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Iterative learning control for linear delay systems with deterministic and random impulses☆

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Abstract

This paper investigates convergence of iterative learning control for linear delay systems with deterministic and random impulses by virtute of the representation of solutions involving a concept of delayed exponential matrix. We address linear delay systems with deterministic impulses by designing a standard P-type learning law via rigorous mathematical analysis. Next, we extend to consider the tracking problem for delay systems with random impulses under randomly varying length circumstances by designing two modified learning laws. We present sufficient conditions for both deterministic and random impulse cases to guarantee the zero-error convergence of tracking error in the sense of Lebesgue-*p* norm and the expectation of Lebesgue-*p* norm of stochastic variable, respectively. Finally, numerical examples are given to verify the theoretical results.

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1. Introduction

The idea of iterative learning control (ILC) arises from Uchiyama in 1978. It is an important branch of intelligent control, which is applicable to robotics, process control, and biological systems. ILC can be applied to not only conventional fields but also new systems such as biomedical engineering [1]. We note that the two dimensional system theory [2] plays an important role in the stability analysis of ILC. In addition, performance assessment of ILC is also a new promising direction and should be mentioned [3].

This control method has attracted much attention from both scholars and engineers because of its simplicity in design and the less requirement of system information to obtain a perfect tracking performance in a finite interval. We note that ILC technology with uniform trial lengths have been fully investigated and widely applied to tracking a given reference for various systems, such as, fractional order systems [4,5], impulsive systems [6,7], and distributed parameter systems [8–10]. In other words, the complete tracking information of the whole iteration can be achieve for all iterations. We also remark that there is a quick development of stochastic ILC [11–13], which shows a promising research direction.

Generally speaking, the conventional ILC imposes many strict conditions on the iteration-invariance of the system such as identical initial state, identical tracking references and identical dynamic uncertainties. Therefore, many papers have been devoted to relax these invariance requirements [14–19]. Among various iteration-invariant conditions, we note that the iteration length is usually required to be uniform in the existing publications. However, in many applications, the iteration length may vary from iteration to iteration even though other conditions retain the same. Examples of functional electrical stimulation for upper limb movement and gait assistance in [20,21] surely support this point. In these applications, the learning iteration would have to terminate early because of safety, which motivates the scholars to dig out how to extend the ILC to non-uniform trial length case. As a result, there are some pioneering works reported this topic such as [22–24], in which the concept of iteration-average operator is offered to compensate the lost trial information. For more recent contributions, we refer to [25–29] and reference therein. In these papers, several design and analysis techniques, including modified λ-norm, iteration-moving-average operator with a stochastic searching mechanism, selection of tracking information under vector relative degree, and recursive interval Gaussian distribution, have been proposed and investigated. However, to the best of our knowledge, there are few ILC papers dealing with delay systems with random impulses. In addition, most convergence analysis of ILC algorithms for uniform and non-uniform trial lengths are discussed in the sense of λ-norm. However, λ-norm cannot objectively quantify the essential characteristics of the tracking error because much conservatism has been introduced in the derivations of contraction mapping inequality applying the λ-norm and Gronwall inequalities. To facilitate the practical engineering applications, one have to derive the convergence in some acceptable sense such as Lebesgue-p norm. In this direction, Ruan et al. initially apply Lebesgue-p norm to study the monotonic convergence of ILC problems [30–32].

As for linear delay systems with permutable matrices, Khusainov, Shuklin and Diblík et al. utilize the notation of delay exponential matrix and variation of constants formula to derive solutions of linear delay systems, for examples, see representation of solution [33–36]; control theory [37–39] and stability [40–43]. Thereafter, many contributions are reported on the application to stability analysis [44–47], controllability [48] and ILC problems [49]. We emphasize that the notation of delay exponential matrix can be widely used in dealing with tracking problem in a given finite time interval. In fact, one can use the representation of