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Adaptive fuzzy prescribed performance control for MIMO nonlinear systems with unknown control direction and unknown dead-zone inputs

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ABSTRACT

In this study, an adaptive fuzzy prescribed performance control approach is developed for a class of uncertain multi-input and multi-output (MIMO) nonlinear systems with unknown control direction and unknown dead-zone inputs. The properties of symmetric matrix are exploited to design adaptive fuzzy prescribed performance controller, and a Nussbaum-type function is incorporated in the controller to estimate the unknown control direction. This method has two prominent advantages: it does not require the priori knowledge of control direction and only three parameters need to be updated on-line for this MIMO systems. It is proved that all the signals in the resulting closed-loop system are bounded and that the tracking errors converge to a small residual set with the prescribed performance bounds. The effectiveness of the proposed approach is validated by simulation results.

1. Introduction

In recent years, adaptive fuzzy control for MIMO nonlinear systems with unknown control direction has attracted considerable attention. In the literatures, one can find that the Nussbaum-type function technique has been applied in many classes of nonlinear system with unknown control direction [1–6]. The stability of these control systems has been investigated by using Lyapunov approach, and the tracking error can converge to zero or a small residual set. In many control engineering, it requires to make the system output behavior satisfying certain quality of performance metrics, such as overshoot, convergence rate, and maximum steady-state error. Meanwhile, many control systems have constraints on their inputs in the form of nonsmooth nonlinearities, such as dead-zone, backlash, hysteresis, and saturation [7–9]. However, in [1–6] these performance metrics cannot be guaranteed and the input nonlinearities cannot be taken into account. Although by choosing appropriately design parameters and sufficiently small initial parameter estimation errors, the transient behaviors can be improved and the tracking errors can be reduced, however, such a choice depend on a trial-and-error process, especially for cases involving unknown nonlinearities. Thus, achieving certain quality of performance metrics becomes very difficult. In recent years, some adaptive fuzzy control schemes have been developed for uncertain nonlinear systems to deal with this difficulty. For instance, H^{∞} tracking performance is achieved for a prescribed attenuation level in [10–12], and the tracking error can converge to a predefined error bounds in [13]. However, the performance metrics concerned in these approaches are only the tracking error, not the above quality of performance metrics.

To implement the above quality of performance metrics, more recently, a significant methodology, named prescribed performance control, has been addressed for a class of feedback linearization MIMO nonlinear systems in [14]. Subsequently, this scheme is further extended to several classes of nonlinear systems. For instance, based on neural networks approximation: (i) Scheme is designed for strict feedback nonlinear systems and for MIMO affine nonlinear systems [15,16]. (ii) Output feedback controller is developed for MIMO uncertain nonlinear systems [17,18]. (iii) Adaptive control is proposed for a robot and for nonlinear mechanisms [19,20]. Based on fuzzy approximation, output-feedback control is designed for uncertain nonlinear systems with unmodeled dynamics and for nonlinear stochastic systems

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with input saturation [21,22]. Without any fuzzy/neural approximation: (i) Output feedback control is developed for uncertain nonlinear systems in canonical form [23]. (ii) Tracking control is designed for a variable stiffness actuated robot [24]. A new prescribed performance control method was proposed for a class of MIMO strict feedback nonlinear systems in [25,26]. However, only the scheme designed for strict feedback nonlinear systems in [15] has dealt with the issue of unknown control direction, while for the feedback linearizable MIMO nonlinear systems [14], this approach is still necessary to assume that the control direction is known a priori. If the control direction is unknown, designing an adaptive control with prescribed performance for this system is still a challenge, especially for cases involving input nonlinearities.

The dead-zone, which can severely affect system performance, is one of the most important nonsmooth nonlinearities raised in actuators, such as hydraulic and pneumatic valves, electric servomotors, and electronic circuits [9,27,28]. It is more advisable to eliminate the effects of the dead-zone in controller design. The early way to cope with dead-zone nonlinearities is an achievable cancellation or a cancellation asymptotically by using their inverses provided that the output of the dead-zone is available for measurement [29–32] or unmeasurement [33–36]. Without constructing the dead-zone inverse, a robust adaptive control scheme and an adaptive compensation algorithm are employed for a class of nonlinear systems in [37,38]. However, the aforementioned adaptive control schemes are only suitable for the unknown nonlinear functions which can be linearly parameterized. When the nonlinear functions are not linearly parameterized, fuzzy adaptive control scheme is investigated for uncertain MIMO nonlinear systems with unknown actuator nonlinearities and unknown control direction in [3], and adaptive fuzzy/neural network backstepping controllers are proposed for strict-feedback nonlinear systems with unknown dead-zone in [39–42]. However, the tracking error in aforementioned schemes can converge to a small residual set instead of a small residual set with the prescribed performance bounds.

In many previous adaptive fuzzy control schemes of MIMO nonlinear systems, the number of updating parameters is related to many factors, such as the number of states, the rules of fuzzy system, and the number of subsystems. A large numbers of parameters to be updated online result in heavy online computation burden. In order to reduce the online computation burden, adaptive fuzzy control approaches with less updatable parameters have been developed for uncertain nonlinear systems in [43–47]. However, these results achieve convergence of the tracking error to a small residual set, instead of prescribed transient and steady state performances of the tracking error. In addition, the number of the updating parameters in these papers is still dependent on the number of subsystems for MIMO systems.

In this paper, an adaptive fuzzy control approach with prescribed performance is developed for a class of uncertain MIMO nonlinear systems with unknown control direction and unknown dead-zone inputs. The control gain matrix is expressed as the sum of a symmetric matrix and a skew symmetric matrix, the properties of symmetric matrix are exploited to design an adaptive fuzzy prescribed performance controller, a Nussbaum-type function is incorporated into the adaptive fuzzy prescribed performance controller to estimate the unknown control direction. The proposed design scheme guarantees that all the signals in the resulting closed-loop systems are bounded and that the tracking errors converge to a small residual set with the prescribed performance bounds. The main contributions of this study are listed as follows.

(1) It does not require the priori knowledge of control direction, and only one Nussbaum-type function is used to estimate the unknown control direction.
(2) Only three parameters need to be adjusted on-line for MIMO systems, no matter how many subsystem there is, while in [43–47], the number of the updating parameters is still dependent on the number of subsystems for MIMO systems.

The rest of the paper is organized as follows. In Section 2, we describe the plant dynamics and control objective. In Section 3, the suggested adaptive fuzzy prescribed performance controller is developed while in Section 4, simulation results are provided to demonstrate the effectiveness of the method. Finally, conclusions are drawn in Section 5.

2. Problem formulation and preliminaries

Consider a class of MIMO nonlinear system in the following form:

$$y_1^{(r_1)} = f_1(x) + \sum_{j=1}^{p} g_{1j}(x)\Upsilon_j(u_j),$$
$$\vdots$$
$$y_p^{(r_p)} = f_p(x) + \sum_{j=1}^{p} g_{pj}(x)\Upsilon_j(u_j), \tag{1}$$

where $x = [y_1, \dot{y}_1, \ldots, y_1^{(r_1-1)}, \ldots, y_p, \dot{y}_p, \ldots, y_p^{(r_p-1)}]^T \in R^L \subset U$ is the system state vector which is assumed to be available for measurement; $L = \sum_{i=1}^{p} r_i$, $u = [u_1, \ldots, u_p]^T \in R^p$ and $y = [y_1, \ldots, y_p]^T \in R^p$ are the system input vector and output vector, respectively; $\Upsilon_j(u_j)$ is the jth actuator nonlinearity which is assumed to be an unknown dead-zone; $f_i(x), i = 1, 2, \ldots, p$ and $g_{ij}(x), i, j = 1, 2, \ldots, p$ are the continuous unknown smooth nonlinear functions.

Denote

$$y^{(r)} = [y_1^{(r_1)}, \cdots y_p^{(r_p)}]^T,$$
$$\Upsilon = [\Upsilon_1(u_1), \ldots, \Upsilon_p(u_p)]^T,$$
$$F(x) = [f_1(x), \ldots, f_p(x)]^T,$$
$$G(x) = \begin{bmatrix} g_{11}(x) & \cdots & g_{1p}(x) \\ \vdots & \ddots & \vdots \\ g_{p1}(x) & \cdots & g_{pp}(x) \end{bmatrix}.$$

Then, (1) can be written in the following compact form:

$$y^{(r)} = F(x) + G(x)\Upsilon, \tag{2}$$

where $F(x) \in R^p$ and $G(x) \in R^{p\times p}$.

The ith unknown dead-zone with input $u_i(t)$ and output $\Upsilon_i(u_i(t))$ is described by [37]

$$\Upsilon_i(u_i(t)) = \begin{cases} m_{ri}(u_i(t) - b_{ri}), & \text{for } u_i(t) \ge b_{ri}, \\ 0, & \text{for } b_{li} < u_i(t) < b_{ri}, \\ m_{li}(u_i(t) - b_{li}), & \text{for } u_i(t) \le b_{li}, \end{cases} \tag{3}$$

where m_{ri} and m_{li} stand for the right and the left slopes of the dead-zone characteristic. It is assumed that $m_{ri} = m_{li} = m_i$, b_{ri} and b_{li} represent the breakpoints of the input nonlinearity.

Assumption 1 (*[37]*). The dead-zone parameters b_{ri}, b_{li}, and m_i are unknown bounded constants, but their signs are known: $b_{ri} > 0, b_{li} < 0, m_i > 0$. The dead-zone output $\Upsilon_i(u_i(t))$ is not available for measurement.

As a result, the output of the ith dead-zone can be reformulated as

$$\Upsilon_i(u_i(t)) = m_i u_i(t) + d_i(u_i(t)), \tag{4}$$