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Low-order continuous-time robust repetitive control: Application in nanopositioning

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ABSTRACT

A low-order repetitive control (RC) design in continuous-time for nanopositioning applications is presented. It focuses on achieving high performance and sufficient robustness to uncertainties. The design is mainly applicable to analog implementation, but due to the exceptionally low order, it also results in a fast and efficient digital implementation. Experimental results for an analog implementation using a bucket brigade device (BBD), as well as a digital implementation, is presented. RC can provide fast and accurate tracking of periodic reference signals, which is useful in many scanning probe microscopy and nanofabrication applications.

1. Introduction

Nanopositioning stages often require control laws with the ability to track periodic reference signals with high accuracy, e.g. in scanning probe microscopy and nanofabrication. Such signals occur in applications such as raster scanning, pick-and-place operations, and mass-production of features [1–3].

Repetitive control (RC) is ideally suited for periodic signals. It is based on the internal model principle [4]: tracking or rejection of periodic exogenous signals can be achieved by embedding a periodic signal model in the control loop. A periodic signal model can be efficiently implemented using a time-delay inside of a positive feedback loop [5–7]. An important feature of RC is that as long the overall control loop is stable the RC scheme is invariant to changes in plant dynamics, subject to the accuracy of the signal model. To guarantee stability, the control law filters must ensure sufficient robustness. The requirement for robustness impacts on the accuracy of the signal model, as one of the most common methods to introduce robustness in RC is to limit the bandwidth of the signal model [6]. However, any linear control law without a periodic signal model, even a bandwidth-limited one, will not achieve the same level of performance for periodic signals.

Recently, RC has been introduced for nanopositioning systems [8–11]. For periodic references, due to the high degree of invariance to changes in plant dynamics and the ability to reject periodic disturbances, RC can address the challenges posed by state-of-the-art mechanically stiff nanopositioner-designs. Such systems often have lightly damped vibration modes, and use piezoelectric actuators which introduces hysteresis and creep [12]. Hysteresis and creep are the main sources of uncertainty, as these phenomena change the effective system gain dependent on input voltage offset, range, and frequency [2]. Hysteresis is also the main source of disturbance, as it generates harmonic distortion on the input for a given stationary excitation signal [13]. The disturbance is then periodic with the same fundamental frequency as the excitation signal, and RC can then provide good rejection. Additional uncertainty is introduced in applications, as it is typically required to move payloads of various masses, thus the vibration modes and the effective gain of the mechanical structure changes every time a new payload is attached. Other effects that introduce uncertainty are inherent variations in piezoelectric actuators, where the effective system gain changes due to temperature, depolarization, and aging.

Robustness for RC is usually taken to mean robustness towards uncertainties in the fundamental frequency of exogenous signals (robust performance), or robustness towards plant modeling uncertainty (robust stability). Methods to improve performance if there is uncertainty or variation in the fundamental frequency of exogenous signals have been proposed in [14–16,9]. Such methods are not applicable in this work, as the reference signal period is considered to be known and accurate and the main disturbance is due to hysteresis which generates harmonic distortion dependent on the reference signal [13].

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Robustness towards plant uncertainty has been studied in [6,7,17–20]. The most common method to introduce robustness in RC is to limit the bandwidth of the signal model. This corresponds to the modified RC system in [6], where a low-pass filter is used to limit the bandwidth and hence relax the stability condition. A robust stability condition is found in [7], where an additive uncertainty weight is considered. Model-matching techniques from robust control theory [21] is applied in [17–19] to synthesize robust control law filters suitable for RC. Model-matching is also proposed in [6] for control law filters synthesis, but without considering robustness weights. In [20] robustness is introduced by accounting for uncertainty via a worst-case plant frequency response generated from measurements. An approximate discrete-time plant inverse filter is then found using system identification techniques. Control law filter synthesis using model-matching or system identification techniques are not suited to the approach taken in this work, as there are constraints on filter order and structure.

RC is very similar to iterative learning control (ILC) [22–25]. The main difference between ILC and RC is that ILC is a finite time problem where the initial values of the states are reset between each iteration. ILC can be applied to unstable systems and it does not require convergence in the solution of the input signal sequence. However, when applying RC it is not required to solve the initial value problem for each iteration step and it can be implemented using analog devices. For convenience, RC can also be plugged into an existing feedback loop to enhance performance with minimal changes to an existing control system [8].

1.1. Contribution

The aim of this work it to synthesize a low-order continuous-time robust RC scheme which can yield high performance and is suitable for analog implementation. This is achieved using a robust damping and tracking control law in combination with a plug-in type continuous-time repetitive control (RC) scheme. Specifically, a robust stability criterion and a tuning procedure for the RC scheme is proposed, and an inexpensive analog implementation of the scheme is presented. This work is an updated and expanded version of [26,27].

1.2. Outline

The lightly damped vibration modes and the hysteresis effect present in many nanopositioning systems can degrade performance and make it difficult to obtain a stable RC system [28]. A modified integral control law [29] is therefore designed and used to mitigate the effects of vibration modes and hysteresis. This kind of control law can be described as a damping and tracking control law. Examples of such control laws applied to nanopositioning systems can be found in [30–35]. Any of these control laws can provide an approximately flat frequency response for the complementary sensitivity function [29], which is one of the features used to reduce implementation complexity in the proposed control scheme. The particular control law used in this work is chosen because it provides the lowest order implementation and incorporates the anti-aliasing and reconstruction filters needed in the system to good effect.

The modified integral control law is combined with continuous-time RC for tracking of periodic references. Robust stability is considered via the selection of a multiplicative uncertainty weight. In order to reduce implementation complexity, the flat frequency response feature is exploited by approximating the complementary sensitivity function with an all-pole Butterworth filter. A Butterworth filter is by definition a filter which provides a maximally flat frequency response, or equivalently, uniform sensitivity in the passband [36]. An optimization problem is solved to find a DC-gain and a cut-off frequency for this Butterworth filter that ensures robust stability with the given multiplicative uncertainty weight. By using two all-pole filters, one for the approximation of the complementary sensitivity function and one to limit the bandwidth of the signal model, the inverse of the approximation combined with the low-pass filter produces a biproper transfer function. The biproper transfer function can then be implemented using a single filter with one input and two outputs, reducing implementation complexity.

Thus, the overall control scheme has exceptionally low order; simplifying the implementation process. A digital and an analog implementation is presented. The digital implementation uses standard digital signal processing (DSP) equipment, and the analog implementation is realized using regular analog filters and a bucket brigade device (BBD) [37–39], which provides the required time-delay. The use of BBDs for RC have previously been investigated [40,41], but using different control law structures and not for motion control. The digital implementation serves as a reference implementation for the subsequent analog implementation.

Experimental results are presented to demonstrate the effectiveness of the overall control scheme, where the proposed control system is applied to a custom-designed piezo-based nanopositioning system.

1.3. Assessment of experimental performance

In [29] several damping and tracking control laws have been surveyed for a similar system as the one considered here. Damping and tracking control laws typically only incorporate integral action, thus only providing asymptotic tracking for constant references. One of the best performing methods in [29], synthesized using model reference control (MRC), yielded a maximum error (ME) of 16% and a root-mean-square error (RMSE) of 11% for a 80-Hz triangle wave reference signal with 1-μm amplitude when there was a dominant vibration mode at 1660 Hz. The corresponding figures for the modified integral control law used in this work applied to the system in [29] were an ME of 24% and an RMSE of 20%. In this work, an ME of 12% and an RMSE of 12% was achieved using the modified integral control law for a 25-Hz modified triangle wave reference signal with 13.5-μm amplitude when there is a dominant vibration mode at 704 Hz.

When applying RC, the tracking performance is significantly improved. In this work, the analog implementation achieved an ME of 0.63% and an RMSE of 0.31% for a 50-Hz triangle wave reference signal with 15-μm amplitude when there is a dominant vibration mode at 704 Hz. This constitutes an improvement of two orders of magnitude compared to the case when only applying a damping and tracking control law.

Experimental results for a similar system using discrete-time RC can be found in [11]. Comparing the results, the presented continuous-time scheme will perform on par with the common discrete-time RC implementation that uses high-order zero-phase tracking error control (ZPETC) model-inversion and signal model bandwidth limitation using zero-phase filtering [42,20]. The discrete-time implementation in [11] achieved an ME of 0.83% and an RMSE of 0.10% for a 40-Hz triangle wave reference signal with 5-μm amplitude when there is a dominant vibration mode at 520 Hz.

2. System description and modeling

2.1. Mechanical model

The nanopositioning stage used in this work is shown in Fig. 1, where the serial-kinematic motion mechanism is designed such