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Decentralized adaptive fuzzy fault-tolerant tracking control of large-scale nonlinear systems with actuator failures

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ABSTRACT

This study is concerned with the problem of decentralized adaptive fault-tolerant control for a class of large-scale non-affine and nonlinear systems with external disturbances and actuator failures including loss of effectiveness and bias. Based on fuzzy logic systems (FLSs) to approximate the appropriate nonlinear functions, a novel decentralized adaptive fuzzy fault-tolerant control scheme is developed via direct adaptive control technique. To tackle the non-affine term with actuator failures, with the help of a non-affine compensation term, the corresponding adaptive mechanism that depends on the unknown upper bound of a defined compounded disturbance is introduced. Meanwhile, by utilizing the on-line estimating information of the unknown upper bound and the unknown parameters of necessary FLSs, a new adaptive fuzzy fault-tolerant controller with the adjustable parameter updated laws is designed to achieve robust tracking performance. Furthermore, it is shown that all the closed-loop signals of the interconnected subsystems are uniformly bounded and the tracking errors asymptotically converge to zero via Lyapunov stability analysis. Finally, numerical simulation results are provided to demonstrate the efficiency of the presented decentralized adaptive fuzzy fault-tolerant tracking design scheme.

1. Introduction

During the past few decades, numerous robust control techniques have been studied for handling nonlinear problem. For example, backstepping design [1,2], adaptive dynamic inverse method [3], and Takagi–Sugeno (T–S) fuzzy systems [4–8], and so on. Apart from the above design approaches. In addition, neural networks (NNs) and fuzzy logic systems (FLSs) have been considered as general tools to handle uncertain nonlinear systems in view of their universal approximation properties and adaption abilities, and there are fruitful results (for more details see e.g. [9–14] and references therein) by utilizing NNs or FLSs to approximate unknown nonlinear functions in the nonlinear large-scale systems.

It is important to point out that, decentralized adaptive tracking control designs for large-scale systems have attracted considerable attention and extensively applied to the complex engineering systems, such as power industry systems, cooperating robotic systems, and chemical and aerospace processes. A number of significant robust adaptive control schemes [15–21] have been developed in this area. In particular, the appropriate decentralized NNs controllers designed in [22–24] were proposed for a class of large-scale nonlinear systems with strong interconnections and disturbances. Sequentially, a decentralized adaptive tracking control was explored in [25] for uncertain large-scale nonlinear systems with time-delayed interconnections and unknown dead-zone inputs. In [26], the decentralized adaptive fuzzy output feedback approach was proposed to handle with a class of large-scale nonlinear systems, and a class of uncertain stochastic nonlinear large-scale systems was studied by decentralized adaptive fuzzy output feedback control scheme in [27]. It is well known that the non-affine and nonlinear systems whose control inputs cannot be expressed in an affine form can represent more general nonlinear systems. In [28–31], the decentralized adaptive tracking control schemes of non-affine and nonlinear large-scale systems were investigated.

On the other hand, actuator failures in practical engineering systems are usually inevitable, and often cause severe performance deterioration of control systems, or even system instability leading to catastrophic events. Consequently, a large number of significant fault-tolerant control schemes of linear systems in [32–37] and nonlinear systems in [38–40] have been developed in this research field. Recently, the authors in [41] considered the

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cooperative adaptive fault tolerant fuzzy tracking control problem of multi-agent systems with time-varying actuator faults. In [42], by introducing a positive integrable time-varying function, a direct adaptive control scheme was proposed to compensate for the actuator nonlinearities. Moreover, the fault-tolerant control problem for a class of continuous-time Markovian jump systems with actuator faults was studied in [43].

Nevertheless, there are few investigations for the large-scale non-affine and nonlinear systems with actuator failures, and the decentralized adaptive control schemes proposed in [28–31] cannot be directly extended to the non-affine and nonlinear interconnected subsystems with actuator failures presented in this paper. In particular, the decentralized adaptive fuzzy fault-tolerant control (FTC) problem was considered in [44] for a class of nonlinear large-scale systems. Unfortunately, the proposed fault-tolerant tracking control method cannot be used to accommodate the non-affine and nonlinear large-scale systems with actuator failures in this paper. The above considerations motivate our study work. Moreover, compared with the existing results, the main contributions of this paper are as follows:

(1) First of all, the uncertain non-affine and nonlinear large-scale system with actuator failures considered in this paper is more general than the ones given in the References [28–30]. In addition, it is important to be pointed that the previous approaches cannot be implemented for the proposed fault systems. The main reason is that the actual control input $u_i(t)$ of the ith subsystem is not effectively designed to accommodate the unknown actuator fault $u_i^F(t)=\rho_i u_i(t)+u_{bi}(t)$ within the non-affine term $f_i(x_i,u_i^F)$. In this paper, for each interconnected subsystem, a simplified design mode that converts the non-affine system into the corresponding affine system is presented through an effective combination of FLSs approximating the desired nonlinear control input functions and a defined compounded disturbance, which includes external disturbance, actuator fault signals and nonlinear functions with FLSs and approximation errors.

(2) In most of the References [11,20,26,27,31,44], the proposed decentralized adaptive tracking control schemes can guarantee that the tracking errors of the each closed-loop subsystems are uniformly ultimately bounded. Different from these works, the asymptotic tracking with zero tracking errors of the interconnected subsystems can be achieved by using the adaptive fuzzy fault-tolerant tracking control approach proposed in this paper.

(3) Furthermore, to deal with the non-affine term $f_i(x_i,u_i^F)$ with actuator fault $u_i^F(t)=\rho_i u_i(t)+u_{bi}(t)$, with the help of a non-affine compensation $f(x,u)$, the corresponding FLSs are used to appropriate the desired control input u_i^* and the designed nonlinear function $\left[\overline{f}_{u_{i,\lambda}}+\overline{f}_{u_{i,\zeta}}(\rho_i-1)-\tau_i\right]u_i$, respectively, see (14) and (18) for details. Accordingly, the canonical form of nonlinear affine system (11) is derived. Meanwhile, under the condition that the upper bounds of the compounded disturbance and the control input gain of state feedback for each interconnected subsystem are unknown, a novel decentralized adaptive fuzzy fault-tolerant tracking controller (21) with proper parameter updated laws (22)–(27) is developed to guarantee that all the closed-loop signals of the subsystems are uniformly bounded and the tracking errors can asymptotically converge to zero via Lyapunov-based analysis.

(4) Besides, by employing weaker assumption conditions than the References [28–30], the actual control input $u_i(t)$ can be expressed by the concise affine form (17) rather than the complex case as in [28–30], and the direct decentralized adaptive fuzzy fault-tolerant tracking control introduced in this paper can guarantee that all the states of the subsystems asymptotically track desired reference signals and can achieve satisfactory control performance in the presence of external disturbances and unknown actuator failures.

The rest of the paper is organized as follows. In Section 2, the preliminaries and some standard assumptions are introduced. The decentralized adaptive fuzzy tracking controllers of the interconnected subsystems and the stability analysis are given in Section 3. Simulation studies are then provided in Section 4 to verify the effectiveness of our proposed control approach. Finally, Section 5 draws the conclusions and future research directions.

2. Preliminaries and problem statement

2.1. Large-scale non-affine and nonlinear system

Consider the following large-scale non-affine and nonlinear system with N interconnected subsystems described by the following state-space representation [28,29]:

$$\begin{aligned}&\dot{x}_{i,j}=x_{i,j+1},\\&\dot{x}_{i,n_i}=f_i(x_i,u_i)+\Delta_i(x_1,x_2,\ldots,x_N)+d_i(t)\\&y_i=x_{i,1}\\&1\le j\le n_i-1,\quad 1\le i\le N,\end{aligned}\tag{1}$$

where $x_i=[x_{i,1},x_{i,2},\ldots,x_{i,n_i}]^T$, $1\le i\le N$, is the state vector of the ith subsystem, the augmented vector $x=[x_1,x_2,\ldots,x_N]^T$ represents full state of the overall system, and $u_i\in\mathbb{R}$ and $y_i\in\mathbb{R}$ are the input and output signals, respectively. The unknown nonlinear function $f_i(x_i,u_i)$ is sufficiently smooth, d_i denotes the external disturbance and $\Delta_i(x_1,x_2,\ldots,x_N)$ is an unknown nonlinear interconnection function, which represents the strong interconnection among the other subsystems for each $i=1,2,\ldots,N$.

Remark 1. In many complex engineering systems, such as power industry systems, cooperating robotic systems, and chemical and aerospace processes can be in the form of the large-scale non-affine nonlinear system (1). At the same time, it is important to note that the large-scale system models in [22–24] are special cases of the ones established in this paper.

Remark 2. For the nonlinear system (1), there is only the state interconnection, and without considering interconnections among the control inputs of the different subsystems. The reason is that the considered problem in this paper is to design a decentralized controller rather than a distributed controller. That is, control input u_i of the each subsystem requires the local information for the state variable x_i, and the states of other subsystems cannot be included in the u_i.

2.2. Fault model

For practical engineering systems, actuator faults are frequently a source of instability and performance deterioration. To handle the fault system effectively, the fault model must be established first. In this paper, actuator faults including loss of effectiveness and bias are considered. Let $u_{ij}^F(t)$ represent the actuator fault signal from the ith interconnected subsystem that has failed in the jth faulty mode, and $u_i(t)$ represents the actual input signal of the ith subsystem. Then, a general actuator fault model is described as follows:

$$u_{ij}^F(t)=\rho_i^j u_i(t)+u_{bi}^j(t),\tag{2}$$

where ρ_i^j is the unknown time-varying actuator efficiency factor, and $u_{bi}^j(t)$ is the bounded time-varying bias signal in the ith subsystem. Following the practical single-input and single-output fault case, it implies that $0<\rho_i^j\le 1, i=1,2,\ldots,N, j=1,2,\ldots,L$.

For the sake of convenience, for all possible faulty modes L, the uniform actuator fault model is exploited

$$u_i^F(t)=\rho_i u_i(t)+u_{bi}(t),\quad i=1,2,\ldots,N\tag{3}$$