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Fault Detection for Networked Control Systems Based on Wireless Sensor Networks

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Abstract: Focusing on a class of networked control systems built around wireless sensor networks (WSN), the controller and the actuator in systems are assumed to be time-driven and the clocks are fully synchronized. The observer based on discrete switched systems is designed to detect faults which occur in the system. Firstly, by studying the transmission characteristics of data with wireless sensor networks, the augmented fault observer is constructed, and the observer is equivalent to the discrete switched system. Secondly, based on Lyapunov stability theory, the stability condition of observer can be viewed as a linear matrix inequality and the stability of system is proved. When the system is normal, if the given inequality condition is satisfied, the observer system is stable. When a fault occurs, the observer can detect the fault by the rapid change of residue. Finally, an illustrative example is given to demonstrate the effectiveness of the proposed method. *Copyright © 2013 IFSA.*

Keywords: Wireless sensor networks, Networked control systems, Fault observers, Discrete switched systems.

1. Introduction

Wireless Sensor Network (WSN) are usually energy constraint, take some cases for example, nodes computation ability and its capacity, power provision from nodes, under this circumstance, energy consumption protocol and useful algorithms are often suitable to make longer lifetime of sensor nodes. In general, wireless communication often consumes much more power than other operations in sensor networks, such as sensing, signal processing and computation. In this case, source nodes usually transit their data to the destination nodes through short range wireless links instead of a few longer ones to save the energy, the benefit of doing this is to save more energy as much as it could, however, doing this can results in the increasing of data transmission delay through the data transferring.

Wireless Sensor Networks can be widely used in many fields, and lots of applications in real life need to deliver a packet before the deadline within a period, in this case, the system cannot afford to tolerate the communication delay. Consider an application of sensor network to monitor the nerve gas attack in the battle field, as soon as a sensor node detects the presence of the poisonous gas, it should immediately report the relevant information, for example, the gas concentration level and its geographical location to the monitoring center [1].

Networked control system (NCS) is shared through network system for each element together to form a feedback control system with closed loop. In

NCS, data from the sensor to the controller, and as well as from the controller to the actuator via communication network, compared with the traditional point to point system link, the control scheme based on network reduce the wiring, increase system stability, easy to installation and maintenance. In recent years, networked control systems are widely used in industrial automation, unmanned aircraft, and mobile communication system.

Node location is another hot problem in WSN. Wireless sensor network node localization technology is through the anchor node coordinates to calculate the blind node coordinates, to identify all sensor nodes location information. The anchor includes a fixed anchor node and mobile anchor node, because the fixed anchor's node random dispersal, the positioning precision is not high; mobile anchor node via a path planning, can try to cover the entire network, for the blind node to provide better quality letter punctuation, improve the positioning accuracy of blind node. Using mobile anchor node to assist other node localization is a more practical approach, but the mobile anchor node must effectively planning path, can reduce energy consumption, and improve the positioning accuracy. So, mobile anchor node path planning problem is the basic problem to solve.

The rest of this paper is organization as follows. In Section 2, we present the flourish research result on Wireless Sensor Network, including node position prediction, localization algorithm for nodes in WSN, filter algorithm for diagnosis based on control system. In Section 3, we give our model to state our problem which we will use in this paper. In Section 4, we design our observer based on Lyapunov Function. In Section 5, we give the stability analysis. In addition, we will give a simulation example to demonstrate the efficiency of our analysis.

2. Related Work

Wireless Sensor Network (WSN) is known as one of the most influential 21 technologies and one of ten technologies can change the world in 21 century [2-4]. A large number of low cost wireless sensors are arranged in the region of interest, sensors quickly form a distributed network through self-organization, are used in a wide range of applications, such as scientific research, military, heath care, and environment monitory [5]. Although WSN technology is in rapid development in recent years, it's far from level of free and mature usage in applications, there are still some open problems to solve, such as node networked control problem. Networked control systems are the closed-loop control systems using the network as the channel of information transmission. The data at physical layer between the controller and the controlled objects in networked control system is transmitted in three ways: wired transmission, wireless transmission and mixed transmission. In the last study, the research on fault detection for wired networked control systems has been widely discussed and got many results. [6-9]. But in many newly constructed network environments, the wireless network plays an irreplaceable role when the application objects can move freely or the environment where the objects in is difficult to use the wired connection. Therefore, the domestic and foreign researchers have devoted great attention to the study of wireless networked control systems, and this study also has been a hot topic in the control community [10].

The system noise statics is often unknown or time varying, an extended Kalman filter (EKF)'s estimation precision is declined significantly when in practical use, and even divergent, in addition, EKF will be lost in the system when it reaches the steady state. Strong tracking filter (STF) can overcome the defects above, but the noise coefficients matrix are set in advance just like EKF, lack of the adaptability when time varying, and easy lead to over regulation, resulting in state pre-measured not smooth enough, cause accuracy reduced and even filter divergence. Literature [11] proposed an adaptive algorithm with improved strength using the limited memory of noise. Literature [12] put forward a kind of system noise estimation using variable factor matrix, to restrain system noise mutation, bur when doing recursive estimation for system noise, the selection for forgetting factor is arbitrary, and the algorithm does not estimate the observation noise, will inevitable affect the filtering effect.

In recent years, the stability of networked control systems research has become a new research hotspot, many scholars did a lot of useful work. In paper [13], it is assumed that the time delay is fixed, in paper [14], although the independent random delay and has the Markov property under the condition of the stability of the system with time delay is discussed, but did not consider the data packet dropout problem. In fact, a networked control system usually exist random delay and data packet dropout.

Fault-tolerant control is another hot topic, as the control systems are becoming larger and larger, more complex control algorithm, equipment effectiveness, safety and reliability problems attracts more and more attention, once fault occurs in control system, it is difficult to estimate the harm, so the fault tolerant control of networked control system is a great theoretical and practical significance research, fault tolerant control of networked control system is different from the traditional control system fault tolerant control, because the data transmission in network bandwidth constraints and information collisions and other reasons, many cases that would make the message transmission inevitably exists time-delay and packet dropout problem. This makes the fault tolerant control of networked control system more complex compared to the general control system. Paper [15] modeled a random time delay networked control system to a discrete jump linear system with Markov delay characteristics, with the help of jump linear system theory and fault-tolerant control theory, study the stochastic networked control systems with actuator failures.

Time delay is always the hot topic, paper [16] augmented state-space model of this kind of NCS is established after some necessary assumptions are made. A kind of state observer that can compensate large network-induced delays in networked control systems is designed based on traditional methods. This novel observer can greatly improve performance of this kind of NCS. Sufficient and necessary conditions for stability of such systems are given. Comparison with traditional state observer is done by simulation.

Currently the study of wireless sensor network is one of the central issues, but the study of fault detection by using wireless sensor network as communication channel of networked control system is rarely few. Such as the paper [17] and [18], they introduced the concept, characteristics, communication structure of wireless sensor network and its security commands. Also the future direction and the latest trends of the research about wireless sensor network were pointed out in papers. However the description of fault detection was rarely mentioned in these two papers, they only emphasized that the protocol of wireless network can identify the failure nodes. The paper [19] to [20] had researched on fault diagnosis just only for wireless sensor network itself, not for networked control system, but the fault detection method referred in those papers can be learned. The paper [21] and [22] only used wireless sensor network to detect the faults of other systems.

Fault detection and diagnosis methods can be divided into three types: the method of analytical model, based on the signal processing method and the method based on knowledge. The method of analytical model is developed at first, a clear diagnosis model based on fault diagnosis. The accuracy of system model based on the signal processing method is not particularly high, so they use the signal model to deal with the problem. The method based on knowledge is accompanied by a system which becomes more and more complicated, because it does not require an accurate mathematical model of object, but also has some "smart" characteristics, so it is a vital method. In the three methods mentioned above, method of analytical model used most in the network control system fault detection and diagnosis, the other two are relatively less.

From the above analysis, we know that most of the current papers concerned about several tings of wireless networked control systems, such as the control, scheduling and routing protocol algorithm and so on [23-26], but few study is on the fault detection of system. So considering a class of networked control systems, this paper provides a fault detection method for those systems by analyzing transmission characteristics of data and using the theory of discrete switched systems. A new idea is provided for fault detection of wireless networked control systems.

3. Problem Statement

The structure of the network control system is shown in Fig. 1. System is composed with controlled object, sensors, controllers, actuators, and network. Network control system's workflow is as follows: First, sensor node sampling object information, sensor data is then sent through the network to the controller node, controller node receives sensor data to calculate the amount of control, and finally, control information of actuator node is send through the network.

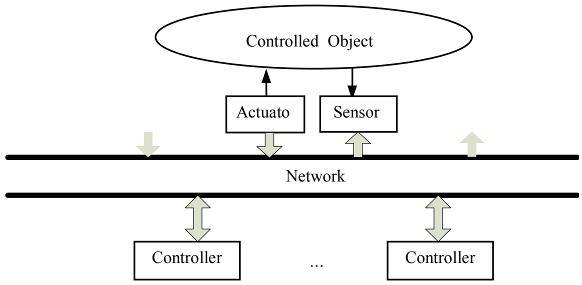

Fig. 1. Networked control system structure diagram.

Compared with the traditional point - to - point direct control system, the main features of the Network control system structure is the direct connection of each node, not a point - to - point, thus this makes the system have a number of distinct features. And due to the intervention of the network, some new problems are inevitably resulted in, including network-induced delay, packet loss, packet out of order, multi- packet transmission information scheduling, control and scheduling co-design. So when we design and analysis the system, we need to consider the impact of these factors on system performance.

There may exist interactive information or two-way transmission between sensor nodes in WSN, but overall, the task of the network is to establish the transmission path from sensor nodes to the base station and transmit the data to the base station, this is an obviously one-way transmission.

Consider a class of wireless networked control systems shown in Fig. 2. The controlled object is

$$\begin{cases} \dot{x}(t) = A_f x(t) + B_f u(t) + f(t) \\ y(t) = C_f x(t) \end{cases}, \quad (1)$$

where $x(t) \in R^n$ is the state vector, $u(t) \in R^m$ is the control vector, $y(t) \in R^l$ is the output vector, $f(t) \in R^n$ is the fault vector. If the system is normal, $f(t)$ is zero, else $f(t)$ is non-zero vector. A_f, B_f, C_f are the appropriate constant coefficient matrixes.

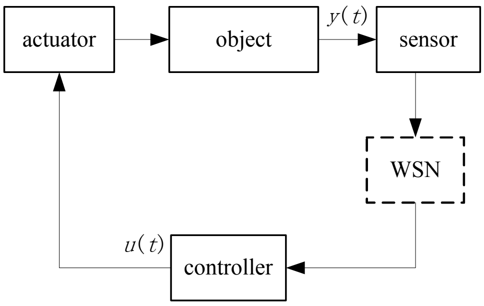

Fig. 2. The control structure of WSN.

We assume that the controller and the actuator are at the same node. They are time-driven and the clocks are fully synchronized. Define sample period as T. The sample signal has a timestamp from which we can get the network delay of the sample signal. The data are transmitted in single packet. The output delay may be greater than T by using WSN, but it has upper bound.

The data of sensor received by controller have timestamps from which we can get the time delay. According to the sample period T, the discrete model is

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) + f(k) \\ y(k) = Cx(k) \end{cases} \tag{2}$$

where $A = e^{A_f T}$, $B = \int_0^T e^{A_f s} ds B_f$, $C = C_f$. And assume that (A, C) is observable.

Known from the theory of wireless sensor, the time delay mainly depends on the transfer count or hop count of the data packet in transmission. d_k^{sc} is the time-varying delay of closed-loop networked control system. d_k^{sc} is a cbounded sequence of integers through analyzing WSN, namely $d_k^{sc} \in \{0, 1, \cdots, \bar{d}\}$, where $\bar{d}$ is the upper bound of network delay.

4. Design Observer

Design the followed observer for system (2)

$$\begin{cases} \hat{x}(k+1) = A\hat{x}(k) + Bu(k) + L_{d_k^{sc}}[y(k - d_k^{sc}) - \hat{y}(k - d_k^{sc})] \\ \hat{y}(k) = C\hat{x}(k) \end{cases} \tag{3}$$

Define the error vector of state estimation

$$e(k) = x(k) - \hat{x}(k)$$

Then the error equation is

$$e(k+1) = Ae(k) - L_{d_k^{sc}} Ce(k - d_k^{sc}) + f(k) \tag{4}$$

Define the augmented vector

$$E(k) = [e^T(k), e^T(k-1), \cdots, e^T(k - \bar{d})]^T \tag{5}$$

Then

$$E(k+1) = (\tilde{A} - \tilde{L}_{d_k^{sc}} \tilde{C}_{d_k^{sc}}) E(k), \tag{6}$$

where $\tilde{A} = \begin{bmatrix} A & 0 & \cdots & 0 & 0 \\ I & 0 & \cdots & 0 & 0 \\ 0 & I & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & I & 0 \end{bmatrix}$, $\tilde{L}_{d_k^{sc}} = \begin{bmatrix} L_{d_k^{sc}} \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$,

$$\tilde{C}_{d_k^{sc}}(k) = \begin{bmatrix} 0 & \cdots & 0 & C & 0 & \cdots & 0 \end{bmatrix},$$

in addition to column $d_k^{sc} + 1$ of $\tilde{C}_{d_k^{sc}}(k)$, other elements are all zero.

d_k^{sc} is time-varying, coefficient matrix $\tilde{A} - \tilde{L}_{d_k^{sc}} \tilde{C}_{d_k^{sc}}$ changes by network delay and switches on the point $\bar{d} + 1$. So the observer system can be viewed as a switched system. We can know from Eq.6 that the delay generated from the hops of data in transmission is measurable and the value of delay may be the any one between 0 and $\bar{d}$. The observer system (6) can be described as followed discrete switched system.

$$E(k+1) = \sum_{d_k^{sc}=0}^{\bar{d}} \omega_{d_k^{sc}} (\tilde{A} - \tilde{L}_{d_k^{sc}} \tilde{C}_{d_k^{sc}}) E(k) \tag{7}$$

where $\omega_{d_k^{sc}} \to \{0, 1\}$, $\sum_{d_k^{sc}=0}^{\bar{d}} \omega_{d_k^{sc}} = 1$.

5. Stability Analysis

Lemma 1 [27]: Consider a discrete switched system

$$x_{k+1} = A_i x_k \text{ namely } x_{k+1} = \sum_{i=1}^{r} \omega_i A_i x_k,$$

where $i = 1, \cdots, r$, $r < \infty$ is the number of subsystems and $\sum_{i=1}^{r} \omega_i = 1$. If there exists a common positive definite symmetric matrix P, so that all subsystems are met

$$A_i^T P A_i - P < 0 \, (i = 1, \cdots, r)$$

So the whole discrete switched system is asymptotically stable.

Note that even if each subsystem of switched system is stable, the whole system is not necessarily stable. The lemma requires all subsystems to have the common positive definite symmetric matrix which meets the Lyapunov stability, so that can guarantee the stability of the entire system.

Theorem 1: For the observer system described as Eq.6, if it has common positive definite symmetric matrix *P* and *Q* to meet the followed inequality, then the observer error system is asymptotically stable.

$$\begin{bmatrix} -P & \widetilde{A}^T P - \widetilde{C}^T_{d_k^{sc}} Q_{d_k^{sc}} \\ P\widetilde{A} - Q^T_{d_k^{sc}} \widetilde{C}_{d_k^{sc}} & -P \end{bmatrix} < 0 \tag{8}$$

where $d_k^{sc} \in \{0,1,\cdots,\bar{d}\}$, $\widetilde{L}_{d_k^{sc}} = P^{-1} Q^T_{d_k^{sc}}$ is the gain matrix.

Proof: Choose the Lyapunov Function $V_k = E_k^T P E_k$, where *P* is a positive definite symmetric matrix, so

$$\begin{aligned} \Delta V_k &= V_{k+1} - V_k \\ &= E^T_{k+1} P E_{k+1} - E_k^T P E_k \\ &= E_k^T [(\widetilde{A} - \widetilde{L}_{d_k^{sc}} \widetilde{C}_{d_k^{sc}})^T P (\widetilde{A} - \widetilde{L}_{d_k^{sc}} \widetilde{C}_{d_k^{sc}}) - P] E_k \end{aligned} \tag{9}$$

Then $\Delta V_k < 0$ is equivalent to

$$(\widetilde{A} - \widetilde{L}_{d_k^{sc}} \widetilde{C}_{d_k^{sc}})^T P (\widetilde{A} - \widetilde{L}_{d_k^{sc}} \widetilde{C}_{d_k^{sc}}) - P < 0 \tag{10}$$

According to Schur Complementary Lemma, we can get

$$\begin{bmatrix} -P & (\widetilde{A} - \widetilde{L}_{d_k^{sc}} \widetilde{C}_{d_k^{sc}})^T \\ \widetilde{A} - \widetilde{L}_{d_k^{sc}} \widetilde{C}_{d_k^{sc}} & -P^{-1} \end{bmatrix} < 0 \tag{11}$$

Note that there are P and P^{-1} in Eq.11, it should be transformed into a linear matrix inequality, so that we can solve it directly with LMI toolbox. By left and right multiplying $diag(I,P)$ at the both sides of above inequality, we can get the followed inequality.

$$\begin{bmatrix} -P & (P\widetilde{A} - P\widetilde{L}_{d_k^{sc}} \widetilde{C}_{d_k^{sc}})^T \\ P\widetilde{A} - P\widetilde{L}_{d_k^{sc}} \widetilde{C}_{d_k^{sc}} & -P \end{bmatrix} < 0 \tag{12}$$

Note that there are product terms P and $\widetilde{L}_{d_k^{sc}}$ in the above inequality, they constitute the bilinear matrix inequalities, and make it difficult to directly solve the gain matrix, therefore, we should do variable substitution, define $Q_{d_k^{sc}} = \widetilde{L}^T_{d_k^{sc}} P$ into Eq. 12, we can get Eq. 8 and the gain matrix of observer $\widetilde{L}_{d_k^{sc}} = P^{-1} Q^T_{d_k^{sc}}$. The proof is concluded.

Because there are $\bar{d}+1$ matrix inequalities in Theorem 1, there are also $\bar{d}+1$ gain matrixes of observer. When ensuring the stability of error system, if make the output error ε_k to be the residue of fault detection, there is $\varepsilon_k = He_k$, H is the output weight matrix.

The fault detection logic is

$$\begin{cases} \|\varepsilon_k\| \le \bar{\varepsilon} & nromal \\ \|\varepsilon_k\| > \bar{\varepsilon} & fault \end{cases} \tag{13}$$

where $\|\varepsilon_k\| = \sqrt{\varepsilon_k^T \varepsilon_k}$, and $\bar{\varepsilon}$ is the selected threshold.

6. Simulation Example

In this section, we consider the networked control systems built around WSNs described as followed

$$\begin{cases} \dot{x}(t) = \begin{bmatrix} 0 & 2 \\ 1.2 & -1.5 \end{bmatrix} x(t) + \begin{bmatrix} 1 \\ 1 \end{bmatrix} u(t) + f(t) \\ y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t) \end{cases}$$

Assume that the sampling period is *T* = 0.1s. The network exists only between sensor and controller. The upper bound of the output delay is $\bar{d} = 1$. The requirement is to design a fault observer that can ensure the stability of the error system and detect the faults effectively.

The discrete model of the object is

$$\begin{cases} x_{k+1} = \begin{bmatrix} 1.0114 & 0.1865 \\ 0.1119 & 0.8716 \end{bmatrix} x_k + \begin{bmatrix} 0.1099 \\ 0.0990 \end{bmatrix} u_k + f_k \\ y_k = \begin{bmatrix} 1 & 0 \end{bmatrix} x_k \end{cases}$$

Define the output weight matrix $K = I$, $H = I$, according to Theorem 1, we can get the followed matrix by using feasp of LMI toolbox.

$$P = \begin{bmatrix} 1.8975 & -2.2678 & 1.3042 & -1.3368 \\ -2.2678 & 1.8397 & 3.817 & -7.401 \\ 1.3042 & 3.817 & 1.9157 & -1.3171 \\ -1.3368 & -7.401 & -1.3171 & 1.0054 \end{bmatrix}$$

When $d_k^{sc} = 0$

$$L_{d_k^{sc}} = [2.1037 \quad 0.5796]^T$$

When $d_k^{sc} = 1$

$$L_{d_k^{sc}} = [0.0643 \quad 0.4143]^T$$

When the system is normal, Fig. 3 shows the curves about the state x_1, x_2 of original system tracked by fault observer.

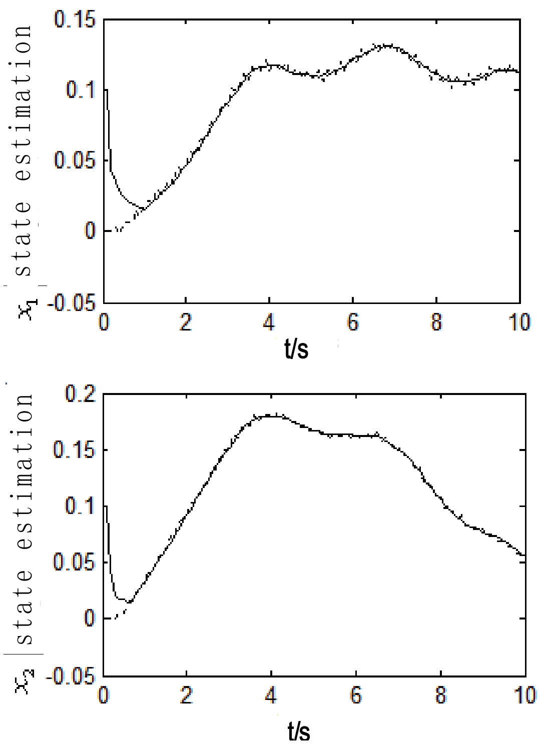

Fig. 3. The result of state estimation.

From the Fig. 4 we can see that there is a certain degree of tracking error at the initial stage of the simulation, when time goes on, the observer can fully track the original system even if not considering the uncertainty of modeling and the external disturbance input.

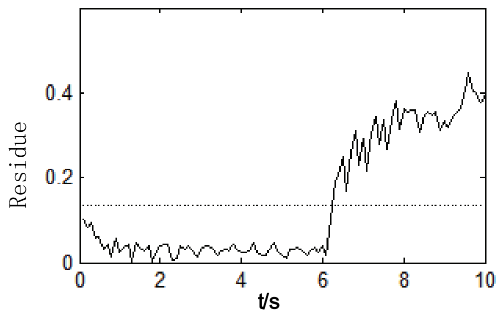

Fig. 4. The result of fault detection.

Assume that the system has step fault at time $t = 6s$, the amplitude is 0.4. We take the threshold of fault detection as $\bar{\varepsilon} = 0.135$, the result of fault detection is shown in Fig. 3.

From the Fig. 3 we can see that the residue changes suddenly and overtakes the threshold quickly when the fault occurs. So the observer can detect the faults of system effectively. Otherwise, the premise of fault detection is that the system has ended the transition process and the observer has been tracking the original system. When the system is in transition process, the result of fault detection is not accurate and the observer may give the wrong alarms.

7. Conclusions

Considering a class of networked control systems built around WSNs, this paper designs a fault observer with the hypothesis that there is output delay in system. And the stability problem of observer is transformed into the same problem of discrete switched system. Its own switching relates with the transfer hops of WSN so as to derive the matrix inequality of the asymptotic stability. A simulation example is given in paper. The result about fault detection in this paper is the preliminary exploration and the effective supplement for wireless networked control system. Compared to the wired networked control system, the study result of fault detection for wireless networked control system is still not rich, so it needs further exploration and research.

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