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Iterative learning-based decentralized adaptive tracker for large-scale systems: A digital redesign approach

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ABSTRACT

In this paper, a digital redesign methodology of the iterative learning-based decentralized adaptive tracker is proposed to improve the dynamic performance of sampled-data linear large-scale control systems consisting of N interconnected multi-input multi-output subsystems, so that the system output will follow any trajectory which may not be presented by the analytic reference model initially. To overcome the interference of each sub-system and simplify the controller design, the proposed model reference decentralized adaptive control scheme constructs a decoupled well-designed reference model first. Then, according to the well-designed model, this paper develops a digital decentralized adaptive tracker based on the optimal analog control and prediction-based digital redesign technique for the sampled-data large-scale coupling system. In order to enhance the tracking performance of the digital tracker at specified sampling instants, we apply the iterative learning control (ILC) to train the control input via continual learning. As a result, the proposed iterative learning-based decentralized adaptive tracker not only has robust closed-loop decoupled property but also possesses good tracking performance at both transient and steady state. Besides, evolutionary programming is applied to search for a good learning gain to speed up the learning process of ILC.

1. Introduction

In the recent years, the decentralized control of large-scale interconnected systems has been one of the popular research topics in control theory. Large-scale systems, such as transportation systems, power systems, communications systems, etc., are essential features of our modern life [1,2]. Many early works on the subject appeared in [3]. The decentralized adaptive control method was initially proposed by Ioannou and Sun [4]. It is shown that even weak interconnections can make a decentralized adaptive controller unstable. Therefore, decentralized adaptive controllers, which guarantee boundedness and exponential convergence of the tracking and parameter errors to bounded residual sets, are developed. In model reference adaptive control (MRAC) theory, the objective is to emulate the dynamics of a specified reference model in response to a family of command signals. Decentralized MRAC has been extensively developed for continuous time systems [4] and discrete-time systems [5].

In general, the disadvantage of the well-known decentralized model reference adaptive control laws is that the convergence of local tracking errors guarantee only to a bounded residual set. In addition, the bounds of this set are unknown and the size depends upon the bound for the strength of the unmodelled interconnections, so such adaptive schemes may be unsuitable for applications, and one needs to develop new methods which would allow this disadvantage to be avoided [6]. Literature [6] proposes a modified local adaptive control scheme which improves the transient performance. It is shown that an appropriate time-delay action in the centralized adaptive control [7] can improve the performance on the controlled system. To acquire good tracking performance for repetitive control tasks, iterative learning control is quite an effective control methodology.

Iterative learning control (ILC) was first proposed by Arimoto et al. [8,9], and its basic idea is that the performance of a system can be improved by learning from the previous iterations when the system executes the same task multiple times. Furthermore, the controller can exhibit perfect control performance according to a less priori knowledge of the system [10–12]. Due to its advantages which are higher efficiency and more convenience, many researchers discuss ardently the subjects of ILC and usually apply the controller in several of physical systems such as industrial robots, computer numerical control (CNC) machines, and antilock braking systems (ABS) [13–15]. In recent years,

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decentralized iterative learning controls [16–18] have been developed maturely and embedded to many industrial processes, such as petrochemical processes and metallurgical processes. For the coupled time varying system consisting of two inverted pendulums, Wu proposed the decentralized local iterative learning controllers to guarantee the asymptotic convergence of the output tracking error [16]. The whole process shown in [17,18] is designed to operate continuously under some optimal operating conditions for a type of large-scale system consisting of N single-input single-output subsystems, and the aim to embed ILC into the procedure of the steady-state optimization of a large-scale system is for improvement of dynamic performance of the transient response which is limited to stable systems only [17,18]. Although the above-mentioned ILC algorithms can guarantee the asymptotic convergence of the control system in the finite time interval, the tracking error might grow large in the early learning stages. While some practical reasons require an increase in the time interval, those pure ILC algorithms might get a slow convergence rate and may not even converge for unstable systems.

The purpose of this paper aims to combine a time-domain feedback decentralized control with an iteration-domain learning control scheme to develop an iterative learning-based decentralized tracker for a type of sampled-data large-scale system consisting of N multi-input multi-output subsystems. Via this kind of combination, the proposed tracker not only possesses a robust closed-loop decoupled property but also has good tracking performance at both the transient and steady state. At first, based on the theory of model-reference-based decentralized adaptive control (MRDAC) [19,20], a stable reference model is constructed to overcome the unknown coupling effect of interconnected subsystems such that the system outputs of the large-scale system closely follows the ones of the reference model. This design process can completely separate the tracker design and the elimination scheme of the coupling effect to simplify the procedure of controller design. Then, according to the given model, an analogue decentralized adaptive controller is developed for trajectory tracking. To consider the practical implementation, the corresponding digital MRDAC tracker based on prediction-based digital redesign technique [21] is presented for the sampled-data large-scale systems. After that, in order to enhance the tracking performance of the proposed tracker at some specified sampling instants, the iterative learning control scheme [22] is embedded to the decentralized MRAC. Via the well-designed reference model constructed by the decentralized MRAC scheme, the convergence of the training process can easily be guaranteed without enlarging sampling rate which might cause worse transient response [22]. Finally, the evolutionary programming (EP) method is utilized to search the best learning rate for ILC update law.

2. Model reference decentralized adaptive control

2.1. Decentralized reference model

Consider an MIMO linear time-invariant (LTI) system consisting of N interconnected MIMO subsystems shown as

$$\Sigma_{pi} : \dot{x}_{pci}(t) = A_{pi}x_{pci}(t) + B_{pi}\left[u_{pci}(t) + \sum_{j=1,j\neq i}^{N} L_{ij}x_{pcj}(t)\right], \tag{1a}$$

$$y_{pci}(t) = C_{pi}x_{pci}(t), \tag{1b}$$

where $i = 1, 2, \ldots, N$, $u_{pci}(t) \in \Re^{p_i}$ is the input, $y_{pci}(t) \in \Re^{m_i}$ is the output, and $x_{pci}(t) \in \Re^{n_i}$ is the state vector to the ith subsystem at time t. The constant system matrices $A_{pi} \in \Re^{n_i\times n_i}$, $B_{pi} \in \Re^{n_i\times p_i}$ and $C_{pi} \in \Re^{m_i\times n_i}$ are assumed to be known. The matrix $L_{ij} \in \Re^{p_i\times n_i}$ represents the given coupling factor connecting the subsystem Σ_{pi} with other subsystems Σ_{pj} for $j \neq i$. Notice that each subsystem Σ_{pi} cannot acquire the cross-state $x_{pcj}(t)$ of subsystems Σ_{pj} for $j \neq i$.

While desired trajectories $r_i(t)$ for $i = 1, 2, \ldots, N$ which may not be generated initially by the analytic reference model are given, the main objective of the paper focuses on designing the corresponding controller for the large-scale system such that each output $y_{pci}(t)$ of subsystems can trace the appointed reference $r_i(t)$ as fast as possible and with the closed-loop decoupling property. To avoid dealing directly with the complicate large-scale system, a decoupling open-loop reference model Σ_{mi} is required and presented as follows:

$$\Sigma_{mi} : \dot{x}_{mci}(t) = A_{mi}x_{mci}(t) + B_{mi}u_{mci}(t), \tag{2a}$$

$$y_{mci}(t) = C_{mi}x_{mci}(t), \tag{2b}$$

where $i = 1, 2, \ldots, N$, $u_{mci}(t) \in \Re^{p_i}$ is the bounded input, $y_{mci}(t) \in \Re^{m_i}$ is the bounded output, and $x_{mci}(t) \in \Re^{n_i}$ is the reference state, which is the tracking target of the state $x_{pci}(t)$ of the subsystem Σ_{pi}. The matrices $A_{mi} \in \Re^{n_i\times n_i}$ are designed as asymptotically stable matrices. The constant matrices $B_{mi} \in \Re^{n_i\times p_i}$ and $C_{mi} \in \Re^{m_i\times n_i}$ are identical to ones of the subsystem Σ_{pi}, respectively, i.e. $B_{mi} = B_{pi}$, and $C_{mi} = C_{pi}$.

As long as the given system (A_{pi}, B_{pi}) is controllable, there exists an inner-loop feedback gain K_{mi} to form the matrices

$$A_{mi} \equiv A_{pi} - B_{pi}K_{mi} \tag{3}$$

based on the linear quadratic regulator design (LQR). The optimal state-feedback control law aims to minimize the following performance index

$$J_i = \int_0^\infty \left\{x_{mci}^T(t)Q_ix_{mci}(t) + u_{mci}^T(t)R_iu_{mci}(t)\right\} \mathrm{d}t, \tag{4}$$

with $Q_i \geq 0$ and $R_i > 0$ for the subsystem Σ_{pi} and decide the inner-loop optimal control

$$u_{mci}(t) = -K_{mi}x_{mci}(t), \tag{5}$$

where $K_{mi} = R_i^{-1}B_{pi}^TO_i$, and O_i is the positive definite and symmetric solution of the following Riccati equation

$$A_{pi}^TO_i + O_iA_{pi} - O_iB_{pi}R_i^{-1}B_{pi}^TO_i + Q_i = 0. \tag{6}$$

Therefore, the corresponding reference model in (2) becomes

$$\begin{aligned}\dot{x}_{mci}(t) &= (A_{pi} - B_{pi}K_{mi})x_{mci}(t) + B_{mi}u_{mci}(t)\\ &= A_{mi}x_{mci}(t) + B_{mi}u_{mci}(t),\end{aligned} \tag{7}$$

where the outer-loop control input $u_{mci}(t)$ is to be further designed in Section 3.1 so that $y_{mi}(t)$ will trace the reference input $r_i(t)$ well.

If the state $x_{pci}(t)$ of subsystem Σ_{pi} approaches the reference state $x_{mci}(t)$ as accurately as possible, i.e. $\lim_{t\to\infty} \|e_{ci}(t)\| = \lim_{t\to\infty} \left\|x_{pci}(t) - x_{mci}(t)\right\| = 0$, then the information of these reference states $x_{mci}(t)$ for $i = 1, 2, \ldots, N$ can be applied to eliminate the unknown effect of the coupling term $L_{ij}x_{pcj}(t)$ presented in (1) such that the reference model possesses the system decoupling property. The main advantage of this structure is that the design procedure of overall control can be separated into two parts. The controller design of the two parts can be considered individually so that the complexity of the overall controller design is simplified considerably. As a result, designers can directly adopt the model to develop a trajectory tracker for the case of the large-scale systems. The next section discusses how to achieve the objective $\lim_{t\to\infty} \left\|x_{pci}(t) - x_{mci}(t)\right\| = 0$.

2.2. Strictly decentralized controller design

Based on the well-designed decoupled reference model (7) with the proposed trajectory tracker in (18), how to eliminate the effect induced by the perturbation of the coupling term $L_{ij}x_{pcj}(t)$