Terminal Control Approach Application for Autonomous Airship Docking

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Abstract. The article considers the position-trajectory approach to the synthesis of the terminal regulator for controlling the airship for the docking task. The control system constructed solves the problem of guiding the airship to the docking position at given moment of time in autonomous mode. The airship control algorithm is based on mathematical model of an airship as rigid body, represented by a system of nonlinear differential equations, without linearization. The procedure for the control law synthesizing and the results of modelling by means of MATLAB are given. The task of docking of two airships, as proposed in EU MAAT project, was considered for simulations. The proposals for the further development of this study are formulated.

1. Introduction

Currently, one of the most promising applications of airships is the transportation of goods and people [1]. Various projects related to the achieving of this goal assume, that system is functioning as follows: an aeronautical platform (cruiser) is operating at a cruising altitude and the airship-shuttle preforms docking to this platform for several needs [2, 3].

It should be noted that a similar task of docking control in near-earth space and for underwater vehicles is carried out using classical approaches [4 – 10], for example, by program control [4, 5] by applying a linear-quadratic controller [6], the method of potential fields [7]. The main emphasis in mentioned works is made on the features of the technical implementation of control systems with high reliability and fault tolerance. Linear regulators with the separation of motion into longitudinal and transverse components are also most often used in the synthesis of the control laws of the airships motion [9, 10]. However, the control systems for the docking of airships, built on the basis of such approaches, are operable in a limited range of velocities and disturbances acting on the airship. It is also difficult to use this approaches when solving the problem of docking in three-dimensional space. Multiply connected nonlinear models are used much less often in the synthesis of control systems for airships. This fact does not allow to effectively control airships or expand their functional capabilities.

Thus, the task of terminal control of the docking of the airship, i.e. the task of bringing this aircraft from the initial position to some desired final position in the space at a given time and taking into account its nonlinear mathematical model is actual.

The most commonly used approach for the problem of terminal control involves two stages:

- selection and calculation of the program trajectory as a certain function of time and
• the solution of the stabilization problem, which ensures the motion of the mobile object along a
given program path [11].
However, the complexity of synthesizing the law of terminal control increases substantially if a
nonlinear model of motion of a mobile object is used. Therefore, this work considers the problem of
terminal control of airships, the model of which is represented by a system of nonlinear differential
equations.

2. Airship mathematical model and statement of the task of terminal control of airship docking
To represent the mathematical model of an airship, we will use two coordinate systems, movable and
fixed, shown in Fig. 1.

![Figure 1. Coordinate systems K (OX^0Y^0Z^0) and K (OXYZ)](image)

Let the mathematical model of an airship, constructed on the basis of the known equations of a
rigid body, be given by a system of nonlinear differential equations and be represented in the
following vector-matrix form [12]:

$$
\dot{Y} = \begin{bmatrix} R_y & 0_{3x3} \\ 0_{3x3} & R_{\omega} \end{bmatrix} X
$$

(1)

$$
M \dot{X} = F_u(X, Y, \delta, l, t) + F_d(P, V, W) + F_v(G, A, R)
$$

(2)

$$
T_{ny} \dot{\delta} + \delta = \Psi_{ny}(U, \delta),
$$

(3)

where $T_{ny}$ – diagonal (m x m) - matrix of time constants of actuators; $\Psi_{ny}(U, \delta)$ – m-vector of non-
linear functions of the right sides of actuators equations; $\delta$ – m-vector of controlled coordinates
(angles of deviation, thrust); $U$ – m-vector of controls generated by the airship control system
depending on the arrangement of actuators, $X = \begin{bmatrix} R_y \\ R_{\omega} \end{bmatrix}$ – m-vector of internal coordinates (state
coordinates); $M$ – (m x m)-matrix of mass-inertial parameters, the elements of which are mass,
moments of inertia, added masses of the airship; $F_u(X, Y, \delta, l, t)$ – m- vector of control forces and
moments, $l$ – vector of design parameters; $F_d(P, V, W)$ – m-vector of nonlinear elements of airship
dynamics; $F_v(G, A, R)$ – m-vector of measured and non-measurable external disturbances; $Y = \begin{bmatrix} P \\ \Theta \end{bmatrix}$ – n-
vector of position $P$ and orientation $\Theta$ of the body coordinate system $K(OX Y Z)$ relative to the fixed
coordinate system $K(OX^0Y^0Z^0)$. Conversion procedure from $F_u(X, Y, \delta, l, t)$ to $U$ is described in [13].

It is required to synthesize such a control algorithm $F_u(X, Y, \delta, l, t)$, which would ensure the movement
of the airship given by the model (1) - (3) from the initial position $Y_0 = (x_0, y_0, z_0, \varphi_0, \delta_0, \psi_0)$ to the
final position $Y_k = (x_k, y_k, z_k, \varphi_k, \delta_k, \psi_k)$ at the given time $t = T_k$.

3. Method of terminal control of airship docking
To solve the problem of synthesis of terminal control, we use the procedure described in [11]. We
define the program trajectory of the motion of the airship in a polynomial form and represent it in a
matrix form:

$$
Y^*(t) = CL(t),
$$

(4)
According to the current values of the coordinates sensors of the external environment \( D \) coordinates and includes the following elements:

The system functions as follows: at the outputs of the sensors of internal and external coordinates \( D_x, D_y \) current values of coordinates \( X \) and \( Y \) are formed. The planner based on the readings of the sensors of the external environment \( D_v \) forms the coefficients of the program trajectory \( Y^*(t) = CL(t) \). According to the current values of the coordinates \( X, Y \) and the specified trajectory \( Y^*(t) \), the control

\[
\begin{bmatrix}
    x_0 \\
    y_0 \\
    \vdots \\
    y_0
\end{bmatrix} \begin{bmatrix}
    \frac{3}{T_k}(x_k - x_0) \\
    \frac{3}{T_k}(y_k - y_0) \\
    \vdots \\
    \frac{3}{T_k}(y_k - y_0)
\end{bmatrix}, \quad L(t) = \begin{bmatrix} 1 \\ t \\ t^2 \end{bmatrix}.
\]

Thus, \( C = (n \times 4) \)-matrix of constant coefficients that depend on the initial and final position of the airship, as well as on the given time point of arrival to the positioning point \( T_k \). Moreover, it can be shown that

\[
\begin{aligned}
\dot{Y}^*(t) &= CD_1 L(t), \\
\ddot{Y}^*(t) &= CD_2 L(t),
\end{aligned}
\]

where

\[
D_1 = \begin{bmatrix}
0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 2 & 0 & 0 \\
0 & 0 & 3 & 0
\end{bmatrix}, \quad D_2 = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
2 & 0 & 0 & 0 \\
-0 & 6 & 0 & 0
\end{bmatrix}.
\]

Formation of the law of terminal control is implemented on the basis of position-trajectory algorithms [14]. To do this, we set the error of the deviation of the real trajectory of motion from the specified program path (4) in the form:

\[
\Psi_{tr} = Y - Y^* = Y - CL
\]

We introduce an additional variable \( \Psi = \Psi_{tr} + T_1 \Psi_{tr} \), where \( T_1 \)-diagonal (n x n) -matrix of time constants, \( \Psi_{tr} = \dot{Y} - CD_1 L \). And we define the desired behavior of a closed system in the form:

\[
\dot{\Psi} + T_2 \Psi = 0
\]

where \( T_2 \)-diagonal (n x n) -matrix of time constants. Thus, the desired behavior of the system, expressed in terms of \( \Psi_{tr} \) is as follows:

\[
\dot{\Psi}_{tr} + T_1 \dot{\Psi}_{tr} + T_2 \left( \Psi_{tr} + T_1 \Psi_{tr} \right) = 0
\]

where \( \Psi_{tr} = \dot{Y} - CD_1 L, \dot{\Psi}_{tr} = \ddot{Y} - CD_2 L \).

Substituting in (11) the equation of the mathematical model of the airship (1), (2) and expressing the corresponding vector of control forces and moments \( F_u(t) \), we obtain the following control law:

\[
F_u(t) = -MR^{-1}\left[\dot{R}X - CD_2 L + T_1 \Psi_{tr} + T_2 \left( \Psi_{tr} + T_1 \Psi_{tr} \right) \right] - F_d - F_v
\]

Structure of closed-loop control system, corresponding to the resulting algorithm is shown in Fig. 2 and includes the following elements: \( D_x \)-sensors of internal coordinates \( X \), \( D_y \)-sensors of external coordinates \( Y \), \( D_v \)-external environment sensor, planner and controller \( F_u(t) \).

\[\text{Figure 2. Structure of a closed system with model (1), (2) and control (12)}\]
calculation module $F_u$ generates control actions in accordance with the expression (6). The value of forces $F_d, F_v$ is formed either by the corresponding sensory system, or by an observer of external disturbances.

4. The terminal control of the airship docking simulation results
Simulation of docking of feeder to cruise was performed for two strategies:

- both airships (cruiser and feeder) are controlled by the described terminal regulator in order to simultaneously arrive at the point of docking;
- the cruiser does not change its mission and does not stop at docking point, the cruiser chases it up at a given time and moves with same speed at the final moment of the terminal control operation.

The results of the simulation of the first docking strategy are presented in Figures 3 – 5. The cruiser airship starts from the point with coordinates (0; 1100; 0) m, the feeder from the point (200; 900; 100) m. The specified docking point is (100; 1000; 200) m, the given terminal task duration is 100 seconds.

![Figure 3. Trajectories of the cruiser and feeder for the first docking strategy](image1)

![Figure 4. Cruiser and feeder altitudes for the first docking strategy](image2)

![Figure 5. Cruiser and feeder velocities for the first docking strategy](image3)

Proposed approach efficiency is confirmed the above simulation results.

Comparing the plots of the cruiser and feeder speed changes in the first case, it can be seen that the maximum cruiser speed is 3.7 m/s and is higher than the maximum feeder speed of 2.6 m/s (Fig. 5), because the trajectory of the cruiser is longer, and in order to reach the final point at a given time $T_k$, the speed of its movement must be higher. Note, that there are possible situations when the energy capabilities of the airship will not allow it to reach a given point at a given moment in time, with a certain increase in the length of the trajectory.
The results of the second variant of docking simulation (when the cruiser airship does not change its mission and the feeder catch it up with it at given time) are presented in Figures 6-8. The cruiser airship moves from the point with coordinates (0; 1000; 100) m, feeder - from the point (0; 900; 0) m. The docking point is not defined (but determined by the position of the cruiser), the time of solving the terminal task is 100 seconds. The cruiser airship is moving along a given mission in a straight line at a constant speed at a constant altitude.

![Trajectories of the cruiser and feeder for the second docking strategy](image1)

**Figure 6.** Trajectories of the cruiser and feeder for the second docking strategy

![Cruiser and feeder altitudes for the second docking strategy](image2)

**Figure 7.** Cruiser and feeder altitudes for the second docking strategy

![Cruiser and feeder velocities for the second docking strategy](image3)

**Figure 8.** Cruiser and feeder velocities for the second docking strategy

Figure 8 shows that at a given point in time (after 100 seconds), the feeder airship chases the cruiser and moves with the same speed.

5. Conclusion
In the article the problem of terminal control of an airship, the model of which is represented by a system of nonlinear differential equations, is solved.

It is worth noting that to solve the terminal problem it is necessary to form a terminal point in time $T_k$ taking into account the energy capabilities of the airship, i.e. it is necessary to take into account the limitations on the control actions and the power of the actuators. The decision of the task of forming the program trajectory of the airship movement, taking into account the limitations on control actions and the power of the actuators, is planned in the future work. It is also necessary to evaluate the influence of external and internal disturbances. In real conditions, in the process of docking of an airship, stationary or non-stationary obstacles may exist in the area of its operation. To avoid obstacles, there are many methods, in the future work it is proposed to use the obstacle avoidance method based on the use of unstable regimes.
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References
[1] Control of Feeder of Novel Cruiser/Feeder MAAT System," SAE Technical Paper 2012-01-2099, 2012, https://doi.org/10.4271/2012-01-2099.
[2] Vucinic, D., Sunol, A., Trancossi, M., Dumas, A. et al., "MAAT Cruiser/Feeder Airship: Connection and Passenger Exchange Modes," SAE Technical Paper 2013-01-2113, 2013, https://doi.org/10.4271/2013-01-2113.
[3] Pshikhopov, V., Medvedev, M., Krukhmalev, V., Fedorenko, R. et al., "Method of Docking for Stratospheric Airships of Multibody Transportation System," SAE Technical Paper 2014-01-2162, 2014, https://doi.org/10.4271/2014-01-2162.
[4] Hablani H.B., Tapper M.L., Dana-Bashian D.J. Guidance and relative navigation for autonomous rendezvous in a circular orbit //Journal of Guidance, Control, and Dynamics. – 2002. – T. 25. – No. 3. – C. 553-562.
[5] Ichikawa A., Ichimura Y. Optimal impulsive relative orbit transfer along a circular orbit // Journal of guidance, control, and dynamics. – 2008. – T. 31. – No. 4. – C. 1014-1027.
[6] Bevilaqua R., Lehmann T., Romano M. Development and experimentation of LQR/APF guidance and control for autonomous proximity maneuvers of multiple spacecraft //Acta Astronautica. – 2011. – T. 68. – No. 7. – C. 1260-1275.
[7] Lopez I., McInnes C.R. Autonomous rendezvous using artificial potential function guidance // Journal of Guidance, Control, and Dynamics. – 1995. – T. 18. – No. 2. – C. 237-241.
[8] Smith S. M. et al. Fuzzy logic control of an autonomous underwater vehicle //Control Engineering Practice. – 1994. – T. 2. – No. 2. – C. 321-331.
[9] Batista P., Silvestre C., Oliveira P. A sensor-based controller for homing of underactuated AUVs //Robotics, IEEE Transactions on. – 2009. – T. 25. – No. 3. – C. 701-716.
[10] Jantrapremjit P., Wilson P.A. Control and guidance for homing and docking tasks using an autonomous underwater vehicle //Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on. – IEEE, 2007. – C. 3672-3677.
[11] Pshikhopov V.Kh. Analytical construction of nonlinear systems of terminal control // Sb. RAS "New concepts of general management theory", M.-Taganrog. 1995. P. 125-141
[12] V.Kh. Pshikhopov, M.Yu. Medvedev, R.V. Fedorenko et al., “Mathematical model of robot on base of airship,” 52nd IEEE Conference on Decision and Control, Firenze, 2013, pp. 959-964.
[13] V. Kh. Pshikhopov, M.Yu. Medvedev, A.R. Gaiduk, R.V. Fedorenko, V.A. Krukhmalev, B.V. Gurenko, Position-Trajectory Control System for Unmanned Robotic Airship, IFAC Proceedings Volumes, Volume 47, Issue 3, 2014, Pages 8953-8958, ISSN 1474-6670
[14] Pshikhopov, V., Medvedev, M., Kostjukov, V., Fedorenko, R. et al., "Airship Autopilot Design," SAE Technical Paper 2011-01-2736, 2011, https://doi.org/10.4271/2011-01-2736.