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Application of leso to dynamic inversion controller for uav flight attitude

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Abstract. Flight attitude control is the key part of UAV control system. In this paper, the dynamics model of UAV attitude angular velocity is established. The angular velocity controller is designed based on the nonlinear dynamic inversion method. Considering the great dependency of nonlinear dynamic inversion method on accuracy of dynamics model, linear extended state observer (LESO) is imported to estimate and compensate the internal and external disturbances of UAV dynamics model. The controller based on dynamic inversion method and LESO is simulated. Results show that UAV angular velocity is able to track the command precisely by dynamic inversion controller together with LESO. Simulation with different LESO bandwidth further illustrates that LESO bandwidth should be set high enough to estimate and compensate the total disturbance of UAV dynamics model accurately and timely to make angular velocity attain its command.

Key words. UAV, flight control, dynamic inversion, LESO, bandwidth.

1. Introduction

High-performance UAV must have an excellent flight control system to precisely track a complex flight trajectory. Flight attitude control and angular velocity control are the key components in the flight control system. For the parametric uncertainty of UAV flight dynamics model and external disturbances, UAV flight control law should have good performance of anti-disturbance.

The nonlinear dynamic inversion method is utilized to construct the corresponding inverse system model based on the mathematical model of control plant. The nonlinearity of control plant model is rejected by nonlinear feedback to achieve the linearization of the control plant. The dynamic inversion method has been applied to a variety of aircraft controller design[1–8], and has obtained a good performance. However, due to the internal and external disturbances of flight dynamics model,

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it is difficult for the dynamic inversion method to guarantee the controller robustness. In order to address this problem, L_1, H_2/H_∞, sliding mode control, adaptive control or μ robust control has been combined with dynamic inversion controller to guarantee the robustness. The neural network, modified state observer and other methods have been applied to observe and eliminate disturbances. However, all of the aforementioned methods increase parameters tuning difficulty.

Based on the active disturbance rejection control, the linear extended state observer (LESO) [9] can effectively estimate the internal and external uncertainties of control plant and be parameterized according to its bandwidth. The linear active disturbance rejection controller is analyzed theoretically and parameter tuning is carried out by frequency domain method. The dynamic tracking and estimation capabilities, and the ability of LESO to eliminate disturbances are analyzed based on frequency domain characteristics of control plant.

In this paper, the nonlinear dynamic inversion method is used to control the UAV attitude angular velocity. The LESO is applied to estimate and compensate the error derived from uncertainty of aerodynamic coefficients. The influence of LESO bandwidth on the estimation and compensation is analyzed. The structure of the paper is as follows: in Section 2, the dynamic model of angular velocity is presented. In Section 3, details of angular velocity control law design based on dynamic inversion and LESO are provided. Section 4 contains the simulation results and discussion. Section 5 illustrates the conclusion which is followed by references.

2. Dynamics model of angular velocity

According to flight mechanics, a nonlinear dynamics model of UAV attitude angular velocity is given by:

$$\dot{\omega} = -I^{-1}\omega^* I + I^{-1}M \tag{1}$$

where $\omega = [p, q, r]^{\mathrm{T}}$ is the angular velocity vector; $M = [M_x, M_y, M_z]^{\mathrm{T}}$ is the aerodynamic moment vector; I is the inertia matrix and ω^* is the rotation matrix,

$$I = \begin{bmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{xy} & I_y & -I_{yz} \\ -I_{xz} & -I_{yz} & I_z \end{bmatrix},$$

$$\omega^* = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix}.$$

The aerodynamic moment components are as follows:

$$M_x = QSb(C_{mx0} + C_{mx}^{\beta}\beta + C_{mx}^{\delta a}\delta a + C_{mx}^{\delta r}\delta r + C_{mx}^{p} p \frac{b}{2V} + C_{mx}^{r} r \frac{b}{2V})$$

$$M_y = QSc\left(C_{my0} + C_{my}^{\alpha}\alpha + C_{my}^{\delta e}\delta e + C_{my}^{q}q\frac{c}{2V}\right)$$

$$M_z = QSb(C_{mz0} + C_{mz}^{\beta}\beta + C_{mz}^{\delta a}\delta a + C_{mz}^{\delta r}\delta r + C_{mz}^{p}p\frac{b}{2V} + C_{mz}^{r}r\frac{b}{2V})$$

where $Q = 0.5\rho V^2$, V is the flight velocity, α is angle of attack, β denotes angle of sideslip, ρ denotes the air density, S denotes the wing area, b denotes the wing length, c denotes the mean aerodynamic chord; C_{mx0}, $C_{mx}^{\delta a}$, $C_{mx}^{\delta r}$, C_{mx}^{β}, C_{mx}^{p}, C_{mx}^{r}, C_{my0}, C_{my}^{α}, $C_{my}^{\delta e}$, C_{my}^{q}, C_{mz0}, $C_{mz}^{\delta a}$, $C_{mz}^{\delta r}$, C_{mz}^{β}, C_{mz}^{p} and C_{mz}^{r} are aerodynamic coefficients; δe,δa,δr are deflections of control surfaces.

3. Angular velocity controller design

3.1. Dynamic inversion controller

The angular velocity dynamic equation(1) could be rewritten as follows:

$$\dot{\omega} = F + Gu \tag{2}$$

where $u = [\delta e, \delta a, \delta r]^{\mathrm{T}}$ is the control input vector,

$$F = \begin{bmatrix} \frac{I_y - I_z}{I_x}rq + \frac{QSb}{I_x}(C_{mx0} + C_{mx}^{\beta}\cdot\beta + C_{mx}^{p}\cdot p\cdot\frac{b}{2V} \\ +C_{mx}^{r}\cdot r\cdot\frac{b}{2V}) \\ \frac{I_z - I_x}{I_y}pr + \frac{QSc}{I_y}(C_{my0} + C_{my}^{\alpha}\cdot\alpha + C_{my}^{q}\cdot q\cdot\frac{c}{2V}) \\ \frac{I_x - I_y}{I_z}pq + \frac{QSb}{I_z}(C_{mz0} + C_{mz}^{\beta}\cdot\beta + C_{mz}^{p}\cdot p\cdot\frac{b}{2V} \\ +C_{mz}^{r}\cdot r\cdot\frac{b}{2V}) \end{bmatrix},$$

$$G = \begin{bmatrix} 0 & \frac{QSb}{I_x}C_{mx}^{\delta a} & \frac{QSb}{I_x}C_{mx}^{\delta r} \\ \frac{QSc}{I_y}C_{my}^{\delta e} & 0 & 0 \\ 0 & \frac{QSb}{I_z}C_{mz}^{\delta a} & \frac{QSb}{I_z}C_{mz}^{\delta r} \end{bmatrix}.$$

From $\det(G) = \frac{Q^3S^3cb^2}{I_xI_yI_z}C_{my}^{\delta e}\left(C_{mz}^{\delta a}C_{mx}^{\delta r} - C_{mx}^{\delta a}C_{mz}^{\delta r}\right)$, when $C_{mz}^{\delta a}C_{mx}^{\delta r} \neq C_{mx}^{\delta a}C_{mz}^{\delta r}$, we can get $\det(G) \neq 0$ and then the matrix G is invertible. Apply the nonlinear dynamic inversion method to angular velocity controller design. Thus the control input is

$$u = G^{-1}\left(\dot{\omega}_d - F\right) \tag{3}$$

$$\dot{\omega}_d = K(\omega_c - \omega) \tag{4}$$

where $\dot{\omega}_d = [\dot{p}_d, \dot{q}_d, \dot{r}_d]^{\mathrm{T}}$ is the desired angular acceleration, $\omega_c = [p_c, q_c, r_c]^{\mathrm{T}}$ is the command of angular velocity, $K = diag(w_p, w_q, w_r)$ is bandwidth of the controller.

3.2. Dynamic inversion controller with LESO

Ideally, the controller equation (3) can ensure UAV achieve the desired angular velocity through the feedback linearization method to counteract the nonlinearity of control plant model. However, due to the uncertainty of UAV aerodynamic coefficients, the nonlinearity of control plant can not be precisely counteracted. Thus, LESO is applied to estimate and compensate the disturbances of control plant.

$$\begin{aligned}\dot{\omega} &= F + \Delta F + (G + \Delta G)u + d_{\mathrm{ex}} \\ &= F + Gu + d\end{aligned}$$

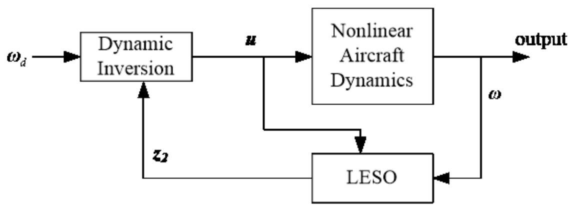

Fig. 1. Block of Control System

Considering the total disturbance of control plant, equation (2) would be rewritten as

$$\begin{aligned}\dot{\omega} &= F + \Delta F + (G + \Delta G)u + d_{\mathrm{ex}} \\ &= F + Gu + d\end{aligned} \tag{5}$$

where d_{ex} represents the external disturbances, $d = \Delta F + \Delta G u + d_{\mathrm{ex}}$ represents the summation of the internal and external disturbances.

In order to eliminate the disturbances, LESO is proposed as follows

$$\begin{cases} e = \omega - z_1 \\ \dot{z}_1 = z_2 + l_1 e + F + Gu \\ \dot{z}_2 = l_2 e \end{cases} \tag{6}$$

where $l_1 = diag(2w_{op}, 2w_{oq}, 2w_{or})$, $l_2 = diag(w_{op}^2, w_{oq}^2, w_{or}^2)$, w_{op}, w_{oq} andw_{or} are LESO bandwidth and the parameters to be tuned. By tuningw_{op},w_{oq} and w_{or}, $z_1 \to \omega$ and $z_2 \to d$ will be achieved [14,17].

The control system block is shown in Figure 1. Thus, the control input is

$$u = G^{-1}(\dot{\omega}_d - F - z_2) \tag{7}$$

$$\dot{\omega}_d = K(\omega_c - \omega) \tag{8}$$

4. Simulation and discussion

The nominal flight state of UAV [10] is straight level flight. TABLE 1 lists the initial parameters.

Table 1. Initial Parameters

Initial Velocity V	100 m/s
Initial Angular Velocity $[p\ q\ r]$	0 rad/s
Controller Bandwidth $[\omega_p\ \omega_q\ \omega_r]$	10 rad/s
Observer Bandwidth $[\omega_{op}\ \omega_{oq}\ \omega_{or}]$	5 rad/s

At 0s, set the angular velocity command at 1 rad/s and the uncertainty of aerodynamic coefficients at 20%. The angular velocity is simulated and shown in Figure 2.

As shown in Figure 2, without uncertainty of aerodynamic coefficients, through single dynamic inversion controller the angular velocity can track the command of 1 rad/s and its steady-state error of output is approximately zero. However, if uncertainty of aerodynamic coefficients applies, single dynamic inversion controller results in a large output error therefore cannot meet the robustness requirements. Because of its estimation and compensation, LESO ensures dynamic inversion controller keep control accuracy in the presence of aerodynamic coefficients uncertainty.

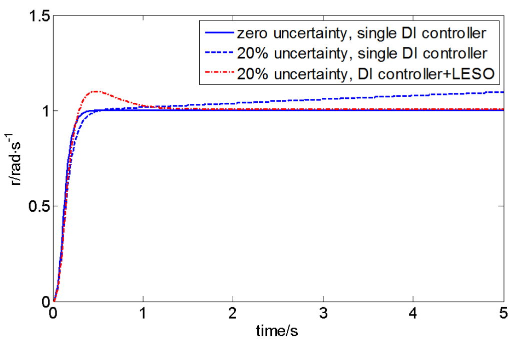

Fig. 2. Curves of Angular Velocity

In order to analyze the influence of LESO bandwidth on the performance of the observer, the angular velocity q is simulated with different LESO bandwidth, as shown in Fig.3.

Figure 3 shows simulation results of zero uncertainty and 10% uncertainty with LESO. When the LESO bandwidth is too low, the speed of estimation is too slow to achieve compensation. Thus, allow angular velocity cannot track the command accurately at a low LESO bandwidth. As LESO bandwidth increases, the estimation performance of LESO also increases, and the tracking error reduces to zero quickly.

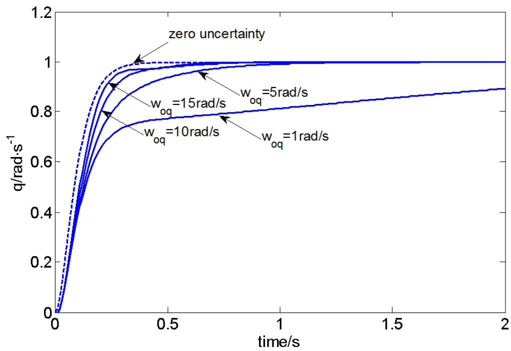

Fig. 3. Curves of q with different LESO bandwidth

5. Conclusion

In this work, dynamic inversion method based controller and LESO are proposed for UAV to track desired attitude angular velocity. If the model of control plant is accurate enough, single dynamic inversion method based controller is able to achieve accurate linearization by nonlinear feedback cancellation. However, if disturbance exists in the model of control plant, the dynamic inversion method will cause large control error. To remove the error, LESO is implemented to estimate and eliminate disturbance in the model of control plant and thereafter greatly improves the robust performance of the dynamic inversion controller. In general, the LESO bandwidth greatly affects the performance of controller. The LESO bandwidth should be high enough to estimate and compensate the total disturbance of control plant timely and accurately.

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