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Brief Papers

Distributed consensus of multi-agent systems with fault in transmission of control input and time-varying delays

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ABSTRACT

This paper discusses the distributed consensus problem of linear dynamical multi-agent systems with missing control input in some intervals and also delay. At first, assuming zero control input in some intervals and delay, the model of system in such conditions is formulated. Then, a distributed adaptive controller based on the relative states of neighboring agents is proposed. By constructing a set of switching Lyapunov–Krasovskii functional, a new delay-dependent exponential ultimately bounded consensus criterion with explicitly exponential convergence rate is established. Furthermore, the obtained condition will be extended to the multi-agent system, when a false signal is injected instead of the nominal control signal in some intervals. Finally, an illustrative example is solved to show the advantage of the proposed approach.

1. Introduction

A group of autonomous agents can perform with more advantages than a single agent in the dynamical systems. For instance, using a multi-agent system (MAS) leads to

- more adaptivity and scalability of system, and
- more robust against the system and environment faults.

Based on the above reasons, the cooperative control of MAS has been an important research topic in the different areas such as distributed control of vehicles [1–3], flocking and swarming in multi-robot systems [4–6], data fusion and data aggregation in wireless sensor networks [7–10], filtering problems in sensor networks [11], control, filtering and estimation problems in networked control systems [12–15], software MAS in video streaming [16], power systems [17], coordinated defense systems such as synchronization of satellites or spacecraft [18–20]. Among the cooperative problems in MAS, consensus problem means the agreement between agents to reach a common assessment or decision based on the distributed information and a communications protocol. Many of the cooperative problems can be thought of as special cases of consensus; for instance, in formation, when the position of each agent in the geometric pattern is not specified a priori. In general, the consensus problem is an interaction principle among agents that is solved by the control approach.

Recently, numerous results have been reported in the consensus problem of MAS. For instance; in [21–24] the analysis of consensus tracking of continuous-time first and second-order MAS has been studied. In [25–27], consensus tracking for a class of second-order non-linear MAS was studied. Consensus of networks of high-order integrators were studied in [28–31] and linear systems in [32–35,36]. Address a distributed tracking problem for multiple Euler–Lagrange systems. It should be noticed that, considering more general model for MAS can leads to more practical results in this field. As an example, in [31] based on the assumed model, the proposed approach can only be applied to consensus problem of MAS. In this reference, the rendezvous problem could not be solved because of the non-zero velocity in consensus area. In this paper, by selecting the generalized linear model for MAS, rendezvous problem can be solved by the proposed control protocol.

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Also, the existing consensus algorithms reported in various papers can be classified into three classes: consensus without a leader [37], consensus with a leader [38] and model reference consensus [39]. In this work consensus without need to leader will be discussed.

In most applications of MAS, delay is inevitable. Delay in such systems is categorized in two types: communication delay between agents and input delay (delay in the transmission of control input to agents). These can occur due to multi-hop communications, movements of the agents, and unavoidable delays in the communication channels. Delay in such systems usually leads to instability, complexity and hidden oscillations of the system. That is why, the consensus problem in MAS with time-delay has attracted the attention of many researchers; for instance, [40] discussed the consensus problem in directed networks with double-integrator dynamics and non-uniform time-varying communication delays via Lyapunov–Razuminkhin theorem [41], investigated second-order consensus of MAS with time-varying delays based on the Lyapunov stability theory [42], studied the robust consensus problem for higher-order MAS subjected to external disturbance and delays in networks. In [41], second-order group consensus for MAS with constant input delay has been discussed. Asymptotic stability of MAS with topology variances and time-varying delays has been addressed in [43].

On the other hand, fault is an unavoidable phenomenon especially in the complex systems. Fault can result in unsatisfactory performance of the system. It can occur due to provisional failures of communication links, network-induced packet loss, temporary intentional interruption applied to the control block, or false data injection by attacker to the control input in some intervals. These conditions lead to occasional corruption of control signal transmitted to agents which may cause instability and oscillation of agent behavior. These faults often exist in MAS due to various factors as stated above. However, fault tolerant consensus of MAS in such conditions has not been fully discussed. Among the papers in the field of MAS, only in [44] the distributed tracking problem of linear higher-order MAS with occasionally missing control inputs has been studied. The proposed method in [44] depends on eigenvalues of Laplacian matrix. This means results are dependent on global information of the communication graph that may not be available in general.

In summary, the following motivations led to the present work: (i) existence of delay in almost all MAS applications with undesirable effect on the performance of system, (ii) the lack of adequate publications dealing with this issue together with occasionally missing control inputs in MAS, and (iii) work reported in paper [44] is only applicable to system with known communication graph which did not cover the whole area of the current research.

The paper is organized in five sections. In Section 2, the required definitions and lemmas are introduced. In Section 3, the model of system with fault in data transmission from control input to the agents and delay is expressed. In Section 4, the sufficient conditions for the system stability are offered. Finally in Section 5, a simulation example is given to show the advantages of the proposed conditions.

2. Preliminaries

I_N represents the identity matrix of dimension N. 1 Denote a column vector with all entries equal to one. $A \otimes B$ denotes the Kronecker product of matrices A and B. $\|x\|$ denotes its 2-norm. For a symmetric matrix A, $\lambda_{\min}(A)$ and $\lambda_{\max}(A)$ denote, respectively, the minimum and maximum eigenvalues of A, and the symbol '$*$ ' stands for symmetric blocks in the matrix inequality.

A directed graph G with the set of nodes $V=\{v_1, v_2, \ldots, v_n\}$, the set of directed edges $\varepsilon = v \times v$, and a weighted adjacency matrix $A_{adj} = [a_{ij}]_{N\times N}$ with non-negative adjacency elements a_{ij}. An edge e_{ij} in graph G is denoted by the ordered pair of nodes (v_j, v_i), where v_j and v_i are called the parent and child nodes, respectively, and $e_{ij} \in \varepsilon$ if and only if $a_{ij} > 0$. Also, the Laplacian matrix $L = [l_{ij}]_{N\times N}$ of G is defined as

$$l_{ij} = \begin{cases} -a_{ij} i \neq j \\ \sum_{k=1, k\neq i}^{N} a_{ik} \quad {}_i i = j \end{cases}$$

Lemma 1. *[1]: Zero is an eigenvalue of L with* 1 *as a right eigenvector and all nonzero eigenvalues have positive real parts. Furthermore, zero is a simple eigenvalue of L, if and only if G has a directed spanning tree.*

Lemma 2. *[45]: For any positive definite matrix $M \in R^{n\times n}$, scalers $\gamma_1 < \gamma(t) < \gamma_2$, and a vector matrix $x : [-\gamma_2 \quad -\gamma_1] \to R^n$ such that the following integrations concerned is well defined, then:*

$$-(\gamma_2 - \gamma_1)\left(\int_{t-\gamma_2}^{t-\gamma_1} \dot{x}^T(s) M \dot{x}(s) ds\right) \leq -[x(t-\gamma_1) - x(t-\gamma_2)]^T$$
$$M[x(t-\gamma_1) - x(t-\gamma_2)]$$

Lemma 3. *[42]: For any positive definite matrix $R \in R^{n\times n}$ we have*
$$DE + E^T D^T \leq DR^{-1} D^T + E^T R E$$

Remark 1. . In this work, it is assumed the communication graph between agents contains a spanning tree. If at least one agent is isolated and do not receive information from other agents, consensus cannot be achieved.

3. Problem statement

In this paper, a network of N agents with linear dynamics is considered. The dynamics of the i-th agent is described by

$$\dot{x}_i = \downarrow A x_i + A_d x_i(t - d(t)) + B u_i(t - d(t)),$$
$$x(\theta) = \downarrow \phi(\theta), \theta \in [-d_2, 0] \tag{1}$$