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Fault-tolerant coordination control for second-order multi-agent systems with partial actuator effectiveness☆

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ABSTRACT

This paper investigates the fault tolerant coordination control problem for second-order multi-agent systems where actuator of each agent suffers from partial loss of effectiveness fault. Firstly, an active fault tolerant control strategy, which combines a healthy control protocol and an estimation of fault severity, is developed for consensus problem of the multi-agent systems, where the communication topology is directed with a directed spanning tree. Then, the active fault tolerant control method is promoted to the containment problem, where velocities of the leaders are time-varying and the communication topology is undirected. Theoretical results show that, with the proposed fault-tolerant control method, consensus and containment of the multi-agent systems can be achieved if estimation error of the estimated fault severity is less than a calculated threshold. Finally, simulation examples are given to illustrate the effectiveness of the theoretical results.

1. Introduction

In recent years, coordination control for multi-agent systems (MAS) has received increasing attention due to its wide range of applications from various areas such as formation control, flocking, ocean sampling, smart grids, and so on [4,13,14,17,32,33,40]. An important problem for coordination control of MAS is consensus, where the goal is to design a consensus protocol such that all agents reach an agreement on a state of interest. So far, various results on the consensus problem have been achieved for first-order [1,11] and second-order MAS [24,26,28,42].

According to whether there exists a leader or not, the consensus problem can be classified into two categories. One category is leaderless consensus where all agents converge to each other [18,19,36,38]. The other category is leader-following consensus where there exists a leader to which all followers converge [6,7,22]. Specially, when there are multiple leaders in

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the MAS, the coordination problem is known as containment, which aims to design a control protocol such that all followers move into the convex hull spanned by the leaders [3,5,12,23,30].

In realistic world, with rapidly growing of scale and complexity, MAS has a greater probability of suffering from faults, e.g., actuator faults, component faults, etc. When faults occur in the system, two challenges arise. One challenge is the fault detection and isolation problem, which aim at identifying location and severity of the fault [21,25,31,44]. The other challenge is the fault-tolerant control (FTC) problem, which focuses on improving reliability of the system when faults happen [9,10,16,37,39]. In this paper, we will investigate the FTC problem for MAS with actuator fault of partial loss of effectiveness. Generally, the FTC problem can be divided into two categories: passive fault-tolerant control (PFTC) and active fault-tolerant control (AFTC) [34,35,45]. In the PFTC, robust controller with fixed control gain is designed such that it can work well with certain type of presumed faults. In [35], a robust adaptive fault-tolerant consensus control scheme was proposed for MAS subject to nonidentical dynamics with undetectable actuation failures. A further investigation was made in [34] for finite-time consensus of uncertain nonlinear MAS, where the topology is singly-way directed. Different from PFTC, AFTC usually regulates its structure or parameters according to the fault information, which enable the controller to react actively to the failures [15,46]. An AFTC strategy containing a fault diagnosis mechanism was proposed in [46] for MAS subject to partial loss of effectiveness of actuators. In [15], an active fault-tolerant cooperative control was investigated for heterogeneous systems with bias actuator fault.

It should be mentioned that, in the existing fault-tolerant control for MAS where a fault diagnosis module is embedded, few of them analyses the accuracy of the fault diagnosis module or the influences of inaccuracy of the diagnosis module to the system performance. On the other hand, a lot of works for fault diagnosis of a single agent has been done in the past decades [8,25,44]. Then, one may ask, firstly, for MAS subject to actuator faults, whether it is feasible to deal with faults by using an AFTC strategy which combines a fault estimation by a fault diagnosis module and an appropriate healthy control protocol? Secondly, if the former method is feasible, are there any requirements on the accuracy of the fault diagnosis module for the containment control problem of the MAS with actuator faults?

In this paper, we examine the coordination control problem for second-order MAS with partial effectiveness of actuator. The communication topologies of the MAS are directed with a directed spanning tree for the consensus problem and undirected for the containment problem. The main contributions of this paper lie in the following aspects. First, an active fault tolerant control method which combines a healthy control protocol and an estimation of the fault severity is proposed for the consensus and containment problems of the MAS. Second, compared with the active fault tolerant control [15,46], the influence of the inaccuracy of the fault diagnosis module onto the system performance is analyzed in this paper. Third, the results show that the proposed control strategy will work well if the error in the estimated fault severity is less than a calculated threshold. This is beneficial in the practicality of the system when implemented in real hardware.

The rest of this paper is organized as follows. Some preliminaries and the problem are formulated in Section 2. An active fault-tolerant consensus for double-integrator MAS with partial loss of effectiveness of actuators is investigated in Section 3. The active fault tolerant control strategy is further investigated for the containment problem in Section 4. Numerical simulations are given to demonstrate the validity of the theoretical results in Section 5. Conclusions are finally drawn in Section 6.

Notation: $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, I_n represents an unit matrix of order n, and 1_n (respectively 0_n) is a n-dimensional column vector with all elements being 1 (respectively 0). $|\cdot|$, $\|\cdot\|_1$, and $\|\cdot\|$ stand for the absolute value of a real number, 1-norm, and Euclidean-norm of a vector or matrix, respectively. For a matrix M, $M>0$ means that M is positive definite, $\underline{\lambda}(M)$ (respectively $\overline{\lambda}(M)$) denotes the minimal (respectively maximal) eigenvalue of M. diag$\{\xi_1, \ldots, \xi_n\}$ represents a diagonal matrix with diagonal entries ξ_i, $i=1,\ldots,n$. $\otimes$ represents the Kronecker product of matrices.

2. Preliminary

In this section, some preliminary results are introduced for the graph theory and matrix theory, and the actuator fault model is formulated.

2.1. Graph theory

Consider a weighed digraph $G=(\mathcal{V},\mathcal{E},\mathcal{A})$, where $\mathcal{V}=\{1,2,\ldots,N\}$ is the node set, $\mathcal{E}\subseteq\mathcal{V}\times\mathcal{V}$ is the edge set, and $\mathcal{A}=[a_{ij}]_{N\times N}$ is the weighted adjacency matrix. If $(i,j)\in\mathcal{E}$, then $a_{ij}>0$, which means that node i can receive information from node j. Otherwise, $a_{ij}=0$. Moreover, we assume $a_{ii}=0$ for all $i\in\mathcal{V}$. The Laplacian matrix $L=[l_{ij}]_{N\times N}$ associated with the adjacency matrix $\mathcal{A}$ is

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

A directed path from node j to node i is a sequence of edges $(i,i_1),(i_1,i_2),\ldots,(i_l,j)\in\mathcal{E}$ with distinct nodes i_k, $k=1,\ldots,l$. A digraph G is said to have a directed spanning tree if there exists a root node such that it has a directed path to any other nodes. For a network with multiple leaders, the topology is said to have a united spanning tree if for each followers there exists at least one leader that have a directed path to it.