Observer-based actuator fault detection for UAV

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Abstract. This paper focuses on the actuator fault detection for UAV. Firstly, the longitudinal dynamics model of UAV with actuator faults and atmosphere turbulence is given. Based on this, an observer-based fault detection filter is applied for residual generation, and a H_i/H_∞ performance index is introduced, which describes the sensitivity to fault as well as the robustness against unknown disturbance, then the design of residual generator is formulated as an H_i/H_∞ optimization problem. And then, the 2-norm based residual evaluation function and the corresponding threshold are used for residual evaluation. Finally, the simulations with certain type of UAV are presented to verify the effectiveness of the proposed method.

Introduction

Nowadays, unmanned aerial vehicle (UAV) is widely used in the fields of research and practical, due to its particular features. Meanwhile, the security and reliability of UAV flight control system (FCS) attracts much attention throughout the world [1]. The actuators are the key part of FCS, and play an important role to guarantee the security and reliability of UAV. However, in long endurance flight mission, actuators inevitably surfing from some faults such as stuck or partial damage etc., the serious situation would leads to the crash accident. One promising approach to improving the safety and reliability of UAV is employing the fault detection method [2].

Many researches have been done at home and abroad for the problem of actuator fault detection [1]-[3]. Among these achievements, observer-based fault detection (FD) proves to be an effective method. Its basic idea is to generate a residual by designing a fault detection filter (FDF), and then the suitable residual evaluation function and threshold are selected to evaluate the residual. For the aircraft would face all kinds of unknown disturbances, like atmosphere turbulence, random noise and so on. So the robust fault detection for UAV has become an important aspect of research. One salutation is to design a FDF, which is decoupled from disturbances, e.g. [3]. While it's difficult to satisfy the conditions of decouple in real systems. Recently, another more commonly used method is H_i/H_∞ optimization technology. It employs H_i norm and H_∞ norm to describe the sensitivity to fault and the robustness against the unknown disturbances, respectively, and based on this, the FDF design is formulated to the optimal H_i/H_∞ performance index problem. This method can achieve a good tradeoff between the sensitivity to fault and robustness against disturbances, and a unified solution has been given for linear system in [4], which is easy to implement in practical.

Considering the practical needs of actuator fault detection for UAV, this paper applies the optimal H_i/H_∞ based method for FDF design. Firstly, the actuator faults are disturbed as additive faults, and the longitudinal dynamics model with actuator faults and disturbances is given. Then the FDF is designed based on optimal H_i/H_∞ based method, and the residual evaluation function and threshold based on 2-norm are determined for residual evaluation. Finally, the simulations with certain type of UAV are illustrated to verify the effectiveness of the proposed approach.

Longitudinal Dynamics of UAV with actuator fault

Here a fixed-wing UAV is considered. The UAV model is based around the six-degree-freedom nonlinear aircraft model. By using the small perturbation theory, the nonlinear model can be linearized. Considering the atmosphere turbulence disturbance, the linearized longitudinal dynamics equations of the UAV is [5]

$$\begin{cases} \Delta\dot{V} = -X_V(\Delta V - w_x) - X_a\Delta a - X_q\Delta q - X_{d_T}\Delta d_T + (X_a + X_q)\,w_g/V_0 \\ \Delta\dot{a} = -Z_V\Delta V - Z_a\Delta a + \Delta q - Z_{d_e}\Delta d_e + Z_V w_x + Z_a\; w_g/V_0 \\ \Delta\dot{q} = -(M_V - M_{\dot{a}}Z_V)(\Delta V - w_x) - (M_a - M_{\dot{a}}Z_a)(\Delta a - w_g/V_0) - (M_q + M_{\dot{a}})\Delta q - \\ \quad (M_{d_e} - M_{\dot{a}}Z_{d_e})\Delta d_e - M_{d_T}\Delta d_T + (M_{\dot{a}} - M_q)w_{gx} \\ \Delta\dot{q} = \Delta q \\ \Delta H = N_V\Delta V - N_V w_x - N_a(\Delta a - w_g/V_0) + N_q\Delta q \end{cases} \tag{1}$$

Where V_0 is the velocity of the aircraft; $\Delta V, \Delta a, \Delta q, \Delta q$ and ΔH are the changes of the aircraft velocity, attack angle, pitching angle, pitching angle rate and height, respectively; Δd_e and Δd_T are the changes of elevator and thrust, respectively; w_x and w_g are the turbulence velocity; w_{gx} is the gradient of w_g along the X axis; $X_V, X_a, X_q, X_{d_T}, Z_V, Z_a, Z_q, Z_{d_e}, M_V, M_a, M_{\dot{a}}, M_q$, $M_{d_T}, M_{d_e}, N_V, N_a, N_q$ are the constant parameters, which are determined by the aircraft configuration parameters and the aerodynamic derivatives in steady state flight.

Actuators are the important parts to guarantee the the security and reliability of aircraft, but they inevitably face unexpected incidents, such as actuator stuck or the rudder damage etc.. The typical actuator faults include stuck, damage and basis fault. Without loss of generality, these faults can be modeled as additive faults. For the FCS is closed-loop system, the introduction of a feedback control makes the impact caused by the early failure or the small amplitude faults masked by the control function. For this reason, it becomes more difficult to detect the actuator faults for UAV [6].

Here the system state variables are selected as $x = [\Delta V \;\; \Delta a \;\; \Delta q \;\; \Delta q \;\; \Delta H]^T$, the input variables are $u = [\Delta d_e \;\; \Delta d_P]^T$, the output variables are $y = [\Delta V \;\; \Delta\bar{a} \;\; \Delta\bar{q} \;\; \Delta\bar{q} \;\; \Delta H]^T$, the unknown disturbances are collectively described as $d = [d_w^T \;\; v^T]^T$, where v is the measurements noise, $d_w = [w_x \;\; w_g \;\; w_{gx}]^T$ is the atmosphere turbulence disturbance. Then the longitudinal model of UAV in the state space form is

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + E_d d(t) + Bf(t) \\ y(t) = Cx(t) + F_d d(t) \end{cases} \tag{2}$$

Where $x \in R^{k_x}$, $u \in R^{k_u}$, $y \in R^{k_y}$, A、B、C are the known system coefficient matrixes, $E_d = [B_d \;\; \mathbf{0}]$, $F_d = [\mathbf{0} \;\; I_{k_y}]$, I_{k_y} is a unit matrix, $\mathbf{0}$ is a zeros matrix, B_d is the turbulence coefficient matrix.

Design of actuator fault detection system for UAV

Considering the longitudinal dynamic system mentioned in Eq. (1), in general, it is always reasonable to assume that the unknown disturbance d is L_2 norm bounded, (C, A) is observable, and $\begin{bmatrix} A - jwI & E_d \\ C & F_d \end{bmatrix}$ has full row rank for all $w \in [0, \infty)$. Then a FDF based on observer is designed as follows to generate residual:

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L\big(y(t) - \hat{y}(t)\big) \\ \hat{y}(t) = C\hat{x}(t) \\ r(t) = R(s)\big(y(t) - \hat{y}(t)\big) \end{cases}$$

(3)

Where r is the residual signal, $\hat{x}$, $\hat{y}$ are the estimates of x, y, respectively; L and $R(s)$ are the observer gain matrix and the post-filter to be designed, respectively.

By defining the state estimation error $e(t) = x(t) - \hat{x}(t)$, it follows from Eq. (2) and Eq. (3) that

$$\begin{cases} \dot{e}(t) = (A - LC)e(t) + (E_d - LF_d)d(t) + Bf(t) \\ r(t) = R(s)\left(Ce(t) + F_d d(t)\right) \end{cases} \tag{4}$$

In frequency domain, the residual can be represented as

$$r(s) = R(s)\left(G_{dm}(s)d(s) + G_{fm}(s)f(s)\right) \tag{5}$$

Where $G_{dm}(s) = C(sI - A + LC)^{-1}(E_d - LF_d) + F_d$, $G_{fm}(s) = C(sI - A + LC)^{-1}B$ are the transfer functions from d and f to r.

For the real UAV system, it's almost impossible to decouple disturbances d from the residual. A promising method is to employ the H_i/H_∞ performance index, in which the sensitivity to fault is evaluated by the non-zero singular value $s_i\left(R(jw)G_{fm}(jw)\right)$, and the robustness against unknown disturbances is evaluated by the H_∞-norm $\left\|R(s)G_{dm}(s)\right\|_\infty$. Then the FDF design is converted to the following H_i/H_∞ performance index optimization problem:

$$\sup_{L,R} J_{i/\infty} = \sup_{L,R} \frac{s_i\left(R(jw)G_{fm}(jw)\right)}{\left\|R(s)G_{dm}(s)\right\|_\infty} \quad , \quad w \in [0, \infty) \tag{6}$$

For this optimization problem, a unified solution has been given in [4], just as follows:

$$L_{opt} = \left(E_f F_f^T + YC^T\right)\left(F_d F_d^T\right)^{-1}, R_{opt} = \left(F_d F_d^T\right)^{-1/2} \tag{7}$$

Where $Y \geq 0$ is a solution of algebraic Riccati equation

$$AY + YA^T + E_d E_d^T - \left(E_d F_d^T + YC^T\right)\left(F_d F_d^T\right)^{-1}\left(F_d E_d^T + CY\right) = 0 \tag{8}$$

By solving the Riccati equation, the optimal solutions (L_{opt}, R_{opt}) can be obtained. Through bringing (L_{opt}, R_{opt}) into Eq. (3), the design of residual generator is accomplished.

In the stage of residual evaluation, the residual evaluation function $J(r)$ based on 2-norm of residual is used. For the evaluation just within finite time is realizable in practical applications, the residual evaluation function $J(r)$ is defined as

$$J(r) = \|r\|_{2,T} = \sqrt{\int_{t_1}^{t_2} r^T(t)r(t)dt} \ , \ T = t_2 - t_1 \tag{9}$$

In fault-free cases, the corresponding threshold J_{th} is confirmed as follows:

$$J_{th} = \sup_{d \in L_2, f=0} \|r\|_2 = \sup\left\|R(jw)G_{dm}(jw)d(t)\right\|_2 \tag{10}$$

By defining $g = \left\|R(jw)G_{dm}(jw)\right\|_\infty, \|d\|_2 \leq d$, according to the unified solutions, γ=1. there exists the following norm inequality

$$\sup\left\|R(jw)G_{dm}(jw)d(t)\right\|_2 \le \left\|R(jw)G_{dm}(jw)\right\|_\infty \sup\left\|d\right\|_2 = gd \tag{11}$$

According to above analysis, the threshold is confirmed to be $J_{th} = d$. The decision logic of fault detection is shown as follows:

$$\begin{cases} J(r) \le J_{th}, & fault\text{-}free; \\ J(r) > J_{th}, & fault \end{cases} \tag{12}$$

Simulation Results

In order to verify the effectiveness of the presented method, simulations are carried on in MATLAB environment with certain type of UAV. The system coefficient matrices shown in (3) respectively are

$$A = \begin{bmatrix} -0.0671 & 9.105 & 0 & -9.8 & 0 \\ -0.0314 & -2.60 & 0.979 & 0 & 0 \\ 0.0132 & -5.37 & -0.965 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & -24 & 0 & 24 & 0 \end{bmatrix} B = \begin{bmatrix} 0 & 0.09461 \\ -0.0020 & 0 \\ -0.1475 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} C = I_5 \; B_d = \begin{bmatrix} -0.0671 & 0.029 \\ -0.0314 & 0.108 \\ 0.0132 & 0.224 \\ 0 & 0 \\ 0 & -1 \end{bmatrix}$$

Consider the measurements noise is a white noise vector, and every element is uniformly distributed between $[-0.1, 0.1]$. Ignoring the gradient disturbance w_{gx}, and the Dryden model is used to describe the turbulence velocity w_x and w_g for simulation purposes, i.e.

$$w_x = w_g = \sqrt{\frac{3V_0 s_w^2}{p L_w}} \frac{V_0/(\sqrt{3}L_w) + s}{[V_0/L_w + s]^2} n \tag{13}$$

Where n is a zero-mean Gaussian white noise, the turbulence scale is $L_w = 480m,$ and the turbulence intension is $s_w = 6\,m/s$. Moreover, the disturbance satisfies $\left\|d\right\|_2 \le d = 1.021$.

The simulations are realized in 100 seconds with 0.01 seconds of sampling time. The evaluation window is set as $T = 1s$. To test the effectiveness of proposed method, following cases are considered.

Case (1): the elevator actuator gets stuck at 20s, and the amplitude of the fault is 0.1° , the detection result is shown on Fig.1.

Case (2): for the reasons of elevator surface damage or icing, the execution efficiency of actuator decline 10% during 20~40s and decline 30% during 60~80s, the detection result is shown on Fig.2.

Case (3): the elevator actuator occurs 0.1° constant basis fault from 20s to 60s, the detection result is shown on Fig.3.

*Case (4): t*he elevator actuator occurs time-varying basis fault during 20~60s, whose amplitude is 0.1° and the frequency is set 0.2Hz, the detection result is shown on Fig.4.

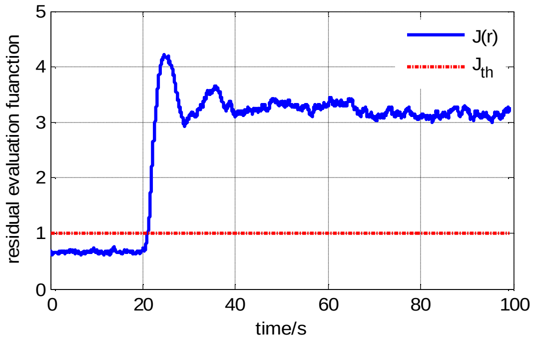

Fig.1 Elevator 0.1° stuck fault detection

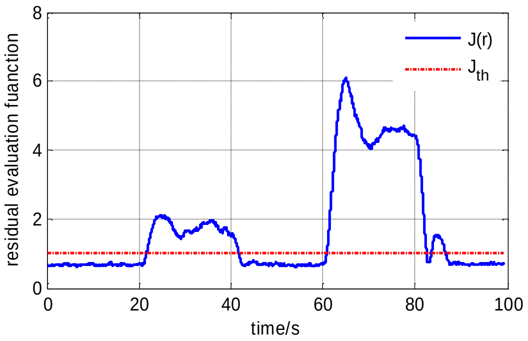

Fig.2 Elevator 10% and 30% damage fault detection

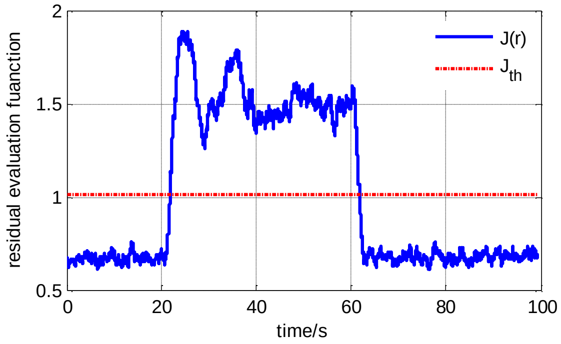

Fig.3 Elevator 0.1° basis fault detection

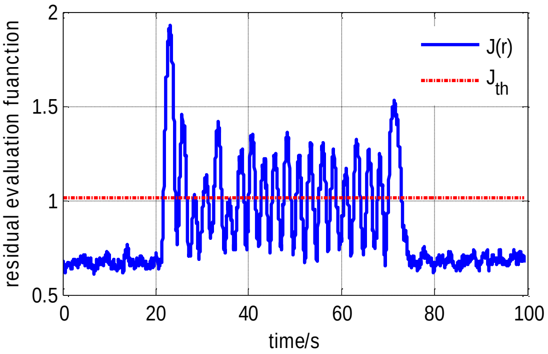

Fig.4 Elevator 0.2Hz time-varying basis fault detection

From the above simulation results shown on the figures from one to four, it is seen that the proposed method can obviously detected different kinds of actuator faults, such as stuck fault, partial damage fault, constant basis fault and time-varying basis fault. Meanwhile, the detection time-delay is small, which means a good real-time of fault detection system. In addition, the design of fault detection system is as simple as to be employed in practical applications.

Summary

In this paper, a simultaneous fault detection method has been proposed to detect actuator faults for UAV. The longitudinal dynamics model of UAV was given firstly, and the actuator faults can be considered as an additive faults. Based on this, the fault model was built. For the purpose of fault detection, a fault detection filter was designed with the optimal H_i/H_∞ performance index. And then, a 2-norm based residual evaluation function and threshold were introduced for residual evaluation to realize the actuator fault detection. Finally, the simulation results show that, this method can simultaneously detect the actuator faults effectively and fleetly. Moreover, the design and implement of the fault detection system is simple in practical applications.

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