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Advanced PI control with simple learning set-point design: Application on batch processes and robust stability analysis

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ABSTRACT

According to the literature statistics, less than 10% of reported iterative learning control (ILC) methods are of the indirect form. Under an indirect ILC, the closed-loop system consists of two loops. Despite of the advantages in controller design and practical implementation, analysis on the corresponding system's stability and robustness becomes troublesome compared with the direct ILC methods. To address this open issue, a combination of PI control and ILC, referred to ILC-based PI control, is therefore developed in this study. Under the proposed ILC-based PI controller, the closed-loop system can be transformed into a 2-dimensional (2D) Roesser's system. Based on the 2D system formulation, a sufficient condition for robust asymptotical stability is first derived for multi-input multi-output linear batch processes. Correspondingly, an advanced PI control with ILC-based set-point is developed which requires smaller memory for operation together with less degree of freedom to design. Moreover, the proposed control algorithm can lead to superior steady-state tracking performance and good robustness against load disturbance and measurement noise, without requiring the internal state information of the process. Finally, the effectiveness and merits of the proposed method are illustrated by application to an injection molding process and a batch reactor, in comparison with a typical PI-type direct ILC method recently developed.

1. Introduction

Presently, there are mainly two ways in combination of iterative learning control (ILC) and the conventional proportional-integral-derivative (PID) controller (including P-, D-, PI-, PD-, PID-type, and so on), as shown in Fig. 1: (1) ILC is used to determine the control signal, where the ILC updating law is designed using a PID control method, for short, termed as PID-type ILC (Kim and Kim, 1996; Bonvin et al., 2006; Ruan et al., 2008; Liu et al., 2010); (2) PID control is used to determine the control signal, where an ILC in the outer loop is used to update some parameters for PID control, for short, denoted as ILC-based PID control (Wu and Ding, 2007; Tan et al., 2007). According to the categorization given in Wang et al. (2009), PID-type ILC belongs to direct ILC and while ILC-based PID controller belongs to indirect ILC.

The simplest form of PID-type ILC, i.e., P-type ILC, is widely considered the original contributions of ILC methods (Uchiyama, 1978; Arimoto et al., 1984; Bristow et al., 2006). Since then, a number of PID-type ILC methods have been developed in the last three decades, e.g., P-type (Xiong and Zhang, 2003; Hou et al., 2007; Tayebi and Chien, 2007), D-type (Arimoto et al., 1984; Chen et al., 1998; Abidi and Xu, 2011) PI-type (Shi et al., 2005a,b), PD-type (Mi et al., 2005; Li and Tso, 2008), and PID-type (Kim and Kim, 1996; Ruan et al., 2008).

In contrast, there are two loops in the ILC-based PID control: a PID controller in the inner loop and an ILC in the outer loop. A key issue relating to an ILC-based PID controller is that: which parameter(s) of the PID controller should be adjusted by the ILC. Typically, an ILC could be used to adjust the set-point (Wu and Ding, 2007), control gain (Xu and Yan, 2004), weight (Jiang et al., 2007), or other related parameters (Bone, 1995; Tayebi and Chien, 2007) for the local controller. If the set-point is chosen as an updating parameter, then this type of ILC-based PID control is named set-point-related (SPR) ILC-based PID control.

According to the literature statistics given in Wang et al. (2009), less than 10% of reported ILC methods have been devoted to the indirect approach. Motivated by the great potential in this research field, a few studies on indirect ILC were proposed recently (Wang et al., 2010; Wu and Ding, 2007; Tan et al., 2007). Particularly, algorithms proposed in Wu and Ding (2007) and Tan et al. (2007) are ILC-based PID control. In Wu and Ding (2007), an anticipatory-type ILC (A-ILC) was used to adjust the set-point for a PID controller, and the proposed scheme was implemented on an X–Y platform. In Tan et al. (2007), ILC was used to update the set-point for a PID controller, and then a standard PID with adaptive gain was used to replace the ILC-based PID. It should be mentioned that the indirect framework has been widely used in run-to-run (R2R) control (Ganesan et al.,

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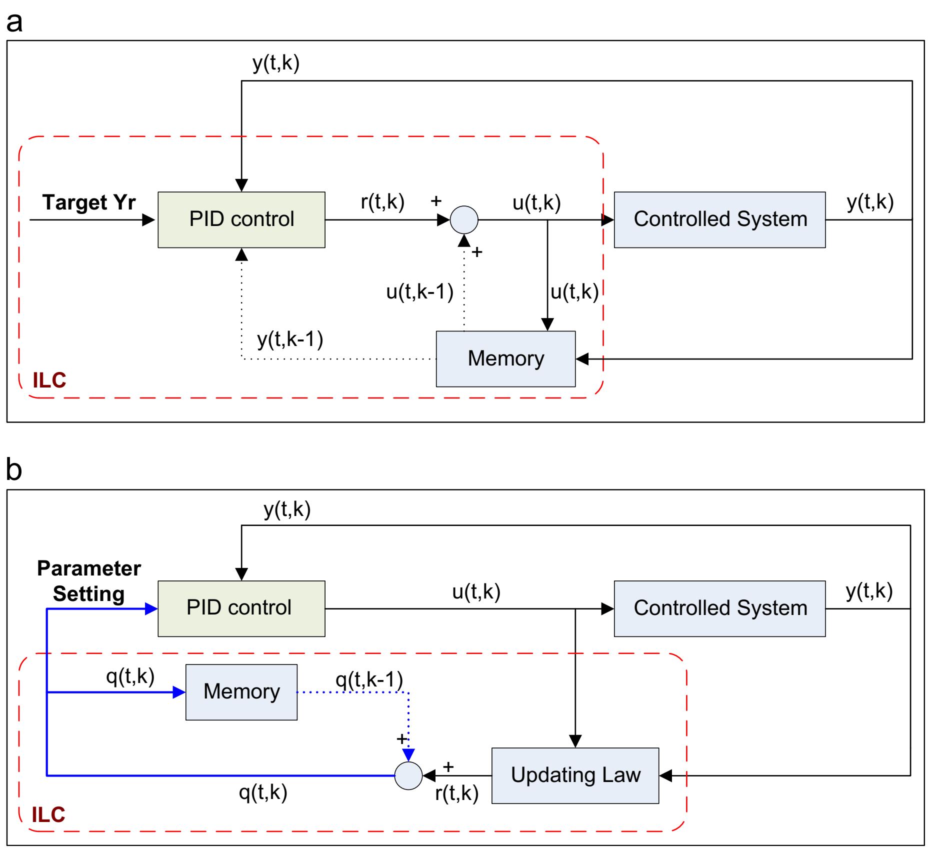

Fig. 1. Block diagram comparison for the PID-type ILC and ILC-based PID controller: (a) PID-type ILC; (b) ILC-based PID controller. The solid lines denotes the real-time information; the dotted lines denotes the information in the previous batch; components in the dashed frames comprise the ILC. In subfigure (b), q could be set-point, control gain, weight, and other parameters for the PID controller.

2007; Hankinson et al., 1997; Busch et al., 2007). However, ILC could be considered an enhanced version of R2R in a 2D sense, so the study of indirect ILC is very prospective.

The current hot issues for direct ILC might be handling of uncertainties, nonlinearities and constraints (Lee et al., 2000; Lee and Lee, 2000, 2003; Cueli and Bordons, 2008; Precup et al., 2008; Li and Zhang, 2010; Yin et al., 2010; Ouyang et al., 2011). In contrast, the closed-loop stability and robustness issues still remain open for indirect ILC even if the controlled plant is linear. These issues must be addressed for industrial batch process control against non-repetitive disturbances and measurement noise (Liu and Gao, 2010b; Nagy et al., 2007; Nagy, 2009). Due to the fact that an indirect ILC method consists of two loops, its stability and robustness are indeed difficult to make clear. A promising way to address these issues is to consider the basic situation, that is to say, the controlled system is linear and the local control is PID. In fact, these issues were first addressed in Wang and Doyle (2009), where the local controller is limited to P-type.

Compared with P-type controller, PI controller has been more widely used in practice, owing to the virtue of guaranteeing of no steady-state tracking error. An ILC-based PI controller is therefore introduced in this study, where a typical PI controller works as the local controller in the inner loop and an ILC works in the outer loop to adjust the set-point for the local controller. A sufficient condition for robust asymptotical stability of the closed-loop system is derived in this paper. The closed-loop system is first transformed into a 2-dimensional (2D) formulation, because the asymptotical stability in both time and batch directions can be studied simultaneously in this formulation. Note that, even though the proposed method has some differences compared with the existing ILC-based PI control methods (Wu and Ding, 2007; Tan et al., 2007), the stability and robustness analysis in this paper is generally applicable for ILC-based PI control schemes.

Throughout this paper, the following notation is used: $\mathbb{R}^p$ represents Euclidean p-space with the norm denoted by $\|.\|$; $M>0$ ($M<0$) means M) is a positive (negative) definite matrix; M^T represents the transpose of matrix M; I and $\mathbf{0}$ respectively denote the identity matrix and the zero matrix with appropriate dimensions; "$*$" represents the transposed elements in the symmetric position; for a 2D signal $\xi(i,j)$, if $\|\xi\|_2=\sqrt{\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\|\xi(i,j)\|^2}<\infty$, then it is in $\mathcal{L}_2$ space, denoted by $\xi\in\mathcal{L}_2$; $V_\Omega(\zeta)\triangleq\zeta^T\Omega\zeta$, where ζ is a vector and Ω is a symmetric matrix; $\|\xi(\cdot,j)\|_{\Omega,T}\triangleq\sqrt{\sum_{i=1}^{T}V_\Omega(\xi(i,j))}$ is termed as the Ω,T-norm of the 2D signal $\xi(i,j)$.

2. Preliminary knowledge

Before presenting the main results, some general knowledge about 2D system is briefly introduced in this section. Consider a Roesser's system (Kaczorek, 1985)

$$\begin{cases}\begin{bmatrix}x^h(i+1,j)\\x^v(i,j+1)\end{bmatrix}=\begin{bmatrix}A_{11}+\Delta A_{11} & A_{12}+\Delta A_{12}\\A_{21}+\Delta A_{21} & A_{22}+\Delta A_{22}\end{bmatrix}\begin{bmatrix}x^h(i,j)\\x^v(i,j)\end{bmatrix}+\varphi(i,j)\\ Z(i,j)=\begin{bmatrix}C_1 & C_2\end{bmatrix}\begin{bmatrix}x^h(i,j)\\x^v(i,j)\end{bmatrix}\end{cases}$$
$$i,j=0,1,2,\ldots, \quad (1)$$

where $x^h\in\mathbb{R}^{n_1}$ is the horizontal state vector; $x^v\in\mathbb{R}^{n_2}$ is the vertical state vector; Z is the output; A_{11}, A_{12}, A_{21}, and A_{22} are the system matrices; C_1 and C_2 are the measurement matrices;