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Observer-based FDI design of networked control system with output transfer delay

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Abstract: Networked control system (NCS) was regarded as a sampled-data control system with output time-delay and a mathematical model was set up. So a fault observer was constructed, and the indicator of system faults-residual was generated. Then fault detection and isolation (FDI) approach based on this observer was introduced. The design algorithm of the FDI observer was summarized. At last, an example is given to show the approach is feasible.

Key words: fault detection; fault isolation; networked control system; observer; time-delay

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带有输出传输时延的网络化控制系统基于观测器的 FDI 设计

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摘要：将网络控制系统(NCS)看成一个具有输出时延的采样控制系统，并建立了其数学模型．接着构造了一个故障观测器，产生了系统故障的指示器残差．然后在此基础上介绍了一种故障检测和分离(FDI)的方法，总结了 FDI 观测器的设计算法．最后，一个实例证明了此方法的可行性．

关键词：故障检测；故障分离；网络化控制系统；观测器；时延

1 Introduction

Networked control system (NCS) is an emerging research topic which has received increasing attention. Nowadays NCS can be found in manufacturing plants, aircraft, automobiles, and many other systems. In NCS, the information not only from sensors to controller but also from controller to actuator is transmitted by network, such as serial communication channel[1].

From Fig. 1, we can see networked control system contains continuous-time plant and discrete-time controller. They can be synchronized by sending synchronous signal through the network. So NCS is factually sampled-data control system. We can discretize the continuous plant of NCS to get the discrete model.

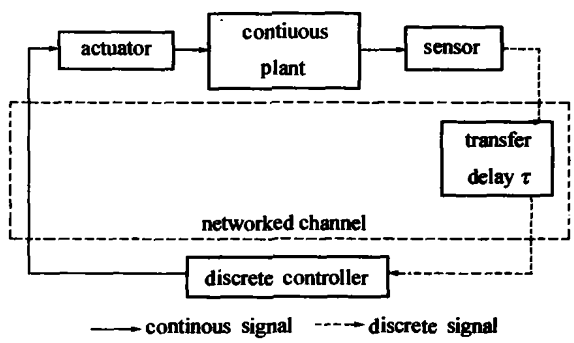

Fig. 1 Networked control system

One of the basic problem of NCS is the time-delay. In this paper the processing time of the observer and controller is omitted. So time-delay is actually transfer-delay τ. Obviously τ is time-variant. We assume the maximum of τ is limited.

For observer-based fault detection and isolation (FDI)

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approach, the generation of residual $r(t)$ is a crucial issue. Generally, fault is detected by comparing the residual to zero: $r(t)$ equals to zero for the fault-free case; otherwise it will be non-zero. If $r(t)$ has a fixed direction when responding to a fault, fault isolation is achieved. Though there are lots of observer-based FDI results, few is for time-delay system.

This paper deals with the fault diagnosis problems of networked control system. An FDI observer is presented. Then the FDI scheme is set up.

2 Problem formulation

From Fig.1, we can get the continuous-time, state-space model of the linear time-invariant plant dynamics

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + B_d d(t) + B_f f(t), \\ y(t) = Cx(t) + Df(t), \end{cases} \tag{1}$$

where $x(t)$ is the state vector, $u(t)$ and $y(t)$ are the control and output vector, $d(t)$ is the unknown input (or disturbance) vector, $f(t)$ is the unknown fault vector, which includes the actuator fault $f_a(t)$ and the sensor fault $f_s(t)$. Matrices A, B, B_d, B_f, C, D are of compatible dimensions.

Discretize (1), we can get

$$\begin{cases} x(k+1) = \hat{A}x(k) + \hat{B}u(k) + \hat{B}_d d(k) + \hat{B}_f f(k), \\ y(k) = \hat{C}x(k) + \hat{D}f(k), \end{cases} \tag{2}$$

where

$$\begin{cases} \hat{A} = \mathrm{e}^{AT},\ \hat{C} = C,\ \hat{D} = D, \\ \hat{B} = \int_0^T \mathrm{e}^{A(T-s)} B\mathrm{d}s, \\ \hat{B}_d \hat{d} = \int_0^T \mathrm{e}^{A(T-s)} B_d d(s)\mathrm{d}s, \\ \hat{B}_f \hat{f} = \int_0^T \mathrm{e}^{A(T-s)} B_f f(s)\mathrm{d}s. \end{cases} \tag{3}$$

Because of the network-induced delay the input of the discrete controller is $w(k) = y(k-\tau_k)$. And τ_k is the sampled periods' number of delay.

Yu Z X et al[2] designed a state observer and proved its observablity. In this paper we extend that and construct an output fault observer which can compensate the transfer delay.

Iterate the following equation

$$x(k+1) = \hat{A}x(k) + \hat{B}u(k) + \hat{B}_d d(k) + \hat{B}_f f(k),$$

we can get

$$x(k-\tau_k) = \hat{A}^{-\tau_k}x(k) - \sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}u(k-i) - \sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}_d d(k-i) - \sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}_f f(k-i), \tag{4}$$

$$w(k) = y(k-\tau_k) = A^{-\tau_k}x(k) - \hat{C}\sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}u(k-i) - \hat{C}\sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}_d d(k-i) - \hat{C}\sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}_f f(k-i) + \hat{D}f(k-\tau_k). \tag{5}$$

The observer with the compensation function has the following structure

$$\begin{aligned} &\hat{x}(k+1) = \\ &\hat{A}\hat{x}(k) + \hat{B}u(k) + F_{\tau_k}(w(k) - \\ &(\hat{C}\hat{A}^{-\tau_k}\hat{x}(k) - \hat{C}\sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}u(k-i))), \\ &y(k) = \hat{C}\hat{x}(k). \end{aligned} \tag{6}$$

Combine (2) and (6),

$$e(k+1) = x(k+1) - \hat{x}(k+1) = L_{\tau_k}e(k) + F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}_d d(k-i) + \hat{B}_d d(k) + F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}_f f(k-i) + \hat{B}_f f(k) - F_{\tau_k}\hat{D}f(k-\tau_k), \tag{7}$$

where $L_{\tau_k} = \hat{A} - F_{\tau_k}\hat{C}\hat{A}^{-\tau_k}$.

Now we have the following theorem:

Lemma 1 To system(1), if $(\hat{A}, \hat{C})$ is observable, then L_{τ_k} can deploy the poles freely for any transfer delay τ_k.

Proof See[2].

3 Residual generation and fault detection

The z-transform of $e(k)$ can be got from (7):

$$e(z) = (zI - L_{\tau_k})^{-1}(F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}_d z^{-i}I + \hat{B}_d)d(z) + (zI - L_{\tau_k})^{-1}(F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k} \hat{A}^{i-\tau_k-1}\hat{B}_f z^{-i}I + \hat{B}_f + F_{\tau_k}\hat{D}^{-\tau_k}I)f(z). \tag{8}$$

The residual $r(t)$ is generated from the error of the actual and estimated measurements of the output:

$$r(k) = Qe_y(k) = Q(y(k) - \hat{y}(k)) = Q\hat{C}e(k) + Q\hat{D}f(k). \tag{9}$$

From (8) and (9), we have

$$r(z) = Q\hat{C}(zI - L_{\tau_k})^{-1}(F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k}\hat{A}^{i-\tau_k-1}\hat{B}_d z^{-i}I + \hat{B}_d)d(z) + [Q\hat{D} + Q\hat{C}(zI - L_{\tau_k})^{-1}(\hat{B}_f - F_{\tau_k}\hat{D}z^{-\tau_k}I + F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k}\hat{A}^{i-\tau_k-1}\hat{B}_f z^{-i}I)]f(z). \tag{10}$$

(10) indicates that the residual r is only relevant with the disturbance d and the fault f. To design a disturbance decoupled residual, we need to make the transfer function from the disturbance to the residual G_{rd} be zero, while G_{rf}, which denotes the transfer function from the fault to the residual, should not be zero. That is

$$G_{rd} = Q\hat{C}(zI - L_{\tau_k})^{-1}E_{\tau_k} = Q\hat{C}(zI-L_{\tau_k})^{-1}(\hat{B}_d+F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k}\hat{A}^{i-\tau_k-1}\hat{B}_d z^{-i}I) = 0, \tag{11}$$

$$G_{rf} = Q\hat{D} + Q\hat{C}(zI - L_{\tau_k})^{-1}(\hat{B}_f - F_{\tau_k}\hat{D}z^{\tau_k}I + F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k}\hat{A}^{i-\tau_k-1}\hat{B}_f z^{-i}I) \neq 0. \tag{12}$$

But it is a complicated process to achieve (11) and (12) because the transfer delay is time-variant. In actual systems, some measures can be taken to change the time-variant delay into relative constant delay in order to simplify the problem[2,3]. So the following lemma is designed to achieve (11).

Lemma 2 Set $H = Q\hat{C}$, then the sufficient conditions for satisfying the disturbance de-coupling requirement (11) are either of the following:

1) $H\hat{B}_d = 0, HF_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k}\hat{A}^{i-\tau_k-1}\hat{B}_d = 0, HL_{\tau_k} = 0;$

2) $H\hat{B}_d = 0, HF_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k}\hat{A}^{i-\tau_k-1}\hat{B}_d = 0, L_{\tau_k}\hat{B}_d = 0.$

Proof (11) can be expanded as

$$G_{rd} = H(zI - L_{\tau_k})^{-1}E_{\tau_k} = z^{-1}H(I+L_{\tau_k}z^{-i}+L_{\tau_k}^2 z^{-2} + \cdots)(\hat{B}_d + F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k}\hat{A}^{i-\tau_k-1}\hat{B}_f z^{-i}I).$$

Obviously when conditions 1) or 2) is satisfied we can conclude $G_{rd} = 0$.

Remark When condition 1) holds true, (12) will be

$$G_{rf} = Q\hat{D} + z^{-1}H(\hat{B}_f - F_{\tau_k}\hat{D}z^{\tau_k}I + F_{\tau_k}\hat{C}\sum_{i=1}^{\tau_k}\hat{A}^{i-\tau_k-1}\hat{B}_f z^{-i}I).$$

The design of F_{τ_k}, L_{τ_k} will be lucubrated in the next section.

4 Fault isolation and design algorithm

In general, fault isolation task can be fulfilled via a directional residual vector. Presume $G_{rf} \in \mathbb{R}^{p\times m}(p < m)$. If G_{rf} has full row rank p, then we can easily find a matrix $P_O \in \mathbb{R}^{m\times p}$ so that $P_O G_{rf} \in \mathbb{R}^{p\times p}$ is invertible. Residue matrix coefficient can be designed as

$$P(z) = \Lambda(z)[P_O(z)G_{rf}(z)]^{-1}P_O, \tag{13}$$

where $\Lambda(z)$ is in a $p \times p$ diagonal form. So the transfer function from fault to residual $P(z)G_{rf}(z) = \Lambda(z)$ is in a diagonal form. The fixed-direction residual make fault isolation possible[4].

If G_{rf} is not of full column rank, the above design method is not feasible. Under such a circumstance, we can achieve optimal fault isolation design. That is to find $P(z)$ which minimizes the following performance index:

$$J_O = \| \Lambda(z) - P(z)G_{rf}(z) \|_\infty, \tag{14}$$

where $\| \cdot \|_\infty$ denotes H_∞-norm which is defined as $\| G \|_\infty = \sup \bar{\sigma}\{G\}$.

The realization of (14) is a standard model-matching problem in robust control. [5] provides the solution of it.

The design procedure of the FDI observer of NCS is summarized as the following algorithm.

Step 1 Choose Q so that $HB_d = 0$.

Step 2 Select F_{τ_k} which satisfies conditions 1) or 2) of Lemma 2. We can use eigenstructure assignment technique by assigning left eigenvectors or alternative right eigenvectors. If it fails, the problem can not be solved. Stop.

Step 3 Compute (12). If $G_{rf} \neq 0$, continue; else if all solutions of Step 2 fail to satisfy (12), the problem can not be solved, stop; otherwise go back to Step 2.

Step 4 If $G_{rf} \in \mathbb{R}^{p\times m}$ has full row rank, compute

$P(z)$ by (13); otherwise use model-matching approach to find $P(z)$ which minimizes (14).

5 Example

Consider the following continuous plant

$$\dot{x}(t)=\begin{bmatrix}1&1\\1&1\end{bmatrix}x(t)+\begin{bmatrix}0\\1\end{bmatrix}u(t)+\begin{bmatrix}0\\1\end{bmatrix}d(t)+\begin{bmatrix}1&0\\1&0\end{bmatrix}f(t),$$

$$y(t)=\begin{bmatrix}1&0\\0&1\end{bmatrix}x(t)+\begin{bmatrix}0&1\\0&1\end{bmatrix}f(t),$$

where $d(k)$ is random and the fault vector is composed of one sensor fault vectors and one actuator, that is $f=[f_a\ \ f_s]^T$.

Set $T=1$ s and $\tau=0.1$ s, Use (3), we can get

$$x(k+1)=$$

$$\begin{bmatrix}4.1945&3.1945\\3.1945&4.1945\end{bmatrix}x(k)+\begin{bmatrix}1.7183\\1.7183\end{bmatrix}u(k)+$$

$$\begin{bmatrix}1.7183\\1.7183\end{bmatrix}d(k)+\begin{bmatrix}3.4366&0\\3.4366&0\end{bmatrix}f(k),$$

$$y(k)=\begin{bmatrix}1&0\\0&1\end{bmatrix}x(k)+\begin{bmatrix}0&1\\0&1\end{bmatrix}f(k).$$

Obviously $\tau_k=1$, follow the design algorithm in Section 4.

Step 1 Choose $Q=[1\quad -1]$ to satisfy $Q\hat{C}\hat{B}_d=0$.

Step 2 Use eigenstructure assignment technique by assigning left eigenvectors, so

$$F_{\tau_k}=F_1=\begin{bmatrix}20.41&19.41\\19.41&20.41\end{bmatrix},$$

and

$$L_{\tau_k}=L_1=\begin{bmatrix}1&1\\1&1\end{bmatrix}.$$

Step 3 Compute (13) according to Remark 2 of Lemma 2, we can get

$$G_{rf}=\left[-\frac{1}{z^2}\quad \frac{1}{z^2}\right]\neq 0.$$

Step 4 Since $G_{rf}\in\mathbb{R}^{1\times 2}$, mutual fault isolation can not be achieved. Set $\Lambda=\begin{bmatrix}1&0\\0&1\end{bmatrix}$, $P=[-z^2\quad z^2]^T$ is found to minimize (14).

Finally, the residual has the form of

$$r(z)=\begin{bmatrix}r_1(z)\\r_2(z)\end{bmatrix}=\begin{bmatrix}1&-1\\-1&1\end{bmatrix}f(z).$$

The random unknown input $d(k)$ and the residual of the fault-free case is shown in Fig.2. And Fig.3 is the simulation result of the residual in the fault case. From the curve it is obvious when both a sensor fault and an actuator fault with amplitude 10 occur at 4 s and 7 s, they can be almost signified by curves 1 and 2 respectively.

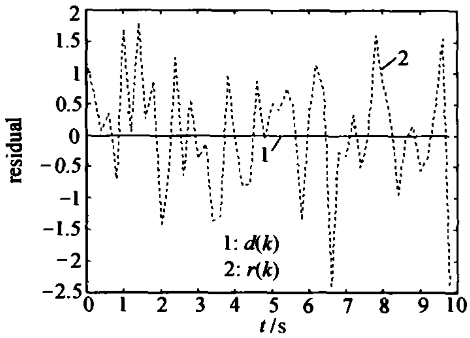

Fig. 2 Fault-free case

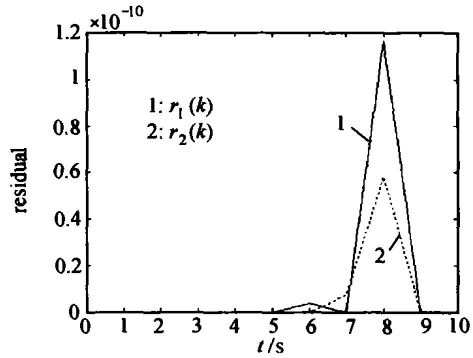

Fig. 3 Fault case

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