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Robust design of feedback integrated with iterative learning control for batch processes with uncertainties and interval time-varying delays

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ABSTRACT

A robust feedback integrated with iterative learning control (FILC) scheme for batch processes with uncertain perturbations and interval time-varying delay is developed. The batch process is modeled as a two-dimensional (2D) Rosser system with a delay varying in a range. The design of FILC scheme is transformed into a robust control problem of uncertain 2D system. New delay-range-dependent stability criteria and stabilization conditions are derived in terms of linear matrix inequalities (LMIs), which depend on not only the difference between the upper and lower delay bounds but also the upper delay bound of the interval time-varying delay. Parameterized characterizations for stabilizing the controller are given in terms of the feasibility solutions to the LMIs. Applications to injection velocity control show that the proposed FILC achieve the design objectives well.

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1. Introduction

Studies on batch process control have attracted considerable attention because batch processes are the preferred manufacturing choice for low-volume and high-value products, and batch processing is widely used in chemical industries [1]. Iterative learning control (ILC) has been used widely to exploit the repetitive nature of batch processes. The challenges for practical applications of ILC are mainly associated with robust convergence and stability against process uncertainties. Recently, a number of robust ILC methods have been presented to cope with structured and unstructured process uncertainties for batch processes. In time domain, by using a LMI approach, Nguyen et al. [2] present the design of iterative learning control based on quadratic performance criterion for linear systems subject to additive uncertainty. From a two-dimensional (2D) view (i.e., time-wise and batch-wise) for batch process control design, a state-space ILC method was presented in terms of using a 2D linear continuous-discrete Roesser's model [3]. Equivalent convergence conditions for ILC design in frequency or/and time domain were analyzed in the recent papers [4]. Meanwhile, in discrete-time domain, robust ILC methods have also been proposed for batch processes with model uncertainties or unmodeled dynamics. On-line adaptive ILC methods [5] were presented to deal with model mismatch using historical data to modify output prediction from cycle to cycle. Based on a 2D system description, a series of ILC methods [6–8] have been developed using a linear quadratic optimal control criterion and robust stability conditions in terms of linear matrix inequalities to deal with a variety of model uncertainties. Model predictive control (MPC) based ILC schemes was proposed to accommodate for implemental constraints in the recent papers [9,10].

Time-delay is a common phenomenon in chemical and other industrial processes, which may give rise to instability of the system. How to deal with time delays has been a hot topic in control community [11]. Recently, the research has been extended to dynamical systems with time-varying delay that varies in a range for which the lower bound is not restricted to be zero for continuous processes [12,13]. Like continuous processes, batch process sufferers also from time-delay, and the delay is typically varying in a range. Very limited results on this topic have been available up to now. In frequency domain, using the Smith predictor control structure, which is known for superior control of time delay processes with a priori knowledge of the time delay, an ILC algorithm [14] was proposed to improve tracking performance of ILC for batch processes with known and fixed time delay; based on the internal model control (IMC) structure, an iterative learning control (ILC) scheme is proposed for batch processes with model uncertainties including time delay mismatch [15]. To deal with output delay of a non-minimum phase plant, a reference shift algorithm was suggested based on a double-loop ILC structure [16]. In

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Nomenclature

Arabic number
$0_{n\times m}$ zero matrix with dimensions $n\times m$

Arabic letters
$\{A, A_d, B, C\}$ state, state-delayed, input and output coefficient matrices of a batch process
$\{\bar{A}, \bar{A}_d, \bar{B}\}$ state, state-delayed and input coefficient matrices of 2D model
$d(t)$, d_m, d_M time-varying delay, lower and upper delay bounds along horizontal direction
$\{E, F, F_d\}$ uncertainty perturbation coefficient matrices of a batch process
$\{\bar{E}, \bar{F}, \bar{F}_d\}$ uncertainty perturbation coefficient matrices of 2D model
$e_k(t)$ tracking output error
FILC feedback integrated with iterative learning control
h_m, h_m lower and upper delay bounds along batch direction
$H(k)$ performance index
$I_{n\times n}$ identity matrix with dimensions $n\times n$
IMC internal model control
K controller gain
LMI linear matrix inequality
MPC model predictive control
N^T transpose of matrix N
R^p Euclidean p-space, with the norm denoted by $||\cdot||$
$R^{p\times q}$ the set of all $p\times q$ real matrixes
r_k updating control law of ILC
$\sup|e_k(t)|$ the maximum absolute value of "$e_k(t)$"
t time index
2D two-dimensional
$x^h(i,j)$, $x^v(i,j)$ state along horizontal and vertical directions
$\{x_k(t), u_k(t), y_k(t)\}$ state, input, output of the process at time t in the kth batch
u_0 initial input of iteration
$V(\cdot)$ Lyapunov function
$V^h(\cdot)$, $V^v(\cdot)$ Lyapunov function along horizontal and vertical directions
$x_{0,k}$ time-wise initial state of the kth batch
y_d given output trajectory

Greek symbols
δ_k the batch wise backward difference operator
$\{\gamma, \gamma_1, \gamma_2, \kappa_0, \kappa_1\}$ any positive integers
$\varepsilon_1, \varepsilon_2$ positive scalars
ρ_{00}, σ_{00} initial boundary conditions of state $x(i,j)$
ρ_{ij}, σ_{ij} boundary conditions of state $x(i,j)$
$\Delta(t)$ perturbation depending on time t
$\{\Delta A(t), \Delta A_d(t)\}$ state, state-delayed perturbations of a batch process
$\{\Delta\bar{A}(t), \Delta\bar{A}_d(t)\}$ state, state-delayed perturbations of 2D model

Subscripts and superscripts
k cycle index
h horizontal direction (time t)
v vertical direction (batch k)

time domain, Park et al. [17] proposed an ILC method in terms of a holding mechanism for the control input during the estimated time delay for operation of batch processes with time delay. In these existing results, only known and fixed delay is considered and conventional ILC methods are used. Time-delay may result in instability of a system. Conventional ILC methods in time domain are likely to cause system performance degradation and even make the system state divergent. It remains as a challenge to find a control method for a batch process with time-varying delay. It has been shown that the feedback control incorporated with ILC technique is an effective tool for studying stability criteria of batch process without time-delay based on 2D system [6–8]. However, to the best of our knowledge, no such results on batch process with time-delay have been available up to now.

This article proposes a robust feedback integrated with ILC design scheme for batch processes with uncertain perturbations and interval time-varying delay. A two-dimensional (2D) Rosser model with a delay varying in a range serves as the foundation of the proposed design. Based on 2D system theory, here a FILC law is designed to guarantee the considered systems asymptotically stable along both the time and the cycle directions. With two lemmas and a new Lyapunov functional proposed, new delay-range-dependent stability criteria and stabilization conditions are derived in terms of linear matrix inequalities, which depend on not only the difference between the upper and lower delay bounds but also the upper delay bound of the interval time-varying delay. Parameterized characterizations for stabilizing the controller are given in terms of the feasibility solutions to the LMIs. The feasibility and effectiveness of the proposed FILC method are demonstrated with injection velocity control.

2. Problem description and 2D system representation

2.1. Problem description

A batch process, which performs repetitively a given task over a period of time (called a batch/cycle), can be described by the following discrete-time model with uncertainties and interval time-varying delay:

$$\begin{aligned}&\Sigma_{P-delay}:\\&x_k(t+1)=(A+\Delta_a(t,k))x_k(t)+(A_d+\Delta_d(t,k))x_k(t-d(t))+Bu_k(t)\\&y_k(t)=Cx_k(t)\\&x(0,k)=x_{0,k};\quad 0\le t\le T;\quad k=1,2,\ldots\end{aligned}\tag{1}$$

where t denotes time, k denotes the cycle index, and $x_{0,k}$ is time-wise initial state of the kth batch run. $x_k(t)\in R^n$, $y_k(t)\in R^l$ and $u_k(t)\in R^m$ represent, respectively, the state, output, and input of the process at time t in the kth batch run. The time-varying delay $d(t)$ along horizontal direction satisfies

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

where d_m and d_M denote the lower and upper delay bounds. $A(t)=A+\Delta_a(t,k)$, $A_d(t)=A_d+\Delta_d(t,k)$, A, A_d, C and B are constant matrices of appropriate dimensions, and $\Delta_{a(t,k)}$ and $\Delta_{d(t,k)}$ are some perturbations of the following forms

$$[\Delta_a(t,k)\quad \Delta_d(t,k)]=E\Delta(t,k)[F\quad F_d]$$

with

$$\Delta^T(t,k)\Delta(t,k)\le I,\quad 0\le t\le T;\quad k=1,2,\ldots$$

where E, F and F_d are known constant matrices with appropriate dimensions. Note that $\Delta(t,k)$ depends on time t only, that is, the uncertain parameter perturbations are repeatable. In fact, $\Delta(t,k)$ may depend on both time t and cycle k, which is called nonrepeatable. So it is important to consider the control of the batch processes with nonrepeatable parameter perturbations. Here although $\Delta(t,k)$ depends on time t only, the designed controller can stabilize

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