Information Sciences 000 (2015) 1–17

Contents lists available at ScienceDirect

Information Sciences

journal homepage: www.elsevier.com/locate/ins

Distributed fault-tolerant control for a class of cooperative uncertain systems with actuator failures and switching topologies

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ARTICLE INFO

Article history:
Received 13 January 2015
Revised 14 October 2015
Accepted 2 November 2015
Available online xxx

Keywords:
Fault-tolerant control
Consensus tracking
Multi-agent systems
Switching undirected topologies

ABSTRACT

This paper studies the distributed fault-tolerant control (DFTC) problem for a class of high-order multi-agent systems (MASs) with switching undirected topologies, heterogeneous matching uncertainties, disturbances and actuator faults including loss of effectiveness, bias, outage and stuck. In this frame work, the communication network of dynamic agents may switch among several undirected connected graphs. It is assumed that the actuator efficiency factors, the lower and upper bounds of the time-varying failures and heterogeneous uncertainties, disturbances and the leader's control input signal, are unknown. Based on the relative information of neighbors, a novel fault-tolerant consensus tracking protocol is designed for each follower node via distributed adaptive mechanism. By utilizing the multiple Lyapunov functions method and algebraic graph theory, a sufficient condition for consensus tracking is established. Furthermore, it is proved that if the topology dwell time is larger than a positive threshold, the state of each follower node synchronizes to that of the leader with a bounded residual error in the presence of actuator faults, heterogeneous matching uncertainties and disturbances. Finally, two numerical examples are given to show the effectiveness of the proposed control scheme.

1. Introduction

In recent year, designing a feasible and effective distributed protocol for each subsystem such that a networked of agents as a whole can perform complex tasks has attracted considerable attention in the integration of communication and control [5,22,26]. Due to its potential applications in many areas, (e.g., formation of flight of satellites, flocking of mobile vehicles, scheduling of automated highway systems [15,27,41,45]), the cooperative control of MASs has received tremendous attention. To date, a series of effective approaches have been made to study the emergence of consensus of high-order MASs, such as leader-following control [6,23,32,49], switching communication networks [25,33,34], cooperative optimal strategy [4,29,44], distributed adaptive protocol [9,16,17,24], coordination formation control [2], and so on.

As well known, in order to achieve a special global common behavior, a large number of agents composed to form a cooperative system via communication networks. Unlike traditional networked control systems [13,14,42,47], the reliability demand of

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http://dx.doi.org/10.1016/j.ins.2015.11.002

MASs rapidly is enhanced due to an increasing number of actuators, sensors and other system components. However, in practical applications, the faulty components in some nodes may cause the system performance deterioration or lead to instability, even affect the global behavior of the multi-agent networks. A typical example is a power grid consisting of a large number of generators, a fault even in a single local power generator may have a severe undesirable impact on the synchronization of power supply. Unfortunately, the conventional fault-tolerant control methods for centralized systems are only useful to ensure the local stability of individual nodes. Motivated by this observation, researchers began to investigate distributed fault-tolerant control for MASs and tried to improve the safety and reliability of cooperative systems.

Generally speaking, the distributed fault-tolerant control approaches can be broadly classified into two categories, that is, passive and active ones. Passive DFTC approaches mainly utilize fixed controllers via robust control theory with respect to a priori fixed set of failures, see for instance in [28,40]. In contrast to the passive strategy, the parameters and/or the structure of the controllers are adjustable with active DFTC approaches, see for instance in [8,10,18]. Recently, the very few active DFTC protocols for MASs subject to actuator failures have been proposed in the literature [30,49]. However, these works focus only on the distributed fault accommodation schemes against loss of effectiveness or additive failures but do not address the outage or stuck actuators in follower nodes. What's more, different from centralized FTC problem [11,19–21,31,37,39,43], the task of designing DFTC controller based on neighborhood information is not only to compensate individual failures, but also to achieve consensus tracking objective via communication networks. Therefore, it is meaningful to further investigate the distributed fault-tolerant tracking control for the agent networks.

In addition, it is worth stressing that the existing DFTC methods in [30,32,49] are commonly required that the communication topology is fixed. But in practical scenario, the underlying network of all agents should be a time-varying graph as both communication links and nodes in the network may experience failures or reconstructions [8,33,34]. Essentially, due to the design of Lyapunov function by using the DFTC schemes in [30,32,49] is dependent on the Laplacian matrix of the underlying graph, the boundedness of closed-loop signals and the global tracking objective cannot be ensured when the network is switching. Therefore, the DFTC protocols in existing works cannot be directly applied any more. On the other hand, many network-connected systems may be controlled in complex operating environments, such as uncertainties, time delay, external disturbances and so on [1,3,12,17,38,42,46], which makes this problem even more difficult in practical applications. To the best of our knowledge, there are few effective techniques available for distributed fault accommodation of MASs under dynamic networks so far.

In this paper, the distributed fault-tolerant tracking control problem for a class of uncertain networked agents with a dynamic leader under switching undirected topologies is investigated. Suppose that the network topology switches among several connected graphs and only part of agents can observe the information of the leader. Compared with the existing works, the results of this paper have three distinct features:

1. By using only relative state information of neighbors to estimate actuator efficiency factors and controller parameters online, a novel active DFTC protocol in individual node is designed, under which the time-varying actuator faults including loss of effectiveness, bias, outage and stuck, can be compensated in real time. Specifically, the distributed control allocation scheme is firstly used to achieve cooperative tracking performance, when some outage or stuck failures occur in the actuators.
2. For the non-identical matching uncertainties and external disturbances, the alternative distributed adaptive protocol with switching mechanism is employed, which can reduce effectively the global consensus tracking error. Moreover, designing of the proposed protocol does not require any prior knowledge, such as the bounds of the leader's input, heterogeneous uncertainties and disturbances.
3. When the undirected network topology is fixed, which is relatively concise to design distributed adaptive fault-tolerant tracking protocol because of the compatibility with the single Lyapunov function in stability analysis; but for the switching undirected topologies case, the existing DFTC approaches given by [30,32,49] will not guarantee the convergence of the parameter estimate errors and global tracking error. To overcome this difficulty, motivated by the switching control approaches in [33–35,48], a constructive cooperative adaptive fault compensation methodology is established on the basis of the multiple Lyapunov functions method and algebraic graph theory. It is shown that with the proposed DFTC scheme, not only the boundedness of all closed-loop signals is ensured, but also global tracking of all followers' states can be achieved.

The rest of this paper is organized as follows. In Section 2, the preliminaries and problem statement are presented. The design approach of the DFTC protocol is presented in Sections 3. In Section 4, two numerical simulations are given to illustrate the proposed DFTC methodology. Finally, Section 5 draws the conclusion.

Notation: $\mathbb{R}^n$ denotes the n-dimensional Euclidean space and $\|\cdot\|$ represents Euclidean norm of vectors or matrices. Let I_k stand for the identity matrix of dimension k. For matrix $A \in \mathbb{R}^{n\times n}$, $\lambda_{\max}(A)$ and $\lambda_{\min}(A)$ are its maximum eigenvalue and minimum eigenvalue, respectively. A^{T} represents the transpose of matrix A. $A \otimes B$ denotes the Kronecker product of two matrices $A \in \mathbb{R}^{m\times n}$ and $B \in \mathbb{R}^{p\times q}$. Let $\mathrm{diag}(A_1, A_2, \ldots, A_n)$ denote a block-diagonal matrix with matrices A_i, $i = 1, \ldots, n$, on its diagonal. Denote by $P > 0$ that P is a symmetric positive definite matrix with an appropriate dimension.

2. Preliminaries and problem statement

2.1. Basic graph theory

Let $\mathcal{G}_{\sigma(t)} = (\mathcal{V}, \mathcal{E}_{\sigma(t)}, \mathcal{A}_{\sigma(t)})$ be a undirected graph with a set of N nodes $\mathcal{V} = \{v_1, v_2, \ldots, v_N\}$, a set of edges $\mathcal{E}_{\sigma(t)} = \mathcal{V} \times \mathcal{V}$, and an associated adjacency matrix $\mathcal{A}_{\sigma(t)} = [a_{ij}(t)] \in \mathbb{R}^{N\times N}$, where $\sigma(t) : [0, +\infty) \to \mathcal{P}$ with $\mathcal{P}$ is an index set for all possible

Please cite this article as: X. Wang, G.-H. Yang, Distributed fault-tolerant control for a class of cooperative uncertain systems with actuator failures and switching topologies, Information Sciences (2015), http://dx.doi.org/10.1016/j.ins.2015.11.002