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Robust PID based indirect-type iterative learning control for batch processes with time-varying uncertainties

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ABSTRACT

Based on the proportional-integral-derivative (PID) control structure widely used in engineering applications, a robust indirect-type iterative learning control (ILC) method is proposed for industrial batch processes subject to time-varying uncertainties. An important merit is that the proposed ILC design is independent of the PID tuning that aims primarily to hold robust stability of the closed-loop system, owing to the fact that the ILC updating law is implemented through adjusting the setpoint of the closed-loop PID control structure plus a feedforward control to the plant input from batch to batch. According to the robust H infinity control objective, a robust discrete-time PID tuning algorithm is given in terms of the plant state-space model description to accommodate for time-varying process uncertainties. For the batchwise direction, a robust ILC updating law is developed based on the two-dimensional (2D) control system theory. Only measured output errors of current and previous cycles are used to implement the proposed ILC scheme for the convenience of practical application. An illustrative example from the literature is adopted to demonstrate the effectiveness and merits of the proposed ILC method.

1. Introduction

Iterative learning control (ILC) method can be adopted to realize perfect tracking or control optimization for industrial and chemical batch processes, owing to the use of repetitive operation information from historical cycles. With the wide application of ILC in engineering applications in the recent years, it has become increasingly appealing to develop robust ILC methods to deal with time-varying uncertainties occurring in a cycle or cycle-to-cycle (batchwise) uncertainties, because many batch processes, e.g. industrial injection molding and pharmaceutical crystallization, are slowly varying from batch to batch, while repeating fundamental dynamic response characteristics [1–4]. As surveyed by Bonvin et al. [5], Ahn et al. [6], and Wang et al. [7], most of existing references have been devoted to time-invariant linear or nonlinear batch processes. The developed robust ILC methods have been in general classified into two types [7], one is called direct-type that means the ILC design integrates the feedback control (responsible for closed-loop stability and no steady output deviation) and the feedforward control (responsible for the setpoint tracking) through the identical closed-loop controller, and another is called indirect-type which implies that either the feedback or the feedforward control could be implemented through different controllers that may be designed relatively independent.

For the direct-type ILC, the traditional proportional-integral-derivative (PID) controller including the P-, PI-, PD-, PID-type is mostly used to execute the integrated control for both the setpoint tracking and closed-loop stabilization, owing to its implemental simplicity, e.g. the P-type ILC [8,9], the PI-type ILC [10,11], the PD-type ILC [12,13], the PID-type ILC [14,15]. The achievable robustness and output tracking performance, however, have not yet been fully explored, in particular for the quantitative performance specifications [16]. Based on a two-dimensional (2D) state-space description of a batch process and using the linear quadratic optimal control criterion in combination with the robust control theory, full-order controller matrices (with respect to the process model order) were used to develop robust direct-type

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ILC methods to accommodate for a variety of process uncertainties [17–21], but at the expense of controller complexity, computation effort, and memory space for storing the historical information of the cycle and controller states.

For the indirect-type ILC, the control structure is typically composed of two loops, one loop constructed in terms of a conventional controller like PID, and another loop used for adjusting the setpoint or the process input similar to a feedforward control manner. Based on the internal model control (IMC) structure, a learning setpoint design was proposed [22] to robustly track the setpoint profile against the process input delay uncertainty. By comparison, a P-type learning algorithm was presented to adjust the setpoint in combination with the model prediction control (MPC) method for tracking the desired profile, which was successfully used to the control of artificial pancreatic beta-cell [23]. Based on the conventional PID control structure, a parallel learning-type PID was added to improve the setpoint tracking performance without sacrificing the closed-loop stability [24]. An alternative anticipatory-type ILC (A-ILC) was developed to adjust the setpoint in terms of the PID control loop for robust tracking of the desired profile [25]. The robust stability condition of a learning-type setpoint design in terms of a PI control loop was analyzed in the recent paper [26]. A quadratic criterion was presented to analyze the ILC convergence in terms of a MPC structure for time-varying linear systems [27]. The achievable tracking performance of an indirect-type ILC scheme was assessed by estimating the minimum output variance bound [28]. Combining with the feedback control design, a two-step ILC design [29] was proposed to adjust the process input for improving the output tracking performance against load disturbance and process uncertainties. For highly nonlinear processes such as crystallization processes, hierarchical ILC and nonlinear MPC based ILC methods [30,31] were proposed to track the desired setpoint profile against batch-to-batch uncertainties.

In this paper, an indirect-type ILC design is proposed based on the widely used PID control structure to accommodate for time-varying process uncertainties. With a state-space model description of the process together with norm-bounded uncertainties, a robust PID tuning algorithm is first given in terms of the H infinity control objective, which is primarily responsible for holding the closed-loop system robust stability and no steady output deviation. Then, an ILC scheme consisting of the learning controllers to adjust the setpoint and the feedforward controllers to adjust the process input is proposed to realize robust tracking against time-varying uncertainties and load disturbance, which is therefore different from the conventional indirect-type ILC scheme. Accordingly, the PID tuning and the ILC design can be made relatively independent of each other in the proposed control scheme, and more flexibility is introduced to devise the control system robust stability and tracking performance, respectively. By establishing the sufficient conditions in terms of linear matrix inequality (LMI) constraints for maintaining robust stability of the PID control loop and the robust convergence of the ILC scheme, respectively, the PID and ILC controllers are derived along with an adjustable robust H infinity performance level. The effectiveness of the proposed method is demonstrated through an illustrative example from the literature. For clarity, the paper is organized as follows: Section 2 briefly describes a batch process with time-varying uncertainties by using a state-space model with norm-bounded uncertainties, and then introduces the proposed indirect-type ILC scheme based on the conventional PID control structure. Correspondingly, a robust PID tuning method is proposed in terms of the robust H infinity control objective in Section 3. By formulating the learning setpoint strategy and feedforward control in the frame of a 2D system, Section 4 presents the proposed ILC design by establishing the sufficient LMI conditions to hold the 2D system asymptotic stability. Section 5 shows an illustrative example to demonstrate the effectiveness and merits of the proposed ILC method. Conclusions are drawn in Section 6.

Throughout this paper, the following notations are used: $\Re^{n\times m}$ denotes a $n\times m$ real matrix space. For any matrix $P\in\Re^{m\times m}$, $P>0$ (or $P\geq 0$) means P is a positive (or semipositive) definite symmetric matrix, in which the symmetric elements are indicated by '*'. P^T denotes the transpose of P. $diag\{\cdot\}$ denotes a block-diagonal matrix. For any vector x and matrix $P>0$, denote $V_P(x)=\|x\|_P^2=x^TPx$. The identity or zero vector (or matrix) with appropriate dimension is denoted by $\boldsymbol{I}$ or $\mathbf{0}$. For a 2D signal, $z(i,j)$, if $\left\|z(i,j)\right\|_2=\sqrt{\sum_{i=0}^{n}\sum_{j=0}^{m}\left\|z(i,j)\right\|^2}<\infty$ for any integers n and m, then $z(i,j)$ is said to be in the $L_2[0,\infty)$ space of all square integrable functions.

2. Problem formulation

A batch process with time-varying uncertainties is generally described by the following observable canonical discrete-time state-space model,

$$P_\Delta:\begin{cases}x(t+1,k+1)=[A_\mathrm{m}+\Delta\tilde{A}(t,k+1)]x(t,k+1)+[B_\mathrm{m}+\Delta\tilde{B}(t,k+1)]u(t,k+1)+\omega(t,k+1)\\ y(t,k+1)=Cx(t,k+1),\quad 0\leq t\leq T_\mathrm{p};\\ x(0,k+1)=x(0),\quad k=0,1,\ldots\end{cases}\tag{1}$$

where t and k denotes the time and batch indices, respectively, and $k+1$ indicates the current batch (or cycle). $x(t,k+1)\in\Re^{n_x}$ denote the state variables, $u(t,k+1)\in\Re^{n_u}$ the control inputs, $y(t,k+1)\in\Re^{n_y}$ the process outputs. Denote by A_m and B_m the nominal state matrices, and by $\Delta\tilde{A}(t,k+1)$ and $\Delta\tilde{B}(t,k+1)$ time-varying uncertainties that are not repetitive from cycle to cycle and practically specified as $\Delta\tilde{A}(t,k+1)=\Delta\bar{A}_1\tilde{\Theta}_1(t)\Delta\bar{A}_2$, $\Delta\tilde{B}(t,k+1)=\Delta\bar{B}_1\tilde{\Theta}_2(t)\Delta\bar{B}_2$, where $\Delta\bar{A}_1$, $\Delta\bar{A}_2$, $\Delta\bar{B}_1$, and $\Delta\bar{B}_2$ are constant matrices, and $\tilde{\Theta}_i^T(t)\tilde{\Theta}_i(t)\leq\boldsymbol{I}$, $i=1$, 2. Denote by T_p the time period of each cycle, and $x(0)$ is the initial resetting condition of each cycle. Note that other process uncertainties such as from input actuator and output measurement may also be lumped into $\Delta\tilde{A}(t,k+1)$ and $\Delta\tilde{B}(t,k+1)$ for analysis.

The control objective is to determine a control law such that the system output can track the desired output profile (or target output trajectory) as close as possible against the process uncertainties and/or load disturbance.

To design an indirect-type ILC scheme, we define the output error in the current cycle $(k+1)$ by

$$e(t,k+1)\triangleq Y_\mathrm{r}(t)-y(t,k+1)\tag{2}$$

where $Y_\mathrm{r}(t)$ denotes the desired output profile, and $y(t,k+1)$ the real output in the current cycle. Correspondingly, the time integral of $e(t,k+1)$ is denoted by $\sum e(t,k+1)$, i.e.

$$\Sigma e(t,k+1)=\sum_{i=0}^{t}e(i,k+1),\quad 0\leq t\leq T_\mathrm{p}\tag{3}$$