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Process Control

Design and Analysis of Integrated Predictive Iterative Learning Control for Batch Process Based on Two-dimensional System Theory☆

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ABSTRACT

Based on the two-dimensional (2D) system theory, an integrated predictive iterative learning control (2D-IPILC) strategy for batch processes is presented. First, the output response and the error transition model predictions along the batch index can be calculated analytically due to the 2D Roesser model of the batch process. Then, an integrated framework of combining iterative learning control (ILC) and model predictive control (MPC) is formed reasonably. The output of feedforward ILC is estimated on the basis of the predefined process 2D model. By minimizing a quadratic objective function, the feedback MPC is introduced to obtain better control performance for tracking problem of batch processes. Simulations on a typical batch reactor demonstrate that the satisfactory tracking performance as well as faster convergence speed can be achieved than traditional proportion type (P-type) ILC despite the model error and disturbances.

1. Introduction

For tracking the reference trajectory in batch processes, ILC [1] is a popular control framework in which the information of previous batches is used to adjust the control input for the next batch. It is widely used and applied to batch processes [2,3] owing to the key characteristic that the convergence condition is not related to the system matrix [4]. However, control performance of batch processes under traditional ILC is usually degraded when the non-repetitive disturbance and uncertain dynamics such as output noise exist within a batch. Meanwhile, the convergence speed is not concerned in most cases.

It is reasonable to combine other control methods with ILC to deal with these situations. Amann [5] applied the predictive idea to the ILC scheme, referred as predictive optimal ILC, and it had been shown that forecast may contribute to the convergence speed. Other researches showed that encouraging results can be obtained by the combination of ILC with feedback control method such as MPC, in which the input was adjusted based on the output prediction of a predefined dynamic model. To overcome the model uncertainty and process disturbances, Chin and Lee [6] proposed a batch MPC (BMPC) algorithm, in which not only the measurements from the current batch but also the information from the past batches was used, and later their work is extended to quadratic BMPC (QBMPC) [7] based on the quadratic ILC (Q-ILC) [8]. Xiong *et al.* [9,10] used shrinking horizon model predictive control (SHMPC) within the batch, while the ILC was used between the batches to improve the tracking performance. In our previous work [11], an integrated scheme was studied further by combining a traditional P-type ILC with MPC. On the other hand, the integration of these two special control schemes should be very careful for the inconsistent predictions [12].

It is noted that these researches mentioned above are all in time domain, however, a batch process can be considered as a standard two-dimensional (2D) system [13]. A typical input affects not only the next time steps of ongoing batch but also the next batches while ILC is used. In view of the 2D system theory, the 2D dynamic of the system, referred as time domain and batch domain, can be taken into account together. Thus, it is feasible that the batch-wise feedforward controller and the time-wise feedback controller can be designed and integrated to realize better control performance. Kurek and Zaremba [14] explained the traditional P-ILC in 2D system theory and proved the convergence condition in the 2D framework. Based on a controlled auto-regressive integrated moving-average (CARIMA) model, Shi and Gao [15] presented an integrated robust learning control framework by using a 2D Roesser model and linear matrix inequalities in order to deal with the uncertain perturbation. In their later works [16,17], an integrated scheme, referred as 2D-GPILC, was proposed to combine

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generalized predictive control (GPC) with ILC. Recently, Mo *et al.* [18] presented a 2D dynamic matrix control (2D-DMC) algorithm and the sufficient conditions of convergence and robustness of the method are discussed.

In spite of these works referred above, few 2D-theory based ILC control framework involves the nature characteristic of system such as the state-transition matrix and system responses. In this paper, according to the 2D Roesser model, an integrated predictive iterative learning control scheme is presented not only to overcome the model error and uncertain process disturbances but also to deliver faster convergence speed than traditional P-ILC performance. In this control scheme, the traditional P-ILC is used from batch to batch, while the input is re-adjusted by involving MPC within the batch. Based on the prediction of the responses of P-ILC, a quadratic objective function is minimized to determine the current input changes. The 2D-IPILC algorithm presented in this paper may provide a suitable framework of combining different types of ILC with MPC. Advantages of those candidate methods can be also contained in this scheme, but the control performance may be affected by the choice of parameter in the algorithm. Simulations are presented to demonstrate control performance of the scheme.

2. Design of 2D-IPILC Method for Batch Process

2.1. Tracking control problem of batch process

In this study, a batch process is considered as a class of single-input-single-output (SISO) linear time-invariant (LTI) system. It is assumed that the batch process operates over a finite time duration and the process can be described by the following discrete-time state-space model:

$$\begin{cases} x(t+1,k)=\boldsymbol{A}\cdot x(t,k)+\boldsymbol{B}\cdot u(t,k) \\ y(t,k)=\boldsymbol{C}\cdot x(t,k)+d(t,k) \end{cases} \tag{1}$$

where k is the batch index, t is the time index and $t\in[1,N]$, N is the number of sampling intervals, $x\in R^n$, $u\in R$, $y\in R$ are state, input and output variables, respectively, $d(t,k)$ denotes output disturbance and $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ are real matrices with appropriate dimensions, respectively.

The task of the proposed control method is to find the input sequence $U_k=[u_k(0), u_k(1) \ldots, u_k(N-1)]^{\mathrm{T}}$ over the time duration such that for a given reference trajectory $Y_d=[y_d(1), y_d(2), \ldots, y_d(N)]^{\mathrm{T}}$, the process output tracking error $e(t,k)=y_d(t)-y(t,k)$ is satisfied with:

$$\lim_{k\to\infty}\|e(t,k)\|\to 0, \qquad \forall t\in[1,N]. \tag{2}$$

Let us define:

$$\begin{aligned} &\eta(t,k)=x(t-1,k+1)-x(t-1,k)\\ &\Delta u(t-1,k)=u(t-1,k+1)-u(t-1,k)\\ &\Delta d(t,k)=d(t,k+1)-d(t,k). \end{aligned} \tag{3}$$

Then the above process in Eq. (1) can be described by the following two-dimensional Roesser model [18]:

$$\begin{bmatrix}\eta(t+1,k)\\ e(t,k+1)\end{bmatrix}=\begin{bmatrix}\boldsymbol{A} & 0\\ -\boldsymbol{CA} & \boldsymbol{I}\end{bmatrix}\cdot\begin{bmatrix}\eta(t,k)\\ e(t,k)\end{bmatrix}+\begin{bmatrix}\boldsymbol{B}\\ -\boldsymbol{CB}\end{bmatrix}\cdot\Delta u(t-1,k) + \begin{bmatrix}0\\ -\boldsymbol{I}\end{bmatrix}\cdot\Delta d(t,k). \tag{4}$$

Therefore, the tracking control problem is to find the input change $\Delta u(t-1,k)$ in the 2D system [Eq. (4)] in order to guarantee the convergence of the tracking error $e(t,k)$.

In this study, the 2D system [Eq. (4)] satisfies the following assumptions.

Assumption 1. All batches run from the same initial conditions, *i.e.* $x(0,k)=x_0$, $(\forall\, k>0)$, such that for the 2D system [Eq. (4)] the boundary condition is satisfied with $\eta(1,k)=0$, $(\forall\, k>0)$.

Assumption 2. The output noise $d(t,k)$ is bounded by a constant $B_d>0$, *i.e.* $\forall\, t, k$, $\|d(t,k)\|<B_d$. Hence, the next inequality holds: $\|\Delta d(t,k)\|\le 2\cdot B_d$.

2.2. Response of P-ILC

Normally, for the above tracking control problem of batch process, the traditional P-ILC can be used here and the change of input from batch to batch can be calculated by the following ILC law [13]:

$$u(t-1,k+1)=u(t-1,k)+\boldsymbol{L}\cdot e(t,k) \tag{5}$$

where $\boldsymbol{L}$ denotes the learning rate.

Substituting the control law [Eq. (5)] in the P-ILC to Eq. (4), the system can be reformed as:

$$\begin{bmatrix}\eta(t+1,k)\\ e(t,k+1)\end{bmatrix}=\begin{bmatrix}\boldsymbol{A} & \boldsymbol{BL}\\ -\boldsymbol{CA} & \boldsymbol{I}-\boldsymbol{CBL}\end{bmatrix}\cdot\begin{bmatrix}\eta(t,k)\\ e(t,k)\end{bmatrix}+\begin{bmatrix}0\\ -\boldsymbol{I}\end{bmatrix}\cdot\Delta d(t,k). \tag{6}$$

Define the state-transition matrices in the 2D system [Eq. (6)] as [13]:

$$\boldsymbol{T}=\begin{bmatrix}\boldsymbol{A} & \boldsymbol{BL}\\ -\boldsymbol{CA} & \boldsymbol{I}-\boldsymbol{CBL}\end{bmatrix},\quad \boldsymbol{T}^{1,0}=\begin{bmatrix}\boldsymbol{A} & \boldsymbol{BL}\\ 0 & 0\end{bmatrix},\quad \boldsymbol{T}^{0,1}=\begin{bmatrix}0 & 0\\ -\boldsymbol{CA} & \boldsymbol{I}-\boldsymbol{CBL}\end{bmatrix}. \tag{7}$$

Then, based on the 2D theory [19], the response of system [Eq. (6)] can be described as follows:

$$\begin{aligned}\begin{bmatrix}\eta(t,k)\\ e(t,k)\end{bmatrix}=&\sum_{i=0}^{t}\boldsymbol{T}^{t-i,k}\cdot\begin{bmatrix}0\\ e(i,0)\end{bmatrix}+\sum_{j=0}^{k}\boldsymbol{T}^{t-1,k-j}\cdot\begin{bmatrix}\eta(1,j)\\ 0\end{bmatrix}\\ &+\sum_{(0,0)\le(i,j)<(t,k)}\boldsymbol{T}^{t-i,k-j-1}\cdot\begin{bmatrix}0\\ -\boldsymbol{I}\end{bmatrix}\cdot\Delta d(i,j)\end{aligned} \tag{8}$$

where:

$$\begin{aligned}&\boldsymbol{T}^{i,j}=\boldsymbol{T}^{1,0}\cdot\boldsymbol{T}^{i-1,j}+\boldsymbol{T}^{0,1}\cdot\boldsymbol{T}^{i,j-1}\\ &\boldsymbol{T}^{i,j}=0\ \ (\text{if}\ \ i<0\ \ \text{or}\ \ j<0).\end{aligned} \tag{9}$$

For clarity of the description, we use the following notations:

$$\boldsymbol{\xi}(t,k)=\begin{bmatrix}\eta(t,k)\\ e(t,k)\end{bmatrix},\quad \bar{e}(i,0)=\begin{bmatrix}0\\ e(i,0)\end{bmatrix},\quad \bar{\boldsymbol{I}}=\begin{bmatrix}0\\ -\boldsymbol{I}\end{bmatrix}. \tag{10}$$

It should be noted that in the response of Eq. (8), it holds $\eta(1,j)=0$, $\forall\, j>0$ according to Assumption 1. Then under the P-ILC, the general response of 2D Roesser model (Eq. (6)) can be rewritten as [19]:

$$\boldsymbol{\xi}(t,k)=\sum_{i=0}^{t}\boldsymbol{T}^{t-i,k}\cdot\bar{e}(i,0)+\sum_{(0,0)\le(i,j)<(t,k)}\boldsymbol{T}^{t-i,k-j-1}\cdot\bar{\boldsymbol{I}}\cdot\Delta d(i,j). \tag{11}$$

Furthermore, in the system response of Eq. (11), $e(i,0)$ $(\forall\, i\in[1,N])$ is the initial tracking error and should have been known, and the noise