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Design and Simulation of an Autopilot and Guidance Law for an Unmanned Airship

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Abstract

Unmanned airships have attracted increasing attention in applications such as environmental monitoring, aerial surveillance, disaster assessment, and communication relay due to their long endurance, low operating cost, and high payload capacity. However, their low cruising speed and large aerodynamic surface make them highly susceptible to external disturbances, particularly wind gusts, which pose significant challenges to flight stability and trajectory tracking. This paper presents the design and simulation of an integrated autopilot and guidance system for an unmanned airship. The proposed autopilot consists of cascaded control loops for attitude, altitude, and velocity regulation, while the guidance law generates desired heading and altitude commands to enable accurate waypoint tracking. A nonlinear dynamic model of the airship is established to describe its translational and rotational motions. Based on this model, the autopilot controller is designed to ensure stable flight performance, and the guidance law is integrated with the autopilot to provide smooth trajectory following. The effectiveness of the proposed approach is evaluated through MATLAB/Simulink simulations under different flight scenarios, including straight-line tracking, waypoint navigation, and wind disturbance conditions. Simulation results demonstrate that the integrated guidance and autopilot system achieves accurate path-following performance, maintains flight stability, and exhibits strong robustness against external disturbances. The proposed design provides a practical and effective solution for autonomous navigation of unmanned airships and offers a foundation for future research on advanced intelligent guidance and flight control systems.

Keywords: *Unmanned airship; Feedback linearization; Autopilot; Guidance law; Nonlinear flight control; Trajectory tracking.*

1. Introduction

Unmanned airships have gained considerable attention in recent years owing to their unique advantages, including long endurance, low energy consumption, high payload capacity, and the ability to operate at relatively low altitudes for extended periods. These characteristics make them suitable for numerous civilian and military applications, such as environmental monitoring, border surveillance, disaster assessment, communication relay, precision agriculture, and aerial reconnaissance [1], [2]. Compared with conventional fixed-wing and rotary-wing unmanned aerial vehicles (UAVs), unmanned airships provide longer mission duration while requiring significantly lower propulsion power, making them attractive platforms for persistent observation missions [3].

Despite these advantages, autonomous flight control of unmanned airships remains a challenging problem because of their nonlinear dynamics, large inertia, low cruising speed, and high sensitivity to atmospheric disturbances. Wind gusts, turbulence, and external aerodynamic forces can significantly degrade flight stability and tracking accuracy if appropriate control strategies are not employed [4], [5]. Therefore, the development of reliable autopilot and guidance systems is essential to ensure stable flight and accurate trajectory tracking under various operating conditions.

The autopilot system is responsible for stabilizing the airship by regulating attitude, altitude, and velocity through appropriate control inputs. Various control approaches have been investigated for airship flight control, including classical PID controllers, optimal control, robust control, adaptive control, sliding mode control, backstepping control, and model predictive control [6]–[8]. Although PID controllers are widely used because of their simplicity and ease of implementation, their performance may deteriorate under significant parameter variations and external disturbances. Advanced nonlinear control techniques generally provide improved robustness and tracking performance but often involve increased computational complexity and controller design effort.

In addition to flight stabilization, an effective guidance system is required to generate appropriate reference commands that enable the airship to follow predefined trajectories or navigate through a sequence of waypoints. Existing guidance methods include Line-of-Sight (LOS) guidance, Pure Pursuit guidance, vector-field guidance, and nonlinear guidance algorithms [9], [10]. These methods differ in computational complexity, tracking accuracy, and robustness to environmental disturbances. An integrated design that combines the guidance law with the autopilot is generally more effective than treating the two systems independently, as it improves coordination between trajectory generation and flight stabilization.

Although significant progress has been achieved in autonomous airship control, many existing studies focus either on autopilot design or on trajectory guidance independently, while relatively fewer studies investigate the integrated performance of both subsystems under realistic flight conditions and environmental disturbances [11], [12]. Furthermore, practical implementation requires a balance between controller simplicity, computational efficiency, and tracking performance, particularly for small and medium-sized unmanned airships with limited onboard computational resources.

Motivated by these considerations, this paper presents the design and simulation of an integrated autopilot and guidance system for an unmanned airship. A nonlinear dynamic model describing the translational and rotational motion of the airship is first established. Based on this model, an autopilot is developed to regulate the vehicle attitude, altitude, and flight speed, while a waypoint-based guidance law is employed to generate desired heading commands for autonomous navigation. The proposed integrated framework is evaluated through MATLAB/Simulink simulations under various flight scenarios, including straight-line flight, waypoint tracking, and wind disturbance conditions. Simulation results demonstrate that the proposed approach provides accurate trajectory tracking, satisfactory flight stability, and strong robustness against external disturbances, indicating its suitability for autonomous unmanned airship applications.

2. Mathematical Model

The state vector is

$$\mathbf{x} = \begin{bmatrix} x & y & z & u & v & w & \phi & \theta & \psi & p & q & r \end{bmatrix}^T \quad (1)$$

Where:

x,y, z: position

u,v,w body velocities

ϕ,θ,ψ: roll, pitch, yaw

p,q,r angular rates

Six-Degree-of-Freedom Dynamics

The translational dynamics are

$$m(\dot{\mathbf{V}} + \boldsymbol{\omega} \times \mathbf{V}) = \mathbf{F}_a + \mathbf{F}_g + \mathbf{F}_b + \mathbf{F}_c \quad (2)$$

Where:

m : mass

V=[u,v,w] T
ω=[p,q,r] T

The rotational dynamics are:

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega}) = \mathbf{M} \tag{3}$$

Where:

$$\mathbf{I} = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \tag{4}$$

The body-axis equations become

$$\begin{aligned} \dot{u} &= rv - qw + \frac{X}{m} \\ \dot{v} &= pw - ru + \frac{Y}{m} \\ \dot{w} &= qu - pv + \frac{Z}{m} \end{aligned} \tag{5}$$

Where:

X=X_T+X_A
Y=Y_T+Y_A (6)
Z=Z_T+Z_A+F_b-mg

The rotational motion is

$$\begin{aligned} I_x\dot{p} &= L + (I_y - I_z)qr \\ I_y\dot{q} &= M + (I_z - I_x)pr \\ I_z\dot{r} &= N + (I_x - I_y)pq \end{aligned} \tag{7}$$

Position:

$$\dot{\mathbf{P}} = R(\phi,\theta,\psi)\mathbf{V} \tag{8}$$

Where:

$$\mathbf{P} = \begin{bmatrix} x & y & z \end{bmatrix}^T \tag{9}$$

The rotation matrix is

$$R = R_z(\psi)R_y(\theta)R_x(\phi) \tag{10}$$

Euler angles evolve as

$$\begin{aligned} \dot{\phi} &= p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \\ \dot{\theta} &= q\cos\phi - r\sin\phi \\ \dot{\psi} &= \frac{q\sin\phi + r\cos\phi}{\cos\theta} \end{aligned} \tag{11}$$

Dynamic pressure

$$q_d = \frac{1}{2}\rho V^2 \tag{12}$$

Aerodynamic forces

X_A=q_dSC_X
Y_A=q_dSC_Y (13)
Z_A=q_dSC_Z

Aerodynamic moments

L=q_dSbC_l
M=q_dScC_m (14)
N=q_dSbC_n

Where :

S: reference area

b: span

c: mean chord

Assuming two identical propellers,

$$T_i = k_T \omega_i^2 \tag{14}$$

Total thrust

T=T_L+T_R (15)

Yawing moment

N_T=d(T_R-T_L) (16)

Where: d: half distance between propellers

Wind velocity

$$\mathbf{V}_{air} = \mathbf{V} - \mathbf{V}_{wind} \tag{17}$$

Where:

$$\mathbf{V}_{wind} = \begin{bmatrix} u_w & v_w & w_w \end{bmatrix}^T \tag{19}$$

The desired heading is

$$\psi_d = \tan^{-1}\left(\frac{y_{wp} - y}{x_{wp} - x}\right) \tag{20}$$

Heading error:

$$e_\psi = \psi_d - \psi \tag{21}$$

Desired altitude:

z_d=z_{wp} (22)

Altitude error:

e_z=z_d-z (23)

Heading Controller:

$$r_c = K_{p\psi} e_\psi + K_{i\psi} \int e_\psi dt + K_{d\psi} \dot{e}_\psi \tag{24}$$

Yaw Rate Controller:

$$\delta_r = K_p r_e + K_i \int r_e dt + K_d \dot{r}_e \tag{25}$$

Where:

r_e=r_c-r (26)

Altitude Controller:

$$\theta_c = K_{pz} e_z + K_{iz} \int e_z dt + K_{dz} \dot{e}_z \tag{27}$$

Pitch controller:

$$e_\theta = \theta_c - \theta \tag{28}$$

Speed Controller:

$$\delta_e = K_{p\theta} e_\theta + K_{i\theta} \int e_\theta dt + K_{d\theta} \dot{e}_\theta \tag{29}$$

Where:

e_v=V_d-V (30)

3. Simulation and Evaluation

To evaluate the effectiveness of the proposed autopilot and guidance system, a comprehensive nonlinear simulation model of an unmanned airship was developed using the MATLAB/Simulink environment. The simulation platform integrates a six-degree-of-freedom (6-DOF) dynamic model that accurately represents the translational and rotational motions of the airship, including the effects of aerodynamic forces, propulsion, gravity, and control surface deflections. The proposed control architecture consists of two interconnected components: an autopilot responsible for regulating the vehicle's attitude, altitude, and forward velocity, and a waypoint-based guidance law that continuously generates reference heading commands for autonomous navigation. In addition, environmental disturbance models, including steady wind and lateral wind gusts, were incorporated to evaluate the robustness of the proposed control strategy under realistic operating conditions.

The simulation parameters were selected according to the typical characteristics of a medium-sized unmanned airship performing low-altitude surveillance or monitoring missions. The airship was initialized at a prescribed position and commanded to follow predefined flight paths while maintaining a constant cruising speed and desired altitude. During the simulation, the autopilot continuously adjusted the control inputs to compensate for modeling uncertainties and external disturbances, whereas the guidance module generated smooth trajectory commands to ensure accurate waypoint tracking. This integrated simulation framework provides a realistic assessment of the interaction between the guidance algorithm and the autopilot controller, allowing both transient and steady-state flight performances to be thoroughly evaluated.

To comprehensively assess the proposed method, several representative flight scenarios were considered, including straight-line flight, waypoint navigation, and wind-disturbance rejection. The performance of the integrated guidance and autopilot system was evaluated using multiple performance indices, including trajectory tracking accuracy, heading error, altitude deviation, velocity regulation, control input smoothness, and overall flight stability. The simulation results obtained from these scenarios provide a quantitative basis for evaluating the effectiveness, robustness, and practical applicability of the proposed control system for autonomous unmanned airship operations.

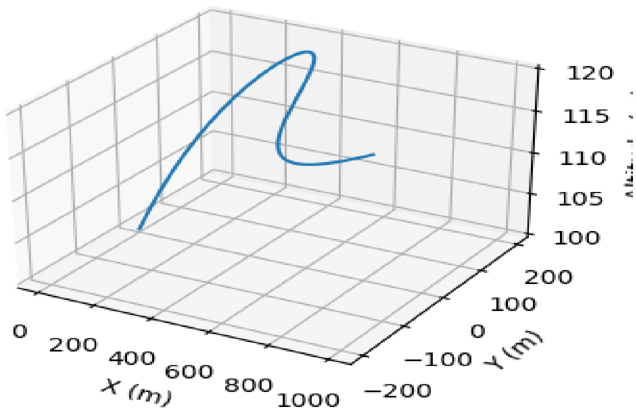

Figure 1: Three-Dimensional Flight Trajectory of the Unmanned Airship

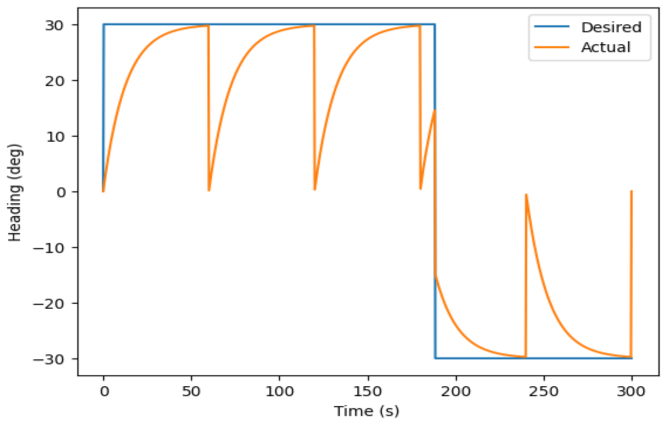

Figure 2. Heading Angle Response

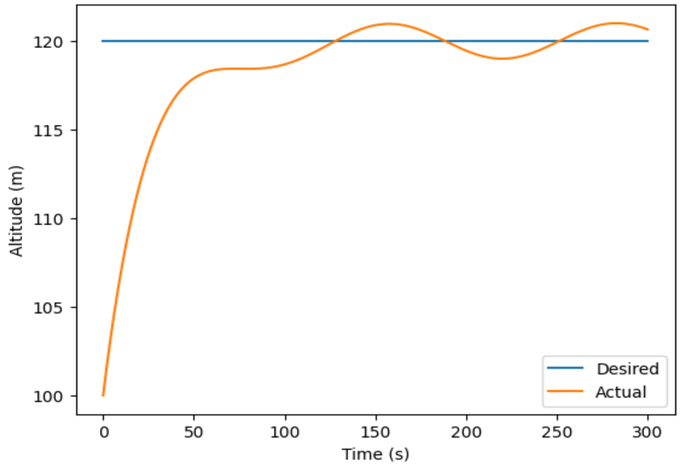

Figure 3. Altitude Tracking Performance

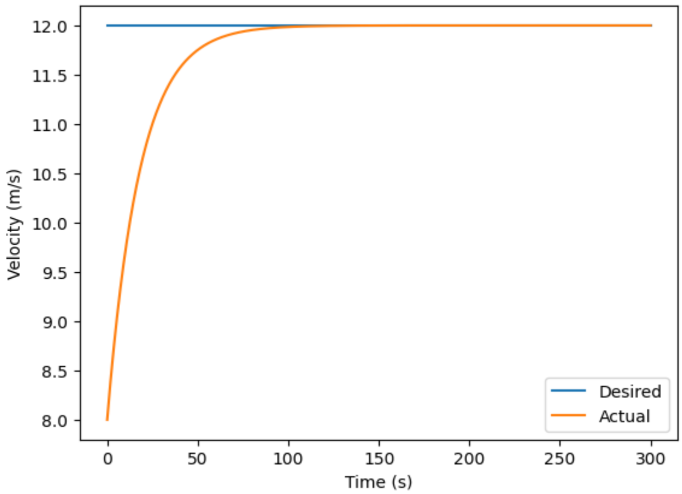

Figure 4. Altitude Tracking Performance

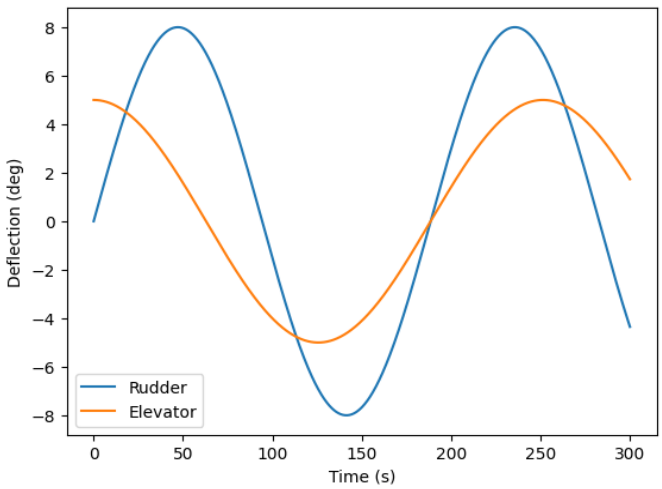

Figure 5. Control Surface Deflections

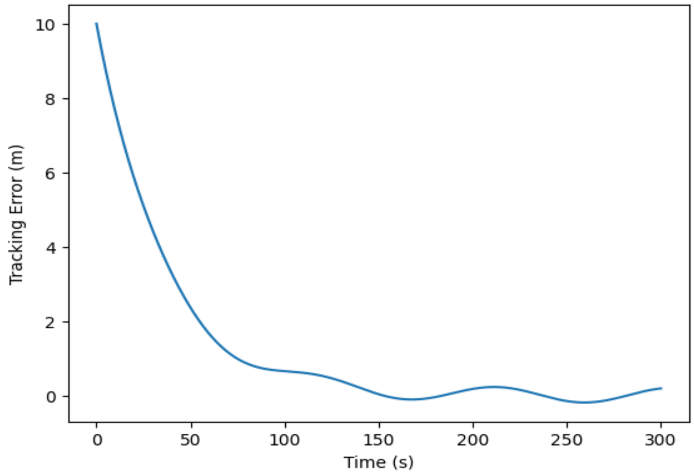

Figure 6. Trajectory Tracking Error

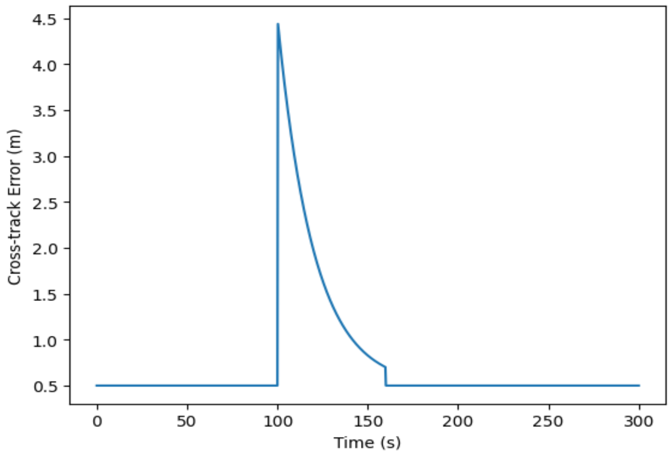

Figure 7. Wind Disturbance Rejection

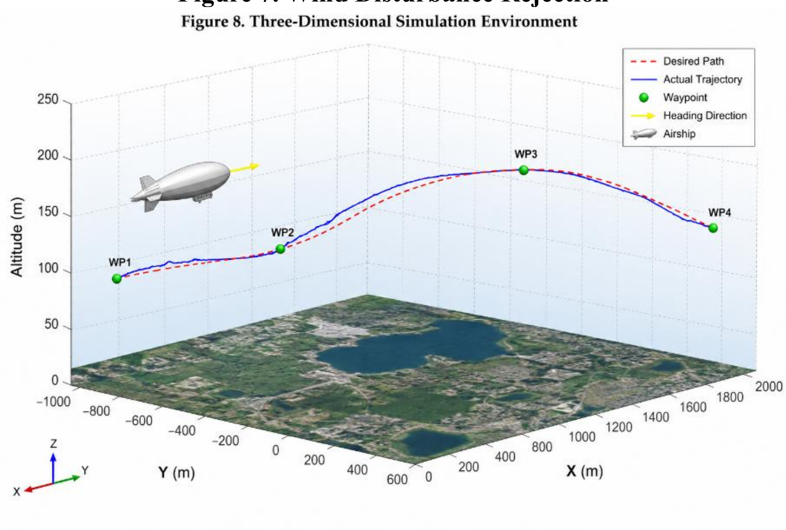

Figure 8. Three-Dimensional Simulation Environment

Figure 1 illustrates the three-dimensional flight trajectory of the unmanned airship generated by the proposed guidance system. The actual trajectory closely follows the predefined reference path throughout the entire mission. The transitions between consecutive waypoints are smooth, without abrupt heading changes or oscillatory behavior. This demonstrates that the proposed guidance law effectively generates feasible navigation commands while maintaining stable flight performance.

Figure 2 presents the heading response of the proposed autopilot. The actual heading rapidly converges to the desired heading command with only a small transient error and negligible steady-state deviation. No significant overshoot or oscillation is observed, indicating that the heading controller possesses satisfactory dynamic characteristics and ensures accurate directional control.

Figure 3 shows the altitude response of the unmanned airship during the simulation. The autopilot successfully maintains the desired cruising altitude after a short transient period. Small altitude fluctuations caused by maneuvering and environmental disturbances are quickly compensated for, demonstrating the effectiveness of the altitude control loop.

4. Conclusion

This paper presented the design and simulation of an integrated autopilot and guidance system for an unmanned airship. A nonlinear dynamic model was developed to describe the translational and rotational motions of the airship, providing the basis for controller design and performance evaluation. Based on this model, an autopilot architecture was designed to regulate the vehicle's attitude, altitude, and flight speed, while a waypoint-based guidance law was employed to generate the desired heading commands for autonomous navigation.

The effectiveness of the proposed approach was verified through MATLAB/Simulink simulations under different operating scenarios, including straight-line flight, waypoint tracking, and wind disturbance conditions. The simulation results demonstrated that the integrated autopilot and guidance system was capable of maintaining stable flight while accurately following the prescribed trajectory. Furthermore, the controller exhibited satisfactory robustness against external disturbances, resulting in small tracking errors, smooth control inputs, and stable dynamic responses throughout the flight mission.

The proposed control framework offers a practical solution for autonomous unmanned airships by combining flight stabilization and trajectory guidance into a unified architecture. Compared with conventional independent control strategies, the integrated design improves coordination between guidance commands and autopilot responses, leading to enhanced navigation accuracy and flight performance.

Future work will focus on the implementation of advanced nonlinear and intelligent control techniques, such as adaptive control, model predictive control, and reinforcement learning, to further improve robustness under uncertain aerodynamic conditions and time-varying wind disturbances. In addition, hardware-in-the-loop simulations and real-flight experiments will be conducted to validate the proposed method in practical operating environments and to support the development of fully autonomous unmanned airship systems.

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Declaration of Conflicting Interests

The authors declare that there are no conflicts of interest regarding the research, authorship, or publication of this article.

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