PI Adaptive Fuzzy Control With Large and Fast Disturbance Rejection for a Class of Uncertain Nonlinear Systems

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Abstract—Design of controllers for uncertain systems is inherently paradoxical. Adaptive control approaches claim to adapt system parameters against uncertainties, but only if these uncertainties change slowly enough. Alternatively, robust control methodologies claim to ensure system stability against uncertainties, but only if these uncertainties remain within known bounds. This is while, in reality, disturbances and uncertainties remain faithfully uncertain, i.e., may be both fast and large. In this paper, a PI-adaptive fuzzy control architecture for a class of uncertain nonlinear systems is proposed that aims to provide added robustness in the presence of large and fast but bounded uncertainties and disturbances. While the proposed approach requires the uncertainties to be bounded, it does not require this bound to be known. Lyapunov analysis is used to prove asymptotic stability of the proposed approach. Application of the proposed method to a second-order inverted pendulum system demonstrates the effectiveness of the proposed approach. Specifically, system responses to fast versus slow and large versus small disturbances are considered in the presented simulation studies.

Index Terms—Adaptive control, fuzzy control, Lyapunov theory, nonlinear systems.

I. INTRODUCTION

Generally, there are two kinds of uncertainties in a system to be controlled. One is caused by a lack of information about system structure and parameters, and the other is due to internal and external disturbances. Due to these uncertainties, the conventional nonlinear methods like feedback linearization usually fail, and the control of nonlinear uncertain systems remains a challenging and yet rewarding problem [1], [2].

Among the methods that address uncertainty in plant dynamics is adaptive control. The objective, in adaptive control, is to introduce an adaptation law that adjusts the parameters of the controller or the system against system uncertainties and disturbances. However, such methods generally guarantee parameter convergence only if parameter changes are slow enough [3], [4]. Moreover, the existing adaptive control approaches commonly require the general structure of the plant, such as its order, to be known.

Fuzzy logic, as an alternative to conventional control methodologies handling uncertainty, has been the focus of numerous studies in the past two decades [5]. Fuzzy logic provides an important tool for utilization of human expert knowledge in complement to mathematical knowledge. This is mainly due to the possibility of making use of fuzzy knowledge-based control to deal with systems whose dynamics are not so well understood and whose models can not be so conveniently established [6], [7]. Therefore, hybrid combinations of the fuzzy logic and adaptive control are an attractive approach for designing robust control systems with high degrees of nonlinearities and uncertainties [8]–[16]. Such hybrid approaches provide the ability to incorporate human expert knowledge about plant dynamics (indirect adaptive control), as well as its operation (direct adaptive control) into the adaptive control methodology.

Literature on adaptive fuzzy controllers has been abundant and growing, particularly during the past decade. As one of the pioneering works in this area, Wang in 1996 [8] proposed a general approach to design of stable adaptive fuzzy controllers based on a fuzzy basis function framework and Lyapunov synthesis. The concept of fuzzy basis function viewed fuzzy logic framework not only as a paradigm for formulating human knowledge, but also as a powerful nonlinear function with universal approximation capabilities. Wang applied his control approach to a second-order nonlinear model of inverted pendulum system. More recently, the problem of controlling a class of uncertain nonlinear systems to follow a reference trajectory was addressed in [9]. There, based on a priori information, a nominal fuzzy controller was first implemented; then, a signal to compensate for both structured and unstructured uncertainties arising from the approximation was synthesized based on the Lyapunov method. Exponential tracking to the reference trajectory up to an ultimately bounded error was achieved. Later in [10], Tang addressed a lack of robustness in conventional adaptive fuzzy methods and proposed an adaptive robust fuzzy control design for a class of nonlinear systems represented by input-output models to follow a reference trajectory in the presence of uncertainties. In 2005, Yang and Zhou [11] developed a new systematic procedure for the synthesis of stable adaptive robust fuzzy controllers for a class of continuous uncertain systems, where Takagi–Sugeno type fuzzy logic systems were used to approximate the unknown unstructured functions in the