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Research article

Adaptive iterative learning control of a class of nonlinear time-delay systems with unknown backlash-like hysteresis input and control direction

Jianming Wei [a,*], Youan Zhang [b], Meimei Sun [a], Baoliang Geng [a]

[a] Department of Control Engineering, Naval Aeronautical and Astronautical University, Yantai 264001, PR China
[b] Department of Electrical and Electronic Engineering, Yantai Nanshan University, Yantai 265713, PR China

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ABSTRACT

This paper presents an adaptive iterative learning control scheme for a class of nonlinear systems with unknown time-varying delays and control direction preceded by unknown nonlinear backlash-like hysteresis. Boundary layer function is introduced to construct an auxiliary error variable, which relaxes the identical initial condition assumption of iterative learning control. For the controller design, integral Lyapunov function candidate is used, which avoids the possible singularity problem by introducing hyperbolic tangent funciton. After compensating for uncertainties with time-varying delays by combining appropriate Lyapunov-Krasovskii function with Young's inequality, an adaptive iterative learning control scheme is designed through neural approximation technique and Nussbaum function method. On the basis of the hyperbolic tangent function's characteristics, the system output is proved to converge to a small neighborhood of the desired trajectory by constructing Lyapunov-like composite energy function (CEF) in two cases, while keeping all the closed-loop signals bounded. Finally, a simulation example is presented to verify the effectiveness of the proposed approach.

1. Introduction

Over the past decades, there was tremendous research aiming at the development of systematic design methods of the iterative learning control (ILC), for controlling nonlinear systems running on a finite interval repeatedly. ILC has become the most appropriate and effective control strategy for such repetitive control tasks. Generally, ILC mainly includes traditional ILC [1–4] and adaptive ILC (AILC) [5–10]. The basic principle of traditional ILC is to generate current control action by exploiting information collected from previous executions based on a learning mechanism, in order to improve control performance from iteration to iteration. However, traditional ILC requires the global Lipschitz continuous condition, which makes it difficult to apply it to certain nonlinear systems. As an alternative solution, AILC successfully overcomes the restriction of global Lipschitz condition. AILC takes advantage of both adaptive control and ILC and finally makes it possible to use fuzzy logic systems or neural networks as approximators to deal with nonlinear uncertainties. In general, the control parameters of AILC are tuned along the iteration axis, and the composite energy function (CEF) [5] is usually constructed to analyze the stability and convergence property of the closed-loop systems. The past decade has witnessed great progress in AILC of uncertain nonlinear systems [6–10].

In practice, control of systems with time delays has been a hot topic. Because time delay exists in a wide range of physical systems and devices, such as turbojet engines, aircraft systems, microwave oscillators, nuclear reactors, rolling mills, chemical processes and hydraulic systems, etc. [11,12]. The existence of time delays may degrade the control performance, and even becomes a source of instability at the worst. Thus, the research on time-delay in systems has always been an essential work for control engineers. Consequently, the control problem of the systems with time delay has drawn much attention [11–17]. In the field of AILC, only a few research results are available to nonlinear systems with time-delays [18–20]. The main difficulty for design is how to deal with uncertainties with time delays. In [18], an AILC strategy was developed for a class of scalar system with unknown time-varying delay and then the method was extended to a class of high-order systems with both time-varying and time-invariant parameters, where the unknown time-varying parameter was estimated during the iteration learning process. However, it required that the uncertainties in the system satisfy both local Lipschitz condition and nonlinear parameterized condition so that adaptive learning laws could be designed to estimate the unknown time-varying parameters. Wei et al. studied the AILC problem of a class of uncertain nonlinearly parameterized systems with unknown time-varying time delays and dead-zone by using parameterization

* Corresponding author.
E-mail address: wjm604@163.com (J. Wei).

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method in [19]. Besides, by utilizing neural approximation technique, a new AILC scheme was proposed to deal with non-parametric uncertainties [20].

Other than time delay, control of nonlinear systems with unknown control directions is also a hot topic in the control field. When there is no priori knowledge about the signs of control coefficients, the control of such systems becomes much more difficult. For this problem, the Nussbaum-type gain has been proved to be one of the most effective tools, and it was first proposed in [21] for a class of first-order systems in 1983. Until now, a large number of correlational studies have been reported in literature to promote the development of Nussbaum-type gain for a variety of control systems [12,22–31]. Among tremendous research results, only a few are conducted from the perspective of AILC [32–34]. The main obstacles of the problem include the manipulation of unknown control direction and stability analysis with CEF, which are different from adaptive control. Through a Nussbaum-type function, a new iterative learning control mechanism was developed for a class of first-order nonlinear system with time-varying uncertainties in [32]. Similar to the design method in [18], Li et al. investigated the AILC for a class of first-order nonlinearly parameterized systems with unknown time-varying delays and unknown control directions, and then extended the research result to a class of higher-order systems with mixed unknown parameters in [33]. In essence, [33] is the extension of [18] and the main difference between them is the incorporation of a Nussbaum-type function while dealing with the unknown direction in [33]. In [34] an iterative learning control strategy was presented for a class of strict feedback nonlinear time-varying systems with unknown control direction, where the time-varying parameters were expanded into Fourier series with bounded remained term, so that the time-varying uncertainties can be transformed into constant uncertainties.

Another challenge in the control of nonlinear systems lies in the existence of non-smooth and nonlinear characteristics, such as dead-zone, hysteresis, saturation and backlash. Therefore, hysteresis is one of the most important non-smooth nonlinearities in a wide range of physical systems and devices, for example, electromagnetic fields, mechanical actuators, and electronic relay circuits [35]. The existence of hysteresis can severely limit system performances and usually lead to undesirable inaccuracies, oscillations and instability [35]. Therefore, the control design for nonlinear systems preceded by hysteresis is a challenging and rewarding research subject. To address such a problem, the principal work is to model the hysteresis nonlinearity for control design. So far, various kinds of mathematical models have been proposed for hysteresis, such as Ishlinskii hysteresis operator [36], Preisach model [37], Krasnoskl'skii-Pokrovskii hysteron [36], backlash-like hysteresis [38], Duhem hysteresis [39]. Among those models, the backlash-like hysteresis model was widely used owing to its better representation of the hysteresis nonlinearity and its facilitation for the controller design [38,40–44]. However, as far as we know, there are few works conducted from the viewpoint of AILC to deal with nonlinear systems with hysteresis nonlinearity in the literature. All the control strategies mentioned above are not applicable to the AILC problem of uncertain time-varying systems due to the particular design process and stability analysis tool.

Motivated by the above observations, in this paper, we study the AILC problem specifically for a class of nonlinear systems with unknown time-varying delays and control direction preceded by a backlash-like hysteresis input. To the best of our knowledge, up to now, no works has been reported in the field of AILC which can deal with this kind of systems. The design difficulty mainly comes from the interactions of unknown time-varying delays, backlash-like hysteresis nonlinearity, unknown control direction and time-varying uncertainties. Our work is not a simple combination of the results of each factor, but an intensive study of synthetic effects of all the factors. In the proposed AILC scheme, neural approximation technique, Nussbaum function method and robust control are utilized synthetically to design the iterative learning controller, and CEF is constructed to analyse the stability and convergence property. Theoretical analysis and simulation examples show that the proposed approach can guarantee that all the signals are bounded and tracking errors converge to a small neighbourhood of the origin. The main contributions of the proposed AILC scheme are highlighted as follows: (1) The time-delay systems with both backlash-like hysteresis and unknown control direction are studied in the field of AILC for the first time, which enlarges the range of AILC scheme; (2) The Nussbaum-type function is introduced into AILC design, which solves the problem of unknown control direction; (3) The possible singularity problem is avoided by a comprehensive usage of integral type Lyapunov function and hyperbolic tangent function; (4) According to the properties of hyperbolic tangent function, a normative stability analysis framework including transient performance analysis is given in two cases.

The organization of this paper is as follows. Section 1 is the introduction. The problem formulation and preliminaries are given in Section 2. In Section 3, the AILC scheme is developed, which is followed by the stability and convergence analysis in Section 4. Results of extensive simulation studies are presented to demonstrate the validity of the proposed scheme in Section 5. Section 6 draws the conclusion.

Throughout this paper, σ denotes the integral variable and $\|\bullet\|$ denotes the Euclidean norm. N is the set of nonnegative integers. For a signal vector $r_k(t)$, define $\|r_k(t)\|_{L_T^\infty} = \max_{(k,t)\in N\times[0,T]}\|r_k(t)\|$ and $\|r_k(t)\|_{L_T^2} = \int_0^T\|r_k(\sigma)\|^2\mathrm{d}\sigma$. If $\|r_k(t)\|_{L_T^\infty} < \infty$, we say that $r_k(t)$ is bounded in L_T^∞-norm, which is denoted by $r_k(t)\in L_T^\infty$. Similarly, we denote the boundedness of $r_k(t)$ in L_T^2-norm by $r_k(t)\in L_T^2$. Obviously, the boundedness in L_T^∞-norm implies the boundedness in L_T^2-norm, because $\|r_k(t)\|_{L_T^2} \le T\|r_k(t)\|^2_{L_T^\infty}$.

2. Problem formulation and preliminaries

2.1. Problem formulation

Consider a class of nonlinear time-delay systems with unknown control direction and uncertain backlash-like hysteresis running on a finite time interval $[0, T]$ repeatedly, which is given by

$$\begin{cases} \dot{x}_{i,k}(t) = x_{i+1,k}(t),\ i = 1, \cdots, n-1 \\ \dot{x}_{n,k}(t) = f(x_k(t), t) + h(x_{\tau,k}(t), t) + g(x_k(t), t)u_k(v_k(t)) + d(t) \\ y_k(t) = x_{1,k}(t),\ t\in[0, T] \end{cases} \tag{1}$$

where $k\in N$ denotes the times of iteration; $y_k(t)\in R$ and $x_{i,k}(t)\in R$, $i = 1, \cdots, n$ are respectively the system output and states; $\bar{x}_{i,k}(t) \triangleq [x_{1,k}(t), \cdots, x_{i,k}(t)]^T$ ($i = 2, \cdots, n-1$) and $x_k(t)\triangleq[x_{1,k}(t), \cdots, x_{n,k}(t)]^T$ are the state vectors; $\tau_i(t)$ are unknown time-varying state delays and $x_{\tau_i,k}\triangleq x_{i,k}(t-\tau_i(t))$, $i = 2, \cdots, n$, $x_{\tau,k}(t) = [x_{\tau_1,k}(t), \cdots, x_{\tau_n,k}(t)]^T$; $f(\bullet,\bullet)$ and $g(\bullet,\bullet)$ are unknown smooth functions, $h(\bullet,\bullet)$ is an unknown smooth functions of time-delay states with upper bound. $d(t)$ is the