Adaptive fault-tolerant control of uncertain nonlinear systems under Actuator failure of unmanned aerial vehicles

Jianqi Wang,Dongmei Wang,Zhibin Cao,Dongwang Li
Key Laboratory of UAV Telemetry & Institute of Aeronautics and Astronautics, Guilin University of Aerospace Technology, Guilin 541004, China

Abstract: With the increasingly extensive application of UAV technology, UAV accidents are increasing, and the safety problem is becoming more and more serious. Therefore, it is urgent to ensure the safety and reliability of UAV. This paper firstly introduces the application requirements and research significance of the fault-tolerant control system of UAV; Secondly, the classification of fault-tolerant control system of UAV is introduced. Finally, taking the nonlinear system of UAV as an example, the controller and its parameters are derived, and Simulink simulation model is established with MATLAB software to verify that the designed adaptive fault-tolerant controller can effectively maintain the stability and reliability of the system.

Key words: fault-tolerant control; Actuator fault; Lyapunov function

1. Introduction

Unmanned Aerial Vehicle(UAV) is more and more widely used in military and civilian fields by its advantages of being more flexible, low cost and small size than man-machine, and the complexity of tasks entrusted to it is also increasing. Therefore, the ability to adapt to complex task environments and cope with interference, emergencies and failures also needs to be improved. In August 2017, the US Army's MQ-1 Predator drone crashed due to actuator failure; In May 2018, a large area crashed in Xi 'an due to communication interference of GPS sensors during a drone formation performance; In June 2019, a Boeing CV2 logistics drone suffered serious damage after an unexpected landing due to strong crosswind. According to the US Military Aircraft Accident Investigation Board, system failures accounted for more than 69 percent of military UAV failures, while system failures accounted for more than 86 percent of civilian UAV failures. Literature lists some common fault types of UAVs. Multi-source interference and various kinds of faults are the main factors leading to UAVs safety accidents. Therefore, it is necessary to enhance the fault-tolerant control of UAV.

Fault-tolerant control system is a redundant control system which can guarantee the original performance index of the system or complete the control task safely under the condition of the performance index reduction when the fault occurs. Early fault-tolerant control technology mainly through hardware redundancy method combined with software processing to minimize the impact of faults. This physical redundancy technology increases mass, maintenance and other costs, making the overall UAV system more complex and more suitable for large aircraft. After years of development, the fault-tolerant control technology of flight control system has achieved fruitful results. For different research objects and fault types, experts and scholars have put forward corresponding fault-tolerant control methods. In this paper, the nonlinear system of UAV is taken as an example, and the adaptive fault-tolerant controller design and simulation experiments are carried out to verify the stability and reliability of the system.

2. Classification of fault-tolerant control systems for UAVS

The fault-tolerant control system is mainly designed to maintain closed-loop system stability and acceptable transient and steady-state performance in the event of component-level failure or failure. Generally speaking, fault-tolerant control systems can be divided into two categories: passive fault-tolerant control systems and active fault-tolerant control systems.

Passive fault-tolerant control systems are generally used for component-level fault determination, and can maintain certain performance of UAVs without fault monitoring, diagnosis and control reconstruction. The key of passive fault-tolerant control system is robust control design to ensure that the faulty control system still has enough closed-loop performance to deal with variable faults with an unchanged controller, so the passive fault-tolerant control system is also known as a reliable control system. Passive fault-tolerant control systems are generally used to deal with external interference, system uncertainty, component-level failures/failures, and sensor noise.

The active fault-tolerant control system reconstructs the control law online according to the real-time information of the control system to adapt to component-level faults, so that the system still maintains stability and certain performance. The control reconstruction of the active fault tolerant control system is to compensate for the changes of system parameters and performance caused by faults. By changing the parameters of the control law or the structure of the controller, the original performance of the system is guaranteed or the safety of the system is still guaranteed in the case of performance degradation. In the active fault-tolerant control method, it can be divided into two forms according to the different reconfiguration control design. (1) Off-line controller reconfiguration design, complete the design of a group of controllers according to known fault types before flight, and switch different controllers according to flight conditions during flight. This method is suitable for all predictable fault situations, but it may cause false alarm and other situations. (2) Online controller reconstruction design, when the fault is detected, online real-time control law reconstruction.

3. Design and verification of fault-tolerant control system of UAV

3.1 Problem Description

This paper will study the following nonlinear system model, assuming that this is a nonlinear system of an unmanned aircraft:

$$\begin{cases}\dot{x}_1 = x_2 \\ \dot{x}_2 = u + d\end{cases} \tag{1}$$

x_1 And x_2 is the state of the system, for the control input of the system u, the control input disturbance d, so that the fault tolerance of the sensor and actuator of the UAV system is:

$$x_i^F = \rho_i x_i \text{ , } i = 1,2$$

$$u = \rho_0 v \tag{3}$$

In the above formula, the external uncertainty interference d is added to the input of the system, $|d| \le D$, ρ_0 and ρ_i is the unknown constant of the uncertainty of the system, whose value range is $0 \le \rho_{i0} \le \rho_i \le 1$, $0 \le \rho_{00} \le \rho_0 \le 1$.

The expected command of the system output x_1 is y_d, and the output actually measured by the sensor is x_1^F and x_2^F. In this way, we set the control objectives of the system as follows: ① Design the control law v of the system so that all signals in the closed-loop system are bounded; ② when $t \to \infty$, $x_1^F \to y_d, x_2^F \to \dot{y}_d$.

3.2 Controller Design

According to the control goal of the system, we will use the reverse step control algorithm combined with Lyapunov function to design the control law v of the UAV nonlinear system.

First define $z_1 = x_1^F - y_d$, $z_2 = x_2^F - a_1 - \dot{y}_d$, then

$$\dot{z}_1 = \rho_1 x_2 - \dot{y}_d \tag{4}$$

$$z_2 = \rho_2 x_2 - a_1 - \dot{y}_d \tag{5}$$

Design the following Lyapunov function:

$$V_1 = \frac{1}{2} z_1^2 \tag{6}$$

the

$$\dot{V}_1 = z_1 \dot{z}_1 = z_1 \left(\rho_1 x_2 - \dot{y}_d \right) \tag{7}$$

Because $0 < \rho_{20} \leqslant \rho_2 \leqslant 1$, and $\rho_{20} \leqslant \frac{\rho_2}{\rho_1}$, therefore $\frac{\rho_1}{\rho_2} \leqslant \frac{1}{\rho_{20}}$

$$\frac{\rho_1}{\rho_2} z_1 z_2 \leqslant \frac{1}{2} \left(\frac{\rho_1}{\rho_2} z_1 \right)^2 + \frac{1}{2} z_2^2 \leqslant \frac{1}{2\rho_{20}^2} z_1^2 + \frac{1}{2} z_2^2 \tag{8}$$

May be obtained by definition

$$z = \rho_2 \dot{x}_2 - \left(-c_1 \dot{z}_1 \right) - \ddot{y}_d = \rho_2 \left(u + d \right) + c_1 \dot{z}_1 - \ddot{y}_d = \rho_2 \left(\rho_0 v + d \right) + c_1 \left(\rho_1 x_2 - \dot{y}_d \right) - \ddot{y}_d \tag{9}$$

Using the adaptive method, the following Lyapunov function is designed

$$V = V_2 + \frac{1}{2\gamma_1} \tilde{\phi}^2 \tag{10}$$

Among them, $\tilde{\phi} = \hat{\phi} - \phi$, $\gamma_1 > 0$. Then

$$\dot{V} = \dot{V}_2 + \frac{1}{\gamma_1} \dot{\hat{\phi}} \tilde{\phi} \leqslant - \mu_1 z_1^2 + \frac{3}{2} z_1^2 + z_2 \left(\mu_2 v + \rho_2 d + \phi x_2^F \right) + C_1 + \frac{1}{\gamma} \dot{\phi} \tilde{\phi} \tag{11}$$

Design adaptive control law for

$$\dot{\hat{\phi}} = \gamma_1 z_2 x_2^F \tag{12}$$

According to the adaptive theorem

$$V(t) \leqslant e^{-\lambda t} V\left(t_0\right) + \int_{t_0}^{t} e^{-\lambda(t-\tau)} \left(\mu_3 N\left(k\right) \frac{1}{\gamma_2} \dot{k} - \frac{1}{\gamma_2} \dot{k} \right) d\tau + \int_0^t C_{2\max} e^{-\lambda(t-\tau)} d\tau$$

namely

$$V\left(t\right) \leqslant e^{-\lambda t} V\left(0\right) + e^{-at} \frac{1}{\gamma_2} \int_{t_0}^{t} \left(\mu_3 N\left(k\right) - 1 \right) \dot{k} e^{a\tau} d\tau + \frac{C_{2max}}{\lambda} \left(1 - e^{-\lambda t} \right)$$

$$\leqslant c_0 + e^{-\lambda t} V\left(0\right) + e^{-at} \frac{1}{\gamma_2} \int_{t_0}^{t} \left(\mu_3 N\left(k\right) - 1 \right) \dot{k} e^{a\tau} d\tau$$

Formula medium $c_0 = \frac{C_{2\max}}{\lambda}$.

Synthesizing the above design process, it can be seen that when $V(t)$ bounded on top $\forall t \in \left[0, t_f\right)$, so that, z_1 and z_2 are bounded on top $\forall t \in \left[0, t_f\right)$. When the λ and γ_2 are large enough, it can be guaranteed that when $t \to \infty$ the z_1 and z_2 are small enough to make $x_1^F \to y_d, x_2^F \to \dot{y}_d$.

3.3 Simulation modeling and verification

Using MATLAB software to establish Simulink simulation model, the model includes nonlinear system dynamic equation, Lyapunov function and reverse step controller and other components, instruction take $y_d = \sin t$, take $d = \sin \pi t$, take $\rho_0 = 0.50$, $\rho_1 = 0.95$, $\rho_2 = 0.95$. Set the simulation time t=20, the simulation results are as follows.

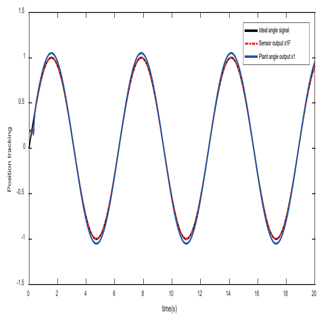

Figure 1 Angular response

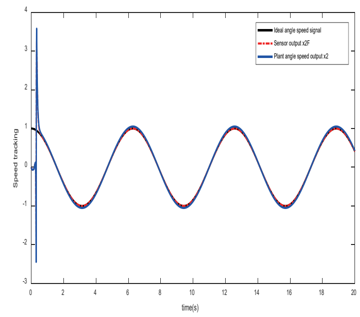

Figure 2 angular velocity response

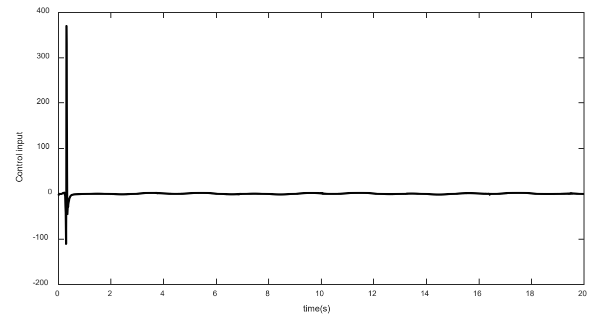

Figure 3 Control input

Figure 1 shows the angular response of the UAV when it is moving, reflecting the tracking of the command when the UAV motor is rotating. The solid black line is the input command of the system, the dotted red line is the actual output of the sensor, and the solid blue line is the actual output of the system. It can be seen from the figure that the output response of the sensor and the output of the system Angle response have a good tracking effect on the ideal Angle response, and the system state is always floating within a reasonable range. Figure 2 shows the angular velocity tracking under this control method, indicating that the output response of the sensor and the output of the system angular velocity have a good tracking effect on the ideal angular velocity response, and the system state always fluctuates within a reasonable range. FIG. 3 is the control input of the system. It can be seen from the figure that after the simulation runs for about 0.5S, the control input of the system tends to be stable and straight, and then fluctuates up and down within a reasonable range, indicating that the control method achieves good control effect.

4. Conclusion

This paper first introduces the application requirements and research significance of the fault-tolerant control system of UAV, then introduces the structure and classification of the fault-tolerant control system of UAV, and then introduces some current research results of the active fault-tolerant control of UAV. Finally, taking the nonlinear system of UAV as an example, the controller and its parameters are obtained through derivation. The Simulink simulation model is established by MATLAB software. The model includes dynamic equation of nonlinear system, Lyapunov function and reverse step controller. The simulation results show that the designed adaptive fault-tolerant controller can effectively maintain the stability and reliability of the system, and it can adaptivelyadjust the control strategy when facingthe uncertainties.

References

[1] Tan Y H, Lai S, Wang K, et al. Cooperative control of multiple unmanned aerial systems for heavy duty carrying[J]. Annual Reviews in Control, 2018, 46:44-57.

[2] LeiGuo,Xiang Yu,Xiao Zhang,Youmin Zhang. Technology of UAV Safety Control System: Progress and Prospect [J]. Science in China: Information Science,2020,50(02):184-194.

[3] QiangHe,Yi Xu,Xiaoqiang Yang. Uav accident case representation and retrieval [J]. Journal of Civil Aviation,2018,2(02):13-17+21.

[4] BankeJiang. Research on fault-tolerant control technology of multi-UAV system based on Distributed observer [D]. Nanjing University of Aeronautics and Astronautics,2019, pp.3-10

[5]Li Z, Liu Y, Walker R, et al. Towards automatic power line detection for a UAV surveillance system using pulse coupled neural filter and an improved Hough transform[J]. Machine Vision and Applications, 2010, 21(5): 677-686.

[6] Bethke B, Valenti M, How J P. Experimental demonstration of uav task assignment with integrated health monitoring[J]. IEEE Robotics automation magazine march, 2010, pp.1-8

[7] Mohr B B, Fitzpatrick D L. Micro air vehicle navigation system[J]. IEEE Aerospace and Electronic Systems Magazine, 2008, 23(4): 19-24.

[8] Chen J, Patton R J. Robust model-based fault diagnosis for dynamic systems[M]. Springer Science & Business Media, 2012, pp.15-20

[9]Zhang Y, Jiang J. Bibliographical review on reconfigurable fault-tolerant control systems[J]. Annual reviews in control, 2008, 32(2): 229-252.

[10]Bates D, Postlethwaite I. Robust multivariable control of aerospace systems[M]. IOS Press, 2002, pp.11-18

This work was financially supported by the National Natural Science Foundation of China. The project number is 61966010.