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Research Article

Neural Back-Stepping Control of Hypersonic Flight Vehicle with Actuator Fault

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This paper addresses the fault-tolerant control of hypersonic flight vehicle. To estimate the unknown function in flight dynamics, neural networks are employed in controller design. Moreover, in order to compensate the actuator fault, an adaptive signal is introduced in the controller design to estimate the unknown fault parameters. Simulation results demonstrate that the proposed approach could obtain satisfying performance.

1. Introduction

Fault diagnosis and fault-tolerant control have been a hot issue since its significance on actual systems with actuator faults. By identifying or estimating unknown faults, the influence of faults could be considered and eliminated in controller design. Representative study on this issue could be found in [1, 2], while in this paper, fault diagnosis have been studied and applied on hypersonic flight vehicle (HFV) whose control methods have attracted a lot of attention. Hypersonic flight vehicle has a much higher speed than traditional aircraft, however due to its special flight environment as well as structure, the controller design of HFV faces more challenges [3].

Currently, most studies on HFV control did not take the actuator fault into consideration. However, unknown fault such as actuator dead-zone is quite common in nonlinear systems and may cause serious consequences [4]. In order to remove the influence caused by actuator fault, several approaches have been studied such as fuzzy control [5], robust control [6, 7], and adaptive compensation [8, 9]. The model of the HFV also contains uncertain nonlinearity. As a result, studies on HFV have concentrated on the estimation of the uncertainty. Among all the methods, neural network has been widely used due to its good performance in approximating unknown nonlinear functions [10].

The model of HFV is highly nonlinear; meanwhile the altitude subsystem could be considered as a strict-feedback system [11]. Therefore, back-stepping method [12–14] in HFV control has been widely studied. To eliminate continuous derivatives of each virtual control in back-stepping design, multiple methods such as dynamic surface control [15] and differentiator [14] are combined with back-stepping which makes the approach practicable. It is noticed that in [16] the multiple actuator fault is considered and the robust design is presented to guarantee the system stability. Moreover, in [17], the input dead-zone is considered where the Nussbaum design is included to make the adaptive design available. In this paper, we try to estimate the parameters of system fault in the hypersonic flight dynamics and then the "dynamic inversion" of the actuator fault can be included in the control signal. The whole design is using a back-stepping control law with neural networks and adaptive method.

The paper is organized in 6 parts. In Section 2, the control-oriented model (COM) of HFV considered in this paper is simply introduced. In Sections 3 and 4, the back-stepping controller based on neural networks and adaptive fault estimation is designed and system stability is analysed.

The simulation results of the designed controller are shown in Section 5. Finally the summary is given in Section 6.

2. Longitudinal Dynamics of HFV with Actuator Fault

The COM in [18] is employed for study:

$$\begin{aligned}\dot{V} &= \frac{T\cos\alpha - D}{m} - g\sin\gamma \\ \dot{h} &= V\sin\gamma \\ \dot{\gamma} &= \frac{L + T\sin\alpha}{mV} - \frac{g\cos\gamma}{V} \\ \dot{\alpha} &= q - \dot{\gamma} \\ \dot{q} &= \frac{M_{yy}}{I_{yy}}.\end{aligned} \quad (1)$$

The detail of the dynamics can be found in [18].

Consider the following actuator fault model:

$$\delta_e = \begin{cases} u - b & \text{if } u \geq b \\ 0 & \text{if } -b < u < b \\ u + b & \text{if } u \leq -b, \end{cases} \quad (2)$$

where u is the designed control input and $b < 0$ is an unknown fault parameter to be estimated.

Remark 1. In HFV systems, the fault will cause error between designed and actual control input and it will result in tracking error or even flight instability.

3. Adaptive Back-Stepping Controller

The strict-feedback form altitude subsystem based on the hypersonic flight dynamics is considered

$$\begin{aligned}\dot{x}_1 &= f_1 + g_1 x_2 \\ \dot{x}_2 &= x_3 \\ \dot{x}_3 &= f_3 + g_3\delta_e,\end{aligned} \quad (3)$$

where $x_1 = \gamma$, $x_2 = \gamma + \alpha$, and $x_3 = q$. f_i, g_i are nonlinear functions of the HFV model.

Assumption 2. In altitude subsystem (3), g_3 is a bounded function.

Flight path angle (FPA) tracking error $\tilde{x}_1$ is defined as

$$\tilde{x}_1 = x_1 - x_{1d}, \quad (4)$$

where x_{1d} is the command signal of FPA which is designed via altitude reference signal.

Step 1. Choose virtual control of x_2 as

$$x_{2d} = \frac{1}{g_1}\left(-f_1 - \varsigma_1\tilde{x}_1 + \dot{x}_{1d}\right), \quad (5)$$

where ς_1 is the control gain.

To avoid the continuous derivative of virtual control, the following first-order differentiator is designed:

$$\begin{aligned}\dot{\varpi}_{2c} &= -l_{20}\sqrt{\left|\varpi_{2c} - x_{2d}\right|}\operatorname{sgn}\left(\varpi_{2c} - x_{2d}\right) + \varpi_{2d} \\ \dot{\varpi}_{2d} &= -l_{21}\operatorname{sgn}\left(\varpi_{2d} - \dot{\varpi}_{2c}\right),\end{aligned} \quad (6)$$

where l_{20} and l_{21} are positive designed parameters.

Step 2. Define the tracking error $\tilde{x}_2$:

$$\tilde{x}_2 = x_2 - x_{2d}. \quad (7)$$

Choose virtual control of x_3 as

$$x_{3d} = -\varsigma_2\tilde{x}_2 + \dot{\varpi}_{2c} - g_1\tilde{x}_1. \quad (8)$$

where ς_2 is the control gain.

The following first-order differentiator is designed:

$$\begin{aligned}\dot{\varpi}_{3c} &= -l_{30}\sqrt{\left|\varpi_{3c} - x_{3d}\right|}\operatorname{sgn}\left(\varpi_{3c} - x_{3d}\right) + \varpi_{3d} \\ \dot{\varpi}_{3d} &= -l_{31}\operatorname{sgn}\left(\varpi_{3d} - \dot{\varpi}_{3c}\right),\end{aligned} \quad (9)$$

where l_{30} and l_{31} are positive designed parameters.

Step 3. Define the tracking error $\tilde{x}_3$:

$$\tilde{x}_3 = x_3 - x_{3d}. \quad (10)$$

Due to the uncertainty caused by imprecise model, the nonlinear function f_3 may be unknown. Therefore its NN-based estimation value is employed in the control law:

$$u_0 = \frac{1}{g_3}\left(-\hat{\omega}_3^T\Theta_3 - \varsigma_3\tilde{x}_3 - \tilde{x}_2 + \dot{\varpi}_{3c}\right), \quad (11)$$

where ς_3 is the control gain and $\hat{\omega}_3$ is the estimation of the optimal NN weights ω_3^*, which is obtained via adaptive law:

$$\dot{\hat{\omega}}_3 = \Gamma_3\tilde{x}_3\Theta_3\left(\overline{x}_3\right) - \Gamma_3\delta_3\hat{\omega}_3, \quad (12)$$

where Γ_3 and δ_3 are positive parameters. Θ_3 is obtained via radial basis function. Define $\tilde{\omega}_3 = \omega_3^* - \hat{\omega}_3$.

In order to eliminate the influence of unknown constant b, signal $\hat{b}$ is introduced in controller design to compensate the actuator:

$$u = u_0 + \hat{b}\operatorname{sgn}\left(u_0\right). \quad (13)$$

The adaptive law is designed as

$$\dot{\hat{b}} = -\Gamma_b g_3\tilde{x}_3\operatorname{sgn}\left(u_0\right) - \Gamma_b\sigma_b\hat{b}, \quad (14)$$

where Γ_b and σ_b are positive designed parameters. Define the estimation error $\tilde{b} = b - \hat{b}$.

Remark 3. In previous work on HFV dead-zone fault control [17], the paper regarded the dead-zone as a part of the compound disturbance, where robust technique is employed. In our paper, we proposed an adaptive law to estimate the unknown fault parameter and added a compensating signal in the controller so that the influence of dead-zone fault could be directly eliminated, which is shown by Figures 3 and 5 in our manuscript.

Define the velocity tracking error as

$$\widetilde{V} = V - V_r, \tag{15}$$

where V_r is the reference signal. Then the following PID controller is designed:

$$\Phi = k_{pv}\widetilde{V} + k_{iv}\int \widetilde{V}(t)\,\mathrm{d}t + k_{dv}\dot{\widetilde{V}}. \tag{16}$$

4. Stability Analysis

Theorem 4. *Consider the HFV altitude system (3) with control laws (5), (8), (11), and (13) and adaptive laws (12) and (14); all of the error signals are uniformly ultimately bounded.*

Proof. The Lyapunov function candidate is chosen as

$$V_L = \sum_{i=1}^{3} V_i, \tag{17}$$

where

$$\begin{aligned} V_1 &= \frac{1}{2}\tilde{x}_1^2 \\ V_2 &= \frac{1}{2}\tilde{x}_2^2 \\ V_3 &= \frac{1}{2}\tilde{x}_3^2 + \frac{1}{2}\widetilde{\omega}_3^T\Gamma_3^{-1}\widetilde{\omega}_3 + \frac{1}{2}\Gamma_b^{-1}\tilde{b}^2. \end{aligned} \tag{18}$$

The derivative of V_L is obtained as

$$\dot{V}_L = \sum_{i=1}^{3}\tilde{x}_i\left(\dot{x}_i - \dot{x}_{id}\right) - \widetilde{\omega}_3^T\Gamma_3^{-1}\dot{\hat{\omega}}_3 - \Gamma_b^{-1}\tilde{b}\dot{\hat{b}}. \tag{19}$$

According to the conclusion in [19], $\dot{\omega}_{2c}$, $\dot{\omega}_{3c}$ in differentiators (6), (9) could estimate $\dot{x}_{2d}$ and $\dot{x}_{3d}$ to arbitrary accuracy. Therefore there exists

$$\dot{x}_{id} = \dot{\omega}_{ic} + \chi_i, \quad i = 2, 3, \tag{20}$$

where $\chi_i \le |\chi_{im}|$, χ_{im} is a positive constant. Substitute the control laws and adaptive laws into (19); there exists

$$\begin{aligned} \dot{V}_L = &-\sum_{i=1}^{3}\varsigma_i\tilde{x}_i^2 + \delta_3\left(\widetilde{\omega}_3^T\omega_3^* - \widetilde{\omega}_3^T\widetilde{\omega}_3\right) + \varepsilon_3\tilde{x}_3 \\ &+ b\tilde{x}_3 g_3\left[\operatorname{sgn}(u_0) - \operatorname{sgn}(u)\right] + \sigma_b\left(b\tilde{b} - \tilde{b}^2\right) \\ &- \sum_{i=2}^{3}\tilde{x}_i\chi_i, \end{aligned} \tag{21}$$

where ε_3 is the bounded inevitable NN reconstruction error satisfying $|\varepsilon_3| \le \varepsilon_{3m}$, where ε_{3m} is a positive constant. Define $\eta = bg_3[\operatorname{sgn}(u_0) - \operatorname{sgn}(u)]$; consider Assumption 1; η is a bounded signal satisfying $|\eta| \le \eta_m$, where η_m is a positive constant.

The following inequalities hold:

$$\begin{aligned} \delta_3\left(\widetilde{\omega}_3^T\omega_3^* - \widetilde{\omega}_3^T\widetilde{\omega}_3\right) &\le \frac{1}{2}\delta_3\left(\left\|\omega_3^*\right\|^2 - \widetilde{\omega}_3^T\widetilde{\omega}_3\right) \\ \sigma_b\left(b\tilde{b} - \tilde{b}^2\right) &\le \frac{1}{2}\sigma_b\left(b^2 - \tilde{b}^2\right) \\ -\sum_{i=2}^{3}\tilde{x}_i\chi_i &\le \sum_{i=2}^{3}\left(\frac{1}{2}\tilde{x}_i^2 + \frac{1}{2}\chi_{im}^2\right) \\ \varepsilon_3\tilde{x}_3 &\le \frac{1}{2}\varepsilon_{3m}^2 + \frac{1}{2}\tilde{x}_3^2 \\ \eta\tilde{x}_3 &\le \frac{1}{2}\eta_m^2 + \frac{1}{2}\tilde{x}_3^2. \end{aligned} \tag{22}$$

The derivative of V_L satisfies

$$\begin{aligned} \dot{V}_L \le &-\varsigma_1\tilde{x}_1^2 - \left(\varsigma_2 - \frac{1}{2}\right)\tilde{x}_2^2 - \left(\varsigma_3 - \frac{3}{2}\right)\tilde{x}_3^2 - \frac{1}{2}\delta_3\widetilde{\omega}_3^T\widetilde{\omega}_3 \\ &- \frac{1}{2}\sigma_b\tilde{b}^2 + \frac{1}{2}\delta_3\left\|\omega_3^*\right\|^2 + \frac{1}{2}\varepsilon_{3m}^2 + \frac{1}{2}\eta_m^2 \\ &+ \frac{1}{2}\sigma_b b^2 + \sum_{i=2}^{3}\frac{1}{2}\chi_{im}^2 \\ \le &-\sigma V_L + P, \end{aligned} \tag{23}$$

where $\sigma = \min\{2\varsigma_1, (2\varsigma_2 - 1), (2\varsigma_2 - 3), \delta_3\Gamma_3, \sigma_b\Gamma_b\}$ and $P = (1/2)\delta_3\|\omega_3^*\|^2 + (1/2)\varepsilon_{3m}^2 + (1/2)\eta_m^2 + (1/2)\sigma_b b^2 + \sum_{i=2}^{3}(1/2)\chi_{im}^2$. Then all of the signals in V_L are uniformly ultimately bounded. This completes the proof. □

5. Simulation

Let altitude increase 152.4 m from the initial value; notice that the signal will pass the following filter to make sure the reference signal is smooth enough for tracking:

$$\frac{\Delta_r}{\Delta} = \frac{\omega_1\omega_2^2}{(s + \omega_1)\left(s^2 + 2\xi\omega_2 s + \omega_2^2\right)}, \tag{24}$$

where $\omega_1 = 0.8$, $\omega_2 = 0.5$, and $\xi = 0.1$. The FPA command signal is obtained as

$$x_{1d} = \arcsin\left(\frac{-k_h\tilde{h} - k_i\int\tilde{h}\,\mathrm{d}t + \dot{h}_r}{V}\right), \tag{25}$$

where $k_h = 0.5$, $k_i = 0.05$, $\tilde{h} = h - h_r$ is the altitude tracking error, and h_r is the altitude reference signal.

The parameters in the controller are set as $\varsigma_1 = 2$, $\varsigma_2 = 2$, $\varsigma_3 = 3$, $k_{pv} = 5$, $k_{dv} = 0.01$, and $k_{iv} = 0.01$. The parameters of first-order differentiator and adaptive laws are chosen as $l_{20} = 120$, $l_{30} = 100$, $l_{21} = 0.9$, $l_{31} = 0.05$, $\Gamma_3 = 0.5$, $\delta_3 = 0.002$,

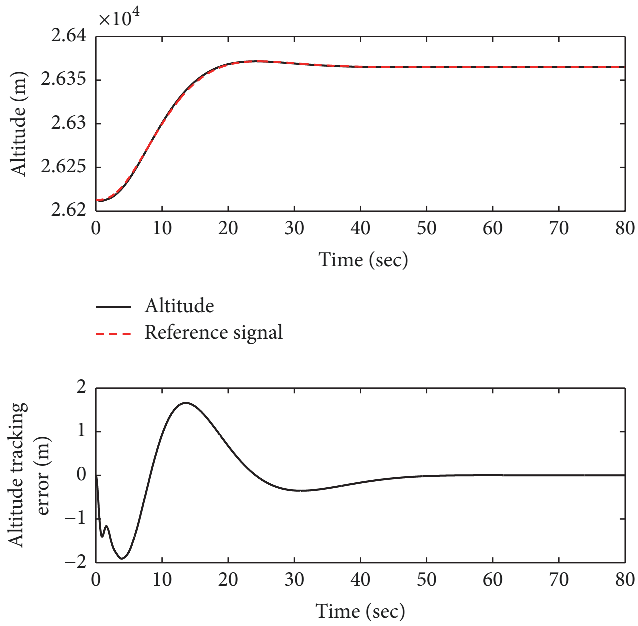

Figure 1: Altitude.

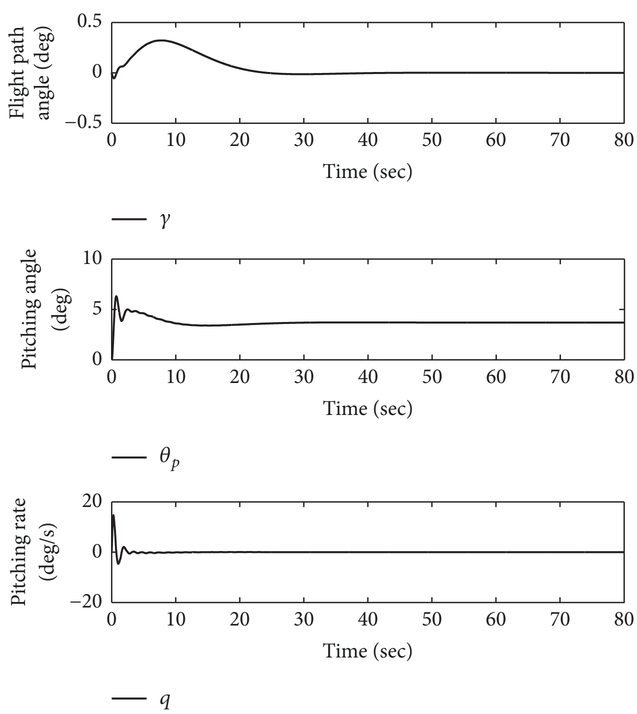

Figure 2: FPA, pitching angle, and pitching rate.

$\Gamma_b = 0.113$, and $\sigma_b = 0.005$. Take the initial states as $h_0 = 26212$ m, $v_0 = 2743$ m/s, $\gamma_0 = 0$ deg, $\alpha_0 = 0$ deg, and $q_0 = 0$ deg/s. The fault parameter is set as $b = 0.05$. The results are as follows.

Figure 1 indicates that the designed controller could obtain good performance on trajectory tracking. Figure 2 shows that the all state variables are bounded. The response of designed adaptive signal $\hat{b}$ and NN weights norm are shown

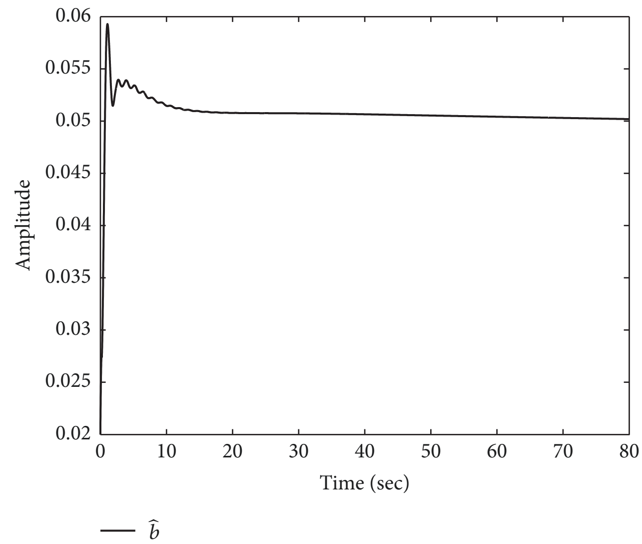

Figure 3: Response of $\hat{b}$.

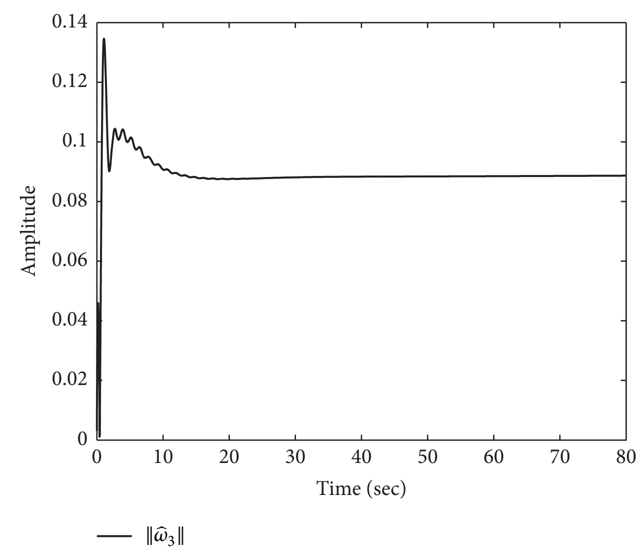

Figure 4: NN weights norm.

in Figures 3 and 4. The designed control input and actual control input are shown in Figure 5, respectively. The results verify that the adaptive compensation design could eliminate the influence of actuator fault.

6. Conclusion

This paper proposes an adaptive back-stepping control law with NN learning for HFV control. The influence of actuator fault is eliminated by constructing an adaptive compensation signal. Meanwhile, the unknown nonlinearity is estimated by neural networks. The simulation results clearly present the consequence of the above design and verify that the approach could reach the desired tracking performance when actuator fault and model uncertainty exist.

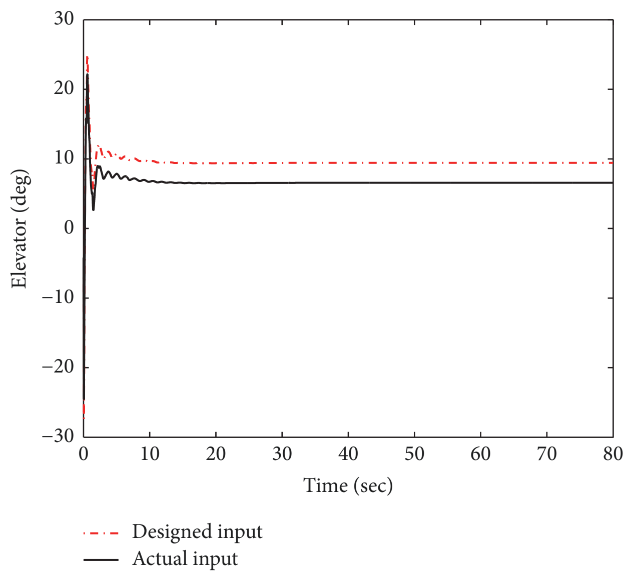

FIGURE 5: Control input.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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