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Fault Tolerant Control for Discrete Networked Control Systems with Random Faults

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Abstract: This paper concerns the fault tolerant control for discrete networked control systems (NCSs) with probabilistic sensor and actuator fault, random delay and packet dropout. The fault of each sensor or actuator happens in a random way, which is described by an individual random variable satisfying a certain probabilistic distribution. Using these stochastic variables in the system model, new type of NCSs fault model is proposed. The merit of the proposed fault model lies in its generalization and reality, which can cover some existing fault models as special cases. By using Lyapunov functional method and linear matrix inequality technology, sufficient conditions for the mean square stable (MSS) of the NCSs can be obtained. Then the reliable controller can be designed. Finally, a numerical example and a practical example are given to demonstrate the efficiency and application of the proposed method.

Keywords: Fault tolerant control, networked control systems, probabilistic failures.

1. INTRODUCTION

Networked control systems (NCSs), in which the information among distributed sensors, controller and actuators exchanges through communication network, have received considerable attention in recent years (see [1-3] and the references therein). However, in most literatures concerning NCSs, the assumption of consecutive measurements has always been made [4], which means that the true measurement signal can always be obtained by the controller or actuators. Unfortunately, this is not always true in practice.

In practical NCSs, because of bandwidth limitation and other characteristics of shared data networks, networked connection has some time-delay and is not as reliable as traditional point-to-point connection, there are mainly two kinds of fault: a) the limited capacity communication networks may cause packet loss, data collision or data quantization; b) affected by aging, disturbances, electromagnetic interference, temporary failure of the sensors or actuators may happen. The fault in the NCSs may degrade the system performance or even make the system unstable, which has brought us new challenges in system modeling and reliable controller design for the NCSs.

Fault tolerant control for the system without network insertion [4-6] or with network insertion [6] has been investigated in the recent years, wherein most of them only considering system with actuator failures. The behavior of faulty devices in a system can be in general described as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t), \\ u^F(t) &= \Xi u(t), \end{aligned} \tag{1}$$

where $u(t)$ is commanding signals to the devices and $u^F(t)$ is the actual outputs of the possibly faulty devices. $\Xi = diag\{\Xi_1, \dots, \Xi_m\}$ is a diagonal matrix and is called the failure matrix or fault matrix. Wherein m is the number of actuators and Ξ_i is the failure status of the ith actuator, '1' for normal and '0' for fail. In the literatures on the similar subject, the following modeling methods of actuator faults have been studied:

a) Ξ_i is known constant values of $\{0,1\}$ or $\Xi_i \in [0,1]$ [7,8].

b) Ξ_i is unkown but the lower and upper bounds is known [6,9].

c) $\Xi_i = I$ but decompose the matrix B in (1) as $B = B_\Omega + B_{\bar{\Omega}}$, where $\Omega \in \{1, 2, \dots, m\}$ denotes the set of actuators that are susceptible to failures and may actuarially fail. The other set denotes the set of actuators that are robust to failure. B_Ω, $B_{\bar{\Omega}}$ correspond to those input channels with index Ω and $\bar{\Omega}$ [10].

d) Ξ_i is stochastic variables with known expectation and variance [4,12,13].

Because of the stochastic character of the random actuator fault and network, method of (4) has been paid much attention more recently [4,12,13]. In these references, the modeling method can be further

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classifiled as: (d.1) $m=1$ and $\Xi \in \{0,1\}$ is a binary Bernoulli distributed variable [4]. In this method, a latent assumption is that all the actuators have the same failure rate and the failure status of the actuators has only two types. (d.2) $m=1$ but $\Xi \in [0,1]$ [4], which can be seen as an improvement of (d.1), considering the partial failures of the actuators. (d.3) $\Xi_i \in \{0,1\}$ but considering different failure rate of the actuators [12]. (d.4) $\Xi_i \in [0,1]$ and considering different failure rate of the actuators [13].

However, the following problems still exist in the references on this topic: 1) there has been seldom effort on the stochastic fault of both sensors and actuators; 2) the investigation for the system model and analysis for NCSs with stochastic fault still need further consideration when considering network-induced delay and packet dropout; 3) affected by aging or electromagnetic interference, the output of the sensor maybe larger than the true measurement, which has not been considered in the existing references.

In order to deal with the problems of 1)-3), this paper investigates the problem of system modeling and reliable controller design for the networked control systems with stochastic sensor and actuator fault, system uncertainties and network-induced delay. Two sets of stochastic variables are proposed to describe the stochastic fault of the sensor and actuator and a new stochastic networked control system model is built, which contains some existing system models as special cases. By using improved Lyapunov method, sufficient conditions for the mean square stability (MSS) of the NCSs can be obtained. By using the proposed algorithm, the reliable controller can be designed, which can guarantee the stability of the stochastic systems with probabilistic sensor and actuator fault. A numerical example and a practical example are given to show the effectiveness of the proposed design procedures.

2. SYSTEM DESCRIPTION AND PRELIMINARIES

Consider the discrete-time linear model of the plant as follows

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k, \\ u_k &= Kx_k, \end{aligned} \tag{2}$$

where $x(k) \in \mathbb{R}^n$ is the state vector, and $u(k) \in \mathbb{R}^m$ is the control input, $A \in \mathbb{R}^{n\times n}$ and $B \in \mathbb{R}^{n\times m}$ are constant matrices and K is the controller feedback gain to be designed.

2.1. Networked delay and controller without sensor and controller fault

Assumption 1: In this paper, the distributed sensors, controller and actuators are assumed to be connected through network. The sensor is clock driven and the controller is event driven. The actuator is event driven and has a logic ZOH. The role of the logic ZOH is to accept a received control packet only if the time stamp of the packet is greater than that of the packet currently stored in the ZOH.

Considering the effect of packet dropout and/or out-of-order, we use $r_1, r_2, ...$ denote the sampling instant of the first, second, … signals which can finally reach the actuator. It should be noted that $\{r_1, r_2, ...\}$ is a subset of $\{1,2,\ldots\}$. If there is no packet dropout and/or out-of-order, $\{r_1, r_2, ...\} = \{1,2,\ldots\}$. And $\{r_{k+1} - r_k - 1\}$ denotes the number of continuous packet dropout. If we further consider the network-induced delay, the controller becomes

$$u_k = Kx_{r_k}, \quad k \in [r_k + \tau_k, r_{k+1} + \tau_{k+1} - 1], \tag{3}$$

where τ_k is the network-induced delay, x_{r_k} is the abbreviation of $x(r_k)$, u_k remains the same value when $k \in [r_k + \tau_k, r_{k+1} + \tau_{k+1} - 1]$ and updates at the instants of $\{r_k + \tau_k\}$, which is a piecewise continuous function.

Define $d_k = k - r_k, x_{r_k}$ can be rewritten as x_{k-d_k}

$$\tau_k \le d_k \le r_{k+1} - r_k + \tau_{k+1} - 1 = d_M.$$

From the definition of d_k, which contains the synthesis information of network-induced delay and packet loss.

2.2. Controller with possible sensor and actuator fault

When considering the possible random sensor fault

$$u_k = K\Xi_1 x_{k-d_k}, \tag{4}$$

where $\Xi_1 = diag\{\Xi_{11}, \Xi_{12}, ..., \Xi_{1n}\}$ with Ξ_{1i} being n unrelated random variables, the expectation α_i and variance $\breve{\alpha}_i^2$ of Ξ_{1i} are known values.

Remark 1: The stochastic variables are introduced to describe the failure status of the sensor. When $\Xi_{1i} = 0$, it means complete failure of the ith sensor at this moment. When $\Xi_{1i} = 1$, it means complete normal case. When $\Xi_{1i} \in (0,1)$, it means partial failure of the ith sensor with the case of output measurement smaller than the real measurement. When $\Xi_{1i} > 1$, it means the output measurement larger than the real measurement.

Remark 2: From the definition of (4), it can be found that the failure rate of the sensors are different from each other, which is governed by the expectation and variance of the proposed stochastic variables.

Similar to the above analysis, when considering the possible fault of both sensor and actuators, the controller (4) can be further described as

$$u_k = \Xi_2 K \Xi_1 x_{k-d_k}, \tag{5}$$

where $\Xi_2 = diag\{\Xi_{21}, \Xi_{22}, ..., \Xi_{2n}\}$ with Ξ_{2i} being m unrelated random variables, the mathematical expectation and variance of Ξ_{2i} are β_i and $\breve{\beta}_i^2$.

Remark 3: In some existing references, the fault type of $\Xi_{1i} \in \{0,1\}$ in [11] and $\Xi_{1i} \in [0,1]$ in [4,13] have been investigated. However, the fault type of $\Xi_{1i} > 1$, that is, the case of the output measurement is greater than the real measurement has not been paid enough consideration, which is one of the motivation of the present paper.

2.3. System model with possible sensor and actuator fault

Define $\bar{\Xi}_1 = \mathbb{E}\{\Xi_1\}$ and $\bar{\Xi}_2 = \mathbb{E}\{\Xi_2\}$, then

$$\bar{\Xi}_1 = diag\{\alpha_1,...,\alpha_n\} = \sum_{i=1}^{n} \alpha_i \Theta_1{}^i,$$

$$\bar{\Xi}_2 = diag\{\beta_1,...,\beta_n\} = \sum_{i=1}^{m} \beta_i \Theta_2{}^i,$$

where $\Theta_1{}^i$ and $\Theta_2{}^i$ are diagonal matrices with the i element is 1 and the other elements are 0.

Substituting the reliable controller (5) into the system (2), we obtain

$$x_k = Ax_k + B\Xi_2 K \Xi_1 x_{k-d_k} = A_{F1}\xi_k + B_F x_{k-d_k} \tag{6}$$
$$x_k = \phi_k, k = -d_M,...,-1,0,$$

where ϕ_k is the initial condition, $\Delta\Xi_i = \Xi_i - \bar{\Xi}_i$

$$A_{F1} = [A \quad B\bar{\Xi}_2 K \bar{\Xi}_1 \quad 0],$$
$$B_F = B(\bar{\Xi}_2 K \Delta\Xi_1 + \Delta\Xi_1 K \bar{\Xi}_2 + \Delta\Xi_1 K \Delta\Xi_2),$$
$$\xi_k{}^T = [x_k^T \quad x_{k-d_k}^T \quad x_{k-d_M}^T].$$

3. MAIN RESULTS

In this section, we are going to derive the sufficient conditions for the MMS of the proposed system (6) by Lyapunov functional method. Firstly, a Lyapunov functional candidate is constructed. After taking the forward difference for the Lyapunov functional and using corresponding analysis method, sufficient conditions for the MMS of system (6) can be obtained.

Theorem 1: System (6) is said to be MSS if there exist matrices $P > 0$, $Q > 0$, $R > 0$, N, M and K with appropriate dimensions, such that for $l = 1,2$

$$\begin{bmatrix} \Pi_{11} & * & * & * \\ \Pi_{21}^l & -R & * & * \\ \Pi_{31} & 0 & \Pi_{33} & * \\ \Pi_{41} & 0 & 0 & \Pi_{44} \end{bmatrix} < 0, \tag{7}$$

where

$$\Pi_{11} = \Upsilon + \Gamma + \Gamma^T, \quad \Upsilon = diag\{Q-P, 0, -Q\},$$
$$\Gamma = \begin{bmatrix} -N & N-M & M \end{bmatrix}, \quad \Pi_{33} = diag\{-P^{-1}, -R^{-1}\},$$
$$\Pi_{21}^1 = \sqrt{d_M} N^T, \quad \Pi_{21}^2 = \sqrt{d_M} M^T,$$
$$\Pi_{31} = \begin{bmatrix} A_{F1} \\ \sqrt{d_M} A_{F2} \end{bmatrix}, \quad \Pi_{41} = \begin{bmatrix} \Pi \\ \sqrt{d_M}\Pi \end{bmatrix},$$
$$\Pi_{44} = diag\{-P^{-1},...,-P^{-1},-R^{-1},...,-R^{-1}\},$$
$$\Pi^T = [\Lambda_1^T \quad \Lambda_2^T \quad \cdots \quad \Lambda_n^T],$$
$$\Lambda_j^T = [\mathfrak{B}_{1j}^T \quad \mathfrak{B}_{2j}^T \quad \cdots \quad \mathfrak{B}_{mj}^T],$$
$$\mathfrak{B}_{ij}^T = [0 \quad \sqrt{v_{ij}} B\Theta_2^j K \Theta_1^j \quad 0],$$
$$v_{ij} = \breve{\alpha}_i^2 \beta_j + \alpha_i \breve{\beta}_j^2 + \breve{\alpha}_i^2 \breve{\beta}_j^2,$$
$$A_{F2} = [A-I \quad B\bar{\Xi}_2 K \bar{\Xi}_1 \quad 0].$$

Proof: The Lyapunov functional candidate is

$$V_k = x_k^T P x_k + \sum_{i=k-d_M}^{k-1} x_i^T Q x_i + \sum_{i=-d_M}^{-1} \sum_{j=k+i}^{k-1} e_i^T Q e_i, \tag{8}$$

where $e_k = A_{F2}\xi_k + B_F x_{k-d_k}$.

Taking the forward difference for the Lyapunov functional and taking expectation on it

$$\mathbb{E}\{\Delta V_k\} = \mathbb{E}\{x_{k+1}^T P x_{k+1} - x_k^T P x_k + x_k^T Q x_k - x_{k-d_M}^T Q x_{k-d_M} + d_M e_k^T R \mathrm{e}_k - \sum_{i=k-d_M}^{k-1} e_i^T R \mathrm{e}_i. \tag{9}$$

Using the free weighing matrix method, we obtain

$$\mathbb{E}\{\Delta V_k\} = \mathbb{E}\left\{ \frac{1}{d_M} \sum_{i=k-d_k}^{k-1} \tilde{\xi}_{k,i}^T F_1 \tilde{\xi}_{k,i} + \frac{1}{d_M} \sum_{i=k-d_M}^{k-d_k-1} \tilde{\xi}_{k,i}^T F_2 \tilde{\xi}_{k,i} \right\} \tag{10}$$

where $\tilde{\xi}_{k,i}^T = [\xi_k^T \quad e_i^T]$,

$$F_1 = \begin{bmatrix} W & d_M N \\ d_M N^T & -d_M R \end{bmatrix}, \quad F_2 = \begin{bmatrix} W & d_M M \\ d_M M^T & -d_M R \end{bmatrix},$$
$$W = \Upsilon + \Gamma + \Gamma^T + A_{F1}^T P A_{F1} + d_M A_{F2}^T R A_{F2} + \sum_{i=1}^{n}\sum_{j=1}^{m} \mathfrak{B}_{ij}^T \left(P + d_M R\right) \mathfrak{B}_{ij}.$$

Using Schur complements and (7), it can be obtained $F_l < 0 (l = 1,2)$. There exist $\lambda > 0$ such that

$$\mathbb{E}\{\Delta V_k\} \le -\lambda \mathbb{E}\{\xi_k^T \xi_k\} \le -\lambda \mathbb{E}\{x_k^T x_k\}. \tag{11}$$

Then MSS of the system (6) can be easily obtained.

Remark 4: From Theorem 1, the solvability of (7) depends on not only the delay bound d_M, but also the failure rate of the actuators and sensors.

It should be noted that criteria in Theorem 1 are nonconvex feasibility problem because of the existence of P^{-1} and R^{-1}, which can be solved similar to the cone complementarity linearization method [14].

4. SIMULATION EXAMPLES

Example 1: Consider the discrete-time system (6) with the parameters

$$A = \begin{bmatrix} 1.1 & -0.1 \\ 0.3 & -0.9 \end{bmatrix}, \quad B = \begin{bmatrix} -0.8 & 0.3 \\ 0.2 & 0.7 \end{bmatrix}. \tag{12}$$

For system (12), to illustrate the efficiency and application of the proposed procedure, we consider the following 3 cases:

Case 1: Setting $\Xi_1 = \Xi_2 = diag\{1,1\}$, $\breve{\alpha}_i = \breve{\beta}_i = 0$, that is, the sensors and actuators are in good working condition. In this case, for $d_M = 6$, by using Theorem 1, the feedback gain K is obtained as

$$K = \begin{bmatrix} 0.1417 & -0.0052 \\ -0.0649 & 0.0049 \end{bmatrix}. \tag{13}$$

Case 2: Setting $\Xi_1 = diag\{0.5, 0.8\}$, $\breve{\alpha}_i^2 = 0.2$, $\Xi_2 = diag\{1.1, 0.6\}$, $\breve{\beta}_i = 0.3$, that is, both the probabilistic failures of sensors or actuators happens as well as measurements distortion, network-induced delay and packet dropout. For $d_M = 6$, the feedback gain K is obtained as

$$K = \begin{bmatrix} 0.2572 & -0.0058 \\ -0.1161 & 0.0102 \end{bmatrix}. \tag{15}$$

For the initial state x0=[0.5;-0.5], the state responses of Case 2 are shown in Fig. 1. From Fig. 1, it can be found that using the proposed method, the controller can stabilize the NCSs with both probabilistic sensor failures and actuator failures.

By using Theorem 1, the maximum allowable delay bound of d_M can be obtained as: $d_M = 10$ for Case 1 and $d_M = 6$ for Case 2. From the computation, it can be found that the probabilistic sensors or actuators faults can degrade the system performance.

Case 3: In the following, we will show the necessary of the proposed reliable control. Suppose that the probabilistic sensors and actuators faults happens and the parameters are shown in Case 3, however, we still use the feedback gain (13) obtained in Case 1. That is, we use the controller designed without unreliable cases to stabilize the system with probabilistic faults. the state responses are shown in Fig. 2. From Fig. 2, it can be found that the system is unstable using feedback gain (13) when failures happens, which demonstrates the necessary and important of the reliable control design for NCSs.

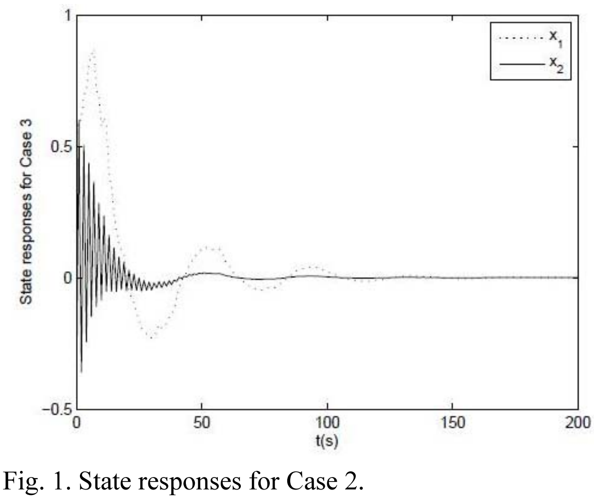

Fig. 1. State responses for Case 2.

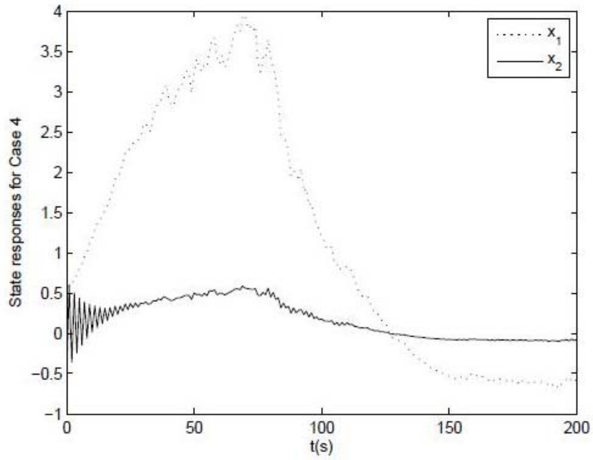

Fig. 2. State responses for Case 3.

Example 2: Considering the discretization of the Vertical Take-Off and Landing (VTOL) aircraft [15]. Using the zero-order hold with a sampling period T=0.2s, the discrete-time VTOL model is given by

$$A = \begin{bmatrix} -0.0717 & -0.0681 & 0.0205 & 0.5076 \\ 6.7971 & 1.2917 & 0.7634 & -3.5029 \\ 2.1633 & 0.2191 & 0.4345 & -1.8614 \\ 0.2966 & 0.0300 & 0.1360 & 0.7606 \end{bmatrix},$$

$$B^T = \begin{bmatrix} -0.0172 & 0.7044 & -0.5131 & -0.0670 \\ 0.0927 & -1.2657 & 0.4350 & 0.0559 \end{bmatrix},$$

For the fault rate $\Xi_1 = diag\{0.8, 0.5, 1, 1.1\}$, $\breve{\alpha}_i^2 = 0.2$, $\bar{\Xi}_1 = diag\{0.6, 0.9\}$, $\breve{\alpha}_i^2 = 0.2$, and $d_M = 17$, using Theorem 1, the controller feedback gain

$$K = \begin{bmatrix} -0.1415 & 0.0122 & 0.0600 & -0.1166 \\ -0.0390 & 0.0212 & 0.0285 & -0.0553 \end{bmatrix}.$$

For the initial state x(0)=[3;5;1;4], the state responses of the VTOL model with both sensors failure, actuators failure and network-induced delay are shown in Fig. 3.

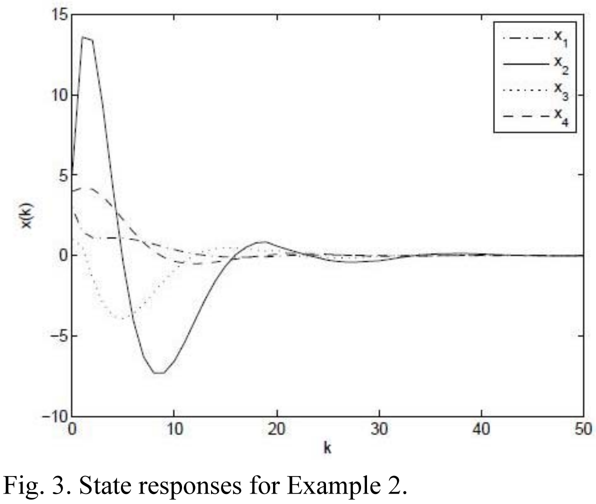

Fig. 3. State responses for Example 2.

From Fig. 3, we can conclude that the system with stochastic sensor and actuator failure can be stabilized under the designed feedback gain.

5. CONCLUSION

This paper considers the fault tolerant control for networked control systems with probabilistic sensors and actuators failures, networked delays and packet losses. The faults of the sensors or actuators are assumed to be occurred in a random way, and their failure rate is governed by two sets of random variables. The merit of the proposed fault model and proposed method lies in its generalization and reality, which can cover some existing fault models as special cases. By Lyapunov functional method, sufficient conditions for the MSS of the NCSs is obtained. The given examples show the efficiency and application of the proposed method.

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