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Single-cycle and multi-cycle generalized 2D model predictive iterative learning control (2D-GPILC) schemes for batch processes

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Abstract

In this paper, iterative learning control (ILC) system is modeled and designed from a two-dimensional (2D) system point of view. Based on a 2D cost function defined over a single-cycle or multi-cycle prediction horizon, two ILC schemes, referred respectively as single-cycle and multi-cycle generalized 2D predictive ILC (2D-GPILC) schemes, have been proposed and formulated in the GPC framework for the 2D system. Analysis shows that the resulted control schemes are the combination of a time-wise GPC and a cycle-wise ILC optimized in 2D sense. Guidelines for parameter tuning have been proposed based on the ultimate performance analysis for the control system. Simulation shows that the multi-cycle 2D-GPILC outperforms the single-cycle 2D-GPILC in term of cycle-wise convergence.

Keywords: Iterative learning control (ILC); Two-dimensional (2D) system; Generalized predictive control (GPC); Dynamic programming

1. Introduction

After its initial development for industrial robot [1], iterative learning control (ILC) has been widely studied and extended for industrial and chemical processes with repetitive or cyclic natures [2–5].

As the repetitive or cyclic processes have limited time duration in each cycle, the conventional ILC algorithms [1] only use the information of previous cycles, resulting in the control input for the entire cycle can be determined before the next cycle. It is essentially a time-wise open-loop feed-forward control that does not have the ability to guarantee control performance along time for the processes with non-repetitive or uncertain dynamics. It has been realized that the good control performance along time index in each cycle is not only necessary for the processes with long time duration but also beneficial for the convergence of the control error along the cycle index. For these reasons, a real-time feedback control has been proposed to combine with the conventional ILC, commonly referred as *feedback feed-forward ILC* [6], to improve control performances along both the time and cycle indices.

The early works of such combination [6], however, design time-wise feedback controller and cycle-wise ILC algorithm separately, having difficulties in system analysis and optimization. Amann et al. [7] developed a feedback feed-forward ILC, referred as norm-optimal ILC, based on the optimization of the following one-cycle-ahead cost function

$$J_{k+1}(\boldsymbol{u}_{k+1}) = \|\boldsymbol{e}_{k+1}\|_{\boldsymbol{Q}}^2 + \|\boldsymbol{u}_{k+1} - \boldsymbol{u}_k\|_{\boldsymbol{R}}^2 \tag{1}$$

where $\boldsymbol{e}_{k+1}$ and $\boldsymbol{u}_{k+1}$ represent the control error and input of the process in the $(k+1)$th cycle, respectively. Extension of this scheme to include the prediction control performances over future cycles has also been proposed [8,9]; the resulted state feedback control is, however, non-causal. With the consideration of both deterministic and stochastic components of the time-varying repetitive process, Lee et al. [2] and Lee et al. [10] proposed model-based ILC schemes,

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referred respectively as BMPC and Q-ILC schemes, based on the optimization of the same quadratic cost function as (1). By modifying and combining the QILC and BMPC techniques Chin et al. [11] developed a two-stage ILC technique. As only the tracking error and the input change along cycle are penalized in cost function (1), it is found that these ILC schemes result in the inverse dynamic control of the process in the ultimate performance. The inverse dynamic control can have perfect tracking, it is, however, hyper-sensitive to high-frequency components of tracking error or disturbance due to the differentiators in the inverse dynamic. It is also not suitable for processes without inverse dynamic or with unstable inverse dynamic. Furthermore, optimization over the entire cycle may lead to heavy computational burden for processes with long time duration.

An ILC system can be viewed as a special two-dimensional (2D) system [12], where the dynamic behavior along the time is determined by the process and the time-wise feedback control, whereas the iterative learning algorithm introduces the dynamic along the cycle. From a 2D system viewpoint, the conventional ILC [1] is only a cycle-wise feedback control with integral action along the cycle index, which guarantees the tracking errors for the cycle-invariant trajectory to be gradually removed along cycle index. To guarantee the performance improvement along both the time and cycle directions, 2D feedback controller is necessary. The feedback feed-forward ILC is actually a 2D feedback control. The major advantage of viewing an ILC system as a 2D system is that the 2D dynamic of the system can be taken into account not only in the process modeling but also in the control performance and controller design, which results in the united design and optimal combination of the time-wise feedback controller and cycle-wise ILC algorithm in the 2D sense. Rogers et al. [13] firstly noted the 2D dynamic characteristics of the ILC system and explored the convergence of the system based on the stability criterion for the 2D system. Geng et al. [14] first proposed to describe ILC system as a 2D system for design and analysis. Their resulted ILC scheme, however, is a conventional ILC. Based on a 2D Roesser model, Kurek et al. [15] and Fang et al. [16] developed feedback feed-forward ILC schemes for deterministic repetitive processes. Shi et al. [5,17] extended robust control concept to 2D Roesser system resulting in an integrated design of robust feedback control and feed-forward ILC for uncertain batch processes.

Generalized Predictive Control (GPC) proposed by Clarke et al. [18,19] is one of the most popular process control strategy. This paper is to extend the philosophy of GPC to the 2D system for design and analysis of ILC system. The resulted ILC schemes in this paper are referred as *Generalized 2D Predictive Iterative Learning Control* (2D-GPILC). Due to the 2D dynamic of the ILC system, a 2D cost function defined over prediction horizon of current cycle is firstly optimized based on the 2D prediction model of the control system, resulting in a feedback feed-forward ILC scheme referred as single-cycle 2D-GPILC scheme. The structure analysis indicates that the resulted 2D-GPILC scheme consists of two types of controls: one is time-wise GPC using the real-time system information to ensure the optimal control performances over the moving prediction horizon along time index, and the other is the cycle-wise ILC using the system information of last cycle to improve the control performance from cycle to cycle. To optimize cycle-wise control performance, a multi-cycle prediction cost function is further proposed and minimized by cycle-wise *dynamic programming*, resulting in multi-cycle 2D-GPILC scheme. As the 2D control performance is optimized over the moving time-wise and cycle-wise prediction horizons simultaneously, the multi-cycle 2D-GPILC outperforms single-cycle 2D-GPILC scheme in the convergence rate along cycle index. The simulations are given to demonstrate the performance of the proposed schemes.

2. Problem formulation

2.1. Process model and iterative learning law

For simplicity, consider a single-input single-output (SISO) plant, which performs repetitively a given task over a finite time duration, called a batch or cycle, described by the following Controlled Auto-Regressive Integrated Moving-Average (CARIMA) model

$$\Sigma_P:\ A(q_t^{-1})y_k(t) = B(q_t^{-1})\Delta_t(u_k(t)) + w_k(t),\quad t = 0,1,\ldots,T;\ k = 1,2,\ldots \tag{2}$$

where t and k represent the discrete-time and cycle/batch index, respectively, T is the time duration of each cycle, $u_k(t)$, $y_k(t)$ and $w_k(t)$ are, respectively, the input, output and disturbance of the process at time t in the kth cycle, q_t^{-1} indicates the *time-wise unit backward-shift operator*, $A(q_t^{-1})$ and $B(q_t^{-1})$ are both operator polynomials

$$A(q_t^{-1}) = 1 + a_1q_t^{-1} + a_2q_t^{-2} + \cdots + a_nq_t^{-n} \tag{3}$$

$$B(q_t^{-1}) = b_1q_t^{-1} + b_2q_t^{-2} + \cdots + b_mq_t^{-m} \tag{4}$$

and Δ_t represents the *time-wise backward difference operator*, i.e. $\Delta_t(f(t,k)) = f(t,k) - f(t-1,k)$. Model Σ_p can be identified from the process input–output data. Uncertain and un-modeled dynamics is included as unknown disturbance $w_k(t)$. For the above repetitive process, introduce an ILC law with the form

$$\Sigma_{\mathrm{ILC}}:\ u_k(t) = u_{k-1}(t) + u_k(t-1) - u_{k-1}(t-1) + r_k(t),\quad u_0(t) = 0,\ t = -1,0,1,\ldots,T \tag{5}$$

where $r_k(t)$ is referred as the *updating law*, and $u_0(t)$ is the *initial profile* of iteration.

Different from the conventional ILC algorithms [6], the above control law refines the input at time t in the kth cycle based on not only the control input at same time in the last cycle but also the input change along cycle index in last step. Let q_k^{-1} represents the *cycle-wise unit backward-shift operator*, the transformation between $u_k(t)$ and $r_k(t)$ can be expressed as