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Application of robust iterative learning algorithm in motion control system

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ABSTRACT

Robustness issue is considered to be one of the major concerns in application of the iterative learning control in motion control systems. The robustness in servo systems is related to parameter uncertainties and noise accumulation. In this paper, both parameter uncertainties and noise are considered in derivation of the error dynamic equation of the ILC algorithm. Based on the error dynamics, the H_∞ framework is utilized to design the robust learning controller. An optimization design process in selecting the proper learning gain and determining the learning function is proposed to ensure that both tracking performance and convergence condition are achieved. Simulations and experiments are conducted to validate the robust learning algorithm which can be applied efficiently to machine tools with the payload varying from 0 to 20 kg. The experimental results demonstrate that the proposed method improves the tracking and contouring performances significantly when performing a complex NURBS curve on a three-axis milling machine.

1. Introduction

Iterative learning control (ILC) is a technique to control the systems operating same tasks repetitively. The idea of ILC is to improve the performance of subsequent tasks by updating the control inputs as a function of the previous control inputs and output errors from trial to trial. The ILC can be applied to robot manipulators [1], machine tools [2], chemical batch process [3], and so on. The ILC was first proposed in the mid-1980 by Arimoto, et al. [4]. Since then, many schemes of the ILC including the 2D theory method [5], inverse system [6], stochastic method [7], and feedback learning operators [8,9] have been proposed by many researchers in the past two decades. Technical review on the methodologies and applications of the ILC is referred to [10].

Among all research issues related to the ILC, system robustness and monotonic convergence of tracking error are major concerns in the implementation of ILC to either linear or nonlinear systems [11]. To overcome the system uncertainty problem, the adaptive iterative learning control was proposed [12,13]. The idea is to use a standard adaptive controller and start parameter estimates at the preceding iteration. The Lyapunov method was adopted to prove the convergence of the algorithm. However, the unknown parameters should be constant during the iteration. Other adaptive ILC algorithms have been proposed to handle system with time-varying parameters using a positive-definite Lyapunov-like sequence [14–16]. By designing the control inputs, the Lyapunov sequence can be made to monotonically decrease along the iteration.

Another approach to ensure system robustness is to utilize the H_∞ theory to formulate the general design framework for the ILC algorithm [17–19]. In these papers, only the performance and robustness analysis of ILC schemes are considered without systematically designing learning controller. In Amann et al. [20], a combined current error feedback and past error feedforward method was proposed using the H_∞ theory. However, there are no systematic way to design the weighting functions for both feedback and feedforward control gains. In [21], the H_∞ mathematical framework was adopted to optimize the speed of L2-convergence. However, the convergence condition cannot be achieved even though the μ-synthesis approach was adopted. Helfrich et al. [22] adopted H_∞ control design approach to design feedback controller while the inverse plant approach is utilized to design feedforward learning function. In the paper by Xu et al. [23], the synthesis problem of the developed iterative learning control (ILC) system is reformulated as the γ-suboptimal H_∞ control problem via the linear fractional transformation (LFT). Although parameter uncertainties can be explicitly included by choosing proper weighting functions in the H_∞ formulation, noise problem was seldom discussed. It was shown that noise accumulation during the iteration could also affect the learning process significantly [24]. Most research applied the zero-phase low-pass filter to solve the noise problem without simultaneous consideration of system uncertainties [25,26].

Based on the previous discussions, it is found that, in addition to tracking performances, parameter uncertainties and noise effect

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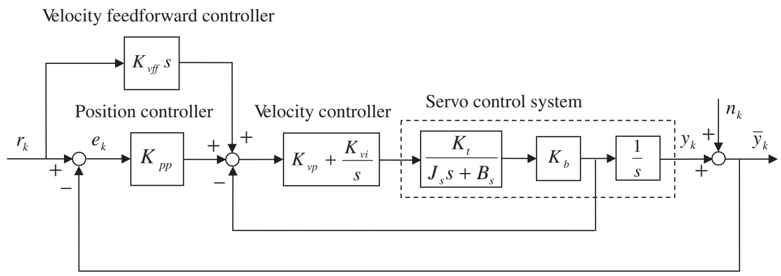

Fig. 1. Architecture of servo control system with measurement noise.

Table 1
Parameters of servo control systems and motion controller.

Axis	Components	Symbols	Units
X-axis	System dynamics	K_t	0.213 N m/V
		J_s	6.320×10^{-5} kg m^2
		B_s	1.716×10^{-3} kg m^2/s
	Position controller	K_{pp}	80.378 1/s
	Velocity controller	K_{vp}	1.273×10^{-1} V s/mm
		K_{vi}	12.666 V/mm
	Feedforward gain	K_{vff}	0.90 1/s
Y-axis	System dynamics	K_t	0.213 N m/V
		J_s	5.288×10^{-5} kg m^2
		B_s	1.609×10^{-3} kg m^2/s
	Position controller	K_{pp}	80.793 1/s
	Velocity controller	K_{vp}	1.068×10^{-1} V s/mm
		K_{vi}	10.840 V /mm
	Feedforward gain	K_{vff}	0.90 1/s
X- and *Y*-axis	Sampling Time	T_s	5×10^{-4} s
	Ball-screw constant	K_b	$5/2\pi$ mm/rad

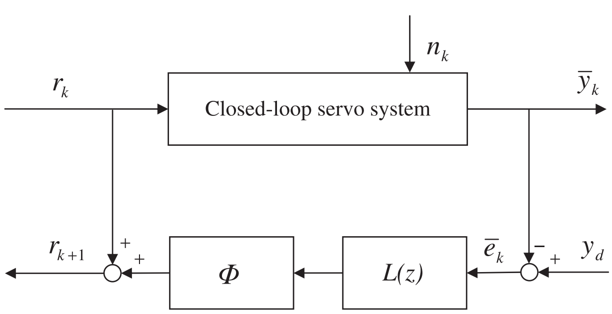

Fig. 2. Architecture of command-based ILC with measurement noise.

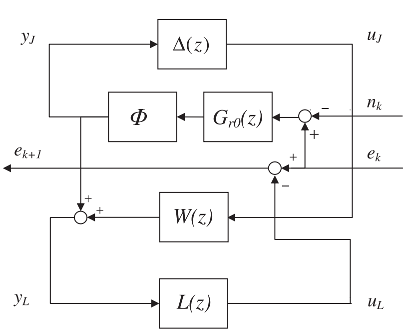

Fig. 3. Architecture of ILC synthesis problem with measurement noise.

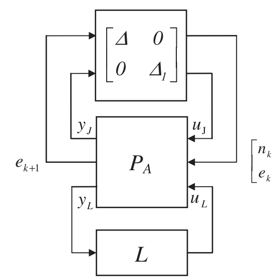

Fig. 4. Linear fractional representation of control problem.

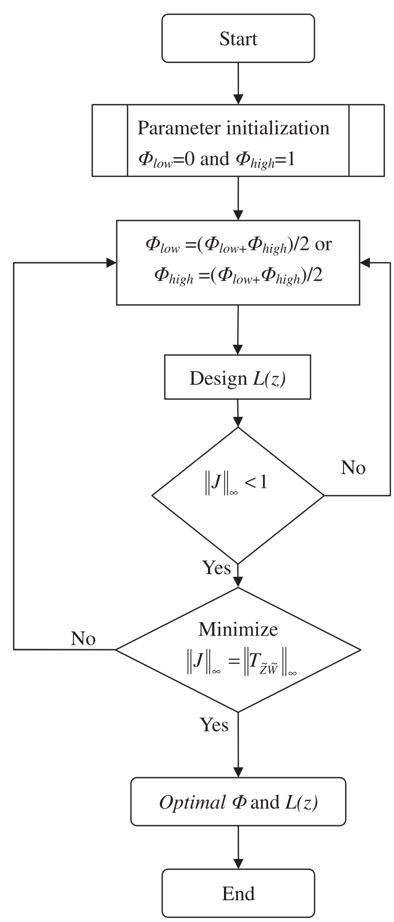

Fig. 5. The flow chart of designing the learning gain Φ and learning function L.

are also very important for the ILC algorithm. Furthermore, the convergence condition may not be satisfied with the current H_∞ or μ-synthesis approach. Based on the above issues, a two-step loop design process is proposed which integrate the learning gain optimization process with the robust H_∞ controller to ensure that the designed controller can achieve both performances and robustness. The first step is to design the H_∞ controller without consider-