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Research article

Synchronized output regulation of leader-following heterogeneous networked systems via repetitive controllers ☆

Feifan Ji [a], Yanjun Li [b], Ji Xiang [a,*]

[a] College of Electrical Engineering, Zhejiang University, China
[b] Key Laboratory of Intelligent System, Zhejiang University City College, China

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ABSTRACT

In this paper, the synchronized output regulation (SOR) problem of leader-following heterogeneous linear networked systems aiming at tracking periodical signals is investigated. Only the output information of each agent is delivered throughout the communication network. For tracking a general periodic signal consisting many sinusoid functions, the dimension of the internal model compensator embedded in each agent will be too high to be implemented in practice. To cope with this difficulty, a distributed repetitive control method is proposed in this paper. A stability condition is developed, as well as the bound of error size. Then it is shown that the controller always exists for any given bound of tracking error. At last, the efficacy of analytic results is illustrated by simulation examples.

1. Introduction

The synchronization or consensus of multi-agent systems plays a ubiquitous role in the study of numerous physical and engineering problems. For instance, coordination of multi-vehicles, synchronization of micro-grid, and distributed control of robotics or spacecrafts, etc. [1–6]. Over the past decade, tremendous research devoted to these studies has developed the theoretical foundations for modeling analysis and solving of multifarious synchronization problems.

Compared with the state synchronization that mostly happens among identical nodes, the output synchronization is more general in the real world and might happen among nonidentical nodes. The problem of synchronized output regulation (SOR) of a linear networked system was firstly investigated in [7]. SOR means that the nodes have their outputs synchronized on the desired trajectory that represents the reference signal to be tracked. The applications of synchronized output regulation include the seamless transfer of single-phase utility interactive inverters [8], multi-vehicle system control [9], and so on. In [10], the SOR problem for SISO agents is solved with a low-gain method. As a landmark of a result, in [11], it was proved that an internal model requirement of every node is necessary and sufficient for synchronizability of the network to polynomially bounded trajectories. The problem of SOR is solved by an internal model and a stabilizing H_∞ controller in [12,13]. The notion of "H_∞ almost output synchronization" is brought in [14]. The bounded L_2 gain synchronization problem using distributed static output feedback control is defined and solved in [15]. In [16], the authors address cooperative control problems in heterogeneous groups of linear dynamical agents that are coupled by diffusive links and analyze the robustness of their output synchronization. And in [17], the output synchronization of a heterogeneous network of agents affected by parameter perturbations is investigated. In [18], passivity-based design is developed for a group of coordination and in [19], the output synchronization problem of networked passive systems with event-driven communication are investigated.

In past works of SOR, the exo-systems being tracked are modeled by a state-space equation such as $\dot{\omega} = S\omega$. If the internal models corresponding to S are embedded in every node and if the entire system including all nodes is stable, the SOR problem is solved [12,7,11]. Here the dimension of S, determining the dimension of corresponding internal models, reflects the complexity of every controlled node. The exo-systems considered in past works are only be modeled while their dimensions have never been taken into consideration. However, when we need to deal with complex periodic signals composed of dozens of sine waves with different frequencies, the dimension of S will be so big. High dimension compensators bring huge computation burden and

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* Corresponding author.
E-mail address: jxiang@zju.edu.cn (J. Xiang).

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hardware cost. For instance, if the multi-agent systems (robots array, etc.) are aiming at tracking a trapezoidal wave which has an enormous amount of harmonic waves, the dimension of S is incredibly high as a result, even though the high-frequency harmonics are always being ignored in practical. To cope with the dimension troublesome, repetitive controller may be a good choice and this is the motivation of this paper.

Repetitive control achieves this goal by the internal model principle, with an infinite-dimensional internal model. Such a model is obtained by putting one or more connected delay lines into a feedback loop. This approach was first proposed in [20] and reached maturity with the paper [21]. In [22], Weiss extended the theory to plants with several outputs, of which only some have to track reference signals with a H_∞ method for stabilizing repetitive systems. Sequentially, the implement of this method of inverter control was reported in [23,24]. In [25] a kind of observer-based H_∞ robust repetitive control system is designed and in [26] repetitive control design for MIMO systems with saturating actuators is considered.

A brief version of the current paper was presented at [27]. For this work, we have made numerous improvements as follows: firstly, in [27], the research is for the homogeneous network while in this paper, we focus on the heterogeneous network. Secondly, the graph structure studied in this paper is directed while in [27] the graph is undirected. At last, in this paper the proof of controllers' existence is given for the completeness of the proposed method.

In this paper, we consider an output synchronization problem of heterogeneous networked systems, aiming at tracking a periodic reference represented by the leader node. The communication topology discussed here is fixed, and nodes interact with each other by exchanging their outputs via a directed graph. Different from the past works of SOR, there exist three main challenges that have never been met or discussed. Firstly, because of the particular structure of repetitive controllers, that is, delay lines are included, the stabilization of the large-scale system with time delay should be reconsidered in a new perspective but not the method in [12]. Secondly, as it has been mentioned before, the tracking error is not exponentially convergent but bounded. Then, finding the upper bound of the error size for the given networked system is necessary. At last, familiar with the second one, designing controllers that not only keep the networked systems stable but also satisfy special given tracking performance is also essential.

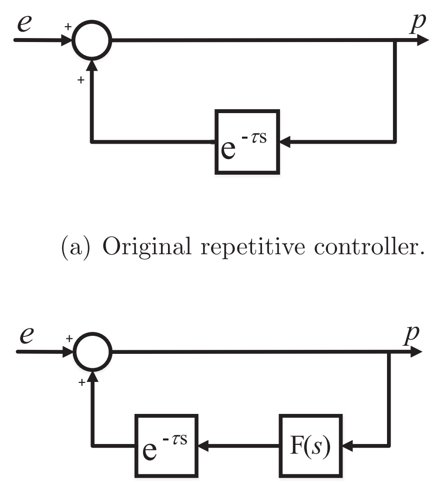
The following of this paper is organized as follows: In Section 2 some preliminaries of repetitive control theory and the formulation of our problem are given. Then, the stability is addressed in Section 3 by an interesting observation that the stabilization of the closed-loop could be treated as a well-known robust-quality problem in robust control theory [28]. In Section 4, an upper bound of error size is obtained while in Section 5, a conservative but practical design method is proposed. It is shown that the design method is always feasible for any given bound of error size. Simulation examples are provided in Section 6.

2. Preliminaries and problem formulation

2.1. Repetitive control theory

Repetitive control strategy achieves asymptotic tracking of periodic signals by a repetitive compensator corresponding to the reference's period. Such a model is obtained by connecting delay lines $e^{-\tau s}$ into a feedback loop as Fig. 1(a) shows. The transfer function from e to p, denoted as $T_r(s)$ is:

$$T_r(s) = \frac{e^{\tau s}}{e^{\tau s} - 1}, \tag{1}$$



(a) Original repetitive controller.

(b) Modified repetitive controller.

Fig. 1. The original and modified repetitive controllers.

and $\frac{1}{e^{\tau s}-1}$ is the minimal model that contains all poles $\frac{2n\pi j}{\tau}$, $|n| \in \mathcal{Z}$. Meanwhile, any periodic signal $r_p(t)$ with a period τ has a Fourier series expansion as

$$r_p(t) = \sum_n r_n e^{\frac{2n\pi j}{\tau} t}. \tag{2}$$

By the internal model principle introduced by [29], the repetitive compensator works as an infinite-dimensional internal model for periodic signals.

However, it always being impossible to stabilize a system with repetitive controllers shown in Fig. 1(a) [21], so a modified one adding a low-pass filter $F_i(s)$ into the feedback loop is shown in Fig. 1(b), from which the transfer function from $e(s)$ to $p(s)$ is

$$\chi(s) = \left(1 - F_i(s)e^{-\tau s}\right)^{-1}. \tag{3}$$

As a cost of stability, the tracking performance will not be so excellent any more. Nevertheless, the accuracy can still be accepted.

2.2. Problem formulation

The dynamics of the agents considered are general linear systems given by

$$\dot{x}_i = A_i x_i + B_i u_i,$$
$$y_i = C_i x_i + D_i u_i, \quad i = 1, 2, \ldots, N, \tag{4}$$

where $x_i \in R^{n_i}$ is the state, $u_i \in \mathcal{R}$ is the control input, $y_i \in \mathcal{R}$ is the output of each agent. We assume that for each node i, the pair (A_i, B_i) is stabilizable. In this paper, all the agents are aimed to track one common trajectory $v \in \mathcal{R}$ that is assumed to be a signal with a period τ,

$$v(t) = v(t + \tau) \quad \forall\, t. \tag{5}$$

Then, the regulated error of node i can be defined as

$$e_i = v - y_i. \tag{6}$$

Plants in the form of (4) and reference v are together viewed as a multi-agent system of $N+1$ subsystems with the reference as the leader and N subsystems of (4) as the followers. The communication topology among these $N+1$ subsystems is described by a digraph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, in which $\mathcal{V} = \{0, 1, \ldots, N\}$ and node 0 is

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