:

$$\begin{bmatrix} g_1\left(F_{es}\right) \\ g_2\left(N_{es}\right) \end{bmatrix} = G_1 \begin{bmatrix} F_{es} \\ N_{es} \end{bmatrix}, \tag{27}$$

where G_1 is a matrix of appropriate dimensions.
In this case equation for definition of function $s\left(V, \omega\right)$ is:

$$\frac{\partial s\left(V, \omega\right)}{\partial\left(V, \omega\right)} = \left(G_1 + L\left(V, \omega\right)\right)M, \tag{28}$$

With consideration of (28) with constant matrix L disturbance estimator equation is:

$$\dot{\hat{z}} = -L\hat{z} - L\left(G_1 + L\right)M \begin{bmatrix} \overline{V} \\ \overline{\omega} \end{bmatrix} - \left(G_1 + L\right) \begin{bmatrix} F \\ N \end{bmatrix}, \tag{29}$$

$$\begin{bmatrix} \hat{F}_{es} \\ \hat{N}_{es} \end{bmatrix} = \left(G_1 + L\right)M \begin{bmatrix} \overline{V} \\ \overline{\omega} \end{bmatrix} + \hat{z}, \tag{30}$$

For the approximation of dynamics of immeasurable disturbances, acting on the airship, it is rational to apply time series. So for piecewise-constant sliding approximation of disturbances matrix G_1 is zero matrix of dimension 6x6. Structure of disturbance estimators (29), (30) are presented in Fig. 4.
Estimator obtains data from navigation system and control algorithm. From navigation system estimator obtains vectors V, ω, δ, and from control algorithm – current values of control actions $F_u(\delta), N_u(\delta)$. Outcome vectors of estimations enters into block of control algorithm.

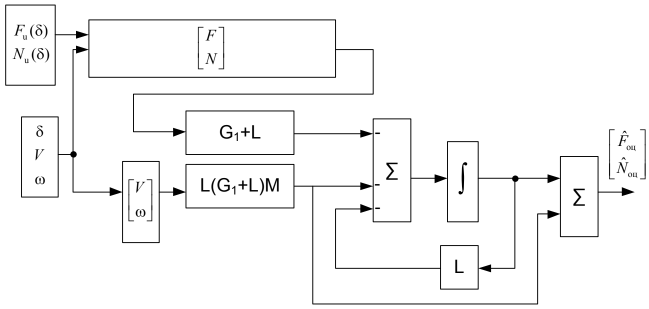

Fig. 4. Structure of disturbance estimator

6. TEST BED

First stage of tests of control system were done with HIL simulation complex, which structure is presented in Fig. 5

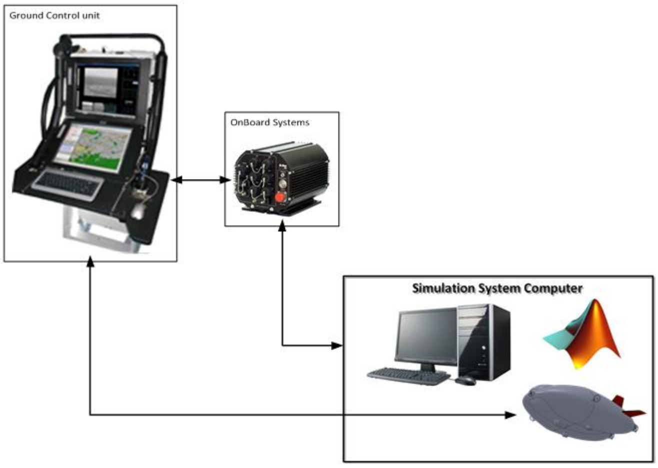

Fig. 5. Structure of HIL simulator

Onboard control system and ground control station are implemented in full, while airship and environment are simulated. Sensors are connected physically or simulated.
The views of onboard control system and ground control station are presented in Fig. 6 and 7.

Fig. 6. Onboard control system

Onboard computer is implemented in processor module CMA22MVD1860HR of PC/104 form-factor, based on processor Intel Core 2 Duo SL9400 (Dual Core 1.86 GHz). On-board computer also includes a communication module for CAN-bus for communication with the actuators. Communication with sensors is occurred with RS-485 interface. There is also a frame-grabber board and power supply board. All these boards are placed into the aluminum housing of Can-Tainer type with a passive cooling. Onboard control system also includes a back-up computer, a navigation system, radio altimeter, air speed sensor, beacon and power system.

Ground control is implemented on an industrial computer HC CO1, and equipped with controlling devices (pedals and joysticks), a display and a navigation system. Communication of onboard system and ground stations are implemented with radio link.

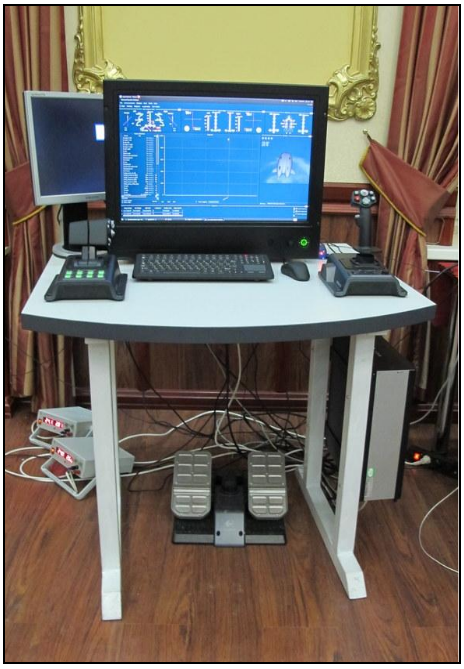

Fig. 7. Ground control station

Fig. 8 and 9 show the results of the test.
The airship is flying along the circle with ground speed of 12 m/s. Flight altitude is 2000 m. Wind speed is 12 m/s. In Fig. 8 and 9 are: FigurePath – airship trajectory in the horizontal plane OXZ; FigureCoords – the coordinates of the airship; FigureReg – thrusts and orientation angles of drives; FigureAngles – angles of yaw, pitch and roll; FigureSpeeds - airship velocities projections in the ground coordinate system and projection of the wind speeds.

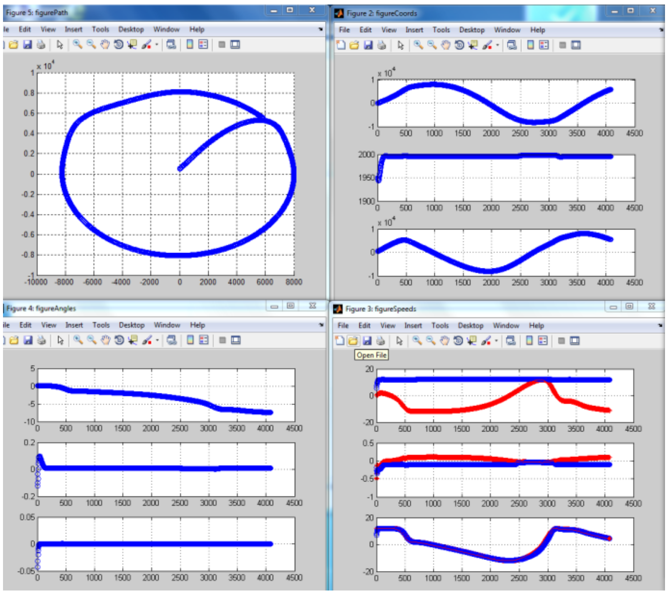

Fig. 8. Trajectories and variables state

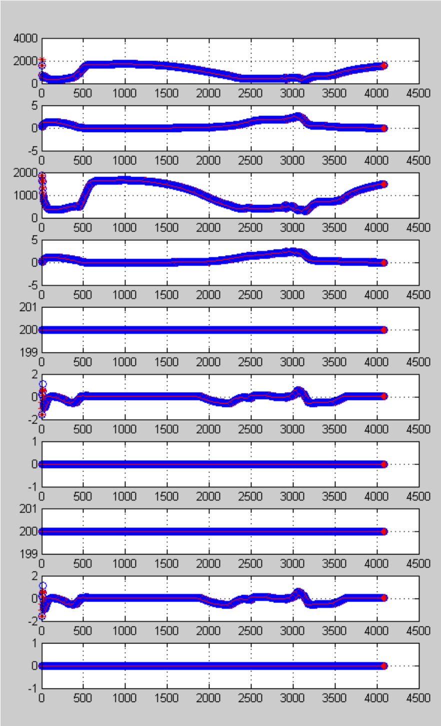

Fig. 9. Thrusts and drives orientation angles

Test shows following results:
– RMSE in linear coordinates for airship steady-state positioning in the absence of wind loads – 33 m;
– RMSE for airship steady-state flight in absence of wind loads: 7.2 m for straight line, 11.3 m for a circle;
– RMSE in a linear velocities for airship steady-state flight with a cruising speed in the absence of wind loads: 1.1 m/s for straight line, 1.33 m/s for a circle.
– Maximum possible wind speed is 13 m/s;
– Maximum possible airspeed of airship is 25 m/s.

7. CONCLUSION

Provided researches have shown that the main drawback of the considered hybrid shaped airship is a big disturbing pitch moment that occurs when airship flying. Also considered prototype has high center of gravity, thereby the airship has small stability margins. To prevent loss of stability and control the control system has the following features:
– Automatic correction of the airship speed from value and direction of wind speed;
– Automatic correction of sideslip angle from value and direction of wind speed;
– Automatic restriction of pitch from value and direction of wind speed and ground speed;
– Automatic correction of angle of attack for power consumption minimizing;
– Using wind streams for power optimal path planning.
For area of large deviations in control system robust control algorithm is implemented. It is described in (Pshikhopov and Medvedev, 2011).
Aerodynamic control surfaces are added in the airship construction for compensation of the disturbing pitch moment.

8. ACKNOWLEDGMENT

This work was supported by Russian Federation President grant HS-1557.2012.10, YD-1098-2013.10 and grant of RFBR 13-08-00315 «Development and research of adaptation methods of position-trajectory control systems of mobile vehicles».

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