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To cite this article: Jing-Bo Zhao et al 2018 J. Phys.: Conf. Ser. 1087 062044

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Observer-Based NCS Fault Diagnosis

Jing-Bo ZHAO 1, Han-Wen SHEN1, Peng-Hao Liao1, Qing-Wei Zhang1

1College of Information and Control Engineering, Qingdao University of Technology, Qingdao, 266520, China
644479770@qq.com

Abstract: This paper proposes a diagnosis scheme based on observer for a class of fault control systems with short delays. Firstly, based on the predictor state of the observer as the input of the controller, a control system with time delay compensation and fault diagnosis is designed. Then the value of the residual generator is compared with the predetermined threshold to judge whether the fault occurs or not. The design of the post filter makes the system more sensitive to external interference and robustness to additive faults is improved, thereby improving the diagnostic rate of faulty systems. Finally, it is verified by numerical simulation that the system design based on the observer can diagnose the system fault well.

1. Introduction

With the automatic and control technology becoming more and more industrialized and large-scale, the research on the fault system stability system for control systems has received increasing attention from experts and scholars. The Lyapunov function is the most common method to achieve the stability condition of NCS. Yue et al. designed a robust $H_{\infty}$ controller for uncertain NCS with both network-induced delay and packet loss. [1] Wu proposed a reliable NCS control algorithm based on Lyapunov stability theory. [2] Zhang et al. studied the stability of NCS in discrete domain with random time-delay. Between the sensor, the controller and the controller, the actuator is modeled as two Markov jump linear systems according to known conditions. [3] But the premise that occurs in the above system is that all the state information of the controlled object must be known. In practical applications, it is usually impossible to obtain all the state information of the NCS. In this case, the observer is usually the most frequently used method.

Among the processing methods that can be used for faulty systems, the observer-based method in the analytical model is the most commonly used state information and control input. Frank has proposed observers on how to improve the sensitivity of fault diagnosis systems and enhance system stability. The method was combined with filters. [4] Bahadorinejad et al. designed a class of optimal fault detection filters with strong pertinence, wide application range, and time-variable and time-invariant systems are all available [5]. Most existing literatures use $H_{\infty}$ optimization. The disadvantages are that the design is complex and the actual operation is difficult. This paper aims at a linear time-invariant system with a short delay, uses a state observer to obtain the fault gain, and establishes an appropriate residual error evaluation function. The fault is diagnosed based on a comparison with known thresholds, and the addition of the filter maximizes system robustness and removes uncertain interferences. Finally, simulations verify that the NCS based on the observer design has a good diagnosis effect on the fault system.
2. System Modeling

For the study of NCS control system with short delay, this paper considers only the time delays $\tau_{sc}^k$ and $\tau_{ca}^k$ from the sensor to the controller and from the controller to the actuator. The basic block diagram of building an equivalent NCS is shown in Figure 1. $\tau_k$ is the network induced delay in the closed system of the entire network control system, and $\tau_k = \tau_{sc}^k + \tau_{ca}^k$ is always present.

Figure 1. The equivalent structure of a network control system

Observer-based NCS fault model is established and the following reasonable assumptions are made:

Assumption 1: The sensor is time-driven and the sampling period is $T$. Both the controller and the actuator are event-driven.

Assumption 2: Total delay is always bounded and less than one sampling period

Assumption 3: The initial state of the system is determined Observer-based NCS fault detection system is shown in Figure 2.

Consider the controlled object model of a linear time-invariant system:

$$
\begin{align*}
\dot{x}(t) &= A_c x(t) + B_c u(t) + B_{cd} d(t) + B_{cf} f(t) \\
y(t) &= C x(t) + D_d d(t) + D_f f(t)
\end{align*}
$$

(1)

The $x(t), u(t), y(t)$ are state vector, control input and state output respectively, $d(t)$ is external interference and $f(t)$ is additive fault. Matrix $A_c, B_c, B_{cd}, B_{cf}, C, D_d, D_f$ are real fixed length matrices with proper dimensions.

The discrete model of the controlled object:
\[
\begin{aligned}
\begin{cases}
    x(k+1) = Ax(k) + \Gamma_0(\tau_k)u(k) + \Gamma_1(\tau_k)u(k-1) + B_d d(k) + B_f f(k) \\
    \psi(k) = Cx(k) + D_d d(k) + D_f f(k)
\end{cases}
\end{aligned}
\]

Build an observer-based residual generator:
\[
\begin{aligned}
    \hat{x}(k+1) &= A\hat{x}(k) + Bv_k + H(\psi_k - \hat{\psi}(k)) \\
    \psi(k) &= C\hat{x}(k) \\
    r_0 &= \psi(k) - \hat{\psi}(k) \\
    r(z) &= R(z)r_0(z)
\end{aligned}
\]

\[
B(\tau_k) = \int_0^T e^{A_s}B_c f dt = \Gamma_0(\tau_k) + \Gamma_1(\tau_k), \quad r_0 \text{ is the system output error estimate, } \quad (A, C) \text{ is measurable, } \quad R(z) \text{ is the post filter evaluation parameter, and } \quad r(z) \text{ is the residual error evaluation function.}
\]

Formula (2), (3) can be introduced:
\[
\begin{aligned}
    r_0(k) &= C e(k) + D_d d(k) + D_f f(k) \\
    r(z) &= R(z)r_0(z)
\end{aligned}
\]

3. Residual Generator Design
The built residual generator is:
\[
r(z) = R(z)r_0(z) = R(z)(\psi(k) - \hat{\psi}(k))
\]

Define the state estimation error:
\[
e(k) = x(k) - \hat{x}(k) \quad e(0) = x(0) - \hat{x}(0)
\]

The estimated error equation is:
\[
e(k+1) = (A - HC)e(k) + \Gamma_1(\tau_k)\Delta v_k + (B_d - HD_d) d(k) + (B_f - HD_f) f(k)
\]

Unknown input and fault signals can affect the residual result, because the network induces the existence of delay \( \tau_k \) and the control input can also influence the residual result. Uncertain delay makes the control system unable to achieve the complete decoupling of residual \( \Gamma_1(\tau_k)\Delta v_k \) and unknown input.

From the integral mean value theorem we can see:
\[
\Gamma_1(\tau_k) = \int_{q-\tau_k}^T e^{A_s}B_c dt = \tau_k e^{A_s}B_c
\]

\[
q(k) = \tau_k e^{A_s}B_c \Delta v_k \quad \text{According to formulas (4), (7) can further be expressed:}
\]

\[
\begin{aligned}
    e(k+1) &= (A - HC)e(k) + q(k) + (B_d - HD_d) d(k) + (B_f - HD_f) f(k) \\
    r_0(k) &= C e(k) + D_d d(k) + D_f f(k) \\
    r(z) &= R(z)r_0(z)
\end{aligned}
\]

And for \( \Delta k \in l_2 \), \( q(k) \) same \( l_2 \) norm bounded. Define \( w(k) = [d^T(k) \quad q^T(k)]^T \), further derivation of equation (9):
\[
\begin{aligned}
    e(k+1) &= (A - HC)e(k) + (B_w - HD_w) w(k) + (B_f - HD_f) f(k) \\
    r_0(k) &= C e(k) + D_w w(k) + D_f f(k) \\
    r(z) &= R(z)r_0(z)
\end{aligned}
\]
Residual error estimation is a core element of network control system fault detection. It is generally based on defined residuals to define the residual estimation evaluation function $J_r$ and then set the threshold $J_{th} > 0$.

$$J_r = \left\{ \begin{array}{ll} k_0 + K_r & \text{error alarm} \\ \sum_{k=k_0}^{K} r^T(k) r(k) & \text{No failure} \end{array} \right\}^{1/2}$$

$k_0$ represents the start time of the residual evaluation, $K_r$ represents the length of the evaluation window, and the threshold is set to:

$$J_{th} = \sup_{f=0} J(r)$$

After knowing the threshold of the residual evaluation, based on the residual error evaluation of the analyzed fault detection, the fault diagnosis can be made using the logical relationship of:

$$\begin{align*}
J_r > J_{th}, & \text{ error alarm} \\
J_r < J_{th}, & \text{ No failure}
\end{align*}$$

**4. Post filter design**

The fault filter design problem can be described as follows: by calculating the observer gain matrix $H$ and the post filter $R(z)$, the other $\rho(A - HC) < 1$ simultaneously satisfy the minimization condition

$$\min_{H,R(z)} \frac{\|G_{rw}(z)\|}{\sigma(G_{zf}(e^{i\theta}))}, \forall \theta \in [0,2\pi)$$

$$G_{rw}(z) = R(z)G_{w}(z) = R(z)[C(zI - A + HC)^{-1}(B_w - HD_w) + D_w]$$

$$G_{zf}(z) = R(z)G_{zf}(z) = R(z)[C(zI - A + HC)^{-1}(Bf - HD_f) + D_f]$$

Considering that the minimization condition is satisfied, the postfilter has the following equation:

$$R(z) = R_0[zI - A - L_0^T C]^{-1}(H + L_0^T + I)$$

$$R_0 = W_0^T, W_0^T$$ is the right inverse matrix of $\theta\theta$. $\theta\theta$ is a matrix with a certain dimension that satisfies

$$\theta\theta = D_wD_w^T + CXC^T.$$ 

At this time, the solution to the post-filter $R(z)$ is transformed to the solution for $R_0, L_0$ that is, to the $(X, L_0)$ solution. $(X, L_0)$ is the solution of the following Riccati equation [6]:

$$\begin{bmatrix}
AXA^T - X + B_wB_w^T & AXA^T + B_wBD_w^T \\
CXC^T + D_wB_w^T & CXC^T + D_wD_w^T
\end{bmatrix} \begin{bmatrix}
I \\
L_0
\end{bmatrix} = 0$$

Note that when $H = -L_0^T$, the postfilter of equation (14) can satisfy the minimization solution of equation (13).

$$\min_{H,R(z)} \frac{\|G_{rw}(z)\|}{\sigma(G_{zf}(e^{i\theta}))} = \frac{1}{\sigma[R_0C(e^{i\theta})A - L_0^T Bf + L_0^T Df + Df]}$$

**5. Simulation Examples**

For the possible fault of the sensor, only consider the impact of short delay, ignore the packet loss and node driver, etc., consider the linear time-invariant control system (1).

$$A_c = \begin{bmatrix}
-2 & 1 \\
2 & -1
\end{bmatrix}, B_c = \begin{bmatrix}
0 \\
1
\end{bmatrix}, C = \begin{bmatrix}
1 & 1
\end{bmatrix}, B_d = \begin{bmatrix}
0.1 \\
1
\end{bmatrix}, B_{cf} = \begin{bmatrix}
0 \\
1
\end{bmatrix}, D_d = D_f = 0$$
When $h = 0.1$, the discretization parameter is:

$$A = \begin{bmatrix} 0.9909 & 0.0861 \\ -0.1722 & 0.7326 \end{bmatrix}, \quad B = \begin{bmatrix} 0.0045 \\ 0.0861 \end{bmatrix}, \quad B_d = \begin{bmatrix} 0.5837 \\ 0.9516 \end{bmatrix}, \quad B_f = \begin{bmatrix} 0.4837 \\ 1.9465 \end{bmatrix}$$

Solutions have to $R(z) = R_0 = 0.4561, H = \begin{bmatrix} 0.9538 \\ 1.1465 \end{bmatrix}$

From the figure below, it can be concluded that the use of the residual signal can be used to diagnose the fault of the system well. For example, the system on the right shows that the fault occurs in 6 seconds. The designed observer based fault diagnosis system can diagnose the system faults very well.
6. Conclusion
Due to the introduction of the network, the complexity of the control system and the probability of failures are increasing. Time delays, packet loss, etc. are common faults in the system. Faults should be diagnosed sooner in order to find out the cause of the fault. In this paper, an observer-based fault diagnosis system designed for short delays can be used to diagnose system faults, and the observer predicts the sensor status. After the residual generator is compared with the threshold, the fault is discovered in time and can be reconstructed by the system to keep up with the actual state performance. The post-filter can eliminate unnecessary interference effects to the greatest degree.

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