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Fault Detection for Wireless Network Control System Based on Sliding Mode Observer

[1] Pengfei GUO, [1] Jie ZHANG, [2] Ming LV, [1] Yuming BO
[1] School of Automation, Nanjing University of Science & Technology,
Nanjing, 210094, P. R. China
[2] Information Overall Department, North Information Control Group Co., Ltd.,
Nanjing, 211153, P. R. China
Tel.: +86 15951890784
E-mail: guopengfeieason@gmail.com

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Abstract: This paper considers the fault detection problem of wireless network control system with time delay and uncertainties. For a class of model which has bounded disturbance and unknown fault, a sliding mode observer is designed for the situation that all the states of the system can be measured and no missing measurement occurs. We convert the design of fault detection observer to the design of reaching motion and sliding motion, by the use of Lyapunov function, a sufficient condition for sliding motion with time delay independent and uncertainties is acquired through linear matrix inequality, while the nonlinear item in observer is also designed. Finally, the effectiveness of proposed method is demonstrated by simulation results. *Copyright © 2013 IFSA.*

Keywords: Fault detection, Wireless network control system (WNCS), Sliding mode observer, linear matrix inequality (LMI).

1. Introduction

With the development of network technology, research and application of wireless network control system attracted more and more attention from scholars [1–5]. Communication using wireless network can save a large number of connections, saving system construction and maintenance costs, and enhance the flexibility of the system components [6]. However, as the system is growing highly modular and complex, system failure probability is also growing, faults can bring disastrous damage to the entire network control system, therefore, fault detection on wireless network control system is essential.

Fault detection based on sliding mode observer has achieved fruitful results in recent years. Qun Zong etc. [7] considered the fault detection problem of distributed networked control system with time delay, for states which are not available for measurement, they designed a transformation matrix to separate measurable states and unknown states, and developed sliding mode observer for fault detection. Christopher Edwards etc. [8] concerned with the use of sliding mode for fault reconstruction and provided a simple way for fault tolerant control scheme. Ming Liu etc. [9] proposed a kind of sliding mode observer, in which a derivative gain and a proportional gain were introduced to provide more design freedom, and the effects of sensor faults were

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eliminated by a discontinuous input term. So sliding mode observer is in widely use.

In this paper, we take time delay and system uncertainties into account, aim to design a sliding mode observer for fault detection. We transform the fault detection problem into the design of reaching motion and sliding motion, propose a sufficient condition based on Lyapunov function, and numerical example is given to show the effectiveness of proposed method.

2. Problem Formulation

Considering a type of WNCS as shown in Fig. 1, information flow is transmitted among all network sensors. However, as sensor nodes may be in dynamic motion, gather information we need everywhere, the structure may not maintain fixed, so connection between sensor nodes maybe interrupted or established as time goes on, this uncertain factor results in the uncertainties in WNCS. As shown in the figure, the solid line denotes fixed connection and dashed line denotes uncertain connection which will be established or vanished. Information changes between sensor nodes are also time consuming, which is reflected as time delay in system, and system model can be described as below:

$$\begin{cases} x(k+1) = (A+\Delta A)x(k) + \sum_{i=1}^{N}(A_d \\ \qquad + \Delta A_d)x(k-i) + Bu(k) \\ \qquad + E_d d(k) + E_f f(k) \\ y(k) = Cx(k) \end{cases} \tag{1}$$

where $x(k) \in R^{n_x}$ denotes system state, $x(k-1) \in R^{n_x}$ denotes the state delay of the system, $u(k) \in R^{n_u}$ denotes the system input, $d(k) \in R^{n_d}$ denotes the unknown disturbance, $f(k) \in R^{n_f}$ is the fault of the system, $y(k) \in R^{n_y}$ denotes system output, ΔA and ΔA_d are internal perturbation arising from uncertain factors, A, A_d, B, E_d, E_f and C are constant matrices with appropriate dimensions.

For system shown in (1), we make the following assumption.

Assumption 1. Perturbation parameter of the system satisfies:

$$[\Delta A \quad \Delta A_d] = GD(k)[H \quad H_d]$$

Respectively, G, H and H_d are known constant matrix, $D(k)$ is time delay uncertain matrix, yet Lebesgue-measurable, and $D^T(k)D(k) \le I$.

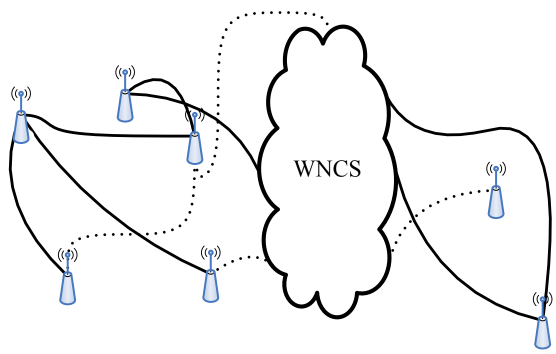

Fig. 1. WNCS with unfixed structure and transmission delay.

Assumption 2. System disturbance has an upper bound, which satisfies $\|d(k)\| \le d$.

Assumption 3. All the states of the system can be measured and no missing measurement occurs.

Assumption 4. $C^T C$ is full rank.

In order to generate a residual signal, we design a sliding mode observer for model (1) as follows:

$$\begin{cases} \hat{x}(k+1) = (A+\Delta A)\hat{x}(k) + \sum_{i=1}^{N}(A_d \\ \qquad + \Delta A_d)\hat{x}(k-i) + Bu(k) \\ \qquad + L[y(k) - \hat{y}(k)] + w(k) \\ \hat{y}(k) = C\hat{x}(k) \end{cases} \tag{2}$$

where $\hat{x}(k)$ and $\hat{y}(k)$ are observed value of states and outputs, L is the gain of observer , $w(k)$ is nonlinear item which needs to be designed, states error and residual can be written as:

$$\begin{cases} e_x(k) = x(k) - \hat{x}(k) \\ e_y(k) = y(k) - \hat{y}(k) \end{cases}$$

So the system error model is:

$$\begin{cases} e_x(k+1) = (A+\Delta A - LC)e_x(k) \\ \qquad + \sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-i) \\ \qquad + E_d d(k) + E_f f(k) \\ \qquad - w(k) \\ e_y(k) = Ce_x(k) \end{cases} \tag{3}$$

We define the sliding surface $s(k)$ and residual of the system $\varepsilon(k)$ as:

$$\begin{cases} s(k) = e_y(k) \\ \varepsilon(k) = e_y(k) \end{cases}$$

If there is no fault, the system residual is zero. In order to detect system fault, we set up residual evaluation function J and fault threshold J_{th} as:

$$\begin{cases} J = \left\{ \sum_{k=1}^{N} r^T(k) r(k) \right\}^{\frac{1}{2}} \\ J_{th} = \sup J \end{cases}$$

So system fault can be detected by comparing J and J_{th}.

$$\begin{cases} J \le J_{th} \ \ No \ \ fault \ \ happens \\ J \ge J_{th} \ \ Fault \ \ happens \end{cases}$$

The method for fault detection is to design a sliding mode observer, which satisfies the two conditions [10]:

1) System error model is asymptotically stable when $s(k+1) = s(k) = 0$

2) Sliding mode manifold satisfies $\|s(k+1)\| < \|s(k)\|$

Condition (1) means that states motion in sliding motion is stable, while condition (2) guarantees all states will be driven onto the sliding surface within finite time.

Besides, a frequently used and important lemma is listed below.

Lemma 1. For any $x, y \in R^n$, $\mu > 0$, the following equation holds.

$$2x^T y \le \mu x^T x + \frac{1}{\mu} y^T y$$

3. Main Results

In this section, sliding mode observer will be designed in two steps for fault detection. First, we are going to proof that states can reach the sliding motion within finite time.

Theorem 1. For system error model (3) which meets assumption 1, 2, 3 and 4, and $w(k) = w_1(k) + w_2(k)$, where $w_1(k) = E_d d$, $w_2(k) = \sum_{i=1}^{N} (A_d + \Delta A_d) e_x(k-i)$, then system states will be driven onto the sliding surface within finite time if there exists a general matrix $L \in R^{n_x \times n_y}$ making (4) holds.

$$\begin{bmatrix} -C^T C & \sqrt{3}(A + GH - LC)^T C^T C \\ * & -I \end{bmatrix} < 0 \tag{4}$$

Proof. Since we have $e_y(k+1) = C e_x(k+1)$, so

$$\begin{aligned} & s^T(k+1)s(k+1) - s^T(k)s(k) \\ & = e_y^T(k+1)e_y(k+1) - e_y^T(k)e_y(k) \\ & = e_x^T(k+1)C^T C e_x(k+1) \\ & \quad - e_y^T(k) C^T C e_y(k) \\ & = e_x^T(k)[(A + \Delta A - LC)^T C^T C(A \\ & \quad + \Delta A - LC) - C^T C] e_x(k) \\ & \quad + 2e_x^T(k)(A + \Delta A - LC)^T C^T C \sum_{i=1}^{N} (A_d \\ & \quad + \Delta A_d) e_x(k-1) + e_x^T(k-1) \sum_{i=1}^{N} (A_d \\ & \quad + \Delta A_d)^T C^T C \sum_{i=1}^{N} (A_d + \Delta A_d) e_x(k-1) \\ & \quad + 2e_x^T(k) \sum_{i=1}^{N} (A_d + \Delta A_d)^T C^T C [E_d d(k) \\ & \quad - w(k)] + 2e_x^T(k) \sum_{i=1}^{N} (A + \Delta A \\ & \quad - LC)^T C^T C [E_d d(k) - w(k)] \\ & \quad + 2e_x^T(k)(A + \Delta A - LC)^T C^T C [E_d d(k) \\ & \quad - w(k)] + [E_d d(k) \\ & \quad - w(k)]^T C^T C [E_d d(k) - w(k)] \end{aligned} \tag{5}$$

According to Lemma 1 and we set $\mu = C^T C$, we have

$$\begin{aligned} & 2e_x^T(k)(A + \Delta A - LC)^T C^T C \sum_{i=1}^{N} (A_d \\ & \quad + \Delta A_d) e_x(k-1) \\ & \le \mu[(A + \Delta A - LC) e_x(k)]^T [(A + \Delta A \\ & \quad - LC) e_x(k)] + \frac{1}{\mu} [C^T C \sum_{i=1}^{N} (A_d \\ & \quad + \Delta A_d) e_x(k-1)]^T [C^T C \sum_{i=1}^{N} (A_d \\ & \quad + \Delta A_d) e_x(k-1)] \\ & = e_x^T(k)[(A + \Delta A - LC)^T C^T C(A \\ & \quad + \Delta A - LC)] e_x(k) + e_x^T(k-1)[\sum_{i=1}^{N} (A_d \\ & \quad + \Delta A_d)^T C^T C \sum_{i=1}^{N} (A_d \\ & \quad + \Delta A_d)] e_x(k-1) \end{aligned} \tag{6}$$

$$\begin{aligned} & 2e_x^T(k)(A + \Delta A - LC)^T C^T C [E_d d(k) \\ & \quad - w(k)] \\ & \le \mu[(A + \Delta A - LC) e_x(k)]^T [(A + \Delta A \\ & \quad - LC) e_x(k)] + \frac{1}{\mu} \{C^T C [E_d d(k) \\ & \quad - w(k)]\}^T \{C^T C [E_d d(k) - w(k)]\} = \end{aligned} \tag{7}$$

$$= e_x^T[(A+\Delta A-LC)^T C^T C(A+\Delta A - LC)]e_x(k) + [E_d d(k) - w(k)]^T C^T C[E_d d(k) - w(k)]$$

$$\begin{aligned} & 2e_x^T(k-1)\sum_{i=1}^{N}(A_d+\Delta A_d)^T C^T C[E_d d(k) - w(k)] \\ & \le \mu[\sum_{i=1}^{N}(A_d+\Delta A_d)e_x(k-1)]^T[\sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-1)] + \frac{1}{\mu}\{C^T C[E_d d(k) - w(k)]\}^T\{C^T C[E_d d(k) - w(k)]\} \\ & = e_x^T(k-1)[\sum_{i=1}^{N}(A_d+\Delta A_d)^T C^T C\sum_{i=1}^{N}(A_d + \Delta A_d)]e_x(k-1) + [E_d d(k) - w(k)]^T C^T C[E_d d(k) - w(k)] \end{aligned} \tag{8}$$

Substituting (6), (7), (8) into (5), we have

$$\begin{aligned} & s^T(k+1)s(k+1) - s^T(k)s(k) \\ & \le e_x^T(k)[3(A+\Delta A-LC)^T C^T C(A + \Delta A - LC) - C^T C]e_x(k) \\ & + 3e_x^T(k-1)[\sum_{i=1}^{N}(A_d + \Delta A_d)^T C^T C\sum_{i=1}^{N}(A_d+\Delta A_d)]e_x(k -1) + 3[E_d d(k) - w(k)]^T C^T C[E_d d(k) - w(k)] \\ & \le e_x^T(k)[3(A+\Delta A-LC)^T C^T C(A \Delta A - LC) - C^T C]e_x(k) + [\sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-1) - w_2(k)]^T 3C^T C[\sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-1) - w_2(k)] + [E_d d(k) - w_1(k)]^T 3C^T C[E_d d(k) - w_1(k)] \end{aligned} \tag{9}$$

we make $w_1(k) = E_d d$, $w_2(k) = \sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-i)$, so we have

$$\begin{aligned} & s^T(k+1)s(k+1) - s^T(k)s(k) \\ & \le e_x^T(k)[3(A+\Delta A-LC)^T C^T C(A + \Delta A - LC) - C^T C]e_x(k) \\ & \le e_x^T(k)[3(A+GH-LC)^T C^T C(A + GH - LC) - C^T C]e_x(k) \\ & \le 0 \end{aligned} \tag{10}$$

By Schur complement, equation (10) is equivalent to

$$\begin{bmatrix} -C^T C & \sqrt{3}(A+GH-LC)^T C^T C \\ * & -I \end{bmatrix} < 0$$

The proof of Theorem 1 is complete. Next, we will proof the system error model is asymptotically stable when in sliding motion.

Theorem 2. For system error model (3) which meets assumption 1, 2 and 3, and $w(k) = w_1(k) + w_2(k)$, where $w_1(k) = E_d d$, $w_2(k) = \sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-i)$, then system is asymptotically stable if there exist a general matrix $L \in R^{n_x \times n_y}$ and $P \in R^{n_x \times n_x}$ making (11) holds.

$$\begin{bmatrix} -P & \sqrt{3}(A+GH-LC)^T P \\ * & -P \end{bmatrix} < 0 \tag{11}$$

Proof. Choose the following Lyapunov function:

$$V(k) = e_x^T(k)Pe(k) \tag{12}$$

Make forward difference of $V(k)$ we have

$$\begin{aligned} & V(k+1) - V(k) \\ & = e_x^T(k)[(A+\Delta A - LC)^T P(A+\Delta A - LC) - P]e_x(k) + 2e_x^T(k)(A+\Delta A - LC)^T P\sum_{i=1}^{N}(A_d+\Delta A_d)e_x(k-1) \\ & + e_x^T(k-1)\sum_{i=1}^{N}(A_d+\Delta A_d)^T P\sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-1) + 2e_x^T(k)\sum_{i=1}^{N}(A_d + \Delta A_d)^T P[E_d d(k) - w(k)] \\ & + 2e_x^T(k)(A+\Delta A-LC)^T P[E_d d(k) - w(k)] + [E_d d(k) - w(k)]^T P[E_d d(k) - w(k)] \end{aligned} \tag{13}$$

According to Lemma 1 and we set $\mu = P$, we have

$$\begin{aligned} & 2e_x^T(k)(A+\Delta A-LC)^T P\sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-1) \\ & \le \mu[(A+\Delta A-LC)e_x(k)]^T[(A + \Delta A - LC)e_x(k)] + \frac{1}{\mu}[P\sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-1)]^T[P\sum_{i=1}^{N}(A_d + \Delta A_d)e_x(k-1)] \\ & = e_x^T(k)[(A+\Delta A-LC)^T P(A + \Delta A - LC)]e_x(k) + e_x^T(k -1)[\sum_{i=1}^{N}(A_d+\Delta A_d)^T P\sum_{i=1}^{N}(A_d + \Delta A_d)]e_x(k-1) \end{aligned} \tag{14}$$

$$
\begin{aligned}
& 2e_x^T(k)(A+\Delta A-LC)^T P[E_d d(k) \\
& -w(k)] \\
& \le \mu[(A+\Delta A-LC)e_x(k)]^T[(A \\
& +\Delta A-LC)e_x(k)]+\frac{1}{\mu}\{P[E_d d(k) \\
& -w(k)]\}^T\{P[E_d d(k)-w(k)]\} \\
& = e_x^T(k)[(A+\Delta A-LC)^T P(A+\Delta A \\
& -LC)]e_x(k)+[E_d d(k) \\
& -w(k)]^T P[E_d d(k)-w(k)]
\end{aligned} \tag{15}
$$

$$
\begin{aligned}
& 2e_x^T(k-1)\sum_{i=1}^{N}(A_d+\Delta A_d)^T P[E_d d(k) \\
& -w(k)] \\
& \le \mu[\sum_{i=1}^{N}(A_d+\Delta A_d)e_x(k-1)]^T[\sum_{i=1}^{N}(A_d \\
& +\Delta A_d)e_x(k-1)]+\frac{1}{\mu}\{P[E_d d(k) \\
& -w(k)]^T\}\{P[E_d d(k)-w(k)]\} \\
& = e_x^T(k-1)[\sum_{i=1}^{N}(A_d+\Delta A_d)^T P\sum_{i=1}^{N}(A_d \\
& +\Delta A_d)]e_x(k-1)+[E_d d(k) \\
& -w(k)]^T P[E_d d(k)-w(k)]
\end{aligned} \tag{16}
$$

Substituting (14), (15), (16) into (13), we have

$$
\begin{aligned}
& V(k+1)-V(k) \\
& \le e_x^T(k)[3(A+\Delta A-LC)^T P(A+\Delta A \\
& -LC)-P]e_x(k)+3e_x^T(k-1)[\sum_{i=1}^{N}(A_d \\
& +\Delta A_d)^T P\sum_{i=1}^{N}(A_d+\Delta A_d)]e_x(k-1) \\
& +3[E_d d(k)-w(k)]^T P[E_d d(k) \\
& -w(k)] \\
& \le e_x^T(k)[3(A+\Delta A-LC)^T P(A+\Delta A \\
& -LC)-P]e_x(k)+[\sum_{i=1}^{N}(A_d \\
& +\Delta A_d)e_x(k-1)-w_2(k)]^T 3P[\sum_{i=1}^{N}(A_d \\
& +\Delta A_d)e_x(k-1)-w_2(k)]+[E_d d(k) \\
& -w_1(k)]^T 3P[E_d d(k)-w_1(k)]
\end{aligned} \tag{17}
$$

we make $w_1(k)=E_d d$,

$w_2(k)=\sum_{i=1}^{N}(A_d+\Delta A_d)e_x(k-i)$, so we have

$$
\begin{aligned}
& V(k+1)-V(k) \\
& \le e_x^T(k)[3(A+\Delta A-LC)^T P(A \\
& +\Delta A-LC)-P]e_x(k) \\
& \le e_x^T(k)[3(A+GH-LC)^T P(A \\
& +GH-LC)-P]e_x(k) \\
& \le 0
\end{aligned} \tag{18}
$$

By Schur complement, equation (18) is equivalent to

$$
\begin{bmatrix} -P & \sqrt{3}(A+GH-LC)^T P \\ * & -P \end{bmatrix} < 0
$$

The proof of Theorem 2 is complete.

4. Equations

In this section, simulations are given for testing the theorems developed in this paper. Consider the system model (1), where

$$
A=\begin{bmatrix} 0.412 & 0.4 & -0.6 \\ 0.376 & 0.367 & 0.91 \\ 0.198 & 0 & 0.22 \end{bmatrix}
$$

$$
A_d=\begin{bmatrix} -0.232 & 0.01 & 0 \\ -0.019 & 0.062 & 0.032 \\ -0.037 & 0.078 & 0.149 \end{bmatrix}
$$

$$
H=\begin{bmatrix} 0.184 & 0.112 & 0.23 \\ 0.097 & -0.16 & -0.156 \\ -0.277 & -0.069 & -0.152 \end{bmatrix} \quad B=\begin{bmatrix} 0.073 \\ 0.045 \\ 0.069 \end{bmatrix}
$$

$$
D(k)=\begin{bmatrix} 0.8\sin(0.7k) & 0 & 0 \\ 0 & 0.8\sin(0.7k) & 0 \\ 0 & 0 & 0.8\sin(0.7k) \end{bmatrix}
$$

$$
G=\begin{bmatrix} 0.1 & 0.2 & -0.1 \\ 0 & 0.23 & -0.76 \\ 0.87 & 0.5 & -0.32 \end{bmatrix} \quad E_d=\begin{bmatrix} -0.021 \\ 0.12 \\ 0.08 \end{bmatrix}
$$

$$
E_f=\begin{bmatrix} 0.27 \\ 0.19 \\ 0.34 \end{bmatrix} \quad C=\begin{bmatrix} 1.92 & 0.7365 & 0.01 \\ 0.873 & 0.512 & 0.013 \\ 0.063 & 0.021 & 0.72 \end{bmatrix}
$$

$$
u(k)=\sin(0.2k) \quad d(k)=1.2\cos(0.1k)
$$

$$
\begin{cases} f_1(k)=1.2 & k=200 \\ f_1(k)=-1.2 & k=300 \\ f_2(k)=1.2 & 200\le k\le 300 \\ f_3(k)=4 & 200\le k\le 300 \end{cases}
$$

Parameters can be acquired based on Theorem 1 and Theorem 2, with N = 2, we have

$$
L=\begin{bmatrix} 15.162 & -26.5702 & -3.3753 \\ 10.1818 & -17.0192 & 2.4713 \\ 5.7506 & -9.3551 & 4.4224 \end{bmatrix}
$$

$$P = \begin{bmatrix} 239.7 & 185 & 744.9 \\ 185 & 142.7 & 574.8 \\ 744.9 & 574.8 & 231.48 \end{bmatrix}$$

Simulation results are shown in Fig. 2, blue solid curve denotes real value, and red dashed one denotes estimate value, which tracks the blue one very well.

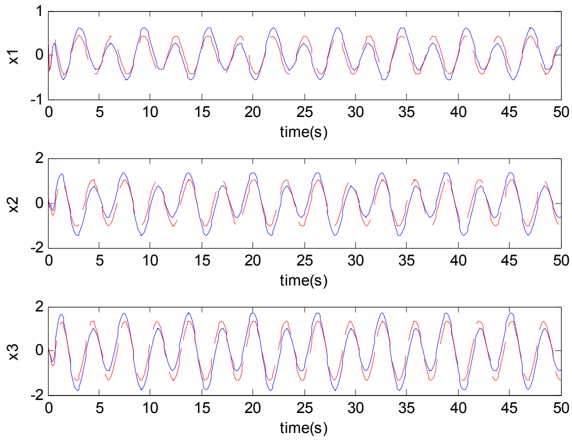

Fig. 2. States estimation.

When fault occurs in the system, residuals are shown in Fig. 3, dashed line denotes threshold value. From figures we can clearly see that when a fault occurs, residual quickly rise above the threshold value, which indicates the fault happens.

5. Conclusion

This paper considers the fault detection problem in wireless network control system. For a class of uncertain model with time delay and disturbance, sliding mode observer is designed for fault detection of the system. We divide the designing process into reachable and stable problems. By the use of Lyapunov function, we acquire the sufficient condition for observer design, and get the gain of observer. Simulation results demonstrate the effectiveness of proposed method.

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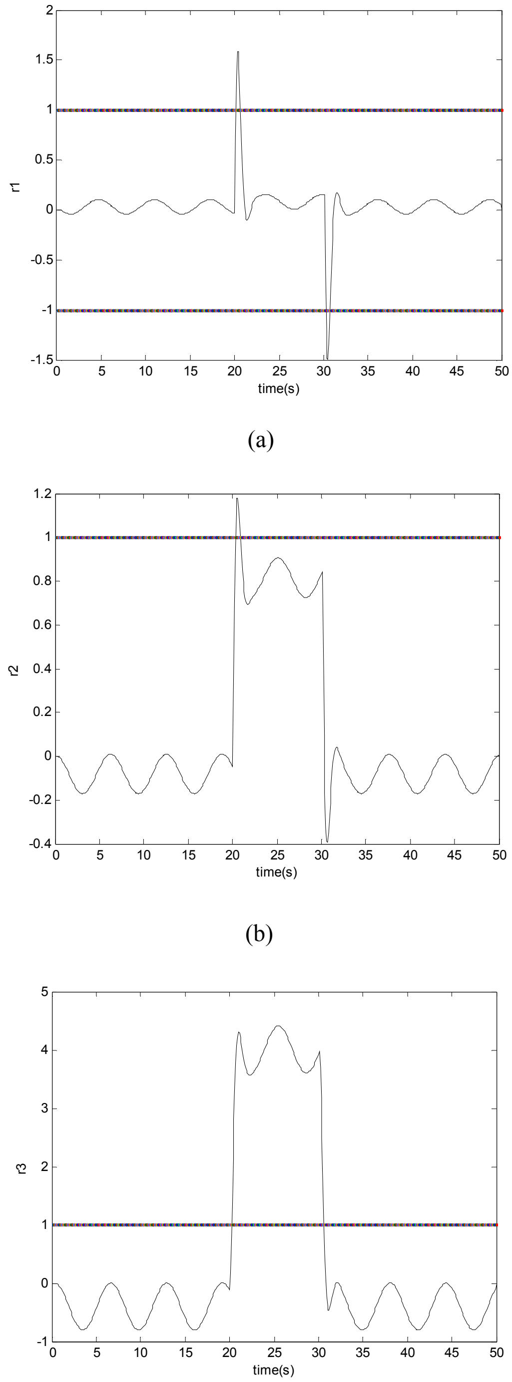

(a)

(b)

(c)

Fig. 3. Residual of states when a fault happens.

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