Journal of Process Control xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Iterative learning fault-tolerant control for differential time-delay batch processes in finite frequency domains☆

Hongfeng Tao [a,*], Wojciech Paszke [b], Eric Rogers [c], Huizhong Yang [a], Krzysztof Gałkowski [b]

[a] Key Laboratory of Advanced Process Control for Light Industry of Ministry of Education, Jiangnan University, Wuxi 214122, PR China
[b] Institute of Control and Computation Engineering, University of Zielona Góra, ul. Szafrana 2, 65-516 Zielona Góra, Poland
[c] Department of Electronics and Computer Science, University of Southampton, Southampton SO17 1BJ, United Kingdom

ARTICLE INFO

Article history:
Received 24 August 2016
Received in revised form
12 December 2016
Accepted 17 December 2016
Available online xxx

Keywords:
Iterative learning control
Batch processes
Finite frequency range design
Fault tolerant control
Time-delay systems

ABSTRACT

This paper develops a fault-tolerant iterative learning control law for a class of differential time-delay batch processes with actuator faults using the repetitive process setting. Once the dynamics are expressed in this setting, stability analysis and control law design makes use of the generalized Kalman–Yakubovich–Popov (KYP) lemma in the form of the corresponding linear matrix inequalities (LMIs). In particular, sufficient conditions for the existence of a fault-tolerant control law are developed together with design algorithms for the associated matrices. Under the action of this control law the ILC dynamics have a monotonicity property in terms of an error sequence formed from the difference between the supplied reference trajectory and the outputs produced. An extension to robust control against structured time-varying uncertainties is also developed. Finally, a simulation based case study on the model of a two-stage chemical reactor with delayed recycle is given to demonstrate the feasibility and effectiveness of the new designs.

1. Introduction

Iterative learning control (ILC) is a method of iteratively updating the control input to a system that repeats the same task over a finite duration. Each execution is known as a trial, or pass, and the sequence of operations is that a trial is completed, where the finite duration is known as the trial length, the system resets to the starting position and then the next trial can begin, either immediately after resetting is complete or after a further period of time has elapsed. Since the first work, widely credited to [1], ILC has become an established area of control systems research, where the survey papers [2,3] are one source of the literature up to their years of publication.

In most designs, a reference trajectory is specified and the current trial error is the difference between this signal and the output. The core aim of ILC is to force the sequence formed by the errors to converge to zero or to within an acceptable tolerance as measured by the norm on the underlying function space. Moreover, this convergence should be monotonic in the trial number.

In application, an ILC law most often constructs the current trial input as the algebraic sum of the input used on the previous trial and a correction term. The correction term can be designed using data from the complete previous trials or a finite number thereof. A particular feature is the possibility to use non-causal temporal information provided it has been generated on a previous trial.

Since this first work, ILC research has found application in many areas, such as robotic systems, e.g., [4,5], motion systems, e.g., [6], automotive systems, e.g., [7] and batch processes, e.g., [8], where for this last area the survey paper [9] is a starting point for numerous applications areas in process control. A particular feature of many applications is experimental testing. There has also been an application in robotic-assisted stroke rehabilitation, e.g., [10,11], with supporting clinical trials. In this last application, the ILC law is used to control the assistive stimulation applied to the relevant muscles in the affected limb as the patient makes repeated attempts at completing a specified

☆ This work is supported by National Natural Science Foundation of China (61273070, 61203092), 111 Project (B12018), the Fundamental Research Funds for the Central Universities (JUSRP51510), the Priority Academic Program Development of Jiangsu Higher Education Institutions and National Science Centre in Poland, grant No. 2014/15/B/ST7/03208.

* Corresponding author.
E-mail addresses: taohongfeng@hotmail.com (H. Tao), w.paszke@issi.uz.zgora.pl (W. Paszke), etar@ecs.soton.ac.uk (E. Rogers), yhz@jiangnan.edu.cn (H. Yang), k.galkowski@issi.uz.zgora.pl (K. Gałkowski).

http://dx.doi.org/10.1016/j.jprocont.2016.12.007
0959-1524/© 2016 Elsevier Ltd. All rights reserved.

finite duration task, e.g., reaching out with the affected arm to an object across a table top. Once an attempt is complete the arm is reset to the starting location and in this time plus a rest period, the control signal for the next attempt can be computed using data collected during the previous attempt. If the patient is improving then as the trial number increases the patients voluntary effort should increase and the applied stimulation decrease. Exactly this feature was detected in the clinical trials.

A common approach to ILC design for discrete dynamics is by a form of lifting. Consider, for simplicity, the single-input single-output (SISO) case where, since the trial length is finite, the input and output on any trial can be represented by super-vectors formed by assembling the values at the sample instants into column vectors. The result is that the ILC dynamics can be represented by a linear matrix difference equation in the error dynamics. Hence tools from discrete linear systems theory can be used to analyze trial-to-trial error convergence and control law design.

Given the finite trial length, trial-to-trial error convergence does not require that the system is stable, i.e., for differential linear dynamics all eigenvalues of the state matrix have strictly negative real parts. Of course, there will be consequences for the transient dynamics along the trials in such a case. One solution is to design a feedback control law to stabilize the dynamics and then apply the ILC design to the controlled dynamics. An alternative is to use a 2D systems formulation, i.e., systems that propagate information in two independent directions, which in ILC are from trial-to-trial and along the trial respectively. Early work on this approach includes [12]. Repetitive processes are a particular subclass of 2D systems have their origins in modeling physical examples [13] for control purposes. These processes are characterized by a series of sweeps, or passes, through dynamics defined over a finite duration. On each pass an output, termed the pass profile, is produced that acts as a forcing function on and hence contributes to the dynamics produced on the next pass.

The repetitive process setting for ILC design has progressed through to experimental verification [4]. Design in this setting is a one step process where the control law includes stabilization of the state dynamics on each trial. Also the design methods extend naturally to robust control design where, unlike the lifted setting, matrices formed as the product of nominal state-space model matrices and those from the uncertainty description are always excluded. Moreover, ILC design in this setting transfers directly to differential dynamics, i.e., to cases where design by emulation is the only or preferred setting for analysis and design.

In many industrial processes, time-delays often occur, e.g., in the transmission of material or information between different parts of a system, which, if not subject to compensation, can cause serious deterioration of the stability and performance. Chemical processes are a common industrial source of time-delay systems and there has been research on ILC design for such systems by treating them as differential batch processes over a finite time on each trial. For example, a robust 2D ILC law combined with the output feedback has been applied to batch processes with state delay and time-varying uncertainties [14].

Industrial control systems usually operate under challenging conditions, which expose the system to faults that, in turn, can cause loss, or serious degradation, of stability and/or performance. Moreover, ILC schemes could be especially sensitive to faults due to the repeated nature of the demand on the control actuator. For such cases, a fault tolerant ILC design is required. Of course, this problem arises in the non-ILC case, see, e.g., [15], where necessary and sufficient conditions for stabilization while retaining a desirable level of the closed-loop performance in the presence of actuator/sensor faults or failures, and also plant-model mismatches, are given.

The design of ILC laws for monotonic trial-to-trial error convergence together with controlled dynamics along the trials, in the SISO case for simplicity, requires frequency attenuation over the complete spectrum. This could be very difficult to enforce in some cases and also in many practical examples, systems properties need only be enforced over finite frequency ranges. Moreover, in other examples it will be required to impose different specifications over finite frequency ranges. One way of solving these problems is to use the generalized Kalman–Yakubovich–Popov (KYP) lemma, see, e.g., [16] for discrete systems with experimental verification in the absence of time delays and no compensation for possible faults. The corresponding results for differential linear systems are given in [17].

This paper develops new results for ILC design applied to differential linear systems with time-delays with the following novel contributions:

- the finite frequency range ILC law design is extended to the fault tolerant control problem for differential linear time-delay batch processes with actuator faults;
- monotonic trial-to-trial error convergence conditions for the controlled ILC dynamics are derived;
- the extension to robust control against structured uncertainty.

This paper is organized as follows: Section 2 describes a class of differential linear batch processes in the state-space form with actuator faults and a time-delay in the state. Also the ILC design problem is formulated in an equivalent differential linear repetitive process setting. In Section 3, the corresponding fault tolerant ILC law is designed and sufficient conditions for its existence are developed in terms of generalized KYP lemma and LMIs constraints, which ensure that the nominal and uncertain controlled dynamics are monotonically convergent and stable over a finite frequency range. Section 4 illustrates the feasibility and effectiveness of the new design by a simulation-based application to a two-stage chemical reactor with delayed recycle streams. Finally, the main results are summarized in Section 5 together with some possible areas for further research.

Throughout this paper, the null and identity matrices with the required dimensions are denoted by 0 and I, respectively, and the notation $X \prec Y$ (respectively $X \succ Y$) is used to represent the negative definite (respectively, positive definite) matrix $X - Y$. The notation $(\star)$ denotes transposed elements in a symmetric matrix and $\rho(\cdot)$ denotes the spectral radius of its matrix argument, i.e., if λ_i, $1 \le i \le q$, denote the eigenvalues of a $q \times q$ matrix, say H, $\rho(H) = \max_{1 \le i \le q} |\lambda_i|$. The symbol diag$\{X_1, X_2, \ldots, X_n\}$ denotes a block diagonal matrix with diagonal blocks $X_1, X_2, \ldots, X_n$ and $\mathrm{sym}(\Lambda) = \Lambda + \Lambda^T$, $\otimes$ denotes the Kronecker matrix product, the superscript * denotes the complex conjugate transpose of a matrix.

The following lemmas are used in the proofs of the main results.

Lemma 1. [18] *Given matrices X, Y, $\Phi = \Phi^T$ and $\Delta(t)$ of compatible dimensions,*

$$\Phi + X\Delta(t)Y + Y^T\Delta^T(t)X^T \prec 0, \tag{1}$$

for all $\Delta(t)$ satisfying $\Delta^T(t)\Delta(t) \preceq I$ if and only if there exists an $\varepsilon > 0$ such that

$$\Phi + \varepsilon XX^T + \varepsilon^{-1}Y^TY \prec 0. \tag{2}$$