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Adaptive iterative learning control of non-uniform trajectory tracking for strict feedback nonlinear time-varying systems with unknown control direction

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ABSTRACT

The iterative learning control problem of strict feedback nonlinear system with unknown time-varying parameters and uncertain control direction is an open problem. An iterative learning control strategy is presented for a class of nonlinear time-varying systems with unknown control direction to solve the non-uniform trajectory tracking problem. Backstepping design technique is applied to deal with system dynamics with non-global Lipschitz nonlinearities. Based on the Lyapunov-like synthesis, we show that all signals in the closed-loop system remain bounded over a pre-specified time interval $[0, T]$, and complete non-uniform trajectory tracking of the system output is achieved. The time-varying parameters are expanded into Fourier series with bounded remained term. A typical series is introduced in order to deal with the unknown bound of remained term and the non-uniform trajectory tracking. Nussbaum function is used to deal with unknown control direction. Finally, a simulation example shows the feasibility and effectiveness of the approach.

1. Introduction

Iterative learning control (ILC) or adaptive iterative learning control (AILC) has become one of the most effective control strategies in dealing with repeated tracking control of nonlinear systems. And the additional requirement of the repetitive mode is that a specified output trajectory on a finite interval is followed to a high precision (or so called exactly tracking). Examples of such systems include robotic manipulators required to repeat a given task to high precision, chemical batch processes, vehicles and man–machine systems. Backstepping method introduced in [1] is regarded as one of the most important developments in adaptive control for high-order non-linear systems. It could be utilized to deal with non-linear systems with certain structure (parametric strict-feedback, parametric pure-feedback and triangular structure) under state transformations.

In the existing literatures, the tracking trajectory must be uniform, for varying tracking trajectory problem along iterative direction, there are only a few well-posed methods to consider it. Actually, the non-uniform trajectory can be considered as an uncertain time-varying parameter along both iterative direction and time domain, therefore, it becomes a challenge problem to study an ILC strategy for uncertain time-varying parametric systems. [2] propose a distributed adaptive fuzzy iterative learning control (ILC) algorithm to deal with coordination control problems in leader-following multi-agent systems in which each follower agent has unknown dynamics and a non-repeatable input disturbance. However, there are still some

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restricts on the trajectory. In [3], for first-order hybrid parametric system, a new iterative learning control law which consists of a feedback term and a learning term was proposed, which enables learning from different tracking control tasks. Recently, a novel adaptive iterative learning control approach was proposed for a class of hybrid parametric nonlinear systems by means of Backstepping method in [4,5]. In [4], a novel adaptive iterative learning control approach was proposed for a class of hybrid parametric nonlinear time-delay systems. The approach consists of a differential-deference type updating law and a learning control law for handling the non-uniform trajectory tracking problem. It avoids the restrictions on the tracking trajectory in the traditional ILC. In [5], adaptive iterative learning control was proposed for a class of second-order strict-feedback nonlinear systems with non-periodically time-varying parameterized uncertainties and unknown control direction. The backstepping and adaptive iterative learning control technique are combined to design the controller. The controller guarantees that all state variables were bounded in L_{pe}-norm and the output tracks the desired trajectory perfectly in L_T^2-norm. But the tracking trajectory is uniform in this paper.

In many industrial applications, the system parameters are completely unknown or partially unknown. When these parameters are unknown time-varying, the controller design problem of the uncertain nonlinear system becomes a challenging topic. When the period of uncertain parameters of the system is known in advance, in [6], by the pointwise integral mechanism, a new adaptive control approach characterized by periodic parameter adaptation was proposed, which complements periodic parameter adaptation control of the first-order uncertain system with mixed linear parameters, such that the tracking error converges to zero asymptotically in L_T^2-norm sense. In [7], a new method of designing a repetitive learning controller for a class of unmatched nonlinear systems with both completely unknown virtual control coefficients and unknown time-varying parameters was proposed, which by incorporating a Nussbaum-type function and backstepping technique, can guarantee uniform ultimate boundedness of the states. In [8], combining the backstepping approach with the pointwise integral mechanism, a novel adaptive repetitive learning control for high-order nonlinear systems with time-varying and time-invariant parameters was proposed. An iterative learning controller was presented for a class of strict-feedback nonlinear systems with time-varying uncertainties in [9]. The learning controller is designed based on the Lyapunov-like synthesis, which can handle system dynamics with non-global Lipschitz nonlinearities. The theoretical analysis shows that all signals in the closed-loop system remain bounded over a pre-specified time interval $[0, T]$, and complete tracking of the system output is achieved. But the control objective of this article is uniform, the bound of remain term and control direction are known.

In the actual system, there exist many uncertainties, so the iterative learning control of uncertain nonlinear system attract extensive concern of the researchers. For control systems with unknown control direction, Nussbaum proposed a control method based on Nussbaum gain function. By using this control method, [10] addresses a new adaptive iterative learning control (AILC) approach for a class of nonlinear parameterized systems with unknown distributed time-varying delays and unknown control direction. In [11], a backstepping repetitive learning control method is proposed for a class of high-order nonlinear systems with triangular structure with unknown control coefficients. It is proved that the output of controlled system converges to the desired trajectory asymptotically along the iterative learning axis through repetitive learning. To the best knowledge of the authors, there is few research result about the iterative learning control problem of strict feedback time-varying nonlinear system with unknown control direction recently. So this is a problem deserving of study.

Motivated by the above discussion, to solve the non-uniform trajectory tracking problem, we propose an iterative learning controller for a class of nonlinear time-varying systems with unknown control direction. The learning controller is designed based on the Lyapunov-like synthesis, which can handle system dynamics with non-global Lipschitz nonlinearities. Nussbaum function is used to deal with the unknown control direction. For the controller design, the time-varying parameters are expanded into Fourier series with bounded remained term, whose bound is unknown. A typical series is introduced in order to handle the unknown bound of the remained term. The theoretical analysis shows that all signals in the closed-loop system remain bounded, and complete non-uniform trajectory tracking of the system output is achieved. Finally, we give a simulation example to show the feasibility and effectiveness of the approach.

2. System description

Consider a class of high-order nonlinear time-varying systems

$$\begin{aligned} \dot{x}_i &= x_{i+1} + \theta^T(t)\varphi_i(\bar{x}_i); \\ \dot{x}_n &= bu(t) + \theta^T(t)\varphi_n(\bar{x}_n); \\ y &= x_1, \end{aligned} \tag{1}$$

where $x = [x_1, \ldots, x_n]^T \in R^n$ is the state vector of the system, which is assumed to be available for measurement, $\bar{x}_i = [x_1, \ldots, x_i]^T$, denoting $x = \bar{x}_n, u \in R$ and $y \in R$ correspond to system input and output, respectively. $x(t_0) = x_0$ represents initial conditions of the system, $\theta(t) \in R^p$ is an unknown continuous time varying vector function. $\varphi_i(\bar{x}_i), \quad i = 1, \ldots, n$ are all known smooth functions, and $\varphi_i(0) = 0, \quad i = 1, \ldots, n$. Both value and sign of b are unknown, that is to say, the control direction is unknown.