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Time-domain prefilter design for enhanced tracking and vibration suppression in machine motion control

Matthew O.T. Cole *, Praween Shinonawanik, Theeraphong Wongratanaphisan

Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand
Centre for Mechatronic Systems and Innovation, Chiang Mai University, Chiang Mai 50200, Thailand

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ABSTRACT

Structural flexibility can impact negatively on machine motion control systems by causing unmeasured positioning errors and vibration at locations where accurate motion is important for task execution. To compensate for these effects, command signal prefiltering may be applied. In this paper, a new FIR prefilter design method is described that combines finite-time vibration cancellation with dynamic compensation properties. The time-domain formulation exploits the relation between tracking error and the moment values of the prefilter impulse response function. Optimal design solutions for filters having minimum H2 norm are derived and evaluated. The control approach does not require additional actuation or sensing and can be effective even without complete and accurate models of the machine dynamics. Results from implementation and testing on an experimental high-speed manipulator having a Delta robot architecture with directionally compliant end-effector are presented. The results show the importance of prefilter moment values for tracking performance and confirm that the proposed method can achieve significant reductions in both peak and RMS tracking error, as well as settling time, for complex motion patterns.

1. Introduction

Motion control of automated machinery and robotic systems usually involves feedback of position and/or velocity measured locally to actuators. Model-free controller formulations, such as standard PID or cascaded position/velocity feedback loops, can then be used even when a machine structure exhibits significant non-rigid behavior. Nonetheless, flexibility within a machine structure may still lead to unmeasured positioning errors and vibration at locations where accurate motion is important for task execution. Control methods that can improve accuracy of motion at non-measurable locations without requiring additional actuation or absolute position measurements and without the need for complete and accurate models of the machine's dynamics are important for various applications. These include industrial robots [1], high-speed positioning stages [2], crane systems [3] and flexible ball-screw drives [4].

Command prefiltering is an effective means to reduce residual vibration in rest-to-rest motion tasks. A well-known approach is to use time-delay filters as input shapers, constructed so as to achieve finite settling time for motion-excited vibration [5,6]. The merits of this approach are that finite-time settling can be achieved with knowledge only of natural frequencies and damping properties for system vibration and that uncertainty in these parameters can be effectively dealt with

* Corresponding author at: Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand.
E-mail address: motcole@hotmail.com (M.O.T. Cole).

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in the design using additional algebraic constraints. Similar properties can be achieved for a wider class of FIR prefilters having continuous or piecewise-continuous impulse response characteristics [8–11,16]. When designing directly for digital implementation, various specifications can be treated via constrained optimization methods [7,9,12,13]. Further possibilities include data-based optimization and on-line adaptation [14,15], optimality with respect to various gain measures [7], low-pass properties [16] and suitability for inclusion within a feedback loop (in inverse form) [17].

When prefilters designed for vibration suppression are applied with closed-loop systems, tracking error is impacted by delay effects from the prefiltering (although multi-dimensional path-following may still be accurate) [15,18,19]. An optimized FIR prefilter design was introduced in [12] for use with ramp profile reference signals and an explicit formulation of time-delay prefilters for ramp reference signals also presented in [20]. Methods to design prefilters for vibration reduction that address the issues of tracking and path-following for more complex motion patterns are still needed. This paper introduces a new design formulation that relates moment values of the prefilter impulse response function to the tracking error arising for arbitrary but smooth reference profiles. The resulting filters can ensure exact tracking with finite settling-time for polynomial reference signals of prescribed degree. This is an important advancement over previous FIR design methods that considered step or ramp reference signals only [8–10,12,16]. It is shown through analysis and experiment that the optimized prefilter designs can significantly reduce tracking error for complex motion trajectories. By combining the prefiltering with standard decentralized feedback control methods, performance comparable with optimal feedback controllers can be achieved without the issue of potential instability due to model error and without the need for additional sensors.

2. Theory

2.1. Problem definition

The dynamic behavior of a feedback-controlled system G (assumed stable) with input prefilter H can be described mathematically in terms of series operations $p_r^* = Hp_r$ and $p = Gp_r^* = GHp_r$. The system output $p(t)$ is the time-varying motion variable, for which a target profile is prescribed by the reference input signal $p_r(t)$. The modified (prefiltered) reference signal is $p_r^*(t)$.

Under the assumption of linear time-invariant (LTI) dynamics, the system operator G may be expressed in transfer function (TF) form

$$G = \frac{b(s)}{a(s)}, \tag{1}$$

where $a(s) = \alpha_N s^N + \cdots + \alpha_1 s + \alpha_0$ and $b(s) = \beta_N s^N + \cdots + \beta_1 s + \beta_0$, with s denoting the derivative operator. The output error is given by

$$e = p_r - p = p_r - \frac{b(s)}{a(s)} p_r^* \tag{2}$$

The objective considered here is to enhance the performance of a given system G by introducing a prefilter H that, for smooth reference signals, can achieve

C1. Zero steady-state output error for smooth time-varying reference signals
C2. Finite settling time for targeted eigenmodes (TF poles)

For filter design purposes, criterion C2 may be formulated as a set of integral constraints involving the prefilter impulse response function (see [7]). In Section 2.2 it will be shown that this is also the case for criterion C1.

Reference prefiltering may be defined in terms of a convolution operation

$$p_r^*(t) = \int_{t_0}^{t_1} h(\tau) p_r(t-\tau) d\tau \tag{3}$$

where $h(t)$ is the prefilter impulse response function, having finite duration corresponding to the interval $t \in [t_0, t_1]$. For causal filtering, $t_0 = 0$ and the impulse response duration is $t_1 > 0$. In cases where preview of the reference function p_r is possible, t_0 may take a negative value.

2.2. Use of moment constraints in prefilter design

Suppose that the reference input is $p_r(t) = t^n$ with integer $n \geqslant 0$ then, from Eq. (3), the lth derivative of p_r^* is

$$\frac{d^l p_r^*}{dt^l} = \frac{n!}{(n-l)!} \int_{t_0}^{t_1} h(\tau)(t-\tau)^{n-l} d\tau \tag{4}$$