Applied Soft Computing 30 (2015) 36–47

Contents lists available at ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

Adaptive fuzzy control for multi-input multi-output nonlinear systems with unknown dead-zone inputs

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ARTICLE INFO

Article history:
Received 7 July 2013
Received in revised form 9 December 2014
Accepted 22 January 2015
Available online 2 February 2015

Keywords:
Fuzzy control
Adaptive control
MIMO nonlinear system
Matrix decomposition
Unknown dead-zone inputs

ABSTRACT

This paper presents an adaptive fuzzy control scheme for a class of uncertain multi-input multi-output (MIMO) nonlinear systems with the nonsymmetric control gain matrix and the unknown dead-zone inputs. In this scheme, fuzzy systems are used to approximate the unknown nonlinear functions and the estimated symmetric gain matrix is decomposed into a product of one diagonal matrix and two orthogonal matrices. Based on the decomposition results, a controller is developed, therefore, the possible controller singularity problem and the parameter initialization condition constraints problem are avoided. In addition, a dynamic robust controller is employed to compensate for the lumped errors. It is proved that all the signals in the proposed closed-loop system are bounded and that the tracking errors converge asymptotically to zero. A simulation example is used to demonstrate the effectiveness of the proposed scheme.

1. Introduction

Thanks to the universal approximation property [1,2], many adaptive fuzzy control schemes have been developed for uncertain single-input single-output (SISO) nonlinear systems [1–14]. Due to the complexity of MIMO systems, most of the schemes proposed for SISO systems cannot be extended directly to MIMO systems. In recent years, several adaptive fuzzy control schemes have been developed for MIMO nonlinear systems [15–28]. The basic idea of some proposed works [17,19,21,27] is that the controllers are generally based on a suitable combination of an adaptive fuzzy controller and a robust compensator. The adaptive fuzzy controller is used to deal with system uncertainties, while the robust compensator is mainly utilized to cope with those ubiquitous modeling approximation errors. In [15,18,22], based on the sliding-mode surface technique and backstepping technique, the stable adaptive fuzzy output feedback scheme is developed for MIMO systems. In general, to obtain an indirect adaptive fuzzy controller for MIMO systems, some of the aforementioned results are needed to calculate the inverse of the estimated gain matrix [16,17,19,21,24,27]. Furthermore, to realize the robust controller, a restriction is required that the control direction must be known a priori. Without the priori knowledge of the control direction, the adaptive fuzzy control of these systems becomes much more challenging. That is why most previous schemes assume that the control direction is known a priori. For instance, in [21,24,28], it is assumed that the control gain matrix is positive definite.

Another important issue of the adaptive fuzzy control of MIMO nonlinear systems is the possible controller singularity problem. To overcome this problem, in [18,16], the authors simply assumed that the estimated gain matrix is always nonsingular. In [17,19,20], a direct adaptive control scheme or a projection algorithm is used to deal with this problem. In [21,24], the regularized inverse of the estimated gain matrix instead of its inverse is utilized to avoid this problem. In [23], a modified CE control law is applied to avoid the possible singularity problem. However, the schemes in [21,23,24] required parameter initialization condition constraints as pointed out in [21]. To avoid this problem, the second adaptive fuzzy control scheme is proposed in [21], however, the another restrictive assumption on the best approximation of the gain matrix is necessary.

In practice, nonsmooth nonlinearities, such as dead-zone, backlash, hysteresis, and saturation, exist in various engineering systems. The dead-zone which can severely affect system performance is one of the most important nonsmooth nonlinearities encountered in actuators, such as hydraulic and pneumatic valves, electric servomotors, and electronic circuits. It is thereby more advisable to take into account the effects of the dead-zone in

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http://dx.doi.org/10.1016/j.asoc.2015.01.057
1568-4946/

the controller design. In most practical systems, the dead-zone parameters are poorly known. To handle these systems, several adaptive control approaches have been developed in recent years [29–38]. In [29], model reference adaptive controllers are designed for linear systems with unknown dead-zones, and adaptive output feedback dead-zone compensation scheme is designed for nonlinear systems with an unknown dead-zone in [30]. The above schemes employed an adaptive dead-zone inverse to counteract the effect of dead-zone, and this technique is also used to eliminate asymptotically the effect of the unknown dead-zone on the closed-loop system in [31,32]. However, the aforementioned schemes can be achieved under the condition that the output of the dead-zone is measurable. Given a matching condition to the reference model, an adaptive controller with an adaptive dead-zone inverse is introduced in [33]. With satisfying a matching condition to the state matrix and the input matrix, a decentralized variable structure controller is proposed for a class of uncertain large-scale systems with dead-zone input [34]. Without satisfying the matching condition, some adaptive state feedback and output feedback controllers using the backstepping technique and the smooth inverse function of dead zone are developed for a class of interconnected nonlinear systems in [35]. Furthermore, an adaptive fuzzy decentralized fault-tolerant control method is developed for a class of uncertain nonlinear large-scale systems with the actuator failures [39]. However, in all of the aforementioned control schemes [33–35], a dead-zone inverse has to be constructed to counteract the effects of dead-zone. By using the new description of a dead-zone and exploring the properties of the dead-zone model intuitively and mathematically, a robust adaptive control scheme and an adaptive compensation algorithm are employed without constructing the dead-zone inverse in [36,37]. When the uncertainty matrix and disturbance satisfy the matching conditions, robust and adaptive variable structure output feedback control of uncertain systems with dead-zone nonlinearity is proposed in [38]. However, the aforementioned adaptive control schemes are only suitable for the following three types of systems: linear systems, the nonlinear dynamics whose models are known accurately and the unknown nonlinear functions which can be linearly parameterized. In the case that the nonlinear functions are not linearly parameterized and the nonlinear systems with unknown dead-zone, fuzzy adaptive control scheme is investigated for the uncertain MIMO nonlinear systems with the unknown actuator nonlinearities and the unknown control direction in [26,40], and adaptive neural network backstepping controllers are proposed for SISO and MIMO nonlinear strict-feedback systems with unknown dead-zone in [41–43]. In addition, adaptive fuzzy output feedback control scheme is developed for a class of SISO nonlinear systems with unknown dead-zone in [44], where the inverse method of the dead-zone is constructed. However, this control scheme cannot be applied to MIMO systems. In [45], based on the backstepping technique, a new adaptive fuzzy output feedback control approach is developed for a class of MIMO strict-feedback nonlinear systems with unknown dead-zone inputs. In [28], a fuzzy adaptive variable-structure controller is investigated for a class of uncertain MIMO nonlinear systems with both sector nonlinearities and dead-zones. However, these underlying results suffered from some fundamental limitations. For instance, in [45], the controllers should be bounded, and in [28], the unknown control gains matrix is symmetric and positive-definite.

Based on the previous results, an adaptive fuzzy control scheme is developed for a class of uncertain MIMO nonlinear systems with nonsymmetric control gain matrix and unknown dead-zone inputs. In the control design, the nonsymmetric control gain matrix is expressed as a sum of a symmetric matrix and a skew symmetric matrix, fuzzy systems are employed to approximate the plant's unknown dynamics, and the estimated symmetric gain matrix is decomposed into a product of one diagonal matrix and two orthogonal matrixes. Adaptive fuzzy controllers are constructed by using the matrix decomposition technique, and a dynamic robust controller is proposed to compensate for the lumped errors. The main originalities of the proposed control scheme are as follows: (1) it can solve for the problem of a nonsymmetric control gain matrix; (2) it does not require a priori knowledge of the control direction due to the fact that the dynamic robust controller is designed; and (3) the proposed controller does not depend upon any parameter initialization constrain. The proposed design scheme guarantees the boundary of signals in the resulting closed-loop systems and the convergence of the tracking errors to zero.

The rest of the paper is organized as follows. In Section 2, the plant dynamics and control objective are described. In Section 3, a brief description of fuzzy systems is reviewed. In Section 4 the suggested adaptive fuzzy control scheme is presented while simulation result is provided to demonstrate the effectiveness of this method in Section 5. Finally, conclusions are drawn in Section 6.

Note that $\|.\|$ indicates the Euclidean norm throughout the paper.

2. Problem formulation and preliminaries

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

$$\begin{aligned} y_1^{(r_1)} &= f_1(x) + \sum_{j=1}^{p} g_{1j}(x)\Gamma_j(u_j) \\ &\vdots \\ y_p^{(r_p)} &= f_p(x) + \sum_{j=1}^{p} g_{pj}(x)\Gamma_j(u_j) \end{aligned} \tag{1}$$

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; $\Gamma_j(u_j)$ is the jth actuator nonlinearity which is assumed to be an unknown dead-zone; and $f_i(x)$, $i = 1, 2, \ldots, p$ and $g_{ij}(x)$, $i, j = 1, 2, \ldots, p$ are the continuous unknown smooth nonlinear functions.

Denoting

$$y^{(r)} = [y_1^{(r_1)}, \ldots y_p^{(r_p)}]^T$$

$$F(x) = [f_1(x), \ldots, f_p(x)]^T$$

$$\Gamma = [\Gamma_1(u_1), \cdots, \Gamma_p(u_p)]^T$$

$$G(x) = \begin{bmatrix} g_{11}(x) & \cdots & g_{1p}(x) \\ \vdots & \ddots & \vdots \\ g_{p1}(x) & \cdots & g_{pp}(x) \end{bmatrix}$$

then, Eq. (1) can be written in the following compact form

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

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 $\Gamma_i(u_i(t))$ is described by[36]

$$\Gamma_i(u_i(t)) = \begin{cases} m_{ri}(u_i(t) - b_{ri}), & \text{for} \quad u_i(t) \geq b_{ri} \\ 0, & \text{for} \quad b_{li} < u_i(t) < b_{ri} \\ m_{li}(u_i(t) - b_{li}), & \text{for} \quad u_i(t) \leq b_{li} \end{cases} \tag{3}$$