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Output consensus of heterogeneous linear MASs by self-triggered MPC scheme

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ABSTRACT

In this paper, a self-triggered Model Predictive Control (MPC) scheme is proposed to solve the output consensus problem of heterogeneous linear Multi-agent Systems (MASs). First, a self-triggered condition is designed to determine the time for solving optimization problem of each agent. Then, a self-triggered MPC scheme is built. The scheme not only formulates the aperiodic control form, but also avoids the design of observers for each agent compared with conventional method. On the whole, the communication load and actuator burden can be reduced. Zeno behavior is excluded by detailed analysis. Moreover, parameters selection of the cost function is introduced and analysis of the scheme feasibility is conducted. Sufficient conditions are developed to guarantee the scheme feasibility. Finally, some simulation examples are given to demonstrate the effectiveness of the scheme.

1. Introduction

Consensus problem is one of the fundamental problem for multi-agent systems (MASs) [1–7], where the tracking consensus problem (with leader) has been extensively studied. For tracking consensus problem, the leader generates a reference signal followed by followers to reach state or output consensus. In practical applications, agents are often with different dynamics, which is known as heterogeneous MASs [8]. Then, the output consensus problem is researched. Some results can be found in [9–16] and references therein. In [9] and [10], a distributed observer was firstly devised and the output consensus of linear MASs was solved under fixed and switching networks, respectively. Since then, many results based on it have emerged. In [11], observer-based feedback controllers were proposed. The output consensus of second-order discrete-time MASs was addressed in [12]. The state-coupled linear MAS with globally reachable topologies reached output consensus by decentralized controllers [13]. Recently, an adaptive distributed observer was proposed, based on which the output consensus was settled [14]. In [15] and [16], the output consensus problem was solved by event-triggered mechanism. It can be noted that observer design is essential, by which each follower can recover the leader's state.

In another research line, MPC has attracted much attention on account of its advantage that it can solve the problem with constraints, such as actuator or physical constraints [17–20]. The basic idea of MPC is that it obtains the optimal control input and future motion trajectories based on current information by solving optimal control problem periodically. Moreover, Takagi–Sugeno fuzzy model [21] based MPC has also been focused. The MPC has been applied to solve the consensus problem of MASs [22–25]. In [22], the consensus problems of single- and double-integrator MASs were solved by MPC schemes. In [23], a MPC method was developed to settle the consensus problem of MASs with switching topology. Furthermore, a spinning MPC scheme was proposed to settle the same issue [24]. In [25], the suboptimal consensus was achieved by receding-horizon optimization. However, most results existing are concerning the state consensus problem. There are few results on the output consensus based on MPC.

For the results mentioned above, the optimization problem is solved periodically for each agent. In other words, they are time-triggered control, which may lead to a waste of computation and communication resources. Then, the event-triggered mechanism behaves its advantage [26–29]. And it is applied known as event-triggered MPC and self-triggered MPC. There have some relevant results on this issue [30–34]. In [30], an event-triggered distributed predictive control for multi-agent systems was studied. And the MASs with bounded disturbances was studied by event-triggered predictive control, where the energy consumption and communication load can be reduced [31]. In [32], authors studied consensus problem of nonlinear case, and the optimization prob-

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lem was solved aperiodically. In [33], authors designed the event-triggered condition for a single system, and the event-triggered MPC schemes were proposed. Furthermore, a self-triggered condition was derived in [34], and based on it a self-triggered MPC framework was established for nonholonomic agents. To the best of our knowledge, there are few results on the output consensus problem solved by event-triggered MPC, especially by self-triggered MPC.

It is worth noticing that for conventional method to solve the output consensus problem [9–16], design of observers for each follower is essential. Each follower should equip with an observer to recover the leader's state. Thus, states of observers need to be transmitted though the communication networks continuously. The communication load is heavy, which can not be ignored. Thus, it is desirable to design a control scheme with low communication resource consumption. On the other hand, MPC has been used to solve the state consensus problem of MASs [22–25]. However, there are few results on the output consensus problem. Then, we consider to extend it to solve the output consensus problem of MASs. For traditional MPC, optimization problem is solved periodically, which may lead to a waste of computation and communication resources. Then, inspired by above works, we consider to apply the event-triggered mechanism to MPC. It is of great significance since it enables the aperiodic solving of optimization problem, which can reduce the computing frequency effectively. In a word, considering that in practical applications, the agents are often with different dynamics, and the output consensus of MASs with self-triggered MPC scheme has not been paid much attention to, it motivates the work in this paper.

Compared with related works, our work has the following advantages. First, observers for each follower are needless compared with conventional method [9–16]. Only the measurement output information of each agent needs to be transmitted through the communication networks, which helps the communication resource saving. Second, we extend the MPC to solve the output consensus problem of heterogeneous linear MASs, which is more challenging and generic. Third, self-triggered mechanism is applied to MPC. It realizes the aperiodic solving of optimization problem.

In this paper, we study the output consensus problem of heterogeneous linear MASs. A self-triggered MPC scheme is proposed, which reduces the computing burden and communication load, as well as the actuator burden. The main contributions are summarized as follows.

- A self-triggered condition is designed to determine the time instants for solving optimization problem. It realizes the aperiodic solving of optimization problem, which saves computational resource. The triggering condition needn't to be verified constantly compared with the conventional event-triggered condition. The triggering time instants can be determined in advance.
- The scheme proposed avoids the observer design for each follower, which reduces the complexity of the systems. Only the measurement output information is used. During two triggering time instants, the constant control input is employed for each agent. The actuator of each agent only acts at triggering time instants. Overall, the communication load and actuator burden can be reduced effectively.
- Zeno behavior is excluded, and a lower bound of triggering interval is obtained. Moreover, parameters selection of cost function is introduced. Sufficient conditions are developed to guarantee the scheme feasibility. It shows that the feasibility is dependent on the prediction horizon and the relationship among parameters.

The paper is organized as follows. In Section 2, preliminaries and the problem formulation are introduced. Output consensus of heterogeneous MASs is discussed in Section 3. In Section 4, relative parameters selection is introduced, and feasibility analysis is conducted. Simulation examples are given in Section 5. Conclusions are made in Section 6.

2. Preliminaries and problem description

2.1. Preliminaries

2.1.1. Notations

R^n denotes the n dimensional Euclidean space. $\mathbf{0}$ denotes the matrix of arbitrary dimensions with all elements being 0. $\|\cdot\|$ denotes the Euclidean norm of vector or the induced two-norm of matrix. $\|x\|_P$ denotes the weighted Euclidean norm of x, i.e. $\|x\|_P = \sqrt{x^T P x}$. T is the transition symbol. $P > 0$ denotes P is positive definite. $\lambda_{min}(P)$ and $\lambda_{max}(P)$ represent the minimum and maximum eigenvalues of P, respectively. A continuous function β: [0, a) → [0, ∞) is a K_∞ function, if the function β is strictly increasing, and satisfies $\beta(0) = 0$ and $\beta(a) \to \infty$ as $a \to \infty$.

2.1.2. Graph theory

A graph is denoted by $G = (V, \varepsilon, A)$. $V = \{1, 2 \dots N\}$ stands for vertex set. ε stands for edge set. If $(i, j) \in \varepsilon$, it means vertex j can receive information from vertex i. $A = [a_{ij}]_{N\times N}$ is the adjacency matrix of graph G with $a_{ii} = 0,$ and $a_{ij} > 0$ if vertex i can receive information from vertex j. If $a_{ij} = a_{ji}$ holds, the graph is undirected, else it is directed. $N_i = \{j \in V \mid (j, i) \in \varepsilon\}$ denotes the neighbor set of vertex i. A path from vertex i to j is a sequence of edges connected with distinct vertexes in G. The directed graph is said to contain a directed spinning tree if there exists a root vertex, from which there exists directed paths to all the vertexes. The communication topology of MASs is described by graph G. Each agent corresponds to the vertex.

2.2. System description

Consider a heterogeneous linear multi-agent systems with followers described as

$$\begin{aligned} \dot{x}_i(t) &= A_i x_i(t) + B_i u_i(t) \\ y_i(t) &= C_i x_i(t) \end{aligned} \tag{1}$$

where $x_i(t) \in R^{n_i}$, $u_i(t) \in R^{m_i}$ and $y_i \in R^p$ represent the state, control input and output of agent i. The matrix A_i, B_i and C_i are of appropriate dimensions. The leader considered in this paper is a static leader. $y_0(t) \in R^p$ denotes the output of the leader. The regulated output of agent i is defined as

$$e_{yi}(t) = y_i(t) - y_0(t) \tag{2}$$

The control object to be addressed is to develop a distributed control scheme, such that $\|e_{yi}(t)\|$ converges to 0, meaning that the output consensus can be reached. In this paper, we redefine approximate output consensus for the sake of analysis.

Definition 2.1. Define a settling time T_{si} and error band Δ with small enough magnitude, such that the regulated output $\|e_{yi}\| \le \Delta$ when $t \ge T_{si}$. Then the approximate output consensus is reached with settling time T_{si}.

Remark 2.1. The approximate output consensus is defined for the subsequent analysis. When the approximate output consensus is reached , then the output consensus can be reached when $t \to \infty$.

Before developing the control scheme, we first consider the communication topology of MASs. On the basis of guaranteeing the control target, the communication topology is simplified, where required information transmission can be reduced. Give an undirected topology as an example in Fig. 1(a). We divide the topology into three layers by principle that all agents which can receive information from upper-layer agents directly are gathered in one