ISSN: 2664-9640

Attitude control of fixed wing UAV with actuator stuck fault

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Abstract

The UAVs(unmanned arieral vehicles) model is essentially a nonlinear, time-varying, multivariable, strongly coupled and complex system affected by environmental disturbance.Firstly, the dynamic model of uav is given, and then an adaptive controller is designed based on the dynamic inverse method. Considering the uav's actuator failures, model or parameter uncertainty and external disturbance, the extended kalman filter is designed on the basis of the corresponding fault detection method to real-time accurate detection of actuator fault location. Then, in the detection of actuator fault at the same time, the controller is designed based on control allocation method refactoring module, refactoring all healthy except fault actuator actuator control instruction;The simulation results show that in the case of actuator failure, the control torque of the UAV with the proposed method can be restored to the vicinity of actuator failure, and compared with the control effect of the adaptive controller alone, the attitude motion of the UAV is finally closer to the fault free state.

Keywords

Actuator fault;fault detection;adaptive controller;reconfigurable control.

1. Introduction

In various fields of today's society, UAVs(unmanned aerial vehicles) has been widely used [1,2], and will complete more tasks. UAVs often carry out long-term high-altitude operations without human direct control. In the case of interference or body damage, UAVs cannot be handled manually. Therefore, they must be able to deal with certain faults and failures, 4] However, once the actuator failure exceeds the UAV's response capability, its flight quality will inevitably be reduced, and immediate measures should be taken to ensure aircraft safety by designing reconfigurable control system. Reconfigurable control system usually includes fault detection system [5,6] and controller reconfiguration system [7,8], and can be combined with adaptive controller.

For the design of fault detection system, reference [9] proposed the method of constructing multi model adaptive estimation, which is based on a group of parallel Kalman filters, and its characteristic is that each specific fault has a corresponding Kalman filter corresponding to it. With regard to the design of controller reconfiguration system, reference [7,10,11] proposes that the control allocation method can be used to construct the virtual control signal in combination with the nature of UAV model without adding redundant controllers, and then reconstruct the UAV controller through the relationship between the UAV controller and the normal controller and the fault controller.

Due to the direct control of UAVs for a long time, its actuator may fail due to wear and interference. For the actuator failure fault, younes [12] and others proposed an intelligent output estimator to detect and diagnose the actuator fault. On this basis, combined with the active fault-tolerant control method, the controller signal is reconfigured to compensate for the

ISSN: 2664-9640

actuator fault. Li Y [13] etc. proposed a new integral sliding mode control method to solve the related problems caused by actuator fault and disturbance, and select appropriate parameters to ensure that the tracking error is bounded. Liu Xiaodong [14] and others generated residuals based on the extended Kalman filter method, and evaluated the generated residuals by using the chi square test, and realized the detection of UAV actuator fault. Zhou Yang [15] and others used the control allocation method to reconstruct the control command corresponding to the health actuator of UAVs to compensate for the unexpected flight attitude caused by the faulty actuator. Wang t et al. Aimed at the problem of actuator fault detection and fault-tolerant control of UAV under uncertain disturbance, the sliding mode control method was used to design the fault-free control scheme, and the backstepping method was used to design the control scheme under the fault condition. After the fault was detected by the sliding mode observer, the control scheme was switched, so as to reduce the impact of the fault actuator on the flight.

In this paper, based on the adaptive controller, a reconfigurable control system which can combine with adaptive controller is designed. The system includes fault detection system and controller reconfiguration system, which can reconstruct the controller while detecting the actuator failure of UAV, so as to realize the stable flight of UAV.

2. Modeling of fixed wing UAV

The attitude motion of UAV in space has three degrees of freedom rotating around the center of mass, which are roll, pitch and yaw motion. The interaction of aileron and lift wing produces roll moment and pitch moment, while that of directional wing and aileron generates yaw moment.

The attitude motion of UAV involves inertial coordinate system,airframe coordinate system and airflow coordinate system, which are represented by letters n ,letters n , b and w respectively. Where α and β are angle of attack and sideslip angle of UAV respectively, which can be obtained from the following formula:

$$\begin{cases} \dot{\alpha} = q + \dfrac{\rho V_T S C_{Z\alpha}}{2m} \alpha V \\ \dot{\beta} = q + \dfrac{\rho V_T S C_{Y1}}{2m} \beta \end{cases} \tag{1}$$

In formula (1): m is UAV mass, and other parameters are described below.

Considering that the roll, pitch and yaw attitude angles of UAVs relative to inertial coordinate system are expressed by φ , θ and ψ respectively, and the attitude angular velocity of UAV relative to aircraft body coordinate system is expressed by p , q and r respectively. The relationships among these variables are as follows:

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \boldsymbol{C}_n^b \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{2}$$

Here $\boldsymbol{C}_n^b$ is the rotation matrix from inertial coordinate system to body coordinate system, which is expressed as follows:

$$\boldsymbol{C}_n^b = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\varphi & \sin\varphi\cos\theta \\ 0 & -\sin\varphi & \cos\varphi\cos\theta \end{bmatrix} \tag{3}$$

According to Newton mechanics, the dynamic equation of UAV attitude system can be deduced as follows:

$$\dot{\boldsymbol{\Omega}}^b = (\boldsymbol{I}^b)^{-1}(\boldsymbol{M}^b - \boldsymbol{\Omega}^b \times (\boldsymbol{I}^b \cdot \boldsymbol{\Omega}^b)) \tag{4}$$

Where: I^b is the moment of inertia matrix of UAV, and $\boldsymbol{\Omega}^b = [p\ q\ r]^T$.

$$\boldsymbol{M}^b = \begin{bmatrix} \bar{q}SbC_L \\ \bar{q}S\bar{c}C_M \\ \bar{q}SbC_N \end{bmatrix}, \boldsymbol{I}^b = \begin{bmatrix} I_{xx} & 0 & I_{xz} \\ 0 & I_{yy} & 0 \\ I_{zx} & 0 & I_{zz} \end{bmatrix} \tag{5}$$

Where: $\bar{q} = \rho V_T^2/2$ is the aerodynamic pressure, V_T is the total airspeed of UAV, ρ is the air density; s is the total wing area; b is the wingspan; $\bar{c}$ is the average chord length; the roll, pitch and yaw moment of UAV are mainly controlled by C_L, C_M and C_N. also

$$\begin{cases} C_L = C_{L\alpha1}\delta_{a1} + C_{L\alpha2}\delta_{a2} + C_{Le1}\delta_{e1} + C_{Le2}\delta_{e2} + C_{L\beta}\beta + C_{L\tilde{p}}\tilde{p} + C_{L\tilde{r}}\tilde{r} \\ C_M = C_{M1} + C_{Me1}\delta_{e1} + C_{Me2}\delta_{e2} + C_{Ma1}\delta_{a1} + C_{Ma2}\delta_{a2} + C_{M\tilde{q}}\tilde{q} + C_{M\alpha}\alpha \\ C_N = C_{N\delta_r}\delta_r + C_{N\tilde{r}}\tilde{r} + C_{N\beta}\beta \end{cases} \tag{6}$$

Among them, the coefficients similar to the structure $C_{\Delta\Delta}$ are shown in Table 1;, respectively δ_{a1}, δ_{a2} are the left and right aileron controllers;, and δ_{e1}, δ_{e2} are the left and right lift wing controllers; δ_r are the directional wing controllers; and $\tilde{p} = bp/2V_T$, $\tilde{q} = \bar{c}q/2V_T$, $\tilde{r} = br/2V_T$ .In order to establish the matrix model of UAV attitude system, $\boldsymbol{x} = [p\ q\ r]^T$, $\boldsymbol{u} = [\delta_{a1}\ \delta_{a2}\ \delta_{e1}\ \delta_{e2}\ \delta_r]^T$,Then equation (4) can be written as follows:

$$\dot{\boldsymbol{x}} = \boldsymbol{F}\boldsymbol{x} + \boldsymbol{G}\boldsymbol{u} \tag{7}$$

Equation(7)is the ideal model of UAV attitude system, the UAV model under model uncertainty and without interference, that is $\boldsymbol{F} = \frac{\partial\dot{\boldsymbol{\Omega}}^b}{\partial\boldsymbol{x}}$, $\boldsymbol{G} = \frac{\partial\dot{\boldsymbol{\Omega}}^b}{\partial\boldsymbol{u}}$.

Considering the actuator failure in the actual operation of UAV, combined with equation (7), the mathematical model of fixed wing UAV attitude motion with integrated uncertainties and actuator failure can be expressed as follows:

$$\dot{\boldsymbol{x}} = \boldsymbol{F}\boldsymbol{x} + \boldsymbol{G}\boldsymbol{u} + \boldsymbol{D} \tag{8}$$

3. Design of reconfigurable control system

Reconfigurable control system includes fault detection and control reconfiguration, which can be combined with adaptive controller to detect fault and reconstruct UAV controller in time. $x_{k+1/k+1}$ and x_d in Fig. 1 are estimated values and expected values of x respectively;

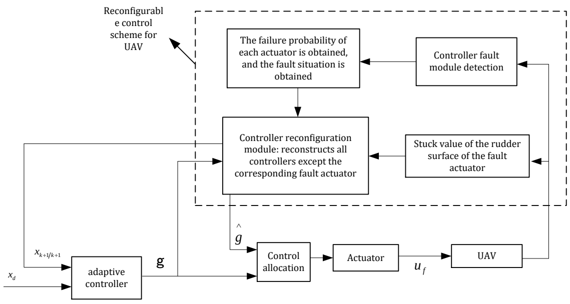

Figure 1: reconfigurable control system of UAV

3.1. Design of UAV adaptive controller

According to the dynamic inverse method and Lyapunov principle, the controller vector u is designed. For equation (8), the tracking error and its integral term are defined:

$$e = x_d - x_{k+1/k+1}, \quad K = \int_0^t e(\tau)d\tau \tag{9}$$

According to formula (9), a Lyapunov function is defined as

$$V(K,e)=\frac{1}{2}e^2+\frac{1}{2}\lambda K^2 \tag{10}$$

In the formula: $\lambda>0$ and $V(K,e)\geq 0$ are positive definite; moreover, deriving formula (10) and substituting it into equation (8), we can get:

$$\begin{aligned}\dot{V}(K,e)&=e\left(\dot{x}_d-\dot{x}+\lambda K\right)\\&=e\left(\dot{x}_d-(Fx+Gu+D)+\lambda K\right)\end{aligned} \tag{11}$$

In order to make formula (11) be: $\dot{V}(K,e)=-ke^2<0$, that is, negative definite:

$$u=G^{-1}\left(\dot{x}_d+ke+\lambda K-Fx-D\right) \tag{12}$$

In formula (12): $k>0,\lambda>0$.

3.2. Design of UAV actuator fault detection system

For UAV, there are five controllers in the controller vector. In order to design the actuator stuck fault detection module, it is necessary to construct the corresponding extended Kalman filter bank. The filter bank includes one filter for actuator no fault stuck fault and five filters for actuator stuck fault. The basic structure of single actuator fault detection module is shown in Figure 2.

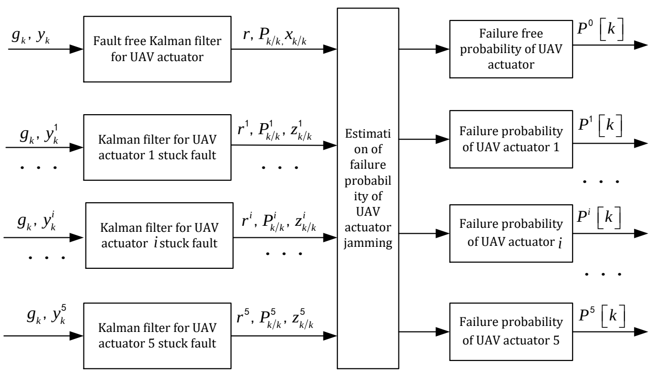

Figure 2 fault detection scheme for single actuator of UAV

The extended Kalman filter for actuator fault free is as follows,

$$\begin{cases}\dot{\boldsymbol{x}}_{k+1/k}=\boldsymbol{F}_k\boldsymbol{x}_{k/k}+\boldsymbol{G}_k\boldsymbol{g}_k+\hat{\boldsymbol{D}}_k\\ \boldsymbol{P}_{k+1/k}=\boldsymbol{F}_k\mathbf{P}_{k/k}\boldsymbol{F}_k^T+\boldsymbol{R}_w\\ \boldsymbol{L}_k=\boldsymbol{C}\ \boldsymbol{P}_{k+1/k}^T(\boldsymbol{C}\ \boldsymbol{P}_{k+1/k}^T\boldsymbol{C}^T+\boldsymbol{R}_v)^{-1}\\ \boldsymbol{x}_{k+1/k+1}=\boldsymbol{x}_{k+1/k}+\boldsymbol{L}_k(\boldsymbol{y}_k-\boldsymbol{C}\ \boldsymbol{x}_{k+1/k})\\ \boldsymbol{P}_{k+1/k+1}=\boldsymbol{P}_{k+1/k}-\boldsymbol{L}_k\boldsymbol{C}\ \boldsymbol{P}_{k+1/k}\\ \boldsymbol{r}_k=\boldsymbol{y}_k-\boldsymbol{C}\ \boldsymbol{x}_{k+1/k}\end{cases} \tag{13}$$

Among them, $\boldsymbol{F}_k=\boldsymbol{F}(\boldsymbol{x}(t_k))$, $\boldsymbol{G}_k=\boldsymbol{G}(t_k)$ and $\hat{\boldsymbol{D}}_k=\hat{\boldsymbol{D}}(t_k)$ are the system matrix and vector of UAV at t_k time, $\boldsymbol{g}_k=\boldsymbol{g}(t_k)$ is the control input of UAV at t_k time, and $\boldsymbol{y}_k=\boldsymbol{y}(t_k)$ is the state measurement vector of UAV at t_k time. $\mathbf{P}_{k/k}$ is the estimated value of state vector error covariance matrix at time t_k, $\mathbf{P}_{k+1/k}$ is the predicted value of state vector error covariance matrix at time t_k to t_{k+1} ,and $\mathbf{P}_{k+1/k+1}$ is the estimation value of state vector error covariance matrix at time t_{k+1}. $\boldsymbol{x}_{k/k}$. $\boldsymbol{x}_{k+1/k}$ and $\boldsymbol{x}_{k+1/k+1}$ are the state estimation value at time t_k , the state prediction value at time t_k and the state estimation value at time t_{k+1} respectively. In particular, the impact of integrated uncertainty on fault detection is offset by the estimated value of integrated uncertainty $\hat{\boldsymbol{D}}_k = \hat{\boldsymbol{D}}(t_k)$, so as to improve the accuracy of state prediction and fault detection.

For the extended Kalman filter design with single actuator fault, firstly, the state vector including the detection controller is designed as follows:

$$z_i = \begin{bmatrix} \boldsymbol{x}^T & \breve{\delta}_i \end{bmatrix}^T i \in [1,5] \tag{14}$$

In this case, the correlation matrix and vector need to be reconstructed into

$$\begin{cases} \boldsymbol{F}_i = \begin{bmatrix} \boldsymbol{F} & \boldsymbol{G}^{(i)} \\ 0 & 1 \end{bmatrix}, \ \boldsymbol{G}_i = \begin{bmatrix} \boldsymbol{G}^{(0,i)} \\ 0 \end{bmatrix} \\ \bar{\boldsymbol{D}}_i = \begin{bmatrix} \hat{\boldsymbol{D}}_i \\ 0 \end{bmatrix}, \bar{\hat{\boldsymbol{D}}}_i = \begin{bmatrix} \hat{\boldsymbol{D}}_i \\ 0 \end{bmatrix} \end{cases} \tag{15}$$

In formula (15): $\boldsymbol{G}^{(i)}$ is the i th column of G .Table $\boldsymbol{G}^{(0,i)}$ shows that column i of G is set to zero.

The discrete representation of attitude can be reconstructed

$$\dot{Z}_{ik+1} = F_{zik} z_{ik} + G_{zik} u_k + D_i + \omega_{fk} \tag{16}$$

The observation matrix of equation (16) is

$$y_{zik} = C_{zik} z_{ik} + v_{fk} \tag{17}$$

The design of Kalman filter in equation (17) is similar to that in equation (13), which can be obtained by replacing corresponding parameters.

Let the actuator failure case be $\bar{\delta}_i$, and the actuator failure free case be $\bar{\delta}_0$. For the case of actuator failure, according to the residual value $\boldsymbol{r}_{ik}$ and covariance matrix $\mathbf{P}_{ik/k}$ at time $t_k = kT_s$ in equation (13), the probability of obtaining $\boldsymbol{y}_k$ under measurement sequence $Y_{k\text{-}1}$ can be obtained.

$$p\left[y = \boldsymbol{y}_k \middle| \breve{\delta}_i = \bar{\delta}_i , Y_{k-1} \right] = \frac{1}{(2\pi)^{\bar{m}/2} \left| \mathbf{P}_{ik/k} \right|^{1/2}} e^{-\frac{1}{2}(\boldsymbol{r}_{ik})^T (\mathbf{P}_{ik/k})^{-1} \boldsymbol{r}_{ik}} \tag{18}$$

For each actuator, failure may occur at any time. Therefore, the same prior probability can be assigned to all faults. Based on this, equation (18) can be simplified as follows:

$$p_n[k] = p\left[\breve{\delta}_n = \bar{\delta}_n \middle| Y_k \right] = \frac{p\left[y = y_k \middle| \left(\breve{\delta}_n = \bar{\delta}_n , Y_{k-1} \right) \right] p_n[k-1]}{\sum_{h=0}^{5} p\left[y = y_k \middle| \left(\breve{\delta}_h = \bar{\delta}_h , Y_{k-1} \right) \right] p_h[k-1]} \tag{19}$$

In formula (19), $n \in (0,5)$ and $p_0(k)$ are the probability of no failure; $p_1(k) \sim p_5(k)$ is the probability of failure of δ_{a1}, δ_{a2}, δ_{e1}, δ_{e2} and δ_r respectively.

3.3 Design of controller reconfiguration system

The coupling relationship of several controllers in the control vector is

$$\begin{cases} C_L = C_{L\alpha1}\delta_{a1} + C_{L\alpha2}\delta_{a2} + C_{Le1}\delta_{e1} + C_{Le2}\delta_{e2} + C_{L\beta}\beta + C_{L\tilde{p}}\tilde{p} + C_{L\tilde{r}}\tilde{r} \\ C_M = C_{Me1}\delta_{e1} + C_{Me2}\delta_{e2} + C_{Ma1}\delta_{a1} + C_{Ma2}\delta_{a1} + C_{M\tilde{q}}\tilde{q} + C_{M\alpha}\alpha \\ C_N = C_{N\delta_r}\delta_r + C_{Ndrag}\left(\delta_{a1} + \delta_{a2}\right) + C_{N\tilde{r}}\tilde{r} + C_{N\beta}\beta \end{cases} \tag{20}$$

In order to facilitate the reconfiguration of the controller, the virtual control instruction can be constructed according to formula (6) and equation (20).

$$\boldsymbol{C}_v=\begin{bmatrix}C_L\\C_M\\C_N\end{bmatrix}=\begin{pmatrix}C_{L\alpha}\left(\delta_{a2}-\delta_{a1}\right)+C_{Le}\left(\delta_{e2}-\delta_{e1}\right)\\C_{M\alpha}\left(\delta_{a1}+\delta_{a2}\right)+C_{Me}\left(\delta_{e2}+\delta_{e1}\right)\\C_{N\delta_r}\delta_r+C_{Ndrag}\left(\delta_{a1}+\delta_{a2}\right)\end{pmatrix}\tag{21}$$

In equation (21) δ_{a1}, δ_{a2}, δ_{e1}, δ_{e2} and δ_r are given by the UAV adaptive controller.

Case 1: for single actuator failure, take actuator $p_i\left(k\right)\geq 0.6$ stuck fault as an example, and the failure probability obtained by fault detection module is 1. The controller instructions δ_{a2}, δ_{e1}, δ_{e2} and δ_r corresponding to the residual health actuator can be reconstructed to offset the unwanted torque caused by the stuck fault of actuator 1. The reconstructed controller instructions are put into vector $\hat{g}$ to replace the role of g in the control process. For the case of actuator 1 fault only, the controller reconfiguration scheme is as follows:

$$\begin{cases}\hat{\delta}_{a2}=\breve{\delta}_{a1}-C_{Lv}^d/C_{La}\\\hat{\delta}_{e1}=\left(\left(C_{Mv}^d-C_{Ma}\left(\breve{\delta}_{a1}+\hat{\delta}_{a2}\right)\right)/C_{Me}-\left(C_{Lv}^d-C_{La}\left(\hat{\delta}_{a2}-\breve{\delta}_{a1}\right)\right)/C_{Le}\right)/2\\\hat{\delta}_{e2}=\left(\left(C_{Mv}^d-C_{Ma}\left(\breve{\delta}_{a1}+\hat{\delta}_{a2}\right)\right)/C_{Me}+\left(C_{Lv}^d-C_{La}\left(\hat{\delta}_{a2}-\breve{\delta}_{a1}\right)\right)/C_{Le}\right)/2\\\hat{\delta}_r=\left(C_{Nv}^d-C_{Ndrag}\left(\breve{\delta}_{a1}+\hat{\delta}_{a2}\right)\right)/C_{N\delta_r}\end{cases}\tag{22}$$

Similarly, the design of control reconfiguration scheme for other single actuator failures is the same as formula (22).

For two cases of actuator failure at the same time. Taking the failure of actuator 1 and actuator 2 in UAV as an example, the reconfigurable controllers are as follows:

$$\begin{aligned}&\hat{\delta}_{e1}=\left(\left(C_{Mv}^d-C_{Ma}\left(\breve{\delta}_{a1}+\breve{\delta}_{a2}\right)\right)/C_{Me}-\left(C_{Lv}^d-C_{La}\left(\breve{\delta}_{a2}-\breve{\delta}_{a1}\right)\right)/C_{Le}\right)/2\\&\hat{\delta}_{e2}=\left(\left(C_{Mv}^d-C_{Ma}\left(\breve{\delta}_{a1}+\breve{\delta}_{a2}\right)\right)/C_{Me}+\left(C_{Lv}^d-C_{La}\left(\breve{\delta}_{a2}-\breve{\delta}_{a1}\right)\right)/C_{Le}\right)/2\\&\hat{\delta}_r=\left(C_{Nv}^d-C_{Ndrag}\left(\breve{\delta}_{a1}+\breve{\delta}_{a2}\right)\right)/C_{N\delta_r}\end{aligned}\tag{23}$$

Similarly, the control reconfiguration scheme design of the other two actuators with simultaneous failure is the same as equation (23).

4. Simulation and analysis

The experimental simulation platform is matlab, and the relevant physical parameters of fixed wing UAV are shown in Table 1[16].

Table 1 Parameters of UAV attitude motion model

Sign	value	unit	sign	value	unit
I_{xx}	2.56	kg·m^2	$C_{L\beta}$	0.087	/
I_{yy}	10.9	kg·m^2	m	28	kg
I_{zz}	11.3	kg·m^2	b	3.1	m
I_{xz}	0.5	kg·m^2	$\bar{c}$	0.58	m
I_{zx}	I_{xz}	kg·m^2	$C_{N\beta}$	0.087	/
$C_{N\delta}$	0.053	/	ρ	1.29	kg/m^3
S	1.8	m^2	V_T	10	m/s

ISSN: 2664-9640

$C_{M\alpha}$	-0.09	/	$C_{L\bar{r}}$	0.036	/
$C_{L\bar{p}}$	-0.19	/	$C_{N\bar{r}}$	-0.21	/
C_{Y1}	-0.38	/	C_{La1}	-0.03	/
$C_{M\bar{q}}$	-9.83	/	C_{La2}	$-C_{La1}$	/
$C_{Z\alpha}$	-3.25	/	C_{Le1}	-0.05	/
C_{Me1}	0.272	/	C_{Le2}	$-C_{Le1}$	/
C_{Me2}	C_{Me1}	/	C_{Ma1}	0.038	/
C_{Ma2}	C_{Ma1}	/			

In order to verify the effectiveness of the reconfigurable control system of UAV under complex motion, the flight state of UAV is assumed to be a spiral upward motion tending to a certain altitude. Three groups of simulation experiments are set up, in which two groups of simulation experiments are completed under the same controller fault. One group only provides adaptive controller for UAV, and the other group adds reconfigurable control system . These two groups of simulation experiments will be compared with UAV simulation results under the fault of UAV, so as to analyze the effectiveness of reconfigurable control system.

According to the curve of failure probability with time given in Fig. 3, it can be seen that the designed actuator fault detection module can accurately detect the stuck fault of UAV in a very short time. On this basis, combined with the designed controller reconfiguration module, when the actuator is stuck, the actuator stuck fault can be detected in time, and the unexpected control torque caused by the faulty actuator can be compensated by reconstructing the control command of the healthy actuator. It can be seen from Fig. 4 that after the actuator is jammed, the control torques of the UAV reconstructed by the controller can be recovered near the expected value.

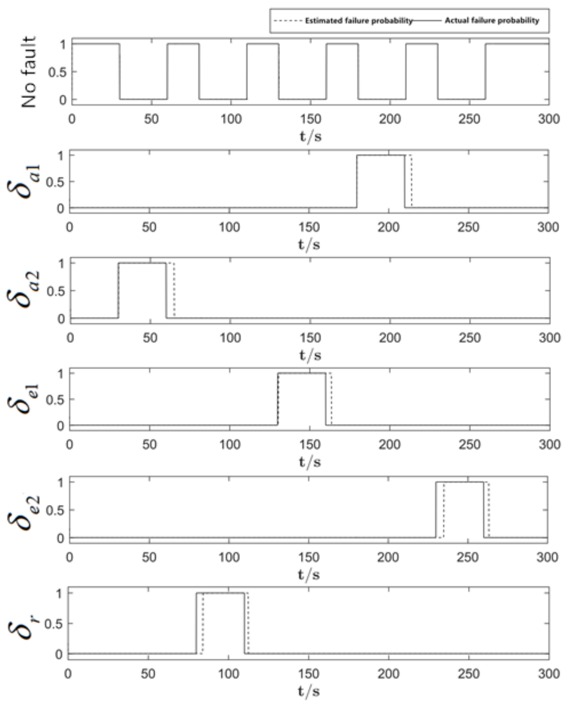

Figure 3 Fault probability estimation

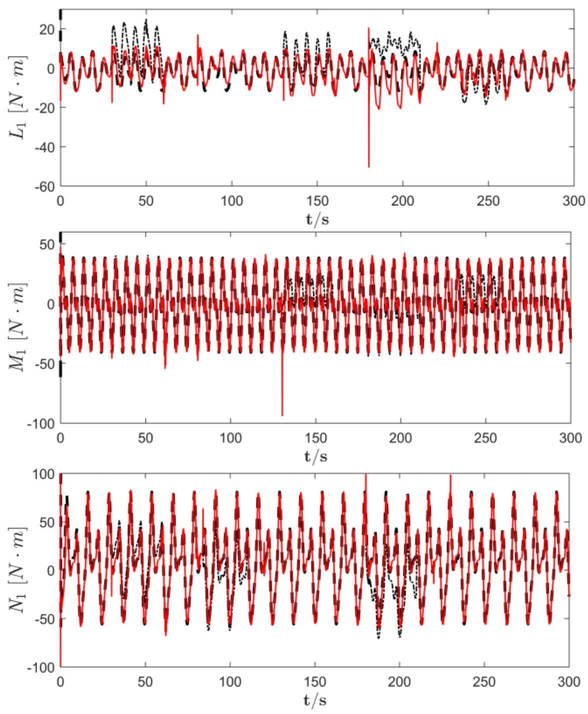

Figure 4 Reconstruction torque

Acknowledgements

This work was supported in part by Sichuan Science and Technology Program (No. 2020YJ0368), Zigong Science and Technology Program (No.2019YYJC03), Nature Science Foundation of Sichuan University of Science & Engineering (Nos. 2018RCL18,2017RCL52); Research Foundation of Department of Education of Sichuan Province (No. 17ZA0271); Foundation of Artificial Intelligence Key Laboratory of Sichuan Province (No.2017RZJ02). The innovation Fund of Postgraduate , Sichuan University of Science & Engineering(y2019014).

References

[1] PARK J K, DAS A, PARK J H. Application Trend of Unmanned Aerial Vehicle (UAV) Image in Agricultural Sector: Review and Proposal[J]. Korean Journal of Agricultural, 2015, 42(3): 269-276.

[2]MENOUAR H, GUVENC I, AKKAYA K, et al. UAV-Enabled Intelligent Transportation Systems for The Smart City:Applications and Challenges[J]. IEEE Communications, 2017,55(3):22-28.

[3]Wang Siming, Li Weijie, Han Lele, etal. Model reference fault tolerant control of six rotor UAV with control allocation[J]. Flight mechanics, 2018,36(02):26-30.

[4]Xie Menglei,Wei Xianli, Wang Huan. Passive fault tolerant control of UAV rudder damage based on ADRC[J]. Tactical missile technology, 2017(06):83-88.

[5]ZHONG Y, ZHANG Y, ZHONG W. Robust Actuator Fault Detection and Diagnosis for a Quadrotor UAV With External Disturbances[J]. IEEE Access, 2018,6:48169-48180.

[6]OLYAEI M H, JALALI H, NOORI A, et al. Fault Detection and Identification on UAV System with CITFA Algorithm Based on Deep Learning[D]. IEEE, 2018.

[7]MORADI R, ALIKHANI A, JEGARKANDI M F. Comparing the Performance of Reference Trajectory Management and Controller Reconfiguration in Attitude Fault Tolerant Control[D]. EDP Sciences, 2018.

[8]XIAOYUN L, WEI D. Reconfigurable Fault Tolerant Control for Spacecraft Based on Modified IMM Algorithm[D]. EDP Sciences, 2018.

[9]DUCARD G J. Fault-Tolerant Flight Control and Guidance Systems: Practical Methods for Small Unmanned Aerial Vehicles[M]. Springer Science ＆ Business Media, 2009.

[10] DUCARD J. Fault-Tolerant Flight Control and Guidance Systems for A Small Unmanned Aerial Vehicle[D]. ETH Zurich, 2007.

[11] SERRADI A, BOLENDER M A. Nonlinear Adaptive Reconfigurable Controller for A Generic 6-DOF Hypersonic Vehicle Model[D]. IEEE, 2014.

[12]AI Y Y, Noura H, Rabhi A, et al. Actuator Fault-Diagnosis and Fault-Tolerant-Control using intelligent-Output-Estimator Applied on Quadrotor UAV[C]//2019 International Conference on Unmanned Aircraft Systems (ICUAS).IEEE, 2019:413-420

[13]Li Y, Yang G. Adaptive integral sliding mode control fault tolerant control for a class of uncertain nonlinear systems[J]. IET Control Theory & Applications, 2018,12(13):1864-1872.

[14]Liu Xiaodong,Zhong Maiying,Liu Hai. Fault detection of UAV flight control system based on EKF[J]. Journal of Shanghai Jiaotong University, 2015,49(06):884-888.

[15]Zhou Yang,Chen Yong, Dong Xinmin, etal. Control allocation method for fault reconfiguration of control surface based on controllability[J]. Flight mechanics, 2018,36(05):34-38.

[16]Tang Yu,Lin Da, Cao Lijia, etal. Attitude control of fixed wing UAV under model uncertainty and disturbance[J]. Electro optic and control, 2020,27(01):85-89.