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Steady-state iterative learning control for a class of nonlinear PDE processes☆

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ABSTRACT

In this paper, a P-type steady-state iterative learning control (ILC) scheme is applied to the boundary control of a class of nonlinear processes described by partial differential equations (PDEs), which cover many important industrial processes such as heat exchangers, industrial chemical reactors, biochemical reactors, and biofilters. Under several practical properties such as physical input–output monotonicity, process stability, and repeatability, the control problem is first transformed to an output regulation problem in the spatial domain. Next, the learning convergence condition of steady-state ILC, the learning rate, as well as the robustness, are derived through rigorous analysis. The adopted ILC scheme fully utilizes the process repetition and deals with both parametric and non-parametric uncertainties. In the end, an illustrative example is presented to demonstrate the performance of the proposed ILC scheme.

1. Introduction

Iterative learning control is a scheme that learns and improves the performance of a system when the control task repeats [1–3]. For processes in repetitive operation mode, e.g., casting [4], rapid thermal processing [5], chemical polymerization/crystallization [6,7], industrial injection molding [8,9], ILC has achieved remarkable control performances. In those applications, different ILC algorithms, from P-type ILC to higher-order PD-type ILC, have been explored and tested. The main idea of ILC is to incorporate control and error information of the previous iterations into the control for the current iteration so as to improve the tracking accuracy, and ultimately achieve the desired control performance. ILC is playing an important role in controlling repeatable processes with parametric or non-parametric uncertainties [10].

Despite the significant progress of ILC for finite dimensional systems, studies on ILC for distributed parameter processes or infinite-dimensional processes are limited due to the interweave of 3D dynamics in the time, space, and iteration domains. Three related works were found in this field, one is based on semi-group theory and the other two are based on Lyapunov theory. In [11], the design of P-type and D-Type ILC laws for a class of infinite-dimensional linear systems is considered using variable separation technique and distributed control. In [12], differential-difference type ILC is argumented with P controller to attenuate the unknown periodic speed variation for a stretched string system on a transporter. In [13], the similar ILC scheme is combined with PD controller to compensate for the unknown periodic motion on the right end for a class of axially moving material systems. While the control variables are boundary forces in [12,13], they are mainly designed for the stability maintainance of mechanical processes. As a matter of fact, many chemical, biochemical, nuclear, thermo, and hydro dynamic processes are inherently nonlinear and are characterized by the presence of strong spatial variations due to the coupling of diffusive and convective mechanisms [14]. The mathematical models, which describe the spatiotemporal behavior of these processes, are typically obtained from the dynamic conservation principles and formulated by partial differential equations. In this work, we extend the framework of ILC to a class of single-input single-output (SISO) quasi-linear PDE processes that include many important industrial processes as special cases, e.g., industrial chemical reactors [15], heat exchangers [16], biochemical reactors [17], and biofilters for air and water pollution control [18]. The control objective is to iteratively tune the velocity boundary condition on one side such that the boundary output at the other side can be regulated to a desired level.

For practical applications of ILC, it is imperative to consider robustness and learning rate when process uncertainties are present [19]. When dealing with distributed parameter systems, especially in the scenario of boundary control and nonlinear PDE processes, the ILC design and property analysis become far more challenging. The existing ILC design and analysis [1–3,20,21] may not be directly applicable. The main result of the paper reveals that, under some physically reasonable properties, such as input–output monotonicity, process stability, and repeatability, the control problem can be first transformed into an output regulation problem in

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