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H_∞ fuzzy adaptive tracking control design for nonlinear systems with output delays

Tzu-Sung Wu *, Mansour Karkoub

Department of Mechanical Engineering, Texas A & M University, Doha, Qatar

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Abstract

In this study, we develop fuzzy adaptive tracking control via two-layer fuzzy observers, variable structure systems (VSS), and H_∞ control algorithm for nonlinear systems with plant uncertainties, output delays, and external disturbances. The Takagi–Sugeno fuzzy dynamic model with adaptation capability is used to approximate the nonlinear system. When the system states are not available, the states estimated from two-layer fuzzy observers combined with VSS are used to develop the fuzzy adaptive controller. In the first layer, the output delays are partitioned into $m + 1$ equal time intervals to construct the same number of fuzzy observers. The output delayed states in each time interval are used as the premise variables in the IF–THEN rules. The second layer of the fuzzy observers uses output delayed error states as its linguistic variables and it is defuzzified from the first layer. Next, we develop a fuzzy adaptive controller to overcome the nonlinearities, output delayed states, and external disturbances such that H_∞ tracking performance is achieved. The Lyapunov criterion and linear matrix inequalities are used to derive the controller. In the present study, our previous method is extended to handle a class of uncertain nonlinear systems with output delays and external disturbances, which is achieved using robust VSS and H_∞ control techniques. A magnetic levitation system and inverted pendulum system are used as simulation examples to illustrate the validity and confirm the performance of our proposed scheme.

Keywords: Fuzzy adaptive control; H_∞ tracking performance; Inverted pendulum system; Linear matrix inequality; Magnetic levitation system; Output delay; Two-layer fuzzy observer

1. Introduction

Processes that need to be controlled or monitored far from the computing unit in real industrial applications generally have unknown and nonlinear dynamics, where only the output states may be available and measurable. In general, the data measured from the output states are transmitted via a low-rate communication system with long transmission lines, which may lead to time delays in the output states (e.g., rolling mill control systems, chemical processes, traffic networks, and telecommunication systems) and to deterioration in the performance and/or instability in the

* Corresponding author. Tel./fax: +974 4 4230548.
E-mail address: tzu-sung.wu@qatar.tamu.edu (T.-S. Wu).

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system. Thus, because the dynamics and system nonlinearities are unknown, it is difficult to synthesize stabilizing controllers/observers for systems with output delays, particularly when tracking the control design (e.g., see [1–4] and the references therein). Systems with delays can be stabilized based on delay-independent stability criteria [5] and delay-dependent criteria [6–8]. Furthermore, less conservative delay-dependent stability conditions can be obtained easily in a linear matrix inequality (LMI) form for time-delay nonlinear systems. This is achieved by using the Takagi–Sugeno fuzzy modeling approach when investigating the delay-dependent property [9]. A fuzzy adaptive control scheme that integrates variable structure systems (VSS) has been developed as a robust strategy for handling uncertain control systems, which may include delayed states. This technique usually yields good results in trajectory tracking problems with good data fitting for unknown and nonlinear systems (for example, see [10–12,18–20]).

Lin et al. [13] proposed a robust fuzzy neural network controller with a nonlinear disturbance observer for a two-axis motion control system using state feedback control, which assumes that all system states are available for measurement. In practice, state feedback control is not always applicable because the system states are not always available. In [14], a high-gain observer was used to estimate the system states for non-affine nonlinear systems. However, the closed-loop system may exhibit a peaking phenomenon during the transient behavior caused by the use of high-gain observers. The design of adaptive observers based on output feedback was proposed in [15], which uses linear dependence conditions. This is achieved after removing unknown parameters and introducing universal function approximators, such as fuzzy systems and neural networks, into the observer structure. In addition to the nonlinearities and uncertainties, the output delay should be included in the dynamic system when considering stability in the control system design (for example, see [1,2,16] and the references therein).

However, the uncertainty bounds of the output delay might not be found easily because of the complex structure of the uncertainties. Thus, a previous study [32] proposed fuzzy adaptive observer-based (FAOB) control by partitioning output delays with equal time intervals to form the fuzzy observers, i.e., two-layer fuzzy systems with two forms of linguistic knowledge and one rule, which improve fuzzy inference with linguistic uncertainties. Recently, various techniques have been proposed that use Riccati-like equations and LMIs in the Lyapunov stability theory to find a single positive-definite matrix, a common positive-definite matrix, or a set of positive-definite matrices to guarantee the stability of the closed-loop fuzzy control system [21–25]. Some design methods for fuzzy adaptive systems use H_∞ in the Lyapunov stability theory [26] and VSS schemes [27,28] to improve the robustness and stability of a system with parameter uncertainties and external disturbances. Conventionally, most of the linguistic input variables in the fuzzy systems used for H_∞ fuzzy adaptive control design are based on measurable system states. However, not all of the states of a controlled system are measurable in the field, which leads to difficulties with the implementation of conventional fuzzy systems. Recently, a chain observer was proposed for estimating the system states of a system with known output time-delays, which assumes that the system parameters are known [29]. The stability of cascade state observers for systems with time-varying output delays in the piecewise area were considered in [30]. Thus, the development of a fuzzy adaptive approach to the control of unknown nonlinear systems based on state observers [31–35] and a two-layer fuzzy observer with output delays [32,33] could yield successful results.

In the present study, we develop fuzzy adaptive tracking control based on two-layer fuzzy observers, VSS, and an H_∞ control algorithm for nonlinear systems with plant uncertainties, output delays, and external disturbances. Fuzzy adaptive systems are introduced to learn the unknown dynamics with two-layer fuzzy observers for estimating the state variables. In the first layer, the output delays are partitioned into $m+1$ equal time intervals to construct the same number of fuzzy observers and the output delayed states in each time interval are used as premise variables in the IF–THEN rules. The second layer of the fuzzy observers uses the output delayed error states as its linguistic variables and it is defuzzified from the first layer. The effects of fuzzy approximation errors on the tracking error are eliminated by using a VSS. After characterizing the stabilization problem in terms of a LMI problem within a prescribed attenuation value and transforming the nonlinear matrix inequalities into LMI forms using a decoupling method, the estimation and tracking errors of the overall control system are guaranteed to be uniformly ultimately bounded (UUB). The H_∞ tracking performance in a closed-loop system can be achieved in a Lyapunov sense. Two-layer fuzzy observers can be viewed as an extension of the type-1 fuzzy logic system and interval observer, thus they can efficiently handle nonlinear systems with plant uncertainties, output delays, and external disturbances. The method presented in [32,33] uses an H_∞ technique without a state variable filter that resulted in undesirable tracking errors due to fuzzy approximation errors. To avoid this problem and to facilitate improved performance, the present study uses a VSS scheme without restrictions on the lumped uncertainty term (ΔB_j) between 0 and 1. Moreover, a state variable filter is used to obtain all the elements of $\boldsymbol{x}$ and $\mathbf{e}$ such that the stability of the estimation error is guaranteed. However, the fuzzy approxima-