Wind Disturbance Rejection in Position Control of Unmanned Helicopter by Nonlinear Damping

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Abstract. This paper presents a new design of a Lyapunov-redesigned control system for large horizontal wind disturbance rejection on a small-scale unmanned autonomous helicopter (UAH). In this paper, the wind disturbance cannot be treated as small perturbations around the equilibrium state any more. Instead, wind disturbances are considered as force/moment disturbances in the state equation. The force/moment caused by the wind can be estimated by the experimental data obtained in the wind tunnel. The whole control system consists of a nominal system controller and a wind disturbance controller. The nominal system controller is designed with back-stepping algorithm while the wind disturbance controller is designed with nonlinear damping algorithm. The nonlinear damping is introduced to ensure that the whole system has a uniformly bounded solution under uncertain large horizontal wind disturbances. Both longitudinal and lateral wind disturbances are considered in the simulation. The simulation results show the wind disturbances are well rejected and the proposed method can be effective for the position control of UAH in windy environment.

Keywords: UAH · Position control · Wind disturbance rejection · Backstepping algorithm · Nonlinear damping

1 Introduction

Unmanned autonomous helicopter (UAH) has been widely used in variety of areas [1]. In the last decades, there is a growing worldwide attention in the field of small-scale UAHs. Autonomous flight control of UAH is essential for the applications in complex environments. This topic has been constantly active both in industry and academia.

Numerous controller design methods have been proposed in last decades. Generally, most of the controller designs are based on model-based-control techniques. Advanced linear control methods like LQG-based controller [2], PD-PID controller [3] are proposed in recent years. However, the stability and robustness of linear methods are not satisfying in complex environments due to the inherent approximate linearization in these methods. Based on nonlinear helicopter system model, many nonlinear control methods have also been reported, such as sliding mode [4], fuzzy gain-scheduling [5], nonlinear model predictive control [6] and backstepping method [7]. The backstepping method could effectively enable systematic and structured

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controller design, especially for the UAH with upper triangle form characteristics of state equation. Furthermore, A few research groups have tried non-model-based control strategies. A neural network-based tracking controller [8] was developed for an unmanned helicopter system with guaranteed global stability in the presence of uncertain system dynamics. Similarly, a reinforcement learning algorithm [9] was proposed for autonomous flight control system, which did not require an exact model of the system. However, these methods all depend on plenty of data from pilot experience, which is not applicable for many scenarios such as windy environments.

Practically, large wind disturbances have become one of the main challenges especially for outdoor applications. Only a few literatures have focused on this subject so far. A sensor was applied to estimate the wind disturbance and the nonlinear feedforward controller was designed to attenuate the vertical and horizontal wind disturbance [10]. An constrained finite time optimal controller (CFTOC) was used to operate an unmanned quadrotor helicopter under severe wind conditions [11]. Some researchers use the active wind gust disturbance compensation method to attenuate large wind disturbance [12–14]. The information of disturbance is obtained by different disturbance observers such as high gain state observer [12], extended state observer [13], Kalman state estimator [14]. However, the observation-based approaches sometimes may introduce inaccurate observations. A new hybrid control architecture [15] was proposed taking advantage of the direct force/moment compensation based on the wind-tunnel experimental data. But the force and moment may not be computed correctly due to the variety of the real condition. Therefore, in this paper, a new control system is designed considering uncertain and large wind disturbances based on the hybrid architecture. Firstly, we design a backstepping controller for the nominal system. And then we adopt nonlinear damping technique to design the wind-rejection part.

The organization of this paper is arranged as follows. Section 2 illustrates the control system design. Section 3 shows the simulation results, and Sect. 4 concludes this paper.

2 Control System Design

2.1 Nonlinear System Model

The six-freedom degree rigid body dynamics [16, 17] are presented as,

$$\dot{\xi}^I = V^I \tag{1}$$

$$V^I = RV^B \tag{2}$$

$$\dot{V}^B = V^B \times \Omega^B + F^B/m + \hat{g} \tag{3}$$

$$J\dot{\Omega}^B = -\Omega^B \times J\Omega^B + M^B \tag{4}$$

where $V^B = (u, v, w)^T$ and $\Omega^B = (p, q, r)^T$ are linear velocity vector and angular velocity vector of the helicopter in the body frame, respectively. J is the inertial matrix; m is the mass of the helicopter; $F^B = [F_x, F_y, F_z]$ is the vector of the external forces and $M^B = [L_m, R_m, N_m]$ is the vector of the external moments. The external forces and moments are assumed acting on the center of gravity of the helicopter. R is the rotation with respect to the attitude angle, and $\hat{g}$ is gravitational vector in the body frame.

The main rotor and fly-bar flapping dynamics represents the relationships between the servo actuator outputs δ_{lon}, δ_{lat}, δ_{ped}, δ_{col} and main rotor flapping angles a_1, b_1, rotor flapping angles c, d. Servo actuator dynamics [18] show the relationships between servo actuator inputs u_{lon}, u_{lat}, u_{col}, u_{ped} and servo actuator outputs.

2.2 Hybrid Control Architecture

The hybrid control architecture proposed by our group previously is applied to achieve attenuation of uncertain large horizontal wind disturbances, Fig. 1 [15].

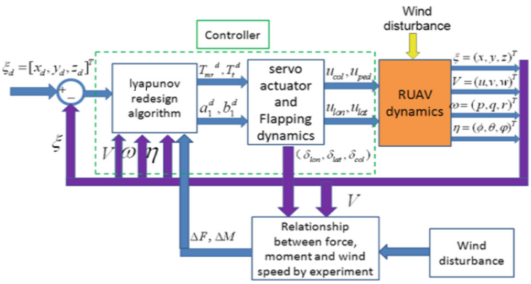


Fig. 1. The block diagram of the proposed control architecture

The nonlinear model of UAH presented in Sect. 2.1 is defined as the nominal system. The force/moment vector $(\Delta F, \Delta M)$ is assumed as the disturbance term including uncertain variables caused by wind disturbances which can be used as an extra input, rather than a small perturbation under a small horizontal wind disturbances. In this case, the disturbance term satisfies the matching condition of Lyapunov redesign. The nominal desired force/moment vector (F^d, M^d) is designed using backstepping algorithm without considering the wind disturbance. A nonlinear damping term (f_c, m_c) is designed to attenuate the wind disturbance term (F^d, M^d). The nonlinear damping term is then fed into the backstepping algorithm to guarantee that the small-scale UAH can be bounded around the desired position in finite time.

2.3 Force/Moment Vector of Wind Disturbances

The force/moment caused by wind can be estimated as follows [15]:

$$\begin{aligned} F_x = & a_{333}\delta_{lat}^3\delta_{lon}^3\delta_{wind}^3 + a_{332}\delta_{lat}^3\delta_{lon}^3\delta_{wind}^2 + \cdots + a_{330}\delta_{lat}^3\delta_{lon}^3\delta_{wind}^0 \\ & + a_{323}\delta_{lat}^3\delta_{lon}^2\delta_{wind}^3 + a_{322}\delta_{lat}^3\delta_{lon}^2\delta_{wind}^2 + \cdots + a_{320}\delta_{lat}^3\delta_{lon}^2\delta_{wind}^0 \cdots \\ & + a_{003}\delta_{lat}^0\delta_{lon}^0\delta_{wind}^3 + a_{002}\delta_{lat}^0\delta_{lon}^0\delta_{wind}^2 + \cdots + a_{000}\delta_{lat}^0\delta_{lon}^0\delta_{wind}^0 \end{aligned} \tag{5}$$

$$\begin{aligned} F_y = & b_{333}\delta_{lat}^3\delta_{lon}^3\delta_{wind}^3 + b_{332}\delta_{lat}^3\delta_{lon}^3\delta_{wind}^2 + \cdots + b_{330}\delta_{lat}^3\delta_{lon}^3\delta_{wind}^0 \\ & + b_{323}\delta_{lat}^3\delta_{lon}^2\delta_{wind}^3 + b_{322}\delta_{lat}^3\delta_{lon}^2\delta_{wind}^2 + \cdots + b_{320}\delta_{lat}^3\delta_{lon}^2\delta_{wind}^0 \cdots \\ & + b_{003}\delta_{lat}^0\delta_{lon}^0\delta_{wind}^3 + b_{002}\delta_{lat}^0\delta_{lon}^0\delta_{wind}^2 + \cdots + b_{000}\delta_{lat}^0\delta_{lon}^0\delta_{wind}^0 \end{aligned} \tag{6}$$

$$\begin{aligned} F_z = & p_{66}\cdot\delta_{col}^6\delta_{wind}^6 + p_{65}\cdot\delta_{col}^6\delta_{wind}^5 + \cdots + p_{60}\cdot\delta_{col}^6\delta_{wind}^0 \cdots \\ & + p_{06}\cdot\delta_{col}^0\delta_{wind}^6 + p_{05}\cdot\delta_{col}^0\delta_{wind}^5 + \cdots + p_{00}\cdot\delta_{col}^0\delta_{wind}^0 \end{aligned} \tag{7}$$

where F_x, F_z, F_z are the forces in different axes, the inputs are cyclic pith input δ_{lon}, lateral cyclic pitch input δ_{lat} and wind velocity δ_{wind}.

The wind tunnel experiment we did before [15] can provide the necessary input data such as δ_{lon}, δ_{lat}, δ_{col} and δ_{wind}, and the resulting force F_x,F_{y},F_{z}. Then we can use means of least squares to identify all the parameters above. The moment on the three axis orientations can be also obtained using the same techniques.

The changes of these forces caused by wind disturbance can be represented as,

$$\Delta F = [\,F\mathrm{x}_w - F\mathrm{x} \quad Fy_w - Fy \quad Fz_w - Fz\,]^T \tag{8}$$

where Fz_w Fy_w Fz_w denotes the force under wind disturbance, F_x, F_y, F_z denote the forces without wind disturbance which means $\delta_{wind} = 0$.

Since the coefficients are known constant, we can treat the wind velocity input δ_{wind} as unknown terms.

$$\Delta F_x = \vec{\Gamma}_{Fx}\cdot\vec{\delta}_x \tag{9}$$

where $\vec{\Gamma}_{Fx} = \begin{bmatrix} a_{333}\delta_{lon}^3\delta_{lat}^3 & \ldots & \mathrm{a}_{ijk}\delta_{lon}^i\delta_{lat}^j & \ldots & a_{001}\delta_{lon}^0\delta_{lat}^0 \end{bmatrix}_{1\times 48}$, $\vec{\delta}_x = [\,\vec{\delta}_{wind} \quad \ldots \quad \vec{\delta}_{wind}]_{1\times 16}^T$ and $\vec{\delta}_{wind} = [\,\delta_{wind}^3 \quad \delta_{wind}^2 \quad \delta_{wind}^1\,]$. The force disturbances in y and z axes can be denoted similarly. In this way, we can get:

$$\Delta F = [\,\Delta F_x \quad \Delta F_y \quad \Delta F_z\,]^T = \begin{bmatrix} \vec{\Gamma}_{Fx}\cdot\vec{\delta}_x & \vec{\Gamma}_{Fy}\cdot\vec{\delta}_y & \vec{\Gamma}_{Fz}\cdot\vec{\delta}_z \end{bmatrix}^T = \vec{\Gamma}_F\vec{\delta}_F \tag{10}$$

In the objective system of this paper, a gyroscope fixed on the tail of the helicopter can attenuate the moment on the z axis. Therefore, with respect to the moment part, we only consider the moment attenuation on the x and y axes. In a similar way, the moment disturbance can be represented as,

$$\Delta M = [\,\Delta M_x \quad \Delta M_y \quad 0\,]^T = \begin{bmatrix} \vec{\Gamma}_{Mx}\cdot\vec{\delta}_x & \vec{\Gamma}_{My}\cdot\vec{\delta}_y & 0 \end{bmatrix}^T = \vec{\Gamma}_M\vec{\delta}_M \tag{11}$$

2.4 Backstepping Control with Nonlinear Damping

In this part, the backstepping algorithm is designed to incorporate the nominal control law and the nonlinear damping term for the helicopter to attenuate uncertain large horizontal wind disturbances, Fig. 1.

First, the nominal control law via backstepping algorithm without considering $(\Delta F, \Delta M)$ is designed [18]. The first Lyapunov function can be chosen as,

$$W_1 = 1/2(\xi^I - \xi_d^I)^T(\xi^I - \xi_d^I). \tag{12}$$

Denote $z_0 = \xi^I - \xi_d^I$ and if the desired velocity V_d^{I} satisfies the following equation:

$$V_d^{\mathrm{I}} = -\alpha z_0 = RV_d^{\mathrm{B}} \tag{13}$$

where α is a controller parameter and $\alpha > 0$, the derivative of the first Lyapunov function is negative definite.

Denote the error between the actual velocity and the desired velocity as $z_1 = V^I - V_d^I = R(V^B - V_d^B)$, we can get the actual derivative of the first Lyapunov function as,

$$\dot{W}_1 = -\alpha z_0^T z_0 + z_0^T z_1 \tag{14}$$

The second Lyapunov function is introduced as,

$$W_2 = 1/2 z_1^T z_1 \tag{15}$$

The time derivative of Eq. (15) can be derived as,

$$\dot{W}_2 = z_1^T R(F^B/m + \hat{g} + V^{\mathrm{B}} \times \Omega^B + \alpha V^B) \tag{16}$$

In order to make $\dot{W}_1 + \dot{W}_2 \leq 0$, we can introduce another controller parameter β and construct an equation satisfies,

$$V^{\mathrm{B}} \times \Omega^B = -\alpha V^B - \beta \Omega^B \tag{17}$$

According to Eq. (17), we get the desired angular velocity Ω_d^B:

$$\Omega_d^B = -\alpha(S(V^B) + \beta I)^{-1} V^B \tag{18}$$

Denote the error between the actual angular velocity and the desired angular velocity as $z_2 = \Omega^B - \Omega_d^B$, and we can obtain the actual derivative of the second Lyapunov function as,

$$\dot{W}_2 = -z_1^T z_0 - z_1^T z_1 + z_1^T RS(V_d^{\mathrm{B}}) z_2 \tag{19}$$

Then, F^d is chosen such that:

$$\begin{cases} z_1^T F^d/m = z_1^T(\beta\Omega^B - \hat{g} - R^T(\xi^I - \xi_d^I) - (V^B - V_d^B))(z_1 \neq 0) \\ F^d/m = -\hat{g}(z_1 = 0) \end{cases} \tag{20}$$

Substituting Eqs. (18) and (20) into Eq. (19), when the angular velocity achieves the desired value, the derivative of the Lyapunov function becomes:

$$\dot{W}_1 + \dot{W}_2 = -\alpha z_0^T z_0 - z_1^T z_1 \leq 0 \tag{21}$$

Next, we choose the third Lyapunov function:

$$W_3 = 1/2 z_2^T z_2 \tag{22}$$

Take the time derivative:

$$\dot{W}_3 = z_2^T(J^{-1}(-\dot{\Omega}^B \times J\dot{\Omega}^B + M) - \dot{\Omega}_d^B) \tag{23}$$

In order to make the overall Lyapunov function $W = W_1 + W_2 + W_3$ satisfies $\dot{W} \leq 0$, the desired moment should be:

$$M^d = J(\dot{\Omega}_d^B - S^T(V_d^B)V^B - z_2) + \Omega^B \times J\Omega^B \tag{24}$$

Then we can verify that:

$$\dot{W} = \dot{W}_1 + \dot{W}_2 + \dot{W}_3 = -\alpha z_0^T z_0 - z_1^T z_1 - z_2^T z_2 \leq 0 \tag{25}$$

For the overall system, since we already obtain the nominal desired force/moment (F^d, M^d) that can stabilize the nominal system. For the next step, we will design a control component (f_c, m_c) according to nonlinear damping to ensure the boundness of the overall system.

The overall control law can be described as,

$$F^B = F^d + f_c,\ M^B = M^d + m_c \tag{26}$$

Then the derivative of the overall Lyapunov function W satisfies:

$$\begin{aligned} \dot{W} = {} & (-\alpha z_0^T z_0 + z_0^T z_1) \\ & + z_1^T R(F^d/m + \hat{g} + V^{\mathrm{B}} \times \Omega^B + \alpha V^B) + z_1^T R(f_c + \Delta F/m) \\ & + z_2^T[J^{-1}(-\dot{\Omega}^B \times J\dot{\Omega}^B + M^d) - \dot{\Omega}_d^B] + z_2^T J^{-1}(m_c + \Delta M) \end{aligned} \tag{27}$$

Defining $w_1^T = z_1^T R/m, w_2^T = z_2^T J^{-1}$, and substituting Eq. (20), Eq. (24) into Eq. (27) result in:

$$\dot{W} = -az_0^T z_0 - z_1^T z_1 - z_2^T z_2 + w_1^T (f_c + \Delta F) + w_2^T (m_c + \Delta M) \tag{28}$$

Substituting Eq. (10)–(11) into Eq. (28), we can get:

$$\dot{W} = -az_0^T z_0 - z_1^T z_1 - z_2^T z_2 + w_1^T (f_c + \vec{\Gamma}_F \vec{\delta}_F) + w_2^T (m_c + \vec{\Gamma}_M \vec{\delta}_M) \tag{29}$$

where $f_c = -k_{fc} w_1 \left\| \vec{\Gamma}_F \right\|_2^2, k_{fc} > 0; m_c = -k_{mc} w_2 \left\| \vec{\Gamma}_M \right\|_2^2, k_{mc} > 0$, we can obtain:

$$\begin{aligned} \dot{W} \leq & -az_0^T z_0 - z_1^T z_1 - z_2^T z_2 - (k_{fc} \|w_1\|_2^2 \left\| \vec{\Gamma}_F \right\|_2^2 - \|w_1\|_2 \left\| \vec{\Gamma}_F \right\|_2 K_F) \\ & - (k_{mc} \|w_2\|_2^2 \left\| \vec{\Gamma}_M \right\|_2^2 - \|w_2\|_2 \left\| \vec{\Gamma}_M \right\|_2 K_M) \end{aligned} \tag{30}$$

where K_F, K_M are unknown upper bound on $\left\| \vec{\delta}_F \right\|, \left\| \vec{\delta}_M \right\|$. It is obviously:

$$\dot{W} \leq -(a-1) z_0^T z_0 - \|X\|_2^2 + \frac{K_F^2}{4k_{fc}} + \frac{K_M^2}{4k_{mc}} \leq -(a-1) z_0^T z_0, \tag{31}$$

where $X = [z_0 \, z_1 \, z_2]^T$, $a > 1$, Since $\|X\|_2^2 \geq \frac{K_F^2}{4k_{fc}} + \frac{K_M^2}{4k_{mc}}$

This shows that the solutions of the state z_0, z_1, z_2 are uniformly bounded around the origin point. So it is clear that in finite time, the position, linear velocity and angular velocity of the UAH can approach a bounded set around the desired ones.

After deriving the reference force and moment (F^B, M^B), we can get the control inputs through main rotor, fly-bar flapping dynamics function and servo actuator dynamics function.

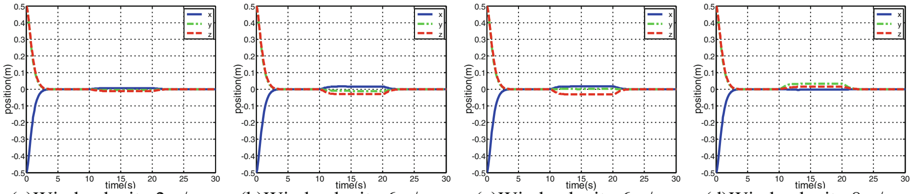
3 Simulation and Discussion

In this section, the proposed control system was simulated in MATLAB/SIMULINK@. Both longitude and lateral wind disturbances are simulated. The initial position is set at (−0.5 m, 0.5 m, 0.5 m) while the desired position is the origin. Gust wind from 0 (longitude) and 270 (lateral) degree directions are simulated respectively.

Case A: There is no wind disturbance at the beginning of 10 s and the last 10 s, and there is a constant wind velocity (varying from 2 m/s to 8 m/s) during 10 s and 20 s.

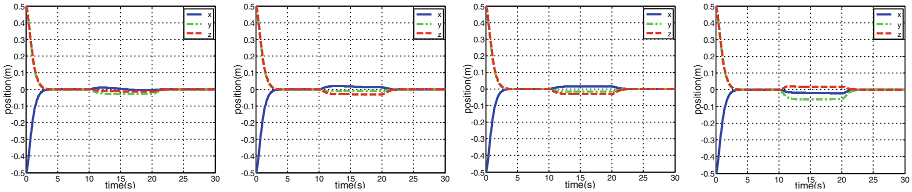
Figure 2 shows the position regulation of the helicopter under the longitude wind disturbance. The chosen parameters are $\alpha = 2.5$, $\beta = 3$. Figure 3 shows the position regulation of the helicopter under the lateral wind disturbance with the controller parameters are $\alpha = 2.5$, $\beta = 3$. Figure 4 shows the control inputs when the longitude velocity of short-period wind is 6 m/s.

Case B: Wind disturbances exist during the whole simulation period (30 s), and the wind velocity is 2 m/s, 4 m/s, 6 m/s, 8 m/s respectively. Figure 6 shows the position regulation of the helicopter under the longitude wind disturbance. The chosen parameters are $\alpha = 2.5$, $\beta = 3$. Figure 5 shows the position regulation of the helicopter under the lateral wind disturbance where the chosen parameters are $\alpha = 2.5$, $\beta = 3$. Figure 7 shows the control inputs when the lateral velocity of long-lasting wind is 6 m/s.



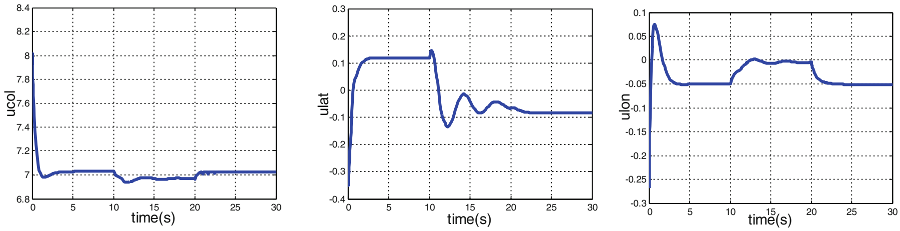
(a)Wind velocity 2m/s (b)Wind velocity 6m/s (c)Wind velocity 6m/s (d)Wind velocity 8m/s

Fig. 2. Performance of the position control in Case A with longitude wind disturbance



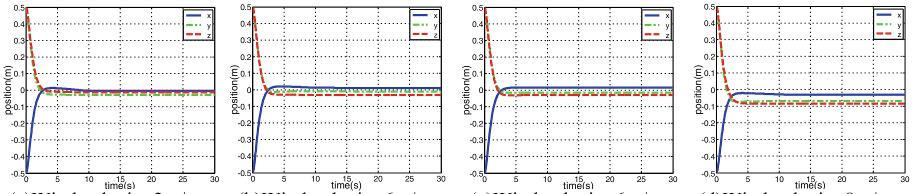
(a)Wind velocity 2m/s (b)Wind velocity 6m/s (c)Wind velocity 6m/s (d)Wind velocity 8m/s

Fig. 3. Performance of the position control in Case A with lateral wind disturbance



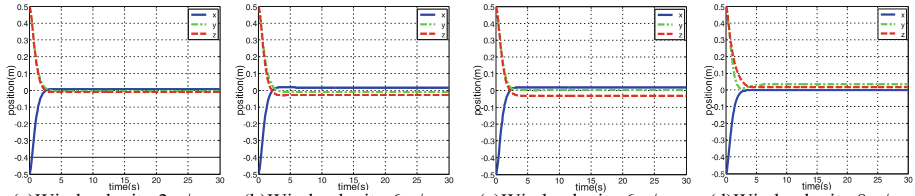
(a)Collective servo input (b)Lateral servo input (c)Longitude servo input

Fig. 4. Control input at the 6 m/s wind of Case A (Gust) from the longitude direction



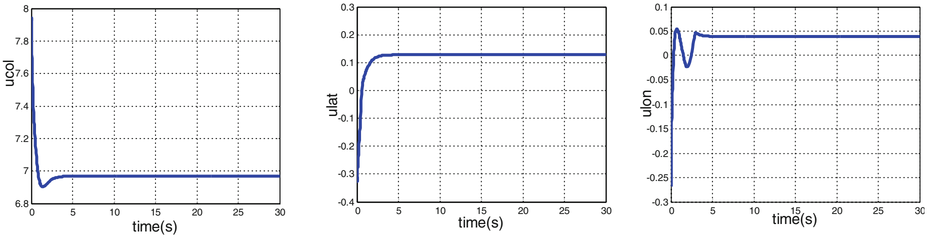
(a)Wind velocity 2m/s (b)Wind velocity 6m/s (c)Wind velocity 6m/s (d)Wind velocity 8m/s

Fig. 5. Performance of the position control in Case B with lateral wind disturbance



(a)Wind velocity 2m/s (b)Wind velocity 6m/s (c)Wind velocity 6m/s (d)Wind velocity 8m/s

Fig. 6. Performance of the position control in Case B with longitude wind disturbance



(a)Collective servo input (b)Lateral servo input (c)Longitude servo input

Fig. 7. Control input at the 6 m/s wind of Case B(long-lasting) from the lateral direction

4 Conclusion

This architecture incorporates a theoretic control design and experiment-based force/moment compensation in order to attenuate large horizontal wind disturbances. In this paper, the experiment-based force/moment was treated as uncertain perturbation and cannot be compensated directly and precisely. The theoretic control design took advantage of the backstepping algorithms. The force/moment compensation can be achieved through a nonlinear damping term based on the wind tunnel experiment data. Simulation results show that the proposed control method can well attenuate large horizontal wind disturbance to the desired position. Compare with the hybrid control architecture [15] we proposed before, when the force and moment may not be computed correctly due to the variety of the real condition, the new control system designed in this paper can still work on well. In the future, the authors will deal with the practical flight trial with proposed controller on a small scaled unmanned helicopter.

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