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Modeling of decentralized linear observer and tracker for a class of unknown interconnected large-scale sampled-data nonlinear systems with closed-loop decoupling property

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ABSTRACT

A novel low-order modeling of decentralized linear observer-based tracker is presented in this paper for a class of unknown interconnected large-scale sampled-data nonlinear systems with closed-loop decoupling property. The appropriate (low-)order decentralized linear observer is determined by the off-line observer/Kalman filter identification (OKID) methodology and has been further improved based on the digital-redesign approach. Then the decentralized digital-redesign tracker with the high gain property is proposed, so that the closed-loop system has the decoupling property. The proposed approach is quite simple and effective for the complicate interconnected large-scale sampled-data system with known or unknown system.

1. Introduction

In recent years, the decentralized control of interconnected large-scale 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 works on the subject have appeared in [3], and various methods have been used to deal with this problem. Among these methods, the well-known methodology is called decentralized adaptive control method, which was proposed by Ioannou [4] in 1986, and first showed that interconnections even though weak can make a decentralized adaptive controller unstable. From then on, a large amount of decentralized adaptive techniques have been developed in [5–17]. However, the methods [5–17] are based on the known system and known interconnections. When the system equation and interconnections cannot be obtained, the previous methods cannot be used any more. As a result, the proposed method for the unknown large-scale system is discussed later.

In this paper, low-order modeling of decentralized linear observer and tracker for a class of (unknown) interconnected large-scale sampled-data nonlinear systems with closed-loop decoupling property is proposed. First, the appropriate (low-)order decentralized linear observer for the sampled-data nonlinear system is determined by the off-line observer/Kalman filter identification (OKID) method [18]. The OKID method is a time-domain technique that identifies a discrete input–output mapping in the general coordinate form by using known input–output sampled data, through an extension of the eigensystem realization algorithm (ERA), so that the order-determination problem existing in the system identification problem can be solved. Then, each subsystem of the large-scale system is identified as a linear model.

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Furthermore, the above observer has been improved based on the digital-redesign approach [19]. The digital-redesign approach is to pre-design an analog controller for the original analog plant and then carry out the digital redesign for the pre-designed analog controller without losing the high-performance tracking purpose. The observer-based digital-redesign tracker is a closed-loop controller with the state-feedback gain K_d and the feed-forward gain E_d used to control the plant to trace the desired trajectory. Sequentially, the decentralized digital-redesign tracker with the high-gain property is proposed, so that the closed-loop system has the decoupling property. And the proposed approach is quite simple and effective for the complicate large-scale sampled-data nonlinear system with known or unknown system equation.

There are many digital-redesign methods reported in literature; however, most digital-redesign techniques are implicitly retained the closed-loop stability and are based on the approximation techniques, in which the discrete system matrix of the original closed-loop analogue control system is approximately estimated and used to develop the digitally redesigned controller by state matching. Because the dimension of the input is generally less than state, the stability of the closed-loop system is not always assured [20]. One of those popular digital-redesign methods is the Tustin (bilinear) transformation. Based on Tustin's approach, the closed-loop stability may become unstable if sampling time is set too large. Recently, the reported results on the stability analysis of digital redesign such as [21–24] have been proposed so that the closed-loop controlled system is stable and longer sampling time is feasible by linear matrix inequality approach.

The rest of the paper is organized as follows. The problem description is given in Section 2. In Section 3, the observer/Kalman filter identification (OKID) method is introduced which is used to obtain the global behavior linear models of the subsystem in the interconnected large-scale system. Section 4 presents the improved observer-based digital-redesign tracker. And the design procedure is listed in Section 5. The simulations of linear/nonlinear systems are illustrated in Section 6 to demonstrate the methodology proposed in this paper.

2. Problem description

Consider the unknown nonlinear system consisting of N inter-connected MIMO subsystems shown as

$$\Sigma_i : \dot{x}_i(t) = f_i(x_i(t)) + g_i(x_i(t)) \left[u_i(t) + \sum_{j=1, j\neq i}^{N} h_{ij}(x_j(t-\tau_{ij})) \right], \tag{1a}$$

$$y_i(t) = C_i x_i(t), \tag{1b}$$

where $i = 1, 2, \ldots, N$, $u_i(t) \in \Re^{p_i}$ is the input, $y_i(t) \in \Re^{m_i}$ is the output and $x_i(t) \in \Re^{n_i}$ is the state vector to the ith subsystem at time t. $f_i(\cdot) \in \Re^{n_i \times n_i}$ and $g(\cdot) \in \Re^{n_i \times p_i}$ are nonlinear functions of the states $x_i(t)$ of Σ_i. The interconnected terms $h_{ij}(\cdot) : \Re^{n_i} \to \Re^{p_i} (j \neq i)$ between subsystems corresponding to the disturbances on the subsystem Σ_i due to subsystems Σ_j which represent the unknown nonlinear functions of the states $x_j(t)$, and τ_{ij} represent the time delays of the interconnections form Subsystem j to Subsystem i.

First, the appropriate (low-)order decentralized linear observer for the sampled-data nonlinear system is to be determined by the off-line observer/Kalman filter identification (OKID) method. Here, the OKID method can be applied to identify each subsystem as its linear model and the individual observer gain can also be obtained. Then, in order to overcome the effect of modeling error on the identified linear model of each subsystem, an improved observer with high gain property based on the digital-redesign approach will be developed to replace the identified observer by OKID. Sequentially, the decentralized digital-redesign tracker with the high gain property shown in Fig. 4 will be proposed, so that the closed-loop system has the decoupling property and well-tracking performance.

3. Observer/Kalman filter identification

In this section, the OKID formulation are derived to compute the system Markov parameters $Y_k = CG^{k-1}H$ and the observer gain Markov parameters $Y_k^0 = CG^{k-1}F$ form the observer Markov parameters $\overline{Y}_k = C\overline{G}^{k-1}\overline{H}$. Then, the combined system and observer gain Markov parameters Υ_k are used to construct a Hankel matrix. Finally, the constructed Hankel matrix is used to obtain the system and observer matrices $[G, H, C, F]$ by ERA.

3.1. Basic observer equation

The discrete-time state-space model of a multivariable linear system can be represented in the following general form:

$$x(k+1) = Gx(k) + Hu(k), \tag{2a}$$

$$y(k) = Cx(k), \tag{2b}$$

where $x(k) \in \Re^n$, $y(k) \in \Re^p$ and $u(k) \in \Re^m$ are state, output, and control input vectors, respectively, and $G \in \Re^{n\times n}$, $H \in \Re^{n\times m}$ and $C \in \Re^{p\times n}$ are system, input, and output system matrices, respectively. Assuming zero initial condition