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Multi-objective Iterative Learning Control using Convex Optimization

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Abstract

This paper presents a multi-objective iterative learning control (ILC) design approach that realizes an optimal trade-off between robust convergence, converged tracking performance, convergence speed, and input constraints. Linear time-invariant single-input single-output systems which are represented by both parametric and nonparametric models are considered. The noncausal filter $Q(\mathrm{q})$ and learning function $L(\mathrm{q})$ are simultaneously optimized by solving a convex optimization problem. The proposed method is applied to a non-minimal phase system and compared with a model-inversion based ILC design. Using the developed ILC design the underlying trade-off between tracking performance and convergence speed is thoroughly/quantitatively analyzed.

Keywords: iterative learning control, $\mathcal{H}_\infty$ control, multi-objective control, convex optimization

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1. Introduction

Iterative learning control (ILC) is widely used in control applications to improve performance of repetitive processes [1, 2]. The key idea of ILC is to update the control signal iteratively based on measured data from previous trials, such that the output converges to the given reference trajectory. The purpose of this paper is to present a multi-objective iterative learning control (ILC) design. More specifically, this paper considers ILC applied to linear time-invariant (LTI), single-input single-output (SISO) systems. The setup is a standard ILC type [1]:

$$u_{j+1}(k) = Q(\mathrm{q})\left[u_j(k) + L(\mathrm{q})e_j(k+1)\right], \tag{1}$$

where $u_j(k)$ is the ILC input signal and $e_j(k)$ is the error signal between the reference trajectory and the output signal. The subscript j denotes the trial number. $Q(\mathrm{q})$ and $L(\mathrm{q})$ are known in ILC literature as the Q-filter and learning function, respectively. The choice of $Q(\mathrm{q})$ and $L(\mathrm{q})$ is the main issue in the design of an ILC algorithm.

Most ILC algorithms in the literature rely on a two-step problem formulation and the design procedures are usually heuristic. The design problem of $L(\mathrm{q})$ is usually formulated first. Various choices of $L(\mathrm{q})$ have been discussed such as P-type [3], PD-type [4], model-inversion [5–7] and phase-lead [8–10]. The first three approaches aim to find a learning function that is closest to the inverse of the system dynamics. These methods are sensitive to model uncertainties, and have difficulties dealing with non-minimum phase systems [8]. The phase-lead type ILC is based on tuning a learning gain and a linear phase-lead variable. Even though some guidelines have been provided to find the optimal variables, the tuning process is typically trial-and-error. The system is required to be reset whenever the parameters are adjusted. After $L(\mathrm{q})$ is found, $Q(\mathrm{q})$ is commonly designed as a low-pass filter. The filter characteristics (i.e. filter type, cut-off frequency and order) are selected by the designer such that robustness and high tracking performance are obtained. On the other hand, [11, 12] consider $\mathcal{H}_\infty$-based ILC methods to design the learning function for the given Q-filter. The solutions are however limited to only causal functions. Finally, [13, 14] proposed

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