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# Adaptive fuzzy control of a non-linear servo-drive: Theory and experimental results

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**Abstract**

Adaptive fuzzy control has been an active research area over the last decade and several stable adaptive fuzzy controllers have been proposed in the literature. Such controllers are generally based on feedback linearization and their parameters are updated by tracking-error-based adaptive laws, designed by Lyapunov synthesis. In this paper, different indirect adaptive schemes have been studied and compared by means of an experimental benchmark consisting of two coupled servo-drives. Parametric and structural changes are introduced to the controlled plant, in order to emphasize the advantages and limitations of the considered adaptive controllers. As the standard composite adaptation laws from the literature were found too sensitive to noise and unmodeled dynamics, a novel variant of the composite adaptation laws has been proposed, based on the filtered prediction error. Experimental results demonstrate that the proposed method improves the controller's tracking performance.


*Keywords:* Adaptive control; Fuzzy systems; Model reference control; Feedback linearization; Lyapunov stability; Electric drive

## 1. Introduction

Recently, there has been an increasing interest in adaptive fuzzy control (AFC) for input-affine non-linear dynamic systems. This interest has been motivated by the demands for high control performance in situations in which an accurate model of the controlled plant is not easily available, or when the plant undergoes unforeseen parameter variations. Fuzzy systems have the potential to play an important role in adaptive control, mainly thanks to their *universal function approximation* property and their amenability to (linguistic) interpretation of the input–output relationships.

The most common stable AFC schemes are based on *feedback linearization* (Wang, 1993, 1996; Spooner et al., 2002) of input-affine models in the controllable canonical form. They mostly employ singleton fuzzy systems to approximate the unknown plant (*indirect schemes*) or the unknown control law (*direct schemes*). The parameters of the antecedent membership functions are usually fixed and the consequent parameters are adapted based on the tracking error by means of stable adaptive laws derived through Lyapunov synthesis.

An adaptive fuzzy controller is expected to comply with the following design requirements: (i) *stability* of the closed-loop system (all signals in the closed-loop must be bounded), (ii) *asymptotic convergence* of the tracking error to zero or to a neighborhood of zero, (iii) robustness with respect to the *approximation error*, unavoidably introduced by any approximator with a finite number of parameters. The approximation error is usually treated as a disturbance acting on the system by means of standard modifications: *an additional non-linear damping term*, usually in a sliding mode framework (Su and Stepanenko, 1994; Han et al., 2001; Fishle and Schroder, 1999; Spooner and Passino, 1996; Chen et al., 1996; Tong et al., 2000; Chang, 2000);

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*a modified adaptive law* such as projection (Wang, 1993, 1996), dead-zones (Koo, 2001), $\sigma$-modification/$\varepsilon$-modification (Skrjanc et al., 2002). Another significant design requirement, though not always explicitly stated, is that the adapted parameters converge to some optimal values (for a time-invariant process) or, at least, that the parameters do not exhibit too large oscillations. This requirement is related to the issue of the interpretability of fuzzy systems (Setnes et al., 1998; Jin, 2000).

Adaptive controllers with *composite adaptive laws* (Hojati and Gazor, 2002), which are based on the *tracking* and the *prediction* errors, have the potential to deal with the aforementioned design issues. In the context of classical adaptive control (Slotine and Li, 1991; Duarte and Narendra, 1989) it has been shown that for linear plants, the composite adaptive laws can significantly improve the closed-loop performance and robustness, essentially as a consequence of a smoother and quicker adaptation process. Also in the AFC literature (Yin and Lee, 1995; Hojati and Gazor, 2002), it has been argued that composite adaptation can provide better performance and improved parameter convergence (under the assumption that the approximation error is sufficiently small).

However, despite the large number of modifications and variants of AFC schemes, there is a tendency to use simple simulation benchmarks to validate the proposed methods (with the notable exception of Ordonez et al., 1997; Mrad and Deeb, 2002; Fishle and Schroder, 1997). This, together with the lack of comparative evaluations, makes difficult to assess the actual applicability and the relative advantages and drawbacks of these methods in a practical context.

The aim of this article is to compare several indirect adaptive schemes by means of a challenging experimental benchmark. The system consists of two coupled servo-drives, where the first one acts as an actuator, while the second one is used to generate non-linear load patterns. The system exhibits noise, parasitic electro-magnetic effects, friction and other phenomena commonly encountered in practical applications.

The performance of the controllers is evaluated in three situations, in which the controlled plant undergoes parametric or structural changes: (i) change of the load torque; (ii) change of the input gain from one constant value to another one and (iii) change of the input-gain function from a constant value to a speed-dependent profile. It is worth noting that, although the occurrence of unforeseen parameter variations in the controlled plant is one of the basic motivations for adaptive control, in the literature, there are hardly any examples of AFC schemes applied in such situations.

Next to the standard AFC schemes, a novel variant of an indirect model reference adaptive controller with composite adaptive laws is introduced in this paper. Such adaptive laws have been devised to overcome some inherent limitations of the standard adaptive laws (based only on the tracking error) and of similar composite adaptive laws proposed in the literature (Yin and Lee, 1995; Hojati and Gazor, 2002). The new adaptation laws have the structure proposed in Hojati and Gazor (2002), but the prediction error is determined by means of the estimation scheme described in Wang (1995). The proposed law does not require the estimation of the $n$th derivative of the plant output, while assuring the *global stability* of the closed-loop system. Moreover, it provides improved control performance, compared to other indirect adaptive controllers (both with standard adaptive laws and with the composite adaptive laws described in Yin and Lee, 1995; Hojati and Gazor, 2002).

The remainder of this paper is structured as follows. Section 2 gives background on indirect model reference AFC. In Section 3, first the basics of composite adaptation are discussed in the context of the references (Yin and Lee, 1995; Hojati and Gazor, 2002) and then the proposed adaptive laws are described. In Section 4, the experimental setup is presented. Section 5 addresses the choice of the controllers' parameters. Section 6 reports on the tracking performance of the AFC schemes, compared to a linear adaptive controller. In Section 7, the performance of the indirect AFC schemes is evaluated under parametric and structural changes of the plant. Section 8 concludes the paper.

## 2. Indirect AFC

### 2.1. Controller structure

Consider an input-affine SISO system in the controllable canonical form

$$x^{(n)} = f(\mathbf{x}) + g(\mathbf{x})u, \tag{1}$$

$$y = x, \tag{2}$$

where $\mathbf{x} = [x, \dot{x}, \ldots, x^{(n-1)}]^{\mathrm{T}} \in \mathbb{R}^n$ is the state vector. It is assumed that $g(\mathbf{x}) > 0$ for all $\mathbf{x} \in X \subset \mathbb{R}^n$. The *control goal* is to track a desired trajectory $y_{\mathrm{m}}$ while keeping all the signals in the closed-loop bounded. The tracking error $e = y_{\mathrm{m}} - y$ is the difference between the trajectory $y_{\mathrm{m}}$ generated by a reference model and the output $y$ of the system. Further, introduce the vector of the tracking error and its $n-1$ derivatives $\boldsymbol{e} = [e, \dot{e}, \ldots, e^{(n-1)}]^{\mathrm{T}}$ and the feedback gain vector $\boldsymbol{k} = [k_n, \ldots, k_1]^{\mathrm{T}}$. If the functions $f(\mathbf{x})$ and $g(\mathbf{x})$ are known, the gains $k_i$ can be chosen such that the roots of the polynomial $h(s) = s^n + k_1 s^{n-1} + \cdots + k_n$ are in the open left-half of the complex plane. The *feedback linearizing* control law

$$u^* = \frac{1}{g(\mathbf{x})}[-f(\mathbf{x}) + y_{\mathrm{m}}^{(n)} + \boldsymbol{k}^{\mathrm{T}}\boldsymbol{e}], \tag{3}$$

then produces the desired linear *error dynamics*:

$$\dot{\boldsymbol{e}} = \boldsymbol{\Lambda}_{\mathrm{c}}\boldsymbol{e}, \tag{4}$$

where $\boldsymbol{\Lambda}_{\mathrm{c}} \in \mathbb{R}^{n\times n}$ is a matrix in the companion form, with the last row containing the vector $-\boldsymbol{k}^{\mathrm{T}}$. The ideal control law (3) guarantees that $\lim_{t\to\infty} e(t) = 0$.