

Improving the impact point accuracy of unpowered flight vehicles under uncertain wind conditions by using parameter-based adaptive control

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ABSTRACT

The paper focuses on the problem of pre-programmed trajectory tracking control under uncertain wind conditions for unpowered flight vehicles operating at transonic and subsonic speeds. In the vertical plane, the trajectory is assumed to be affected by the environment at low altitudes, where complex and unpredictable winds often occur, manifesting randomly as gusts, turbulence, or longitudinal winds. The influence of wind can cause significant deviations from the pre-programmed trajectory by hundreds of meters. To cope with these wind effects and improve the impact point deviation, an adaptive control combining Linear Quadratic Regulator (LQR) and Recursive Least Squares (RLS) based on model parameter estimation is implemented. Consequently, the adaptive LQR exhibits a flexible response and achieves high accuracy in tracking the pre-programmed trajectory. Compared with a non-adaptive one, adaptive LQR shortens the impact point deviation from tens of meters to meters.

Keywords: Unpowered flight vehicles; Pre-programmed trajectory tracking; Wind models.

1. INTRODUCTION

In recent decades, research on unpowered flight vehicles (UFVs) has been receiving increasing interest, although general terminology has yet to be unified. Several studies have addressed a variety of key issues for UFVs, including modeling [1-3], flight guidance laws [4, 5], flight control [6, 7], range-extension trajectories [8, 9], and maneuver trajectories [10]. Building upon this topic, the paper presents the problem of pre-programmed trajectory tracking control of UFVs during the target approach stage (stage 3).

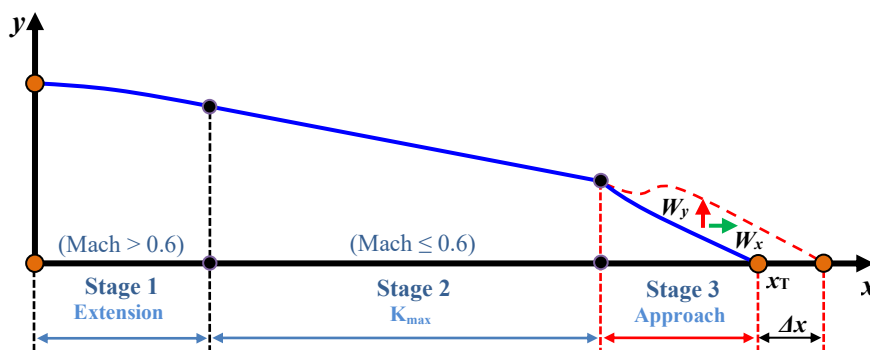


Figure 1. Schematic of the pre-programmed trajectory of UFVs.

Previous studies have shown that the pre-programmed trajectory of UFVs consists of 3 stages [8-10]: Range extension, K_{max} , and target approach (figure 1).

There are several reasons why it is necessary to focus on the pre-programmed trajectory tracking control for UFVs during stage 3 (target approach).

It can be seen that during stages 1 and 2, UFVs operate at a high altitude, maintain a considerable range from the target, possess substantial reserves of kinetic and potential energy, have a stable GNSS satellite signal, and have a relatively long flight duration. Therefore, the control to correct the trajectory error of UFVs can be considered to be highly effective. However, when entering stage 3, UFVs operate at low altitudes below 3,000 meters and range less than 20 kilometers from the target, controlling UFVs may be more difficult for some reasons. During this stage, UFVs may encounter difficulty in updating or correcting their position using GNSS satellite signals due to adverse weather conditions, obstructive terrain, or electronic countermeasures. Under such adverse flight conditions, if combined with unpredictable wind effects, the impact point of UFVs may deviate significantly by hundreds of meters from the pre-programmed trajectory, even though the terminal stage 3 only lasts a few tens of seconds.

Assuming that UFVs use a combined GNSS/INS navigation system, when the GNSS satellite signal is completely unavailable, the INS can continue to operate independently, with the cumulative error from its sensors remaining negligible for several tens of seconds. With the aim of reducing the impact point deviation of UFVs, this work tries to use controls to compensate for trajectory errors induced by unpredictable wind effects. However, the PID control application has difficulty in selecting coefficients K_P , K_I , and K_D suitable for wind variation. Meanwhile, traditional LQR control uses the fixed-parameter system model; therefore, its adaptability is limited, and it lacks flexibility. As a result, the impact point deviation of UFVs from the pre-programmed trajectory remains relatively large, which can reach several tens of meters.

To improve the impact point accuracy of UFVs under unpredictable wind conditions, this work uses the adaptive LQR, where the control is continuously updated based on real-time parameter estimation to compensate for trajectory errors induced by unpredictable wind effects. The parameter-adaptation mechanism is formulated based on flight dynamics. This work focuses on the control of UFVs in the vertical plane, and the measurement errors of the control system have not yet been considered.

2. LQR-BASED ADAPTIVE CONTROL FOR UFVs OPERATING IN UNPREDICTABLE WIND ENVIRONMENT

2.1. Wind models

The paper investigates the effects of unpredictable winds on the dynamics of UFVs in the vertical plane. These winds, whose amplitude, frequency, and scale are uncertain, can vary randomly. To comprehensively capture the extreme conditions that UFVs might encounter, the study uses several representative wind models, including gusty wind, turbulent wind, and longitudinal wind (either headwind or tailwind along the flight path). The wind models are presented in table 1 [11-13].

Table 1. Wind models.

Type	Gusty wind	Longitudinal wind	Turbulent wind	Unit	Wind field
	Step	$1 - \cos(*)$	Gaussian		
W =	W_0	$\frac{W_0}{2} \left(1 - \cos\left(2\pi \frac{x - x_s}{L}\right) \right)$	$W_0 + \sigma_w \cdot z_w$	m/s	$x_s \leq x \leq x_e$

Where:

$L = x_e - x_s$, the wind field is defined between x_s and x_e coordinates;

σ_w - The standard deviation of wind fluctuations around the mean wind W_0 (wind amplitude);

$z_w \sim \mathcal{N}(0, \sigma_w^2)$, i.e., a normal random variable with zero mean and variance (σ_w^2).

2.2. Flight dynamics of UFVs under the influence of wind

When analyzing the UFV operations under wind conditions, its velocity is considered in terms of airspeed (V_a) and groundspeed (V_g) (figure 2).

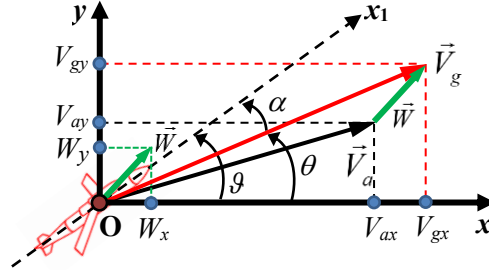


Figure 2. Schematic of the relationship among flight kinematic angles, airspeed, and groundspeed of UFVs under wind influence.

According to the effect of wind (W), the aerodynamic forces are calculated based on the airspeed V_a , while the trajectory coordinates are calculated based on the groundspeed V_g .

- Lift force:

$$Y_a = \frac{1}{2} C_y \rho V_a^2 S_{ref} \quad (1)$$

where C_y - Lift coefficient, ρ - Density of atmosphere, S_{ref} - Reference area of UFVs.

When wind is present, the angle of attack (α) changes, causing the lift coefficient and its lift force to vary. Based on the analysis of the velocity components (figure 2), the angle α under wind conditions is determined as follows:

$$\alpha = \vartheta - \theta = \vartheta - \text{atan}(V_{gy} / V_{gx}) \quad (2)$$

At that time, the lift coefficient is calculated as:

$$C_y = C_{y0} + C_y^\alpha [\vartheta - \text{atan}(V_{gy} / V_{gx})] \quad (3)$$

Where C_{y0} is the lift coefficient at $\alpha = 0$, and C_y^α is the partial derivative of the lift coefficient with respect to the angle of attack (α). In this paper, it is assumed that the wings of the UFV have a symmetric airfoil, which does not generate lift at $\alpha = 0$, i.e., $C_{y0} = 0$ [14]. The value of C_y^α is taken as 5.4 [rad⁻¹], based on semi-empirical aerodynamic graphs [15].

Groundspeed: The groundspeed components in the vertical plane (figure 2) are calculated as:

$$\vec{V}_g = \vec{V}_a + \vec{W}; \quad \begin{cases} V_{gx} = V_{ax} + W_x \\ V_{gy} = V_{ay} + W_y \end{cases}; \quad V_g = \sqrt{V_{gx}^2 + V_{gy}^2} \quad (4)$$

2.3. Design of trajectory control for UFVs

Design of control based on LQR theory

Since the velocity components (V) cannot be directly controlled, the trajectory tracking control law for the fixed-wing UFV is developed based on the deviations in position coordinates and trajectory angles relative to the pre-programmed trajectory. To describe an UFV control system using LQR theory [16, 17], the equations of motion in the vertical plane [11] are linearized with respect to range-based coordinates and take the following form:

$$\begin{cases} \frac{dy}{dx} = \tan \theta \\ \frac{d\theta}{dx} = \frac{Y}{mV^2 \cos \theta} - \frac{g}{V^2} = \frac{g(n_y - 1)}{V^2 \cos \theta} \end{cases} \quad (5)$$

Where: x - Range coordinate; y - Altitude coordinate; θ - Flight path angle; V - Velocity; Y - Lift force; g - Gravitational acceleration; n_y - Normal load factor.

From (5), the state variables and control input are formulated as follows:

$$\begin{cases} X = [\Delta y \quad \Delta \theta]^T \\ u = n_y = n_{yref} + \Delta n_y \end{cases} \quad (6)$$

$$\Delta x = x - x_{ref}; \quad \Delta y = y - y_{ref}; \quad \Delta \theta = \theta - \theta_{ref} \quad (7)$$

Where: x , y , and θ - Actual trajectory parameters;

x_{ref} , y_{ref} , and θ_{ref} - Pre-programmed trajectory parameters (known, previously calculated);

Δx , Δy , and $\Delta \theta$ - Trajectory errors;

n_y - Normal load factor (total control);

n_{yref} - Pre-programmed normal load factor (known, previously calculated);

Δn_y - Error-compensating normal load factor (unknown, to be determined).

Problem statement:

Given that an UFV control system is formulated in state space representation:

$$\frac{d}{dt} [\Delta y \quad \Delta \theta]^T = A [\Delta y \quad \Delta \theta]^T + B n_y \quad (8)$$

With the state feedback control law:

$$n_y = n_{yref} + \Delta n_y = n_{yref} - K [\Delta y \quad \Delta \theta]^T \quad (9)$$

Based on equation (5), the state matrix A and the control matrix B are determined as follows:

$$A = \begin{bmatrix} \frac{\partial \frac{dy}{dx}}{\partial y} & \frac{\partial \frac{dy}{dx}}{\partial \theta} \\ \frac{\partial \frac{d\theta}{dx}}{\partial y} & \frac{\partial \frac{d\theta}{dx}}{\partial \theta} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{(\cos \theta)^2} \\ -\frac{C_y \rho_0 e^{(-y/y_p)} S}{2m y_p \cos \theta} & \frac{C_y \rho_0 e^{(-y/y_p)} S \sin \theta}{2m (\cos \theta)^2} \end{bmatrix} \quad (10)$$

$$B = \begin{bmatrix} \frac{\partial \frac{dy}{dx}}{\partial n_y} \\ \frac{\partial \frac{d\theta}{dx}}{\partial n_y} \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{g}{V^2 \cos \theta} \end{bmatrix} \quad (11)$$

where the pressure scale height $y_p \approx 8,434$ meters in the standard atmosphere [18].

Objective:

The objective is to determine the control input $\Delta n_y(t)$ that ensures control performance in correcting the UFV's trajectory errors.

Optimization goal:

From the Riccati equation is given:

$$A^T P + PA - PBB^T R^{-1} P + Q = 0 \quad (12)$$

Find an optimal feedback gain matrix $K = R^{-1} B^T P$ to minimize the cost function J :

$$J = \frac{1}{2} \int_{t_0}^t X^T (Q + K^T R K) X dt \rightarrow \min \quad (13)$$

and obtain the optimal control input $\Delta n_y^*(t)$, which ensures optimal performance in correcting the trajectory tracking error;

Where weighting matrices Q and R are selected to balance the trade-off between state deviation and control effort. In this work, equal importance of state variables Δy and $\Delta \theta$, the state weighting matrix is set as $Q = \text{diag}([0.1, 0.1])$. Besides, to prevent excessive control action, the control weighting matrix is set as $R = 0.5$.

To satisfy the fundamental requirements of parameter-adaptive control, the expressions (2) and (3) are integrated into the matrices (10) and (11).

Integration of adaptive mechanism using the RLS algorithm

To improve the accuracy of LQR control under uncertain wind conditions, the Recursive Least Squares (RLS) algorithm [19] is integrated to provide adaptive capability by updating the system model online. As part of the adaptive LQR controller, RLS performs real-time parameter estimation, enabling the system matrices to reflect current dynamics. By minimizing the influence of outdated data through a forgetting factor (λ), RLS enables real-time identification of system parameters, which are then used by the LQR controller to recompute the optimal feedback gain matrix K at each time step (figure 3).

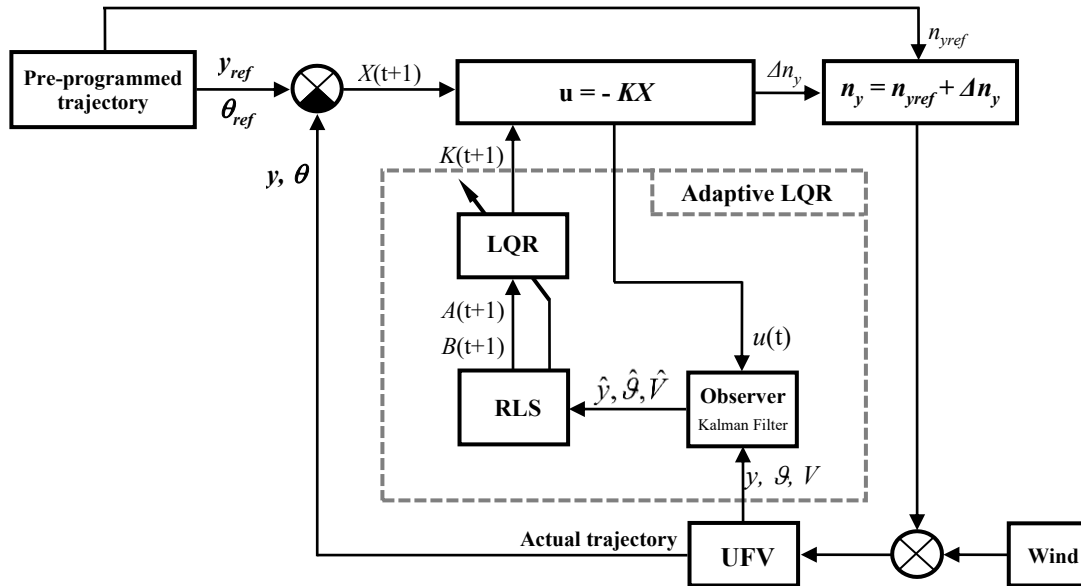


Figure 3. Schematic of the RLS-based adaptive LQR controller for UFVs.

Parameter estimation: To achieve accurate and adaptive modeling during control, a Kalman Filter observer estimates the system states in real time by predicting dynamics and correcting with measured outputs. These estimated states, along with input and output data, are fed into the RLS to perform online identification of the system matrices A and B .

Adaptation mechanism: To ensure stability and tracking ability, a forgetting factor λ varying in the range $[0.85, 0.98]$ is used in the RLS to prioritize new data under strong wind, while

maintaining numerical stability under low input excitation. This factor is adaptively tuned based on the measured variations of the angle of attack (α), as defined in formula (2) of Subsection 2.2. Based on this, RLS updates the system matrices $A(t+1)$ and $B(t+1)$ at each time step using current state estimates. These updated matrices are then used by the LQR to recalculate the optimal feedback gain $K(t+1)$, from which the new control input $u(t+1)$ is computed.

2.4. Solving the trajectory tracking control problem of UFVs

The problem of UFV trajectory control involves two main components: solving the flight dynamic equations (14) to model the system's behavior, and designing an optimal adaptive control law to ensure accurate and robust trajectory tracking under uncertain wind.

$$\begin{cases} m\dot{V}_g = -X_a - G \sin \theta \\ mV_g \dot{\theta} = Y_a - G \cos \theta \\ J_z \dot{\omega}_z = (m_z^{\delta_e} \delta_e + m_z^{\omega_z} \omega_z + m_z^{\alpha} \alpha) \rho V_a^2 b_a S_{ref} / 2 \\ \dot{\theta} = \omega_z; \quad \alpha = \theta - \text{atan}(V_{gy} / V_{gx}) \\ \dot{x}_g = V_g \cos \theta; \quad \dot{y}_g = V_g \sin \theta \end{cases} \quad (14)$$

To solve the control problem of UFVs, a computational program including a flight dynamics model and an adaptive LQR algorithm is developed and simulated using MATLAB/Simulink.

3. RESULTS AND DISCUSSION

3.1. Input data

The dynamic parameters of the UFV are adopted from references [8-10]. The fixed-wing UFV is characterized by a mass of 250 [kg] and a reference area of 0.5 [m²]. Initial trajectory conditions: altitude $H_0 = 12,000$ [m]; velocity $V_0 = 270$ [m/s]; flight path angle $\theta_0 = 0^0$.

3.2. Trajectory tracking control under the impact of gusty winds

Figures 4 and 5 and table 2 show the results of the UFV pre-programmed trajectory tracking control under the influence of the gusty wind: The amplitude of 10 [m/s] and the wind field length of 100 meters, starting at the range coordinate of 81 kilometers.

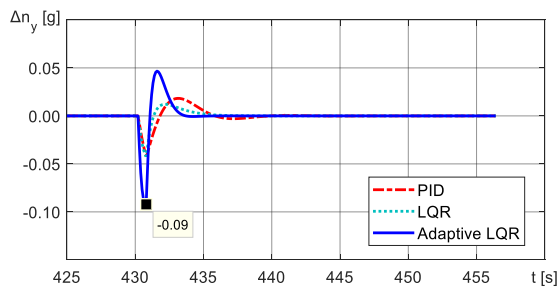


Figure 4. Response of controllers under gusty wind.

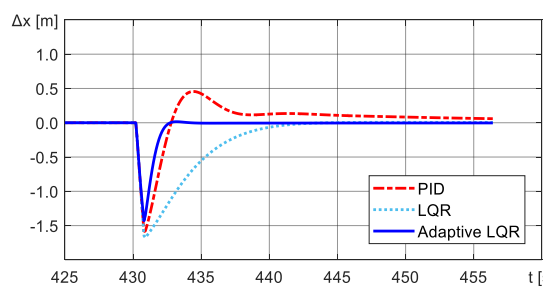


Figure 5. Range coordinate error of controllers under gusty wind.

As a result, all three controllers can maintain accurate trajectory tracking under gusty wind conditions (figures 4 and 5). However, the PID controller exhibits slow convergence and strong oscillations, making it less effective in compensating for wind disturbances. The LQR provides smoother control with moderate performance, while the adaptive LQR achieves the fastest and most stable response in minimizing the trajectory error.

Table 2. Quantitative comparison of control performance.

Controllers	Convergence time [s]	Absolute overshoot $ \Delta n_y _{\max}$ [g]
PID	≈ 10	≈ 0.04
LQR	≈ 6	≈ 0.04
Adaptive LQR	≈ 3.5	≈ 0.09

According to the findings in table 2:

Convergence time: The PID takes around 10 seconds to approach zero, the LQR converges at around 6 seconds, while the adaptive LQR converges in under 3.5 seconds.

Overshoot and system overload: The PID and LQR exert smaller control actions of about 0.04 [g] but over a longer duration, whereas the adaptive LQR issues stronger commands immediately, around 0.09 [g], and quickly returns to zero. Although the adaptive LQR generates a brief peak load, the system avoids prolonged overload. Moreover, since this control amplitude is very small compared to the system overload of 2.5 [g], it does not significantly affect overall control performance.

3.3. Trajectory tracking control under large-scale winds

During stage 3, uncertain wind is assumed to affect the UFV starting at a range of 81 kilometers until the end of the stage. To simulate its impact on the pre-programmed trajectory, both turbulent and longitudinal winds are used. Turbulent wind is modeled as a Gaussian random variable with a mean velocity of 5 [m/s] and a standard deviation of 2 [m/s], and longitudinal wind is modeled using a type of 1-cos(*) with a peak velocity of 12 [m/s].

Simulation results:

- UFV's angle of attack (α) under the influence of winds:

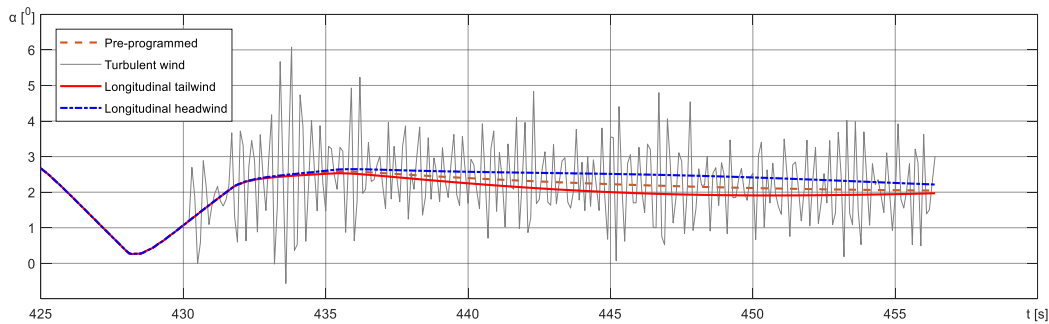


Figure 6. Angle of attack error under different wind conditions.

- UFV's trajectory and impact point deviations:

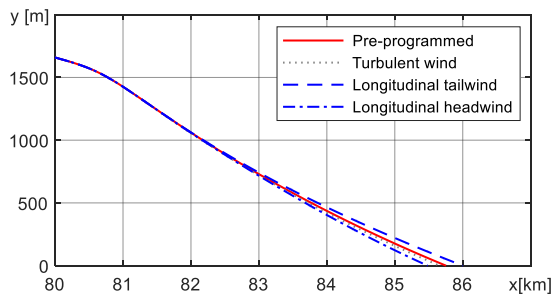


Figure 7. Trajectory errors under different wind conditions.

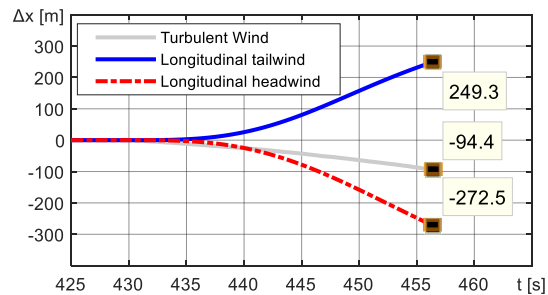


Figure 8. Impact point errors under different wind conditions.

- Performance results of UFV's pre-programmed trajectory tracking:

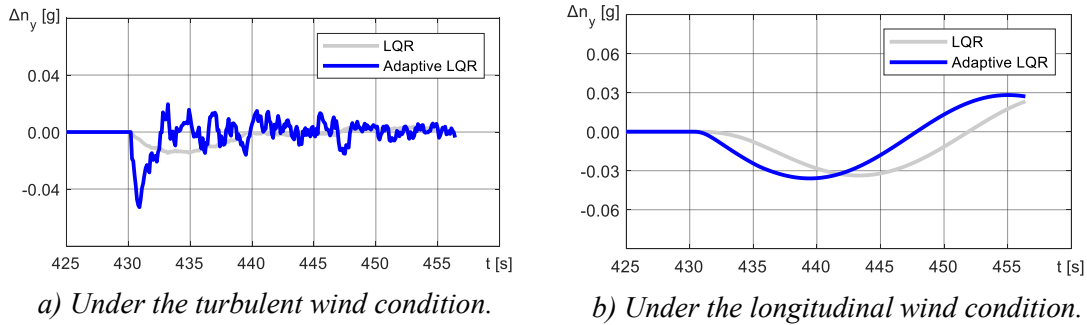


Figure 9. The error-compensating normal load factor for wind-induced trajectory errors.

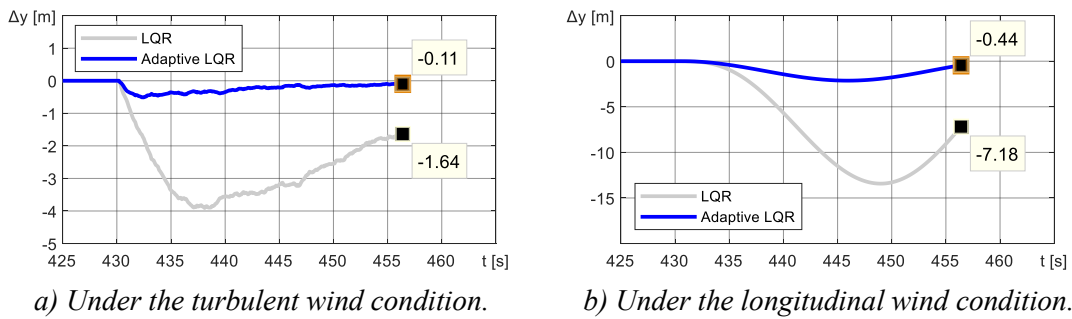


Figure 10. Altitude errors.

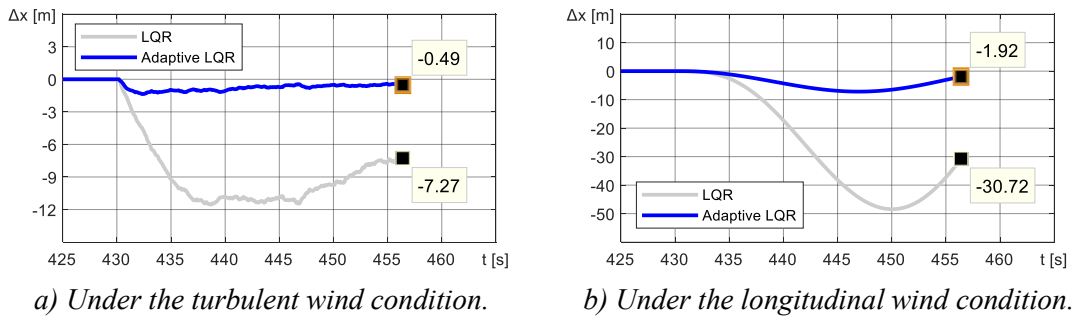


Figure 11. Impact point deviations.

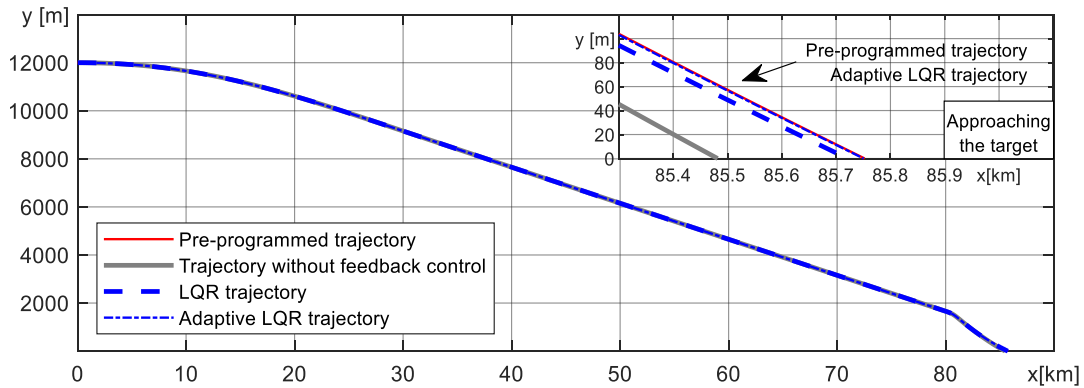


Figure 12. Entire mission trajectory of the UFV.

Discussions:

As discussed, the presence of wind alters the angle of attack (α), thereby changing the lift force and resulting in a deviation between the actual trajectory and the pre-programmed trajectory (figures 6 and 7). In the absence of deviation compensation control, uncertain winds cause impact point deviations of the UFV of up to approximately 100 meters under turbulent wind conditions, and about 250 to 300 meters under longitudinal wind conditions, depending on the severity of the wind (figure 8).

Compared with the non-adaptive controller, the adaptive LQR exhibits faster and more flexible responses (figure 9). The main advantages of the adaptive LQR in compensating for trajectory deviations are summarized as follows: the normal load factor (Δn_y) adapts rapidly, showing small amplitude variations within 0.04 [g] (figure 9). The altitude error (Δy) and impact point error (Δx) remain small (figures 10 and 11).

Root mean square error (RMSE): Under the longitudinal wind condition, the non-adaptive LQR shows an RMSE(x, y) of 32.43 meters, while the adaptive LQR achieves 4.87 meters. These values are smaller under turbulent wind conditions.

For impact point accuracy: Under turbulent wind conditions, the non-adaptive LQR shows an impact point deviation of approximately 7 meters, while the adaptive LQR reduces it to less than 1 meter (figure 11a). Notably, under longitudinal wind conditions, the non-adaptive LQR shows a deviation of up to 30 meters, while the adaptive LQR reduces it to below 2 meters (figure 11b).

For the entire mission trajectory: The adaptive LQR trajectory of the UFV almost coincides with the pre-programmed trajectory (figure 12).

In summary, the adaptive LQR demonstrates superior responsiveness and helps significantly correct the impact point under unpredictable wind conditions.

4. CONCLUSIONS

Based on the flight dynamics model of the unpowered flight vehicle, an adaptive LQR scheme with parameter estimation has been developed. The adaptive mechanism is indirectly formulated through the relationship between the angle of attack and wind variation. The results show that the adaptive LQR ensures system stability, provides effective deviation compensation, and accurately tracks the pre-programmed trajectory under uncertain wind conditions. The actual adaptive-controlled trajectory closely aligns with the pre-programmed trajectory. In terms of practical application, the adaptive one can significantly reduce impact point deviations of UFVs under the influence of wind, bringing the impact point deviation down from several tens of meters to just a few meters, thereby enhancing mission efficiency. Besides, the adaptive LQR control algorithm is considered suitable when developed and implemented on onboard embedded computers.

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TÓM TẮT

Nâng cao độ chính xác điểm rơi của phương tiện bay không động cơ trong điều kiện gió bất định bằng điều khiển thích nghi tham số

Bài báo trình bày bài toán điều khiển bám quỹ đạo chương trình trong điều kiện gió bất định của phương tiện bay không người lái - không động cơ hoạt động ở dải tốc độ cận âm và dưới âm. Trong mặt phẳng đứng, quỹ đạo được giả định chịu tác động môi trường ở độ cao thấp, nơi thường xuất hiện gió không thể dự báo trước, như gió giật, nhiễu động và gió dọc theo hướng bay. Ảnh hưởng của gió có thể làm biến dạng quỹ đạo và gây ra sai lệch điểm rơi đến hàng trăm mét so với quỹ đạo chương trình. Để đối phó với ảnh hưởng của gió và cải thiện sai lệch vị trí điểm rơi, điều khiển tối ưu tuyến tính toàn phương LQR thích nghi tham số động được áp dụng. Kết quả, điều khiển LQR thích nghi phản ứng linh hoạt với biến thiên gió, kịp thời sửa sai lệch và bám quỹ đạo chương trình với độ chính xác cao. So với bộ điều khiển không thích nghi, LQR thích nghi giúp làm rút ngắn sai lệch điểm rơi từ hàng chục mét xuống mét.

Từ khóa: Phương tiện bay không động cơ; Điều khiển bám quỹ đạo chương trình; Mô hình gió.