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Insensitive leader-following consensus for a class of uncertain multi-agent systems against actuator faults

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ABSTRACT

This paper is concerned with the leader-following consensus control problem for a class of multi-agent systems against actuator faults and some perturbed factors as state-dependent uncertainties and multiplicative controller coefficient variations. The follower agents are supported to be connected by a multi-layer network structure, which can be described by a directed graph among different layers and an undirected graph in the same layer. Without requirement of knowledge of eventual faulty factors of actuators and perturbed factors of agents, a class of distributed controllers is constructed to ensure that follower agents can track the leader agent based on adaptive updates. Lyapunov functions are addressed to prove that asymptotic consensus of multi-agent systems can be achieved in the presence of partial loss of effectiveness on bias-actuators and uncertainties in agents and controllers. Finally, multiple coupled aircrafts are used to verify the efficiency of the proposed method.

1. Introduction

In the past decades, the study on multi-agent systems has attracted much attention from various fields of sciences and engineering. A variety of studies for multi-agent systems have been applied in a large amount of practical control systems, for example, synchronization of power-driven machine and coupled oscillators, rendezvous of space shuttles, formation control of vehicular platoons, cooperative control of mobile robots, and etc (see e.g., 1–3). A common property of stabilization and tracking performance of the systems is described by consensus that is a typical collective behavior of multi-agent systems. As a multi-agent system can be classified into a networked control system, the consensus problem is seriously influenced by networked time-delays [4–7], uncertainties and disturbances [8–10], partial measurements and packet dropouts [11,12], limited communication data transmission rates [13–15], controller coefficient variations [16], and actuator faults [17–22].

A leader-following multi-agent team is composed of agents by connection with communication networks. Based on graph theory, it can be confirmed that the topology structure plays a paramount role in consensus by reacting on information exchanges among agents [23,24]. Many important results have been provided under the special topology structures which can be formulated by directed graph and undirected graph [25–27], spanning tree [28] and dynamic interaction topology [29,30]. Recently, multi-layer topology structure has been seriously considered in the existing literatures with hierarchical control strategies because of its wide application in formation and swarm control (see e.g., [31–37]). In that structure, agents are divided into multi-layers in terms of communications with top-to-bottom partition, and the lower layer agents can only receive signals from the upper layer agents. It means that communicated signals from the upper layer agents are original tracking signals of agents located in the lower layers. Therefore, any perturbed factor in an agent such as uncertainties, inaccuracy measurement and sensitive variations can result in serious influences on the follower agents. To achieve acceptable consensus results, suitable topology structure and strong robust controllers are necessary to be designed to compensate for the effects of perturbed factors.

In the above mentioned perturbed factors, model uncertainties commonly exist in an agent due to inaccuracy modelling for a practical system. Robust control methods have been given to deal with some kinds of uncertainties in multi-agent systems, e.g., polytopic uncertainties [8], sector-bounded and Lipschitz condition-based uncertainties [9]. But some nonlinear uncertainties which are state-dependent and cannot satisfy these conditions have rarely been investigated in the existing literatures. Besides, small variations on controller coefficients may also result in huge performance degradation of systems. Thus, the gain variations (uncertainties) of consensus controllers should be widely studied based

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on insensitive control designs. In [16], a quantized insensitive consensus controller was constructed for a Lipschitz nonlinear multi-agent systems against additive interval-bounded controller coefficient variations. However, few studies have been given to deal with multiplicative controller coefficient variations in consensus controller designs. For the sake of enhancing robustness and to achieve high accuracy consensus of systems, more effective works for state-dependent uncertainties and multiplicative variations of controllers are still worthy to be studied.

Actuator faults that is a more serious issue than those perturbed factors should also be further considered for the safety of operating systems. To guarantee reliability and performance of systems, the designs of fault tolerant control (FTC) for systems have become increasingly popular in multi-agent systems. Over the past thirty years, many types of actuator faults have been investigated, including loss of effectiveness, outage, bias and stuck faults. Except some popular methods such as linear matrix inequality (LMI), fault detection and isolation (FDI)-based methods (see e.g., [38,39]), an adaptive method was recognized as an effective method to compensate for all types of actuator faults (see e.g., [40–42]). In recent years, the adaptive method has been largely used in the fault tolerant consensus control of multi-agent systems in the cases of loss of effectiveness [21], and bias/stuck-actuator faults [17,22]. Besides, guaranteed cost consensus and finite time consensus have been dealt with in FTC multi-agent systems with partial loss of control effectiveness, and bias/stuck-actuator faults in [18] and [20], respectively.

In this paper, we address the insensitive fault-tolerant consensus control problem for a class of leader-following multi-agent systems. The topology structure can be formulated by a directed graph. It is described that signals can be transmitted by the upper layer agents to the lower layer agents. The partial loss of control effectiveness and bias-actuator faults, state-dependent uncertainties and multiplicative controller coefficient variations are further investigated by distributed consensus controller designs. Each faulty effect factor and bounds of perturbed signals are assumed to be unknown. Some adaptation laws are proposed to on-linely estimate the limits on the effects of actuator faults and perturbed factors. Based on the estimations, an adaptive switch compensation control strategy is proposed to solve the leader-following consensus problem. On the basis of Lyapunov stability theory, the adaptive closed-loop multi-agent system can be guaranteed to be asymptotic consensus even in the cases of failures on actuators and uncertainties in agents and controllers.

The rest of the paper is organized as follows. The multi-layer topology structure and robust FTC problem formulation are described in Section 2. In Section 3, the distributed adaptive state feedback controller is developed. Section 4 gives its application of leader–follower multiple aircraft example and simulation. Finally, conclusion is given in Section 5.

2. Problem statement and preliminaries

In this paper, we assume the network topology can be described by a multi-layer topology structure (see Fig. 1 for example). In the structure, signals flow from upper layer to lower layer in one direction, while in the same layer, every agent is interconnected by network and signals are assumed to be undirected transmission. Note that here, we assume that a leader agent can receive information from its connected follower agents for more active consensus behaviors. Based on the structure, we divide all agents into p multi-layers. A leader agent is classified into the top layer (Layer 1), and a set Δ_{N_1} for the leader agent is defined as:

$$\Delta_{N_1} := \{\text{leader agent } m\};$$

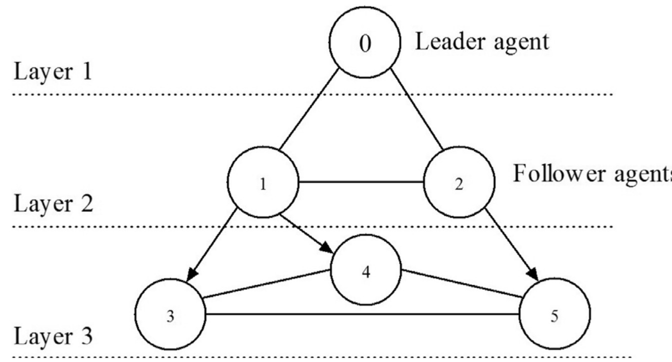

Fig. 1. An example of multi-layer networked multi-agent systems with one leader agent and five follower agents.

Agents connected with the leader agent are classified into the second layer (Layer 2), and a set for those agents is defined as:

$$\Delta_{N_2} := \{\text{follower agent } j = 1, 2, \ldots, N_2 : \text{connect with the leader agent}\}.$$

In the similar manner, through top-to-bottom partition, we classify agents connected with the agents in $\Delta_{N_{g-1}}$, $g = 3, \ldots, p$ into Layer g, and the corresponding set is defined as

$$\Delta_{N_g} := \{\text{follower agent } j = N_{g-1} + 1, \ldots, N_g : \text{connect with the agents in } \Delta_{N_{g-1}}\}.$$

Now, we consider a networked linear time-invariant leader agent M described by equations of the form:

$$\dot{x}_m(t) = Ax_m(t) + \sum_{i \in \Delta_{N_2}} a_{mi} c_{mi} (x_i(t) - x_m(t)) + v_m(t), \tag{1}$$

and the ith follower agent S_i, $i = 1, 2, \ldots, N$ as

$$\dot{x}_i(t) = (A + \Delta_{A_i}(x_i(t), t))x_i(t) + u_i(t), \tag{2}$$

where $\{x_m(t), x_i(t)\} \in R^n$ are, respectively, the states of the leader agent and the ith follower agent; $u_i(t) \in R^n$ is the control input of the ith follower agent; $v_m(t) \in R^n$ is the external force of the leader agent to make sure the states of leader agent satisfying $\|x_m\| \le \bar{x}_m$, where $\bar{x}_m$ is a positive constant; a_{ij} represents the topological structure of the network, where $a_{ij} = 1$ denotes the link between the ith agent and the jth agent, while $a_{ij} = 0$ denotes the link is disconnection; $c_{ij} > 0$ is a topology weighted parameter representing the coupling strength of agent i; Besides, A is a real known constant matrices with appropriate dimensions; $\Delta_{A_i}(x_i(t), t)$ stands for the time-varying and state-dependent model uncertainty of system matrix A, which satisfies the following condition:

$$\|\Delta_{A_i}(x_i(t), t)\| \le \theta_{1i} \|x_i(t)\|^{d_i} + \theta_{2i}, \tag{3}$$

where θ_{1i} and θ_{2i} are unknown positive constants, and $0 < d_i \le \bar{d}$ is the unknown order of state-dependent uncertainties, $\bar{d}$ is its known bound.

Remark 1. For an agent system, e.g., an unmanned aerial vehicle and an intelligent vessel, the system matrix A can be basically obtained in modelling process based on Newton's Second Law of motion [43]. But the dynamical model is seriously affected by states such as its velocity, acceleration, and attitude at some special situation. Thus, the state-dependent uncertainty $\Delta_{A_i}(x_i(t), t)$ is more general to describe the inaccuracy of system modelling.

Remark 2. In this paper, if the control input matrix in (1) and (2) is denoted by $B \in R^{n \times m}$, we assume that $m = n$ and $B = I \in$