

ADRC-Based UAV Control Scheme for Automatic Carrier Landing [†]

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Abstract: In this paper the problem of atmospheric disturbances during the UAV carrier landing operation is considered. A UAV dynamics model, and a wind gust and airwake disturbance model are introduced. A LADRC-based cascade control scheme is developed for fixed-wing UAVs. In the control scheme, three ADRC controllers are designed for attitude control, and another two ADRC controllers are designed for course and altitude tracking. Finally, a series of simulations are implemented in Simulink and the results are presented to demonstrate the performance of the proposed control scheme.

Keywords: automatic carrier landing; UAV control; ADRC; atmospheric disturbances; carrier airwake

1. Introduction

Automatic carrier landing for UAVs is one of most critical challenging operations; the marine environment can introduce various disturbances to UAV control when landing on a carrier. Carrier motion, disturbance due to carrier airwake and atmospheric turbulence make it very hard to ensure a safe landing operation. A lot of studies have been conducted on this problem and some control schemes have been proposed accordingly [1–4]. In [5], an MPC controller was designed for a linearized UAV system to handle the landing task with carrier heave motion. In [6], an autoregressive model was used to predict the carrier motion and a preview control scheme was used to reject the disturbances. In [7], an ADRC-based controller was designed for UAV control but only the pitch dynamics were considered. In this paper a detailed UAV model and disturbances model are introduced, and a control scheme with outer loop (navigation control) and inner loop (attitude control) is proposed based on the LADRC method to reject disturbances during the landing operation.

This paper is organized as follows: A typical fixed-wing UAV model and empirical models of atmospheric disturbances are introduced in Section 2. In Section 3, an ADRC double-loop control scheme is proposed and corresponding controllers are designed. Results of simulation experiments are illustrated in Section 4. And some concluding remarks are given in Section 5.

2. Mathematical Model

In this section we briefly describe UAV dynamics, then the considered fixed-wing UAV model is given, followed by a model of atmospheric disturbances.

2.1. Fixed-Wing UAV Model

In the literature, various models are used to describe UAV dynamics, including the linear uncoupled model and the nonlinear cross-coupled model. This section presents a nonlinear 6-DOF UAV model with cross-couplings between yaw, roll and pitch motion.



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The body diagram of a fixed-wing UAV is shown in Figure 1. The 6-DOF UAV dynamics can be fully described using 12 states, i.e., $X = [p_n, p_e, h, u, v, w, \phi, \theta, \psi, p, q, r]$. In this paper some states are ignored since guidance law design is beyond the scope of this paper (a Dubins path is used as a reference trajectory, see Section 3). Furthermore, we assume that the UAV is not equipped with a rudder and the yaw angle ψ is controlled by the roll maneuver. The equations for describing the necessary controlled variables are given by (1)–(8).

$$\dot{h} = u \sin \theta - v \sin \phi \cos \theta - w \cos \phi \cos \theta; \quad (1)$$

$$\dot{u} = rv - qw - g \sin \theta + \frac{\rho V_a^2 S}{2m} C_u + \frac{\rho S_{prop} C_{prop}}{2m} [(K_{motor} \delta_t)^2 - V_a^2]; \quad (2)$$

$$\dot{v} = pw - ru + g \cos \theta \sin \phi + \frac{\rho V_a^2 S}{2m} C_v; \quad (3)$$

$$\dot{w} = qu - pv + g \cos \theta \cos \phi + \frac{\rho V_a^2 S}{2m} C_w; \quad (4)$$

$$\dot{\phi} = p + q \sin \phi \tan \theta + r \cos \phi \tan \theta; \quad (5)$$

$$\dot{\theta} = q \cos \phi - r \sin \phi; \quad (6)$$

$$\dot{p} = \Gamma_1 pq - \Gamma_2 qr + \frac{1}{2} \rho V_a^2 S b [C_p + C_{p_{\delta_a}} \delta_a]; \quad (7)$$

$$\dot{q} = \Gamma_5 pr - \Gamma_6 (p^2 - r^2) + \frac{\rho V_a^2 S c}{2J_y} [C_m + C_{m_{\delta_e}} \delta_e], \quad (8)$$

where u, v, w are roll axis, pitch axis and yaw axis components of airspeed V_a in the UAV body frame, respectively; ϕ, θ, p, q are roll and pitch angles, and their angular velocities; $\delta_t, \delta_a, \delta_e$ are control variables of throttle, aileron and elevator, respectively; C_u, C_v, C_w, C_p, C_m are terms related to UAV aerodynamics; their definitions can be found in [8].

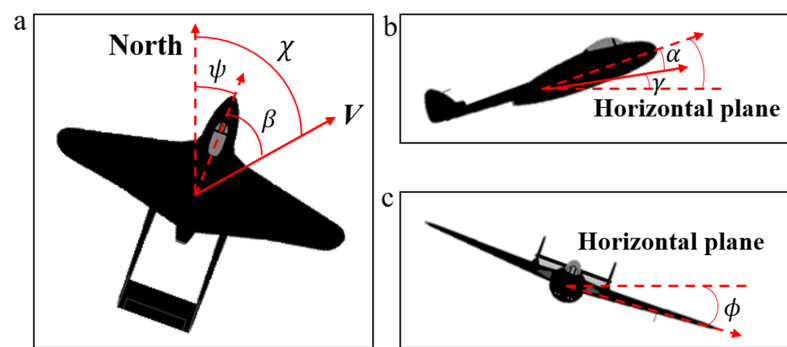


Figure 1. UAV body diagram: (a) vertical view; (b) end view; (c) front view.

Airspeed is calculated using Equations (2)–(4):

$$V_a = \sqrt{u^2 + v^2 + w^2}; \quad \dot{V}_a = \frac{u\dot{u} + v\dot{v} + w\dot{w}}{V_a} = \dot{u} \cos \alpha + dV_1,$$

where α is the angle of attack and dV_1 is a disturbance related to sideslip angle β .

Then, Equations (2)–(4) can be replaced by (9) after some substitutions:

$$\dot{V}_a = -g \sin(\theta - \alpha) - \frac{\rho V_a^2 S}{2m} [C_D + C_{D_{\delta_e}} \delta_e] + \frac{\rho S_{prop} C_{prop}}{2m} [(k \delta_t)^2 - V_a^2] + dV_2, \quad (9)$$

where $C_D, C_{D_{\delta_e}}$ are some coefficients and dV_2 is a disturbance similar to dV_1 . Their definitions are given in [8].

2.2. Disturbance Model

In this paper two primary disturbance sources are considered: atmospheric turbulence (wind gust) and carrier airwake. Throughout the whole flight, the UAV is under the influence of wind gust, while disturbance due to airwake only affects the landing process, i.e., when the UAV is close to the carrier. Experiments show that a reliable wind turbulence model should include a steady component and a random component (gust), which can be generated by filtering Gauss white noise with zero mean and unit variance:

$$H_u(s) = \sigma_u \sqrt{\frac{2V_a}{L_u}} \frac{1}{s + \frac{V_a}{L_u}}; H_v(s) = \sigma_v \sqrt{\frac{3V_a}{L_v}} \frac{s + \frac{V_a}{\sqrt{3}L_v}}{(s + \frac{V_a}{L_v})^2}; H_w(s) = \sigma_w \sqrt{\frac{3V_a}{L_w}} \frac{s + \frac{V_w}{\sqrt{3}L_w}}{(s + \frac{V_a}{L_w})^2},$$

where H_u, H_v, H_w are the transfer functions; $\sigma_u, \sigma_v, \sigma_w$ are the gust intensities on corresponding axes; and L_u, L_v, L_w are the gust wavelengths [8]. Airwake starts to affect the UAV at about 800 m from the carrier; the resulting disturbance can be divided into four parts: free air turbulence component, steady component, periodic component and random component. The main factor is the steady component, which is usually described by empirical expressions [6]

$$\begin{cases} u_s(t) = 0.0072t^5 - 0.1739t^4 + 1.5532t^3 - 5.9699t^2 + 6.7692t + 10.4033 \\ w_s(t) = 0.0001t^5 - 0.0088t^4 + 0.1769t^3 - 0.8082t^2 - 1.4727t + 7.0433 \end{cases}$$

where u_s denotes the axial airwake disturbance; w_s denotes the normal airwake disturbance; and t denotes time before touchdown.

3. ADRC Control Scheme Design

In this section, a cascade LADRC scheme is designed for UAV control during landing operation. As shown in Figure 2, in the inner loop three single ADRC controllers are designed for attitude control and airspeed control. In the outer loop, navigation control is achieved through two ADRC controllers, which determine the desired attitude. The course, altitude and airspeed command are generated by path planning and a guidance algorithm; in this paper a simple guidance strategy and Dubins path are used; details can be found in [8].

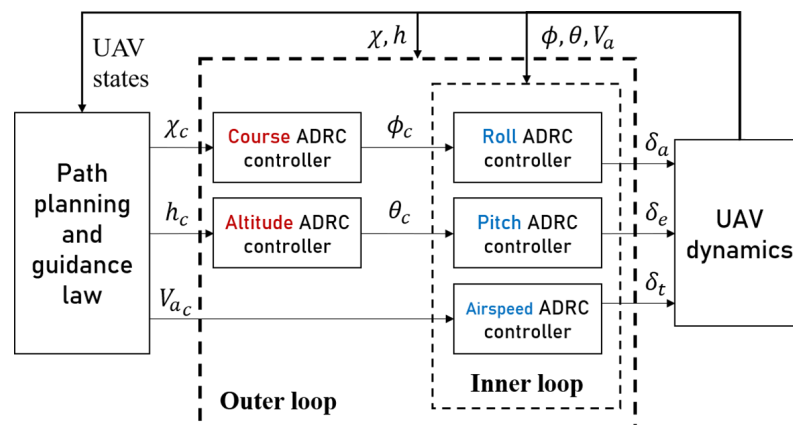


Figure 2. Cascade ADRC control scheme for fixed-wing UAV.

Similar to PID, the ADRC technique can be used only in SISO systems. In Figure 3a the structure of a LADRC controller for roll control is shown. A typical LADRC controller consists of three parts: linear tracking differentiator (LTD), linear state error feedback control law (LSEF) and linear extended state observer (LESO). The LTD is used to generate a smooth transient profile; for simplicity it will not be discussed here; its definition can be found in [8]. In practice, the LSEF is usually a PD controller; its parameter tuning will be discussed later in the end of this section. The LESO is the most important part of the ADRC

controller; it estimates the “total disturbance” based on the input and output of the system. Consider an example of a second-order SISO system:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2, d(t), t) + bu, \\ y = x_1 \end{cases} \quad (10)$$

where $d(t)$ is an unknown external disturbance and f is the total disturbance. The LESO for this system can then be constructed as a Luenberger observer. Treating total disturbance f as an additional state x_3 for system (10), the corresponding LESO is then given by

$$\begin{cases} \dot{z}_1 = z_2 + l_1(y - \hat{y}) \\ \dot{z}_2 = z_3 + bu + l_2(y - \hat{y}), \\ \dot{z}_3 = h + l_3(y - \hat{y}) \end{cases} \quad (11)$$

where y is the output measurement, which is state z_1 ; z_3 is estimation of the total disturbance; h is a derivative of f ; and l_1, l_2, l_3 are the observer gains. In [9], a tuning method for these coefficients in a second-order system was proposed: $l_1 = 3\omega_o$; $l_2 = 3\omega_o^2$; $l_3 = \omega_o^3$, ω_o is the LESO bandwidth.

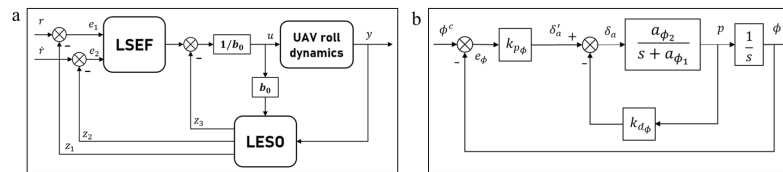


Figure 3. (a) ADRC controller structure; (b) roll angle control diagram.

The ADRC controllers for different state variables have to be designed individually, as shown in Figure 3a. According to Equations (5)–(9), both of the dynamics of roll and pitch can be simplified as SISO systems:

$$\begin{cases} \dot{\phi} = p \\ \dot{p} = f_\phi + b_\phi \delta_a; \\ y = \phi \end{cases} \quad \begin{cases} \dot{\theta} = q \\ \dot{q} = f_\theta + b_\theta \delta_e, \\ y = \theta \end{cases}$$

where f_ϕ, f_θ are the total disturbances to be estimated and $b_\phi = \frac{1}{2}\rho V_a^2 S b C_{p\delta_a}$, $b_\theta = \frac{\rho V_a^2 S c}{2J_y} C_{m\delta_e}$ are control gains.

Since Equation (9) is nonlinear in control input δ_t , we must first linearize it to design the LESO for the airspeed dynamics. Let $\bar{V}_a = V_a - V_a^*$ be the deviation of V_a from trim, and $\bar{\theta}$ and $\bar{\delta}_t$ be the corresponding deviations. The new airspeed dynamics linearized around the trim condition are described as

$$\dot{\bar{V}}_a = -g \cos(\theta^* - \alpha^*) - \frac{\rho V_a^* S}{m} [C_D^* - \frac{\rho S_{prop} C_{prop}}{m} V_a^*] \bar{V}_a + \frac{\rho S_{prop} C_{prop}}{m} k^2 \delta_t^* \bar{\delta}_t + dV_3,$$

where dV_3 is the disturbance; all the parameter definitions can be found in [8].

Analogously, we can determine a SISO system for airspeed dynamics:

$$\begin{cases} \dot{\bar{V}}_a = f_v + b_v \delta_t; \\ y = \bar{V}_a \end{cases}; b_v = \frac{\rho S_{prop} C_{prop}}{m} k^2 \delta_t^*.$$

Then, according to (11) the LESOs for airspeed, pitch and roll systems are designed as follows:

$$\begin{cases} \dot{z}_{\phi 1} = z_{\phi 2} + l_{\phi 1}(\phi - z_{\phi 1}) \\ \dot{z}_{\phi 2} = z_{\phi 3} + b_\phi \delta_a + l_{\phi 2}(\phi - z_{\phi 1}); \\ \dot{z}_{\phi 3} = h_\phi + l_{\phi 3}(\phi - z_{\phi 1}) \end{cases}; \begin{cases} \dot{z}_{\theta 1} = z_{\theta 2} + l_{\theta 1}(\theta - z_{\theta 1}) \\ \dot{z}_{\theta 2} = z_{\theta 3} + b_\theta \delta_e + l_{\theta 2}(\theta - z_{\theta 1}); \\ \dot{z}_{\theta 3} = h_\theta + l_{\theta 3}(\theta - z_{\theta 1}) \end{cases}; \begin{cases} \dot{z}_{v1} = z_{v2} + b_v \delta_t + l_{v1}(\bar{V}_a - z_{v1}) \\ \dot{z}_{v2} = h_v + l_{v2}(\bar{V}_a - z_{v1}) \end{cases}$$

Altitude dynamics (1) can be simplified as follows and course dynamics in conditions of coordinated turn with zero wind are described in [8].

$$\dot{h} = V_a \theta + d_h, \quad d_h = u \sin \theta - V_a \theta - v \sin \phi \cos \theta - w \cos \phi \cos \theta; \quad \dot{\chi} = \frac{g}{V_a} \phi + d_\chi, \quad d_\chi = \frac{g}{V_a} (\tan \phi - \phi).$$

Then, the LESOs for altitude and course dynamics are given by

$$\begin{cases} \dot{z}_{h1} = d_h + V_a \theta_c + l_{h1}(h - z_{h1}) \\ \dot{z}_{h2} = h_h + l_{h2}(h - z_{h1}) \end{cases}; \quad \begin{cases} \dot{z}_{\chi1} = d_\chi + \frac{g}{V_a} \phi_c + l_{\chi1}(\chi - z_{\chi1}) \\ \dot{z}_{\chi2} = h_\chi + l_{\chi2}(\chi - z_{\chi1}) \end{cases}.$$

To ensure adequate performance of LESOs, their bandwidths $\omega_{o_v}, \omega_{o_\phi}, \omega_{o_\theta}, \omega_{o_h}, \omega_{o_\chi}$ must be chosen properly. A large bandwidth allows fast tracking without overshooting but, at the same time, high bandwidth could make the system very sensitive to noise. In this paper, bandwidth choice is made based on the natural frequency of the observer system.

Figure 3b shows a PD control diagram of the roll angle; the natural frequency of this second-order system can be calculated as follows:

$$\omega_\phi^2 = k_{p_\phi} a_{\phi2}; \quad k_{p_\phi} = \frac{\delta_a^{max}}{e_\phi^{max}} \text{sign}(a_{\phi2}); \quad \omega_\phi = \sqrt{|a_{\phi2}| \frac{\delta_a^{max}}{e_\phi^{max}}},$$

where δ_a^{max} is the maximum elevator deflection and e_ϕ^{max} is the maximum roll angle. All the coefficients in Figure 3b can be found in [8].

Analogously, natural frequency for pitch, airspeed, altitude and course dynamics can be determined. Then, LESO bandwidths can be chosen empirically as $\omega_{o_\phi} = 2\omega_\phi$; $\omega_{o_\theta} = 2\omega_\theta$; $\omega_{o_v} = 2\omega_v$; $\omega_{o_h} = \frac{\omega_{o_\theta}}{2}$; $\omega_{o_\chi} = \frac{\omega_{o_\phi}}{2}$. Since the total disturbance is estimated by LESO, the estimation then can be used to compensate control input to make the control system robust and adaptive. Thus, the LADRC control law is formed as $(u_0 - f)/b$. $u_0 = k_p(r - z_1) + k_d(\dot{r} - z_2)$ is the control law given by LSEF, r is the reference signal, z_1, z_2 are the LESO outputs, $k_p = 2\omega_c, k_d = \omega_c^2$ are the LSEF control gains and ω_c is the LSEF controller bandwidth, in practice it is usually chosen between 4 and 20 [9].

4. Simulation Results

The ADRC control scheme proposed in Section 2 is implemented in the Simulink environment; to verify its advantages over PID controllers in terms of robustness and insensitivity to disturbances, several experiments are conducted to simulate the UAV carrier landing operation with ADRC and PID, respectively. The longitudinal and lateral dynamics of UAVs are usually discussed separately; to validate the effectiveness of the proposed algorithm on both of the dynamics, two stages of landing are considered: the orbit following and the final approach. The orbit is a spiral route over the carrier; it allows the landing officers to prepare the flight deck and ensure a safe landing. In the experiment the orbit is a Dubins path connected by four waypoints, which are shown in Table 1. The Dubins path algorithm can be found in [8]. And, for simplicity, a 3.5-degree glide slope is used as the final approach route.

Table 1. Initial conditions of final approach simulation.

Object	North Coordinate (m)	East Coordinate (m)	Altitude (m)	Course Angle (deg)	Velocity (m/s)
UAV	0	0	500	0	35
Carrier	1000	0	5	0	0

Figure 4 shows wind gust turbulence and airwake disturbance. To better demonstrate the disturbance rejection performance of ADRC, in the experiment the gust intensity is multiplied by 20.

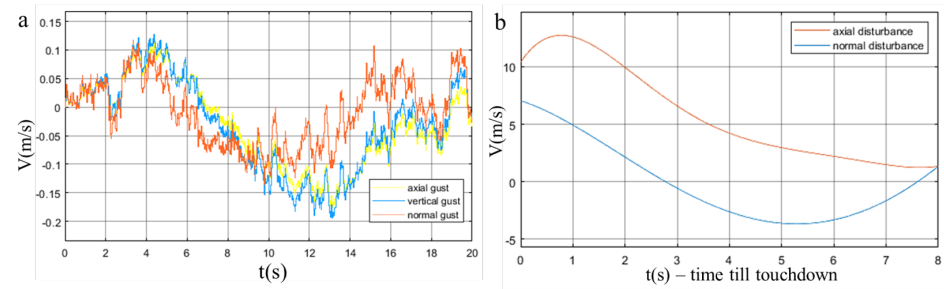


Figure 4. (a) Gust velocity in UAV body frame; (b) airwake disturbance velocity.

In the experiment a benchmark circle following maneuver that excites all the lateral states is used to illustrate lateral control performance. As shown in Figure 5, even in the existence of intense wind gust ADRC can still follow the circle with high accuracy and from the tracking error result it can be seen that ADRC does suppress high-frequency noise.

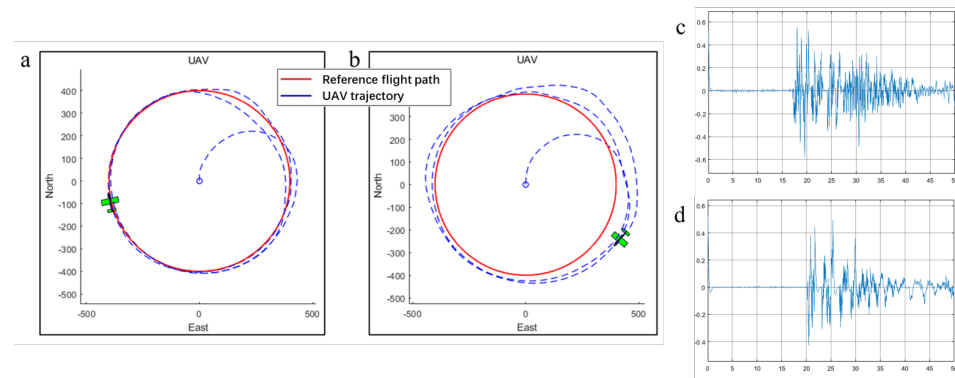


Figure 5. (a) Circle following with ADRC; (b) circle following with PID; (c) PID roll tracking error; (d) ADRC roll tracking error.

Figure 6 shows that in terms of path following performance ADRC is far more effective and accurate than PID. The east position error of the ADRC algorithm at the end point is 11.5 m, which is almost two times less than the PID error, 19.4 m.

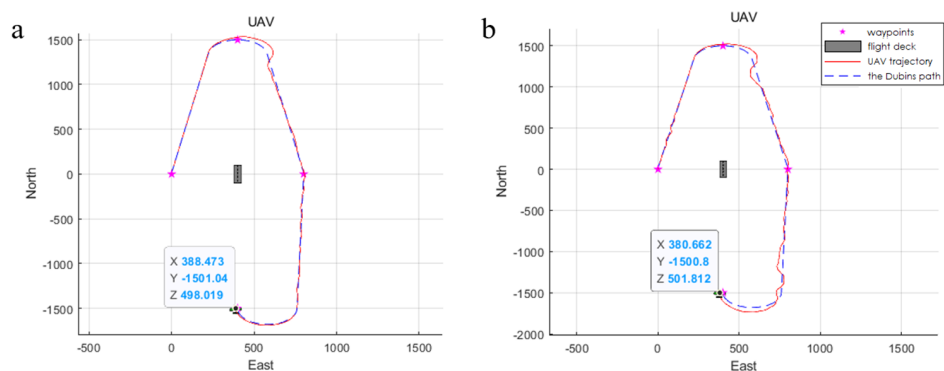


Figure 6. (a) ADRC orbit following result; (b) PID orbit following result.

Figure 7 shows the results of final approach simulations. It can be seen that ADRC provides a smoother approach route than PID and the ADRC position error at touchdown point is 2.44 m, which is about half the PID error, 4.95 m. The initial conditions of UAV and carrier are shown in Table 1.

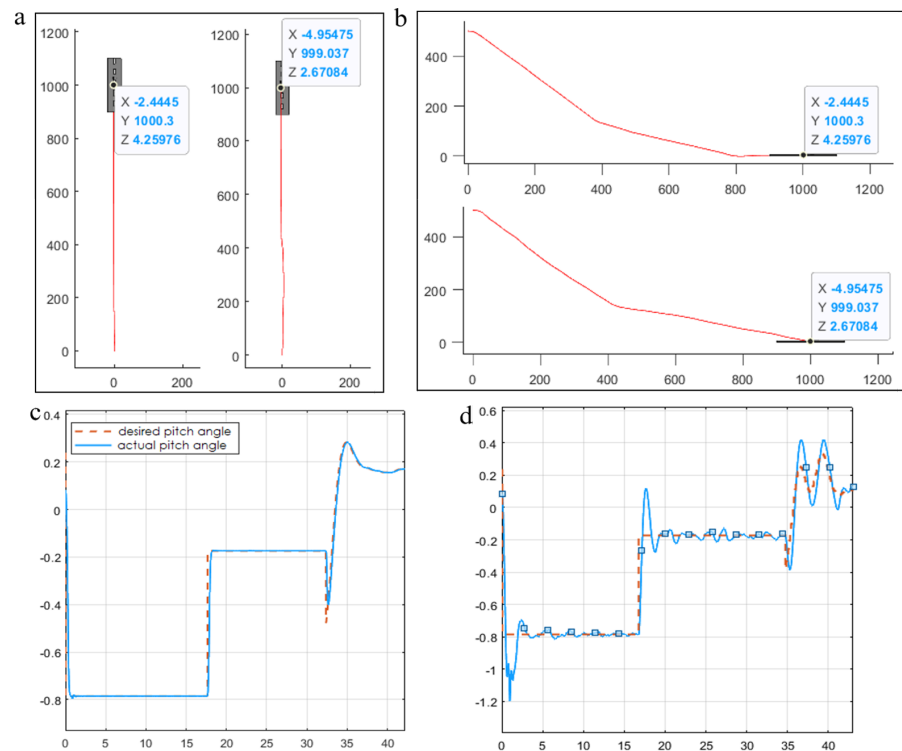


Figure 7. (a) Vertical view of final approach results (left: ADRC, right: PID); (b) end view of final approach results; (c) ADRC pitch tracking result; (d) PID pitch tracking result.

5. Conclusions and Future Work

This paper described our work on the topic of automatic UVA carrier landing. In this work a cascade ADRC control scheme was proposed for fixed-wing UAVs. The influence of wind gust and atmospheric disturbance due to carrier airwake was studied. In addition, a UAV dynamics simulation system was developed in the Simulink environment and the proposed control scheme was tested by a series of simulations. The results verified the effectiveness of the ADRC control scheme compared to the PID control:

- The controller design and parameter tuning processes for ADRC are much easier than for PID;
- The ADRC control system has excellent robustness and accuracy even in the presence of intense disturbances.

As further work on this project, we will try to exploit the total disturbance information more comprehensively; an adaptive navigation method based on the LESO will be studied as an extension of the UAV control system proposed in this paper.

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Abbreviations

The following abbreviations are used in this manuscript:

ADRC	Active disturbance rejection control
LADRC	Linear active disturbance rejection control
LTD	Linear tracking differentiator
LSEF	Linear state error feedback control law
LESO	Linear extended state observer

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