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Robust design of integrated feedback and iterative learning control of a batch process based on a 2D Roesser system

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Abstract

To improve stability and convergence, feedback control is often incorporated with iterative learning control (ILC), resulting in feedback feed-forward ILC (FFILC). In this paper, a general form of FFILC is studied, comprising of two feedback controllers, a state feedback controller and a tracking error compensator, for the robustness and convergence along time direction, and an ILC for performance along the cycle direction. The integrated design of this FFILC scheme is transformed into a robust control problem of an uncertain 2D Roesser system. To describe the stability and convergence quantitatively along the time and the cycle direction, the concepts of robust stability and convergence along the two axes are introduced. A series of algorithms are established for the FFILC design. These algorithms allow the designer to balance and choose optimization objectives to meet the FFILC performance requirements. The applications to injection molding velocity control show the good effectiveness and feasibility of the proposed design methods.

Keywords: Iterative learning control (ILC); Tracking error compensator; 2D Roesser system; Robust control; Robust H_∞ performance; Injection molding; Linear matrix inequality (LMI)

1. Introduction

Iterative learning control (ILC) is originally developed for the manipulation of industrial robots [1], in which it performs a given task repetitively. Recently, increasing efforts have been devoted to extend this to processes with less repeatable natures, such as batch reactor, batch distillation, and injection molding [2–5]. The conventional ILC [5,6], which refines the control input of the current cycle by using only the information of previous cycles, is susceptible to process uncertainties and non-repeatable perturbations. The conventional ILC, as an open-loop scheme, does not have the ability to improve the tracking performance along the time within a cycle.

To counter those problems, feedback controller has been proposed to be used together with an ILC scheme, resulting in the so-called *feedback feed-forward iterative learning control* (FFILC). The norm-optimal ILC proposed by Amann et al. [7,8] is such a scheme combining a state feedback controller with a feed-forward ILC scheme. Several robust ILC schemes [9–13], developed recently, are also FFILC schemes containing a feed-forward ILC scheme and a robust feedback controller. These works focused on the robust stability or the convergence along the cycle with little analysis on the performance improvement along time direction. The convergences of both cycle and time directions are important to the control practioners. This paper is to explore the design of both ILC and feedback control in an

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integrated fashion to meet the control performance specification along both directions.

Different FFILC schemes exist, depending on the forms of ILC and feedback controllers selected. In this paper, we will consider a general FFILC scheme illustrated in Fig. 1, where the solid arrow lines represent the current cycle feedback information flow, while the dot arrow lines represent the cycle-to-cycle information flow. Process P_Δ is a class of linear repetitive process with uncertain parameter perturbations. Two feedback controllers, a state feedback controller C_s and a tracking error compensator C_c, are integrated with the feed-forward ILC scheme, as shown in dash-line box. The state feedback controller is introduced to enhance the robust stability of the system; the feedback compensator is employed to improve the tracking performance along the time within a cycle, while the feed-forward ILC law is used to guarantee the convergence along the cycles.

This paper is to design feedback controllers C_s and C_c as well as feed-forward ILC law C_l in an integrated fashion such that the FFILC system is robust stable and has satisfactory convergence for any uncertain initial condition and norm-bounded perturbation. The design problem of this FFILC system is transformed into a robust control problem of a special 2D Roesser system with both uncertain parameter perturbation and external disturbance.

To describe and analyze the tracking performance of the system along the time and the cycle axes, new concepts and convergence indices are introduced to describe the dynamical behaviors of the corresponding 2D Roesser system in horizontal and vertical propagation directions. Sufficient conditions for robust stability of the 2D Roesser system are derived. A series of new algorithms for FFILC design are presented. Compared to the existing designs [9–12], the proposed algorithms can not only guarantee the robust stability and robust convergence, but also allow the designer to choose compensator structure and balance and optimize the convergence rate along the time and/or the cycle directions. In this paper, the feed-forward ILC law and the two feedback controllers are designed together based on linear matrix inequality (LMI) optimization techniques [19,23], resulting in less computation than the existing methods. The feasibility and effectiveness of the proposed designs are demonstrated with injection velocity control.

This paper is organized as follows: the mathematical description and design objectives of the FFILC system are presented in Section 2 together with its transformation into an equivalent uncertain 2D Roesser system. In Section 3, the robust control problem of the uncertain 2D Roesser systems are studied, leading to new stability conditions. Based on these conditions, a series of optimization algorithms for designing FFILC law are proposed in Section 4. The selection of compensator structure is discussed in Section 5. In Section 6, the feasibility and effectiveness of the proposed design algorithms are demonstrated through injection velocity control. Finally, the conclusions of this paper are given in Section 7.

2. System description and 2D system representation

2.1. System description

Throughout this paper, the following notations are used: $\mathbb{R}^n$ represents Euclidean n space with the norm denoted by $\|\cdot\|$. $\mathbb{R}^{n\times m}$ is the set of $n\times m$ real matrices. For any matrix $M\in\mathbb{R}^{n\times n}$, $M>0$ ($M\geqslant 0$) means M is a positive (semi-positive) definite symmetric matrix. I and $\mathbf{0}$ denote the identity matrix and zero matrix with appropriate dimensions, respectively, and diag$\{\cdots\}$ denotes a block diagonal matrix. For a 2D signal $w(i,j)$, if $\|w\|_2=\sqrt{\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\|w(i,j)\|^2}<\infty$, then $w(i,j)$ is said to be in ℓ_2 space, denoted by $w\in\ell_2$.

The basic structure of the FFILC system considered in this paper is shown in Fig. 1, consisting of the following four components.

- *Process P_Δ*. The process P_Δ of interest is a process repetitively performing the same task over a certain period of time, called cycle. At the kth cycle, the process is assumed to be described by the following discrete-time linear model with uncertain parameter perturbations.

$$\begin{cases} x_k(t+1)=(A+\Delta_a(t,k))x_k(t) \\ \qquad\qquad +(B+\Delta_b(t,k))u_k(t) \\ y_k(t)=Cx_k(t) \end{cases} \tag{1}$$

$$x_k(0)=x_{0k},\quad 0\leqslant t\leqslant N,\quad k=1,2,\ldots$$

where the subscribe k denotes the cycle index, t is the discrete time, N (>0) is the size of the cycle,

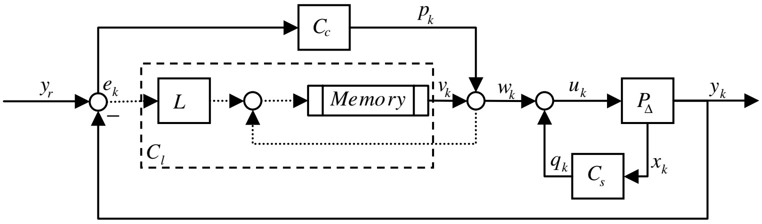

Fig. 1. Block diagram of an FFILC system: (P_Δ) process; (C_l) Feed-forward ILC; (C_c) tracking error compensator and (C_s) state feedback controller.