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A consensus-based multi-agent approach for estimation in robust fault detection

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ABSTRACT

This paper is devoted to distributed estimation in robust fault detection for sensor networks with networked-induced delays and packet dropouts by using a consensus-based multi-agent approach. Utilizing the information interaction and coordination among the neighboring networks based on multi-agent theory, we design novel and multiple agent-based robust fault detection filters (RFDFs) subject to only partial estimated and measured information. Asymptotically stable sufficient conditions for the innovative constructed filters are derived in the form of linear matrix inequality (LMI) and the threshold fit for each agent-based RFDF is determined. An illustrative example is given to demonstrate the effectiveness of the consensus-based multi-agent approach for the estimation in robust fault detection.

1. Introduction

The design of fault detection has attracted more and more attention in recent years for the industrial systems with the nature that the effects of unknown inputs, control inputs, disturbances, model uncertainties and the possible faults are coupled, and that the modeling error is unavoidable. Therefore, the technology of fault detection should complete a favorable tradeoff between the robust to unknown inputs, control inputs and model uncertainties and simultaneously sensitive to faults [1,2]. As the current and potential application in industrial and manufacturing automation, sensor network technologies have been developed significantly in sensing, communication and computing with a large number of nodes, and the networks are always large-scale systems [3,4]. As a result, the distributed estimation or filtering for sensor networks is more and more advisable and attractive recently than the centralized estimation and the traditional decentralized estimation as the partial and neighboring information is supplied, which can decrease or even eliminate the difficulty, complexity and inaccuracy in information transmission and processing, etc.

On the other hand, a major research effort has been put into the investigation of the coordination and cooperation of multi-agents during recent decades. Benefiting from the inherent properties of multi-agent structures, such as modularity, scalability, adaptability, flexibility and robustness, the overall design and control of large scale systems can be attained in a coordinated and distributed manner. Especially, the consensus problem and methods of multi-agent systems have received more extensive consideration nowadays [5–11]. This is due to the broad applications of multi-agent systems in many areas, e.g., multiple mobile robots [11–14], flocking or swarming behaviors [15,16], and formation control [17–19].

In this paper, we employ the consensus-based multi-agent approach to complete distributed estimation in robust fault detection, and the observer-based robust fault detection filters (RFDFs) are first designed for sensor networks with networked-induced delays and packet dropouts, which are called the observer-based RFDFs here. The main contributions of this paper can be given as follows: (1) unlike the classical RFDF in [1,2], the agents in our work perform distributed sensors to interact with other agents (sensors) to calculate a global state estimate and construct the agent-based RFDFs. Specifically, compared with the conventional filtering in the single sensor [1,20], the filter in our work in fault detection can estimate the system state and the residual signal in a distributed fashion with the consensus-based multi-agent approach, based not only on the estimated and measured information of sensor *i*, but also partially on its neighboring sensor's estimates. This can enhance the property of observability and estimated capacity of the sensors in robust fault detection. (2) The interchanges of estimates rather than

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measurements among neighboring nodes can supply more freedom and flexibility in choosing information transmission through the network, and reduce the uncertainty of state estimates computed by each node. (3) These novel constructed filters in fault detection with the consensus methodology enable us to alleviate bandwidth use largely, especially in weakly interconnected networks, such as the communication in partially neighboring nodes or transition of only some required information. (4) In the design of agent-based RFDFs, we transfer the system under study to an equivalent multiple-delay system, construct a new Lyapunov–Krasovskii functional by considering the minimum and maximum delay which has wider application, and derive less conservative stability conditions for the agent-based filters in the form of linear matrix inequality (LMI). And in process of dealing with the inequality, we utilize some lemma to calculate it more directly and easily. Moreover, the threshold fit for each agent-based RFDF is determined in our work to increase accuracy and get more realtime in detecting faults.

The paper is organized as follows: Section 2 introduces the basic algebraic graph theory and formulates the problem under consideration. Section 3 presents the agent-based robust fault detection filters design for the transformed closed-loop system. A numerical example is provided in Section 4 to demonstrate the usefulness and applicability of the proposed method, and Section 5 concludes the paper.

Notation: The notation used throughout the paper is fairly standard. The superscript T stands for matrix transposition. R^n denotes the n-dimensional Euclidean space. The notation $*$ is used as an ellipsis for terms induced by symmetry. The notation $P>0\ (\geq 0)$ means that P is real symmetric and positive definite (semi-definite). Z^- are the sets of non-positive integers. $\otimes$ denotes the Kronecker product. $\mathbf{1}_n$ represents the vector $[1,1,\ldots,1]^T$ with the dimension n. 0 denotes zero value or zero matrix with appropriate dimensions. $\|\cdot\|$ denotes the Euclidean norm of a vector and its induced norm of a matrix, and $L_2[0,\infty)$ is the space of square-summable infinite sequence.

2. Graph theory and problem formulation

2.1. Graph theory

Graph theory is an effective mathematical tool to describe the coordination problems and model the information exchange among agents by means of directed or undirected graphs. In this note, we consider a network of n agents (nodes), and model the interaction of them as a connected graph $\mathcal{G}$ with no self-loop including the directed and undirected graphs. If $\mathcal{G}=(\mathcal{V},\mathcal{E})$ is a directed graph with vertex set $\mathcal{V}=\{1,2,\ldots,n\}$ and edge set $\mathcal{E}\in\mathcal{V}\times\mathcal{V}$. The associated adjacency matrix $A_L(\mathcal{G})=[a_{ij}]\in R^{n\times n}$, in which a_{ij} means that information can flow from agent j to agent i and can also be denoted by (j,i). If $(j,i)\in\mathcal{E}$, $a_{ij}=1$; otherwise, a_{ij}=0. Define the in-degree matrix as $D_L(\mathcal{G})=diag\{d_i\}\in R^{n\times n}$. Then the Laplacian matrix of $\mathcal{G}$ can be defined as $L(\mathcal{G})=D_L(\mathcal{G})-A_L(\mathcal{G})$. Let $L(\mathcal{G})=[l_{ij}]\in R^{n\times n}$ and then $l_{ij}=d_i$ when i=j, otherwise, $l_{ij}=-a_{ij}$ as $i\neq j$. While $\mathcal{G}$ is an undirected graph in which the pairs of nodes are unordered, then the edge (i,j) denotes that agents i and j can obtain information from each other. We call the set of agents from which agent i can receive information a neighboring set N_i with $N_i=\{j|(j,i)\in\mathcal{E}\}$. The directed graph $\mathcal{G}=\{\mathcal{V},\mathcal{E}\}$ has a directed spanning tree if and only if $\{\mathcal{V},\mathcal{E}\}$ has at least one node with a directed path to all other nodes, and an undirected graph can also be viewed as a special case of a directed graph. Moreover, a graph is called weakly connected if there is at least one spanning tree in the graph [21].

2.2. Problem formulation

In this note, we study the design of agent-based RFDFs for the discrete-time networked linear time-variant (LTI) systems described by

$$x(k+1)=Ax(k)+Bu(k)+B_f f(k)+B_w w(k),$$
$$y_i(k)=C_i x(k),\quad \forall i=1,2,\ldots,n \tag{1}$$

where $x(k)\in R^p$ is the state vector, $u(k)\in R^m$ the control input vector, $y_i(k)\in R^r$ the measurement outputs and n the number of agents (sensors). $w(k)\in R^q$ is the unknown input vector (including disturbances, uninterested fault as well as some norm-bounded unstructured model uncertainty), $f(k)\in R^s$ the fault to be detected and isolated. A, B, C_i, B_f, B_w are known matrices with appropriate dimensions. We denote C as a matrix stacking all the output matrices C_i, and assume that (C,A) can be detectable. Besides the output $y_i(k)$, agent i can also receive $\hat{y}_{ij}(k)=C_{ij}\hat{x}_j(k)$ from the neighboring node $j\in N_i$ as the estimated outputs of agent i. Define $\overline{C}_i$ as a matrix stacking the matrix C_i and C_{ij} for all $j\in N_i$, and the pair $(\overline{C}_i,A)$ $(\forall i)$ are assumed to be detectable.

2.2.1. Residual generation

For the purpose of residual generation, we will design n RFDFs based on n sensors presented in the following:

$$\hat{x}_i(k+1)=A\hat{x}_i(k)+Bu(k)+E_i(\hat{y}_i(k)-y_i(k))$$
$$\qquad +\sum_{j\in N_i}a_{ij}H_{ij}C_{ij}(\hat{x}_j(k-\tau_{ij}(k))-\hat{x}_i(k-\tau_{ij}(k))),$$
$$\hat{y}_i(k)=C_i\hat{x}_i(k),$$
$$r_i(k)=V_i(\hat{y}_i(k)-y_i(k))+\sum_{j\in N_i}a_{ij}M_{ij}C_{ij}(\hat{x}_j(k-\tau_{ij}(k))-\hat{x}_i(k-\tau_{ij}(k))),$$
$$\forall i=1,2,\ldots,n \tag{2}$$

where $\hat{x}_i(k)\in R^p$ and $\hat{y}_i(k)\in R^r$ represent the state and output estimation vectors on the agent node (sensor node) i, respectively, and $r_i(k)\in R^s$ is the so-called residual signal. The dynamics of the RFDFs are based on both distributed and local observers weighted with E_i, V_i and consensus-based multi-agent approach with weighting matrices H_{ij}, M_{ij}, which are affected by the information received from neighboring nodes.

We say that the design parameters of each agent-based RFDF are the distributed observer gain matrices E_i, H_{ij} and residual weighting matrices V_i, M_{ij} for $\forall i=1,\ldots,n$ and $j\in N_i$, which can asymptotically solve the consensus problem that the estimated states of agent-based RFDFs satisfy $\lim_{k\to\infty}\|\hat{x}_i(k)-x(k)\|=0$ for all $i\in\{1,\ldots,n\}$, i.e. the consensus error is asymptotically stable. Meanwhile, we will design the agent-based RFDFs to complete that the generated residual r_i is as sensitive as possible to fault f and as robust as possible to control input u and disturbance w.

The communication between the neighboring agent-based RFDFs may be affected by the delay, which includes the effect of network-induced delays and also packet dropouts considered as the extended delay [22] in observers in the robust fault detection. The equivalent time-varying bounded delay $\tau_{ij}(k)$ represents the time difference between the current time instant k and the instant when the last packet sent by j was received at node i, as shown in Fig. 1. Suppose that there are together l different delays, and then we can denote $\tau_r(k)\in\{\tau_{ij}(k),\ i,j\in\{1,\ldots,n\}\}$, $\tilde{C}_r\in\{C_{ij},\ i,j\in\{1,\ldots,n\}\}$ with $r\in\{1,\ldots,l\}$, and H_{ij}, M_{ij} are denoted by H_r, M_r similarly. The equivalently time-varying bounded delay $\tau_r(k)$ satisfies that $1\leq\tau_1\leq\tau_r(k)\leq\tau_2$, in which τ_1 and τ_2 are known positive integers.

Considering $e_i(k)=\hat{x}_i(k)-x(k)$ and $\tilde{r}_i(k)=r_i(k)-f(k)$, we obtain

$$e_i(k+1)=(A+E_iC_i)e_i(k)+\sum_{j\in N_i}a_{ij}H_{ij}C_{ij}(e_j(k-\tau_{ij}(k))-e_i(k-\tau_{ij}(k)))$$
$$\qquad -B_f f(k)-B_w w(k),$$