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Robust unknown input observer based fault detection for high-order multi-agent systems with disturbances

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ABSTRACT

This paper is devoted to fault detection (FD) for high-order multi-agent systems with disturbances. In order to detect the fault occurred in one agent, the unknown input observer (UIO) is constructed in its neighbor. Two cases are considered, if the perfect UI decoupling condition is satisfied, the UI does not affect the residual; if the condition is not satisfied, this paper proposes a method of partitioning the UI into two parts, such that a subset of the UI does not appear in residual dynamics, and the influence of the other UI is constrained. Simulations are given to demonstrate the effectiveness of the proposed method.
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1. Introduction

In recent years, with the rapid advancement in industry, the systems needed to be analyzed are becoming more and more complex. As a powerful tool to deal with complicated system, multi-agent technology has attracted considerable attention in recent years [1–8], and has been applied in a lot of areas, such as industrial processes [9], satellite constellations [10], microgrid [11], mobile robots [12], and multiple nonholonomic unicycles [13].

In practice, the requirement of system reliability has increased. Hence, more and more attention has been devoted to the problem of FD [14–21]. In multi-agent systems, if an agent becomes faulty, the overall system performance will suffer a severe undesirable impact. It should be noted that the existing works of FD mainly focus on the centralized systems, and these methods are not easy to be applied to multi-agent systems. Compared with the centralized FD method, the method of distributed FD, using less network resources and having lower computation complexity, is much more applicative for multi-agent systems.

The problem of FD for multi-agent systems has attracted considerable interest over the recent decades. In [22], the problem of FD for discrete-time Markovian jump linear systems with input disturbance and measurement noise was addressed, and the FD method was applied to multi-agent systems. In [23,24], based on the sliding mode observer, the methods of FD for multi-agent systems were proposed. However, the chattering problem of sliding-mode observer might cause insensitive to incipient faults. For unmanned vehicles, in order to detect the possible faults, [25] presented actuator fault detection and isolation filters. In [26], for unreliable networks, three algorithms were achieved to detect and identify misbehaving agents. Through utilizing the consensus method for multi-agent systems, [27] constructed robust FD filters which were subject to only partial estimated and measured information. Based on the theory of differential geometry, in [28], an active fault recovery strategy was proposed for multi-agent systems with every node having Euler–Lagrange equation dynamic. Utilizing the distributed function calculation technique, the method of FD for multi-agent systems was proposed in [29]. In [30], for heterogeneous multi-agent systems, distributed fault detection and isolation filter was designed.

The fault signal and the disturbance are generally unknown, hence, UIO is a useful method to deal with the problem of FD. In [31], a bank of unknown input observers were constructed to detect the fault for two classes of multi-agent systems. For discrete-time second-order multi-agent systems, the method of FD was proposed in [32].

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It should be noted that in [24–26,29,31], the influence of disturbances was not considered. However, in practice, disturbances are inevitable. In order to detect the fault, the authors of [32] constructed FD observer for multi-agent systems with zero mean white noises. It is worth pointing out that the types of disturbances may be various in practice. Note that UIO is a powerful technique on FD [31,32]. However, in traditional UIO design process, the perfect UI decoupling condition must be satisfied, while it is common that this condition is not satisfied. Besides, the methods proposed in [31,32] are not easy to be applied to address the problem of FD for multi-agent systems with more than one faulty agent.

Motivated by the above works, in order to detect the fault in the multi-agent systems, a novel robust unknown input observer design method is proposed. The main contributions of this paper are summarized as follows: (1) The fault in one agent can be detected by the observer constructed in its neighbor agent. Residual is robust to the UI, containing possible faults in other agents, which means that the proposed method can be applied to address the problem of FD for multi-agent systems with more than one faulty agent. (2) If the perfect UI decoupling condition is satisfied, we construct UIO, and the influence of UI on the residual is removed completely. (3) If the condition is not satisfied, which is common in practice, the methods proposed in [31,32] cannot be applied. For the purpose of solving this problem, the method of partitioning the UI into two parts is proposed, such that the influence of a subset of UI on the residual is removed completely, and the influence of the other UI on the residual is constrained by the H_∞ performance index, i.e., the residual is robust to the UI. (4) For the purpose of controlling the estimation transient response, regional pole constraints are considered in this paper.

The outline of this paper is as follows. Some foundational descriptions are recalled in Section 2. Method of FD for multi-agent systems is proposed in Section 3. In Section 4, two examples are presented to illustrate the effectiveness of the proposed method. Finally, Section 5 concludes this paper.

In this paper, the notations employed are fairly standard. B^T and $\|x\|$ stand for the transpose of a matrix B and the Euclidean norm of a vector x, respectively. $\otimes$ denotes the Kronecker product. $|N|$ is the cardinality of the set N. C^+ denotes the Moore–Penrose of a matrix C. I stands for an identity matrix with appropriate dimension. $P>0$ means that the matrix P is real symmetric and positive definite.

2. Problem formulation and preliminaries

In this paper, we assume that the graph $G=\{V,E,A\}$ is a weighted undirected graph, in which $V=\{V_1,V_2,\ldots,V_N\}$ stands for the vertex set, and $E=\{(V_i,V_j):V_i,V_j\in V\}\subset V\times V$ stands for the edge set, the adjacent matrix of graph G is described as $A=[a]_{ij}\in R^{N\times N}$ with entries defined as follows:

$$a_{ij}=\begin{cases}0, & i-j\\ 1, & (V_i,V_j)\in E\\ 0, & \text{otherwise}\end{cases}$$

The neighborhood set of the node V_p is denoted by

$$N_p=\{V_j\in V:(V_p,V_j)\in E, p\neq j\}.$$

A sequence composed of different nodes $V_{i_0},V_{i_1},\ldots,V_{i_l}$, where $i_0=i$, $i_l=j$, $(V_{i_r},V_{i_{r+1}})\in E$, $0\le r\le l-1$, is called a path from V_i to V_j. If there is at least one path between any two nodes in G, we say that graph G is connected. Matrix $L=[l]_{ij}$ is the Laplacian matrix of the graph G with entries defined as

$$l_{ij}=\begin{cases}\sum_{j=1}^{N}a_{ij}, & i=j\\ -a_{ij}, & i\neq j\end{cases}$$

For the purpose of describing conveniently, subscripts will be used to denote the corresponding nodes in the following paper.

Considering a class of high-order multi-agent systems consisted of N agents, the dynamic of agent i is described as

$$\begin{cases}\dot{x}_i(t)=A_1x_i(t)+B_1u_i(t)+Q_1f_i(t)+Q_2d_i(t)\\ y_i=C_1x_i(t)\end{cases} \tag{1}$$

where $x_i(t)\in R^n$, $u_i(t)\in R^n$, $y_i(t)\in R^m$, $d_i(t)\in R^{m_2}$ are the state, known input, output and disturbance vectors, respectively, and signal $f_i(t)\in R^{m_1}$ stands for the unknown fault vector needed to be detected. Matrices A_1, B_1, Q_1, Q_2 and C_1 are known matrices with appropriate dimensions. We assume that matrices Q_1 and Q_2 are of full column rank. Note that this assumption is not restrictive, the interested reader can refer to [31].

In this paper, the following lemmas are useful:

Lemma 1 (*Hieu Trinh [33]*). *For given matrices C, E and equation HCE=E, a solution for H exists if rank(CE)=rank(E). A general solution for H is given by*

$$H=E(CE)^+ +Z(I-(CE)(CE)^+) \tag{2}$$

where $(CE)^+$ is the Moore–Penrose of CE, Z is an arbitrary matrix with appropriate dimension.

Lemma 2 (*Yu, Chilali et al., [34,35]*). *For LMI resign $D(\alpha,r,\theta)$ in which the vertical line at $-\alpha$ bounds the stability region, where r is the radius of the disc region whose centre is $0+0j$, and θ is the angle of sector of the r and centre of the disc region circle. The eigenvalues of a given matrix $W\in R^{n\times n}$ belong to the region $D(\alpha,r,\theta)$ if and only if there exists a symmetric positive definite matrix $X\in R^{n\times n}$ such that the following conditions hold:*

$$\begin{bmatrix}\sin\theta(WX+XW^T) & \cos\theta(WX-XW^T)\\ \cos\theta(XW^T-WX) & \sin\theta(WX+XW^T)\end{bmatrix}<0 \tag{3}$$

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