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Robust adaptive fault-tolerant control for leader-follower flocking of uncertain multi-agent systems with actuator failure

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ABSTRACT

In this work, we study the flocking problem of multi-agent systems with uncertain dynamics subject to actuator failure and external disturbances. By considering some standard assumptions, we propose a robust adaptive fault tolerant protocol for compensating of the actuator bias fault, the partial loss of actuator effectiveness fault, the model uncertainties, and external disturbances. Under the designed protocol, velocity convergence of agents to that of virtual leader is guaranteed while the connectivity preservation of network and collision avoidance among agents are ensured as well.

1. Introduction

One of the common collective behaviors in the nature is the flocking that is one of the main subjects in the cooperative control of multi-agent systems. The classic model of flocking was proposed by Reynolds in 1986 [1]. Over the years, the primitive model was improved and many algorithms were investigated by researchers to realize the goals of flocking motion [2–4]. Furthermore, in the recent years the flocking algorithms considering practical limitations have been investigated by various scholars, for example flocking with input saturation [5], more general linear dynamics [6,7], and uncertain dynamics [8–11].

In the leader-follower flocking problems, existence of uncertainty and external disturbances in the dynamic of multi-agent systems may lead to loss of connectivity, collision among agents and deterioration of velocity convergence of agents to virtual leader. In recent years, few works have been reported on flocking in the presence of uncertainty in model of agents and external disturbance. In [8] an adaptive protocol for a nonlinear second order system with an unknown parameter, in [9] an adaptive protocol for a double-integrator system with a nonparametric uncertainty which is reducible to a parametric uncertainty and constant disturbance problem, in [10] an observer based protocol for a double-integrator system with a modeled external disturbance, and in [11] an adaptive protocol for an uncertain Lagrange dynamic considering linear parameterizing assumption have been investigated. However, there are some shortcomings in these works. For example they considered only uncertainty in the system matrix and uncertainty in the input matrix was neglected. Besides, they did not consider external disturbances along with the model uncertainty. Note that when the system matrix uncertainty is considered along with either input matrix uncertainty or external disturbance, the whole control action is “polluted” and the designed protocol will not have the required performance. Thus developing a robust adaptive protocol by considering both input and system matrices uncertainties as well as external disturbances is more indispensable.

One of the cases where uncertainty exists in input matrix is the actuator failure problem. Occurrence of failure in actuator of one or more agents besides presence of uncertainty and external disturbances can lead to more undesirable performance of closed-loop system. During the past decades, various fault-tolerate control methods have been proposed [12,13], which could be classified into active and passive methods. In the passive methods, the robust adaptive control idea, due to not needing online information about the occurred faults is the most common methods. However, there is few works on fault-tolerate cooperative control of multi-agent systems [14–18], particularly using robust adaptive method [16]. In [14] the additive bias fault, in [15] the partial loss of effectiveness fault, and in [16–18] both of them have been studied along with parametric uncertainty and external disturbances. Nevertheless, none of these protocols is applicable to flocking problem.

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In this paper, the flocking problem of multi-agent systems in the presence of uncertainties in agents' dynamics, unknown external disturbances, and actuator failure is studied. To design control protocol and analyze its stability in these circumstances are more challenging compared to those studied in the existing works.

The major contributions of this paper are summarized as

1. A novel robust adaptive fault-tolerant controller is proposed here for flocking problem of multi-agent systems, which is distributed such that each agent only requires its own information and those of its neighbors.
2. Our proposed controller can cover most of the existing works on flocking problem with uncertainty and external disturbances [8–11] because; each agent is considered as an uncertain second order linear dynamics which is more general, the actuator fault addressed here includes both bias and partial loss of effectiveness faults, and the framework of controller to deal with healthy and faulty actuators is unique.
3. The complicated and costly process of fault detection and diagnosis is not required here. There are a few works in consensus without employing fault diagnosis mechanism [16–18]. Apart from the dissimilarities between the cooperative control objectives in flocking and consensus, the major differences between our method and theirs are asymptotic velocity convergence instead of residual convergence and simplicity of the protocol. In this paper, by defining a new positive function as Lyapunov candidate and using conservative bounds on external disturbances and additive bias fault of actuators instead of their exact values in adaptive low, a robust adaptive control protocol is developed such that not only ensures asymptotic velocity convergence of agents to that of virtual leader but has simple structure as well.

The remainder of the paper is organized as follows. In Section 2, some preliminaries and model description are given. The main theoretical results and numerical simulations are presented in Sections 3 and 4, respectively. Finally, conclusions are given in Section 5.

2. Backgrounds and model description

Consider N mobile agents moving in an n-dimensional Euclidean space. Suppose that all agents have the same sensing radius r. Let ε_0 and ε be positive constants such that $\varepsilon_0 \le \varepsilon < r$. Consider an undirected dynamic graph as $G(t) = (\mathcal{V}, \mathcal{E}(t))$ with a set of vertices $\mathcal{V} = \{1, 2, \dots N\}$, whose elements represent agents in the group, and a set of links $\mathcal{E}(t) = \{(i, j) | i, j \in \mathcal{V}\}$ such that

1. Initial links are defined by $\mathcal{E}(0) = \{(i, j) | \varepsilon_0 < \|q_i(0) - q_j(0)\| < r - \varepsilon_0, i, j \in V\}$, where $q_i(0)$ and $q_j(0)$ are initial position of agents i and j respectively.
2. If $(i, j) \notin \mathcal{E}(t^-)$ and $\|q_i(t) - q_j(t)\| < r - \varepsilon$, then (i, j) is a new link to be added to $\mathcal{E}(t)$.
3. If $\|q_i(t) - q_j(t)\| \ge r$, then $(i, j) \notin \mathcal{E}(t)$.

In the mentioned process, the hysteresis is crucial for preserving connectivity of dynamically interactive network [4].

The adjacent matrix of graph $G(t)$ is denoted by $\mathcal{A}(t) = [a_{ij}]$ such that if there exists a link between vertices i and j then $a_{ij} = a_{ji} > 0$, otherwise $a_{ij} = a_{ji} = 0$. Furthermore, the Laplacian matrix, $L(t) = [l_{ij}]$, of graph $G(t)$ is defined as $l_{ii} = \sum_{j \ne i} a_{ij}$, $l_{ij} = -a_{ij}$ for $i \ne j$. The eigenvalues of Laplacian matrix $L(t)$ satisfy $0 = \lambda_1(L) \le \lambda_2(L) \le \dots \le \lambda_N(L)$. If G is connected then $\lambda_2(L) > 0$ [2].

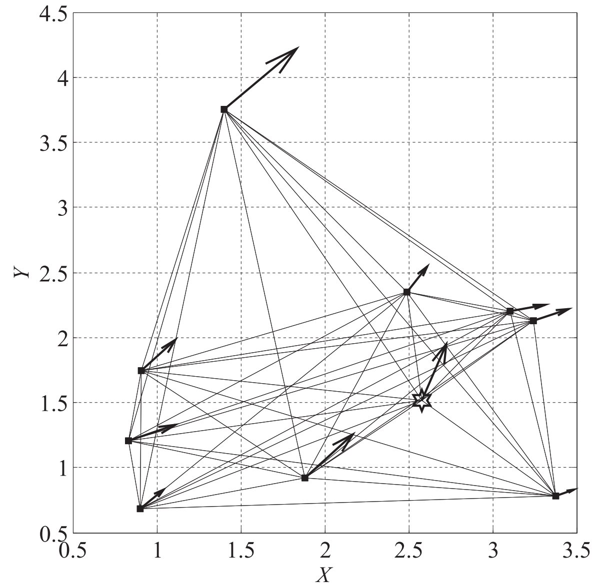

Fig. 1. Initial position of the multi-agent group.

Consider the dynamic of each agent as follows

$$\begin{cases} \dot{x}_i = \bar{a}_{11} x_i + \bar{a}_{12} p_i + b_1 u_i + s_1 d_i \\ \dot{p}_i = \bar{a}_{21} x_i + \bar{a}_{22} p_i + b_2 u_i + s_2 d_i \end{cases}, \quad i = 1, 2, \dots, N, \tag{1}$$

where $x_i \in \mathbb{R}^n$, $p_i \in \mathbb{R}^n$ are states of agent i, $u_i \in \mathbb{R}^n$ is the control input of agent i, and d_i denotes external disturbance acted on agent i. $\bar{a}_{11} = a_{11} + \Delta a_{11}$, $\bar{a}_{12} = a_{12} + \Delta a_{12}$, $\bar{a}_{21} = a_{21} + \Delta a_{21}$, and $\bar{a}_{22} = a_{22} + \Delta a_{22}$, where a_{11}, a_{12}, a_{21}, and a_{22} are the known nominal values of dynamics in (1), Δa_{11}, Δa_{12}, Δa_{21}, and Δa_{22} are their perturbations, s_1, b_1, b_2, and s_2 are known constants.

Assumption 1. It is assumed that there are two unknown constants ρ_{21} and ρ_{22} such that $|\Delta a_{21}| \le \rho_{21}$ and $|\Delta a_{22}| \le \rho_{22}$ and two known constants ρ_{11} and ρ_{12} such that $|\Delta a_{11}| \le \rho_{11}$ and $|\Delta a_{12}| \le \rho_{12}$, and $b_2 > 0$.

The control input of each agent is considered as combination of two terms: state feedback and cooperative protocol. A cooperative protocol commonly includes three terms, one for the gradient term of artificial potential function to keep agents together and avoid collision among them, one for velocity consensus to regulate velocity of each agent to a common vector and one for the navigational feedback of virtual leader to make the agents track the virtual leader. In this paper, it is assumed that virtual leader moves in a fixed direction with constant velocity p_γ as follows

$$\dot{q}_\gamma = p_\gamma, \tag{2}$$

where $q_\gamma \in \mathbb{R}^n$ represents position state of the virtual leader.

Furthermore, the following connectivity preserving potential function is considered which has been proposed in [4]

$$V(\|q_{ij}\|) = \frac{r}{\|q_{ij}\| (r - \|q_{ij}\|)}, 0 < \|q_{ij}\| < r, \tag{3}$$

where $q_{ij} \in \mathbb{R}^n$ is the relative position of agents i and j i.e. $q_{ij} = q_i - q_j$.

In a failure-free actuator, the injected control input to the system equals the designed control input. But when a fault accrues in actuator, the acted control input on the system is no longer equal to the designed one. In this paper, the faulty actuator is modeled as follows