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Brief paper

Distributed adaptive fault-tolerant control of uncertain multi-agent systems☆

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ABSTRACT

This brief paper presents a distributed adaptive fault-tolerant leader-following consensus control scheme for a class of *nonlinear uncertain* multi-agent systems under a bidirectional communication topology with possibly asymmetric weights and subject to process and actuator faults. A local fault-tolerant control (FTC) component is designed for each agent using local measurements and suitable information exchanged between neighboring agents. Each local FTC component consists of a fault diagnosis module and a reconfigurable controller module comprised of a baseline controller and two adaptive fault-tolerant controllers activated after fault detection and after fault isolation, respectively. By using an appropriately chosen Lyapunov function, the closed-loop stability and asymptotic convergence property of leader–follower consensus are rigorously established under different operating modes of the FTC system.

1. Introduction

The study of distributed multi-agent systems (MAS) focuses on the development of control algorithms that enable a team of interconnected agents to accomplish desired team missions (see, for instance, Ren and Beard (2008), and the references cited therein). Adaptive control methods for achieving consensus in uncertain MAS have also been proposed by assuming the absence of faults. For instance, interesting adaptive algorithms are presented recently to handle parametric uncertainty for directed graphs in Ding and Li (2016) and Wang, Huang, Wen, and Fan (2014), and unstructured uncertainty for undirected graphs in Wang, Wen, and Huang (2017), respectively.

In order to ensure reliable and safe operations of MAS, there have been significant research interest in the development of distributed fault diagnosis and accommodation schemes. A distributed fault detection and isolation (FDI) strategy is proposed by Arrichiello, Marino, and Pierri (2015) for a team of first-order networked robots, and Shames, Teixeira, Sandberg, and Johansson (2011) developed a distributed fault detection method for interconnected second-order linear time-invariant systems. Distributed fault diagnosis and estimation schemes for systems with more general structures have also been proposed (see, for instance, Davoodi, Khorasani, Talebi, and Momeni (2014); Reppa, Polycarpou, and Panayiotou (2015); Zhang, Jiang, and Cocquempot (2015); Zhang, Jiang, and Shi (2016)). Additionally, several researchers have also investigated the problem of distributed fault-tolerant control (FTC) of MAS. Li (2013) and Semsar-Kazerooni and Khorasani (2010) focus on fault-tolerant consensus control of MAS with linear dynamics. A fault-tolerant tracking control method for accommodating actuator faults in linear and Lipschitz nonlinear MAS was developed by Zuo, Zhang, and Wang (2015). The aforementioned distributed FTC results are derived based on a critical assumption regarding the interconnection topology, i.e., the corresponding Laplacian matrix is symmetric. Moreover, detailed fault information acquired by the fault diagnosis procedure is very valuable to FTC, since the objective of FTC is to compensate for the effect of such faults. There exist limited results on the systematic design of integrated fault diagnosis and FTC schemes for MAS with *both actuator and process faults*, especially for *nonlinear uncertain*

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agents under an interconnection topology whose Laplacian matrix is *asymmetric* .

In this paper, we investigate the problem of integrated design of fault diagnosis and fault-tolerant leader–follower consensus control for a class of nonlinear uncertain MAS, which are interconnected via a bidirectional communication topology with possibly asymmetric weights and are subject to process faults, actuator faults, and unstructured modeling uncertainties. In a previous paper (Zhang, Parisini, & Polycarpou, 2004), a centralized adaptive FTC method for a class of nonlinear systems was presented, where the centralized fault-tolerant controller has access to all the measurements in the overall system. In contrast, the distributed FTC problem for leader–follower multi-agent systems considered in this paper is much more challenging. First, the interconnection topology between follower agents are considered to be bidirectional but possibly with asymmetric weights. The resulting asymmetric Laplacian matrix significantly increases the complexity of the stability analysis. For instance, the methods for stability analysis presented in Cao and Ren (2012), Khalili, Zhang, Polycarpou, Parisini, and Cao (2015), Wang, Wen, and Huang (2012) and Wang et al. (2017), which utilize the symmetric property of the Laplacian matrix to solve the leader–follower consensus problem for undirected symmetric graphs, are no longer applicable. It is also worth noting that the asymmetric weights of the graph under consideration do not assume the critical detail-balanced condition considered in the literature (Chen, Lewis, & Xie, 2011; Zhang, Yang, Zhao, & Wen, 2013), which makes the stability analysis more challenging. Second, in the leader-following topology considered in this paper, the time-varying leader only communicates to a small subset of follower agents, and each follower agent exchanges measurement information only with its neighbors through an unbalanced interconnection topology. This makes it more difficult to accomplish the asymptotic convergence property of leader-following consensus error in the presence of faults and modeling uncertainty. For instance, the well-known Lyapunov function described in Zhang, Lewis, and Qu (2012) (Lemma 12) would only guarantee uniformly ultimately bounded (UUB) results, where the consensus errors will be dependent on bounds on the fault functions and modeling uncertainties.

In the presented fault diagnosis and accommodation architecture, a local FTC component is designed for each agent by utilizing local measurements and state information exchanged between neighboring agents. Each local FTC component consists of a baseline controller and two adaptive fault-tolerant controllers. The baseline controller guarantees robust leader-following performance with respect to modeling uncertainty. A decentralized fault diagnosis component is used for detecting and isolating faults in each local agent. Based on local fault diagnostic information, two adaptive fault-tolerant controllers are utilized after fault detection and after fault isolation, respectively. An appropriately chosen Lyapunov function is presented to circumvent the technical difficulty in the design and analysis of the fault-tolerant leader-following controllers. Based on adaptive approximation and adaptive bounding control techniques, the closed-loop asymptotic stability property of leader-following consensus is rigorously established under different operating modes of the FTC system, including the time-period before fault occurrence, between fault detection and possible isolation, and after fault isolation.

The rest of this brief paper is organized as follows. The problem formulation is given in Section 2. The design and analysis of the fault-tolerant control algorithms between fault detection and isolation, and after fault isolation are rigorously investigated in Sections 3 and 4, respectively. In Section 5, a simulation example is used to illustrate the effectiveness of the FTC method. Finally, Section 6 provides some concluding remarks.

2. Problem formulation

2.1. Graph theory notations

A directed graph $\mathcal{G}$ is a pair $(\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{\upsilon_1, \dots, \upsilon_P\}$ is a set of nodes, $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is a set of edges, and P is the number of nodes. An edge is an ordered pair of distinct nodes (υ_j, υ_i) meaning that the ith node can receive information from the jth node, and υ_j is a neighbor of υ_i. An undirected graph is a special case of a directed graph where $(\upsilon_i, \upsilon_j) \in \mathcal{E}$ implies $(\upsilon_j, \upsilon_i) \in \mathcal{E}$ for any $\upsilon_i, \upsilon_j \in \mathcal{V}$. A graph contains a directed spanning tree if there exists a node called the root such that the node has directed paths to all other nodes in the graph.

The set of neighbors of node υ_i is denoted by $N_i = \{j : (\upsilon_j, \upsilon_i) \in \mathcal{E}\}$. The weighted adjacency matrix $\mathcal{A} = [a_{ij}] \in \Re^{P\times P}$ associated with the directed graph $\mathcal{G}$ is defined such that $a_{ii} = 0$, $a_{ij} > 0$ if $(\upsilon_j, \upsilon_i) \in \mathcal{E}$, and $a_{ij} = 0$ otherwise. The topology of an intercommunication graph $\mathcal{G}$ is said to be fixed if each node has a fixed neighbor set and a_{ij} is fixed. For undirected graphs $a_{ij} = a_{ji}$ and for balanced graphs $\sum_{j=1}^{P} a_{ij} = \sum_{j=1}^{P} a_{ji}$. The Laplacian matrix $L = [l_{ij}] \in \Re^{P\times P}$ is defined as $l_{ii} = \sum_{j\in N_i} a_{ij}$ and $l_{ij} = -a_{ij}, i \neq j$. Both $\mathcal{A}$ and L are symmetric only for balanced undirected graphs. The sum of the elements on each row of the Laplacian matrix is zero, therefore 0 is an eigenvalue of the Laplacian matrix. The directed graph $\mathcal{G}$ has a spanning tree if and only if the Laplacian matrix of the graph $\mathcal{G}$ has a simple zero eigenvalue. More detailed description of graph theory can be found in Ren and Beard (2008).

2.2. Distributed multi-agent system model

Consider a set of M follower agents with the dynamics of the ith agent, $i = 1, \dots, M$, being described by

$$\dot{x}_i = \phi_i(x_i) + u_i + \eta_i(x_i, t) + \beta_i(t - T_{iu})\theta_i u_i + \beta_i(t - T_{if})f_i(x_i) \quad (1)$$

where $x_i \in \Re^n$ and $u_i \in \Re^n$ are the state vector and input vector of the ith agent, respectively, $\phi_i : \Re^n \mapsto \Re^n$, $\eta_i : \Re^n \times \Re^+ \mapsto \Re^n$ and $f_i : \Re^n \mapsto \Re^n$ are smooth vector fields. Specifically, η_i and ϕ_i represent the modeling uncertainty and known nonlinearity, respectively.

The term $\beta_i(t - T_{if})f_i(x_i)$ in (1) denotes the change in the dynamics of ith agent due to the occurrence of a process fault. Specifically, $\beta_i(t - T_{if})$ represents the time profile of the process fault which occurs at some unknown time T_{if}. In this paper, the time profile function $\beta_i(\cdot)$ is assumed to be a step function, which represents an abrupt fault. Additionally, for isolation purposes, we assume that there are $r_i - 1$ types of possible nonlinear process fault functions associated with the ith agent; Specifically, each process fault function f_i^w, $w = 1, \dots, r_i - 1$, is described by

$$f_i^w(x_i) \triangleq [(\theta_{i1}^w)^T g_{i1}^w(x_i), \dots, (\theta_{in}^w)^T g_{in}^w(x_i)]^T, \quad (2)$$

where θ_{ip}^w, for $i = 1, \dots, M$, and $p = 1, \dots, n$, is an unknown parameter vector assumed to belong to a known compact set Θ_{ip}^w (i.e., $\theta_{ip}^w \in \Theta_{ip}^w \subseteq \Re^{z_{ip}^w}$), and $g_{ip}^w : \Re^n \mapsto \Re^{z_{ip}^w}$ is a known smooth vector field. As described in Zhang et al. (2004), the process fault model described by (2) characterizes a general class of nonlinear process faults where the vector field g_{ip}^w represents the functional structure of the wth process fault, and the unknown parameter vector θ_{ip}^w characterizes the fault magnitude.

Furthermore, the term $\beta_i(t - T_{iu})\theta_i u_i$ in (1) represents the changes in the dynamics of ith agent due to the occurrence of an actuator fault. Specifically, $\theta_i = \mathrm{diag}\{\theta_{i1}, \dots, \theta_{in}\}$ represents the actuator fault magnitude, where $\theta_{ip} \in [\bar{\theta}_{ip}, 0]$ is an unknown parameter characterizing the occurrence of a partial loss of effectiveness fault in actuator u_{ip}, for $i = 1, \dots, M$, $p = 1, \dots, n$.