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Adaptive fuzzy predictive sliding control of uncertain nonlinear systems with bound-known input delay

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ABSTRACT

In this paper, a new Adaptive Fuzzy Predictive Sliding Mode Control (AFP-SMC) is presented for nonlinear systems with uncertain dynamics and unknown input delay. The control unit consists of a fuzzy inference system to approximate the ideal linearization control, together with a switching strategy to compensate for the estimation errors. Also, an adaptive fuzzy predictor is used to estimate the future values of the system states to compensate for the time delay. The adaptation laws are used to tune the controller and predictor parameters, which guarantee the stability based on a Lyapunov-Krasovskii functional. To evaluate the method effectiveness, the simulation and experiment on an overhead crane system are presented. According to the obtained results, AFP-SMC can effectively control the uncertain nonlinear systems, subject to input delays of known bound.

1. Introduction

For many engineering applications such as process control, combustion engines, network control systems, transportation traffic, biosystems, and flight control systems, the control design problem is limited by two main factors. The mentioned systems contain the nonlinear dynamics which cannot be modeled precisely. In addition, the time delays are ubiquitous in these systems that leads to instability. Because the higher performance of the controlled system is a prerequisite, the time delay and unknown dynamics are considered as the main design factors in recent researches. Among delay systems, the control problem of the input delay systems are more complicated than state delay.

The existing control algorithms for the delay system can be considered in some categories. Three elements help to categorize the works. In general, the delay can be in the states, input, or both of them. Also, the system dynamics cab be either linear or nonlinear. The third element relates to the designer's knowledge from the dynamics and delay, i.e., the dynamics and delay can be known, uncertain, and unknown.

Typical proposed control approaches for linear systems with unknown input delays cannot be directly extended to nonlinear plants. In addition, many nonlinear systems have uncertainties in their dynamics, and the control problem becomes more challenging in the presence of input delay [1]. Hence, study and control of such systems have been the focus of many different researches.

To evaluate the effectiveness of control methods for linear time-delay systems, a measure of disturbance attenuation was introduced by Jankovic and Magner [2]. In two other studies, a predictive active disturbance rejection and a delay variable decomposition based approach are proposed and implemented for linear systems [3,4]. By adapting the reduction model approach, a control law was derived for LTI systems with an arbitrary pointwise constant delay in the inputs [5]. A least upper bound of input delay perturbation that does not destroy the exponential stability properties of the closed-loop linear system was obtained by Karafyllis and Krstic [6]. Fu et al. investigated the regional stability by using a new Lyapunov–Krasovskii functional for linear time-delay systems in the presence of actuator saturation and delay. An LMIs based optimization problem was solved to maximize the estimated domain of attraction in [7]. For the case of exactly known state and input delays, a control scheme was developed based on the nested predictor for LTI systems, to achieve the same characteristics equation for the system with or without input delay [8]. In the mentioned studies the input delay is assumed to be known and constant. Zhou et al. identified some special classes of linear systems with both state and input time-varying delays that can be stabilized by static state feedback [9]. For linear networked

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systems, subject to transfer delays, packet-loss and packet-disordering, Rahmani et al. presented a variable selective control methodology by extending the variable sampling period idea [10].

Many other studies have also addressed the problem for nonlinear systems. A quantized feedback with constant delay was designed in [11], which stabilizes the origin of nonlinear systems semi-globally practically. For a class of nonlinear systems with both input and state delays, closed-loop stability and input and state constraints satisfaction were achieved by a receding horizon control [12]. The reduction model technique was used to stabilize the time-varying nonlinear systems with distributed input delay in the integral form [13]. The main assumptions in these studies are that the system dynamics are available and delay is a known constant. Global state feedback stabilization for high-order nonlinear systems with time-varying delays, and a control framework for a nonlinear time-delayed teleoperation system are two other examples [14,15]. Karafyllis et al. employed a baseline stabilizing feedback law for a delay-free system, to control the nonlinear system in the presence of delay using future state vector estimation from an inter-sample predictor [16]. Bekiaris-Liberis investigated global asymptotic stability of a nonlinear system with simultaneous input and state delays which was controlled by a predictor feedback and infinite-dimensional backstepping transformation of the actuator state [17]. The global asymptotic stability in the presence of a time-varying input delay was proved with the aid of a strict Lyapunov function for a class of nonlinear systems. This compensation method was designed by construction of the backstepping transformations for different states with different prediction windows [18]. The constant delay assumption for input was relaxed to bound known delay in later works such as in [19] but the system must be known yet.

Saturated control of an uncertain nonlinear Euler–Lagrange systems with time-delayed actuation was examined in [20], through Lyapunov-based stability analysis, to prove uniformly ultimately bounded (UUB) tracking despite dynamics uncertainties. Also, a tracking controller was developed for these systems with parametric uncertainty and additive bounded disturbances by Sharma et al., assuming that the input delay is constant and known [21]. Jiao et al. considered a special class of nonlinear systems with known linear dynamics and uncertain nonlinear term which is subject to time delays in both state and input [22]. They designed an adaptive controller by constructing appropriate Lyapunov–Krasovskii functional where the delay are bounded and rate limited.

The adaptive control scheme combined with back-stepping and fuzzy logic system to ensure that the closed-loop system is semi-globally uniformly ultimately bounded, for a class of high order nonlinear systems with known constant input delay was studied in [23]. Na et al. proposed an adaptive neural network observer and predictor to compensate the known constant input delay for an unknown nonlinear system [24].

Although many control approaches were proposed for the linear systems with unknown input delays, they cannot extend in an obvious way to nonlinear plants [1]. The previous works on nonlinear plants could not cope with the complete control problem i.e., when an unknown dynamics is subject to unknown input delay. Thus, an important step toward solving this open problem is to find an stabilizing controller for a more general form of it in comparison with the existing techniques.

In this paper, a new control approach is proposed for nonlinear systems to circumvent the unknown dynamics and unknown bounded input time-delay. Here, an adaptive fuzzy sliding mode controller (AFSMC) that control the uncertain nonlinear chaotic systems [25] and unknown robotic systems [26], is modified to compensate for uncertain dynamics and unknown input delay by employing a predictor of future system states. The controller consists of two main elements which are a fuzzy system that approximates an ideal sliding-mode controller, and a secondary segment to compensate the errors by a switching strategy. The fuzzy output vector and estimation error bound are both tuned by adaptive laws [26]. The controller is similar to AFSMC but new Lyapunov–Krasovskii function is developed instead of traditional Lyapunov function of AFSMC. An adaptive fuzzy predictor (AFP) also estimates future value of the system states by minimizing the difference between the estimated and actual values of states throughout the prediction horizon. Hence, the new approach is basically an Adaptive Fuzzy Predictive Sliding Mode Control (AFP-SMC) method.

The main contributions of the paper in controlling of unknown nonlinear system with input delay are: (i) removing the need for known dynamics and uncertainty bounds using the AFSMC and (ii) guaranteeing the closed-loop UUB stability for unknown time-varying input delays. The theoretical results are later verified by comparative simulations on a chaotic nonlinear benchmark problem.

The rest of the paper is organized as follows: problem statement is presented in Section 2. Section 3 introduces the predictor and controller design, and the closed-loop stability is analyzed in Section 4. Sections 5 and 6 include the simulation and experiment studies on the proposed method for different types of delays. Concluding remarks are given in Section 7.

2. Problem definition

Here in this section, considered model of the nonlinear system is described and discussed. To this end, consider a nonlinear system with input time-delay in form of

$$\begin{cases} x^{(n)}(t) = f(\mathbf{x}) + g(\mathbf{x})u(t-\tau) \\ y(t) = C\mathbf{x} \end{cases} \tag{1}$$

where $\mathbf{x} = [x_1, \ldots, x_n]^T \in \mathbb{R}^n$, $y(t) \in \mathbb{R}$, $u(t) \in \mathbb{R}$, and C is a known constant row vector. Furthermore, $f(\mathbf{x})$ and $g(\mathbf{x})$ are scalar, smooth and not necessarily known nonlinear functions. τ is bound-known and rate-limited, i.e., $0 \le \tau \le \overline{\tau}$ and $\dot{\tau} \le 1$. The objective is to design a stabilizing control for tracking of a reference input, $y_d(t)$, which is assumed to be bounded and n-times differentiable. As is customary, it is assumed that $u(t-\tau) = 0$ when $t < \tau$.

In many engineering applications, it is feasible to find or estimate the maximum size of input delay. For example the input delay usually depends on the computation and actuators lag, that is measurable off-line. As a specific example, in the process control and active suspension control, the basic actuators are valves. There are at least two delays in these systems that relate to the calculation time of control signal and the actuation time of valves, because the valves open gradually.

Time delay reduces the performance and leads to destabilize control systems. When there is a difference between the real time delay τ and the known bound of delay $\overline{\tau}$, the system encounters an additional uncertainty. Thus, there are three types of uncertainties in the system. First one is related to the unknown nonlinear dynamics of the system i.e., $f(\mathbf{x})$, and $g(\mathbf{x})$. Second uncertainty arises from the delay of control input. The last one originates from the error between the calculated control signal for the prediction horizon $t+\overline{\tau}$ and the required control input in the real receiving time $t+\tau$. Based on this fact, AFSMC which can handle the nonlinearities and unknown dynamics properly, as it is used in combination with an adaptive fuzzy predictor such that the delay effect and uncertainties are eliminated within the prediction horizon $\overline{\tau}$.