

## Nonlinear adaptive control using neural networks and its application to CSTR systems

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### Abstract

In this paper, adaptive tracking control is considered for a class of general nonlinear systems using multilayer neural networks (MNNs). Firstly, the existence of an ideal implicit feedback linearization control (IFLC) is established based on implicit function theory. Then, MNNs are introduced to reconstruct this ideal IFLC to approximately realize feedback linearization. The proposed adaptive controller ensures that the system output tracks a given bounded reference signal and the tracking error converges to an  $\epsilon$ -neighborhood of zero with  $\epsilon$  being a small design parameter, while stability of the closed-loop system is guaranteed. The effectiveness of the proposed controller is illustrated through an application to composition control in a continuously stirred tank reactor (CSTR) system. © 1999 Elsevier Science Ltd. All rights reserved.

**Keywords:** Nonlinear systems; Input–output feedback linearization; Adaptive control; Multilayer neural networks; CSTR

### 1. Introduction

Recently, active research has been carried out on neural network control for nonlinear dynamic systems [1–16]. The massive parallelism, natural fault tolerance and implicit programming of neural network computing architectures suggest that they are good candidates for implementing real-time adaptive control for nonlinear dynamical systems. In the NN control design based on backpropagation (BP) learning algorithm [1–3], sufficient off-line training is required before control action is initiated for achieving a stable closed-loop system. To deal with such a requirement, stable adaptive NN design methods have been proposed based on Lyapunov stability theory in [4–9], which are applicable to affine nonlinear system described by

$$\begin{cases} \dot{x} = f_1(x) + g_1(x)u \\ y = h(x) \end{cases} \quad (1)$$

where  $f_1(x)$  and  $g_1(x)$  are smooth vector fields. In practice, many physical systems such as chemical reactions, PH neutralization and distillation columns are inherently

nonlinear, whose input variables may enter in the systems nonlinearly as described by the general form

$$\begin{cases} \dot{x} = f(x, u) \\ y = h(x) \end{cases} \quad (2)$$

where  $x \in R^n$  is the state vector,  $u \in R$  is the input and  $y \in R$  is the output, and  $f(\cdot, \cdot)$  and  $h(\cdot)$  are smooth vector fields. To solve the control problem for general nonlinear systems, neural networks have been used in [10–13] for emulating the ‘inverse controller’ to achieve tracking control through off-line training. It has been shown that the adaptive controller proposed in [13] can guarantee the stability of the closed-loop system when the uniformly persistently exciting (PE) condition is satisfied.

Multilayer neural networks are general tools for modelling nonlinear functions since they can approximate any continuous nonlinear function to any desired accuracy over a compact set [17]. In this work, a new direct adaptive controller is developed for non-affine system (2) using MNNs and Lyapunov stability technique. It is shown that the tracking error converges to a small neighborhood of zero and the closed-loop stability is guaranteed without the requirement for off-line training and PE condition. The paper is organized as follows. Section 2 describes the class of nonlinear systems under study and the concept of input–output

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# Application Of Neural Networks To Adaptive Control Of Nonlinear

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