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Delay-range-dependent robust 2D iterative learning control for batch processes with state delay and uncertainties

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ABSTRACT

This paper proposes the design of the integrated output feedback and iterative learning control (ILC) for batch processes with uncertain perturbations and interval time-varying delays, where the main idea is to transform the design into a robust delay-range-dependent H_∞ control of a 2D system described by a state-space model with varying delays. A sufficient criterion for delay-dependent H_∞ noise attenuation is derived through linear matrix inequality (LMI) by introducing a comprehensive 2D difference Lyapunov–Krasovskii functional candidate and adding a differential inequality to the difference in the Lyapunov function for the 2D system. Based on the criterion obtained, the delay-range-dependent output feedback controller combined with ILC is then developed. The developed system ensures that the closed-loop system for all admissible uncertainties is asymptotically stable and has a prescribed H_∞ performance level in terms of the LMI constraint. The controller is obtained by solving an LMI optimization problem with simple calculations and less constraint conditions. Moreover, the conditions can also be directly extended from delay-range-dependent to general delay-dependent stability. Applications in injection velocity control demonstrate the effectiveness and feasibility of the proposed method.

1. Introduction

Recently, iterative learning control (ILC) has been increasingly practiced for industrial and chemical batch processes because of its ability to improve system performance progressively for setpoint tracking and load disturbance rejection using historical cycle data [1]. As surveyed in papers [2,3], many ILC methods that achieve perfect tracking for linear or nonlinear batch processes have been proposed in both continuous and discrete-time domains. And most ILC studies on the practical applications mainly focus on finding robust convergence and stability conditions subject to repetitive load disturbances [4]. In fact, batch processes, particularly chemical ones, do not repeat well due to environmental impacts and operating condition changes, which shows that batch processes have a certain degree of nonrepeatability (or uncertainty) [5,6]. The only use of ILC for such processes can lead to poor control performance in both convergence and stability. Therefore, ILC has been proposed for use in batch-to-batch learning together with *feedback control* for handling batch uncertainty, leading to the common practice of combining ILC for iterative learning (a *feed-forward*-type controller) and the traditional feedback design for feedback control in actual implementations. Moreover, a number of robust ILC methods have recently been proposed to cope with structured and unstructured process uncertainties in batch processes. And several ILC methods have been developed using a 2D linear quadratic optimal control criterion combined with robust control theory to deal with various model uncertainties [7,8a,8b,8c]. More recently, model-predictive-control-based ILC schemes have also been proposed to satisfy implementation constraints [8d,9–11]. To address the problem of model–plant mismatches from batch to batch and to guarantee tracking performance, previous studies have suggested that model prediction errors in the previous batch runs be screened to determine a model-based ILC algorithm in the current batch run [12,13]. In particular and based on the estimation of the minimum variance bounds of the tracking error, Chen and Kong [14] proposed an online adaptive ILC strategy to optimize the tracking performance.

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Another important issue for industrial chemical processes is time delay, which is a source of instability and performance degradation in many control systems and makes ILC design more difficult for batch processes with time-varying uncertainties. Up to the present, though results on this topic are rather limited, researchers did give some new and useful results in both frequency domain and time domain. In the frequency domain, concern is mainly focused on control performance improvement associated with both input and output uncertain delays. For example, an ILC algorithm based on Smith predictor control structure was proposed by Xu et al. [15] to improve the tracking performance of batch processes with evident time delays. To cope with uncertain input delays, Liu et al. [16] developed an internal-model-control-based ILC method. Moreover, a reference shift algorithm based on a double-loop ILC structure [17] was suggested to deal with the output delay of a nonminimum phase plant. New results can also be seen in the time domain. An ILC method in terms of the holding mechanism was proposed for the control input during the estimated time delays for batch processes [18]. For batch processes with a fixed input delay, Xu et al. [19] proposed a dead-time compensation approach of ILC design to obtain perfect tracking. Subsequently, Tan et al. [20] developed a phase lag compensation method of ILC to cope with this input delay. As is known, state delays always exist if batch processes are described by state–space models since they are associated with the setpoint change. Moreover, process input or output delays can also cause state delays in state–space models [21,22]. Although robust stabilization methods for 1D batch processes with time-varying state delays have recently been proposed [23–25], only a few have been reported on robust control methods for these processes. Moreover, since steady tracking and robust state convergence in both the time direction and the batchwise direction are both important from cycle to cycle, the ILC design for batch processes can be transformed into control schemes for a class of 2D systems with two "time" directions [26]. There have already been a few results, such as a robust 2D closed-loop ILC combined with the output feedback scheme for batch processes with state delay and time-varying uncertainties [27] and robust state feedback ILC scheme for batch processes with interval time-varying delays and uncertainties using 2D Rosser and Fornasini–Marchesini (2D-FM) models [28a,28b], respectively. The shortcomings of the aforementioned methods are in the use of redundant free-weighting matrices with high computation burden and restriction conditions. Moreover, the conditions cannot be extended to general delay-dependent stability cases.

In this paper, robust output feedback integrated with the ILC design scheme for batch processes with uncertain perturbations and interval time-varying delays are considered to obtain robust tracking and state convergence. The merit of the proposed is that it uses a differential inequality without redundant free-weighting matrices, which enables lower computation burden and restriction conditions and thus can be extended to general delay-dependent stability cases. The design of the proposed is as follows. Firstly, to reflect the uncertain perturbations of the process' dynamic between cycles, norm-bounded process uncertainties and the estimated lower and upper bounds of state delay variations are formulated into a state-space model. Secondly, to serve for the design of the proposed closed-loop ILC, the derived state-space model is further transformed into a 2D form with varying delays. Thus measured output errors of current and previous cycles can be used to design an ILC with dynamic output feedback to achieve stability conditions. Thirdly, by introducing a 2D Lyapunov–Krasovskii functional candidate and a differential inequality, a sufficient delay-range-dependent criterion that bears asymptotic stability and the prescribed closed-loop H_∞ performance level for all admissible uncertainties is established through linear matrix inequality (LMI) optimization approaches. Finally, a practical example for the injection molding is given to demonstrate the effectiveness of the proposed ILC method.

Throughout the present paper, the following notations are used: R^n represents Euclidean n space with the norm denoted by $\|\bullet\|$. For any matrix M, $M>0$ ($M<0$) means that M is a positive (negative) definite matrix. M^T represents the transpose of matrix M. I and $\mathbf{0}$ denote the identity and zero matrices with appropriate dimensions, respectively. An asterisk (*) represents the symmetric element of a matrix, and $|\bullet|$ denotes the absolute value of "•." For the 2D signal $\omega(t,k)$, if $\left\|\omega(\cdot,\cdot)\right\|_{2D-2e} = \sqrt{\sum_{t=0}^{N_1}\sum_{k=0}^{N_2}\left\|\omega(\cdot,\cdot)\right\|^2} < \infty$ for any integer $N_1, N_2>0$, $\omega(t,k)$ is said to be in the ℓ_{2D-2e} space, as denoted by $\omega(\cdot,\cdot)\in\ell_{2D-2e}$.

2. Problem description and 2D system representation

The target $\sum_{P-delay}$ is a process that repetitively performs the same task over a certain period of time (called a batch/cycle). At the *kth* cycle, the process can be described by the following discrete-time model with uncertainties and interval time-varying delays:

$$\sum\nolimits_{P-delay}: \quad \begin{cases} x(t+1,k) = (A+\Delta_a(t,k))x(t,k) + (A_d+\Delta_d(t,k))x(t-d(t),k) + (B+\Delta_b(t,k))u(t,k) \\ y(t,k) = Cx(t,k) \\ x(t,k) = x_{0k}; \quad 0 \le t \le T;\ k = 0,\ 1,\ 2,\cdots \end{cases} \tag{1}$$

where the subscript k denotes the batch, t is the time index, $x(t,k)\in R^n$, $y(t,k)\in R^l$, and $u(t,k)\in R^m$ are the state, output, and input of the process, respectively, at time t in the *kth* batch run, $x_{0,k}$ is the initial boundary state of the *kth* batch run, $\{A, A_d, B, C\}$ consists of the nominal system matrices with appropriate dimensions, and $d(t)$ is the time-varying delay depending on time t (horizontal direction) that satisfies

$$d_m \le d(t) \le d_M \tag{2}$$

where d_m and d_M denote the lower and upper delay bounds, respectively. The matrices $\Delta_a(t,k)$, $\Delta_d(t,k)$, and $\Delta_b(t,k)$ are uncertain perturbations at time t in the *kth* batch with the following structures:

$$\begin{bmatrix} \Delta_a(t,k) & \Delta_d(t,k) & \Delta_b(t,k) \end{bmatrix} = E\Delta(t,k)\begin{bmatrix} F & F_d & F_b \end{bmatrix}$$

with

$$\Delta^T(t,k)\Delta(t,k) \le I$$

where E, F, F_d and F_b are known constant matrices with appropriate dimensions. Here, $\Delta(t,k)$ is viewed as the function of both time t and batch k. If $\Delta(t,k)$ only depends on time t, then the uncertain parameter perturbations are called repeatable. Otherwise, they are unrepeatable. Although conventional ILC schemes can effectively deal with repeatable parameter perturbations, the control of the batch