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Large dynamic range nanopositioning using iterative learning control

Gaurav Parmar*, Kira Barton, Shorya Awtar

Department of Mechanical Engineering, University of Michigan, 2350 Hayward Street, Ann Arbor, MI 48109, United States

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ABSTRACT

This paper presents the control system design and tracking performance for a large range single-axis nanopositioning system that is based on a moving magnet actuator and a flexure bearing. While the physical system is designed to be free of friction and backlash, the nonlinearities in the electromagnetic actuator as well as the harmonic distortion in the drive amplifier degrade the tracking performance for dynamic commands. It is shown that linear feedback and feedforward proves to be inadequate to overcome these nonlinearities. This is due to the low open-loop bandwidth of the physical system, which limits the achievable closed-loop bandwidth given actuator saturation concerns. For periodic commands, like those used in scanning applications, the component of the tracking error due to the system nonlinearities exhibits a deterministic pattern and repeats every period. Therefore, a phase lead type iterative learning controller (ILC) is designed and implemented in conjunction with linear feedback and feedforward to reduce this periodic tracking error by more than two orders of magnitude. Experimental results demonstrate the effectiveness of ILC in achieving 10 nm RMS tracking error over 8 mm motion range in response to a 2 Hz band-limited triangular command. This corresponds to a dynamic range of more than 10^5 for speeds up to 32 mm/s, one of the highest reported in the literature so far, for a cost-effective desktop-sized single-axis motion system.

1. Introduction and background

Nanopositioning is one of the key enabling technologies for measurement and manipulation of matter at the micro and nano scales [1]. Because of their nanometric (<10 nm) *motion quality* (accuracy, precision, and resolution), nanopositioning systems are employed in various sensitive applications that require relative scanning motion between a probe and a substrate. However, one of the main drawbacks of currently available nanopositioning systems is their small motion range of a few hundred microns per axis [2,3]. Increasing this range to several millimeters will enable large-size substrates in a number of applications such as scanning probe microscopy [4], scanning probe lithography [5], scanning beam lithography [6], and nanometrology [7].

The ongoing research efforts in the area of large range translational nanopositioning systems can be broadly classified into three categories. The first category is of positioning systems that have friction and backlash in one or more of their physical components, such as the bearing or transmission. The motion stage in these cases is supported by rolling [8–10] or sliding [11–13] guideways. Either direct-drive linear motors [9,12,13] or rotary motors coupled with lead-screw drives [8,10,11,14] are used for actuation. For these systems, linear feedback controllers do not offer adequate positioning performance due to the nonlinear and parameter-varying characteristics of friction, especially in the micro-dynamic regime [15]. Implementation of advanced controllers [8,10,13] has shown some performance improvements over linear feedback, especially for point-to-point positioning. However, achieving nanometric tracking performance for dynamic commands remains to be a challenge.

To overcome the performance limitations associated with friction, another approach has been to mount a small range, high motion quality positioning system (fine stage) on top of a large range, friction-based traditional motion system (coarse stage) [9,11,12,14]. The idea is to use the fine stage to compensate for the positioning errors of the coarse stage, thereby improving the overall positioning performance. The major challenge here, in achieving nanometric tracking performance, lies in the control system design to ensure coordination between the coarse and fine motion systems [14].

Separately, there has been a considerable effort focused on large range nanopositioning systems that are based on non-contact and frictionless operation. These systems rely on magnetic [16–18], aerostatic [19–22], or flexure bearings [2,23,24] for motion guidance, and generally employ direct-drive electromagnetic actuators. Each of these constructions presents unique control design challenges to achieve nanometric motion quality. For example, electromagnetic bearings and well as actuators suffer from force-stroke nonlinearities [17]. Additionally, the noise

* Corresponding author. Tel.: +1 7342392928.
E-mail address: parmar@umich.edu (G. Parmar).

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and distortion in the actuator driver degrades the positioning performance [24], also shown later in this paper. Air bearings exhibit sustained vibrations in both load-bearing as well as motion direction [25,26]. In case of flexure bearings, one of the major drawbacks has been their limited range of motion. Recent research [2,27] has shown up to 10 mm motion range in multi-axis flexure bearings, which is sufficient for intended applications. However, poorly damped high frequency poles and zeros in flexures limit the closed-loop performance [2]. Additionally, they require higher actuation effort to overcome the spring stiffness.

The motion quality of nanopositioning systems is dictated by the tracking error, which is the difference between the commanded and the measured position. Tracking error may be evaluated for either point-to-point positioning commands or for path-following commands. Point-to-point positioning is concerned with moving the motion stage from one point to another and staying there for some finite period of time. Only the final position is relevant and the path taken to reach that position is not. On the other hand, in the more general case of path-following, such as raster scanning, the motion stage is moved along a periodic trajectory in time and space, and position at each point along this trajectory is important. Obtaining nanometric tracking performance for such dynamic commands is relatively challenging because a linear controller may not provide adequate command following and disturbance rejection over a desired finite frequency range. While many of the above-mentioned references [2,8–10,16–18,20–24] have reported large range (>1 mm) and high resolution (<10 nm *Root Mean Square* or RMS) for point-to-point positioning commands, only a few have shown nanometric positioning performance for dynamic commands over a large motion range (Table 1). It should be noted that due to differences in the motion range, frequency content, and type of command trajectory used, it is not possible to compare the tracking performances of these systems in a consistent manner. However, it can be observed that the nanometric tracking performance is reported either over a small motion range or for slower or quasi-static commands.

Although lithographic steppers and scanners used in semiconductor manufacturing do provide large range and nanometric motion quality at relatively higher speeds [28], these machines are not targeted toward niche low-cost desktop applications mentioned before. Achieving such specifications in a cost-effective and desktop-sized setup is still a challenging problem, which is the focus of this paper.

In previous work [29], the design, fabrication, and testing of a single-axis nanopositioning system employing a flexure bearing and moving magnet actuator was presented. Point-to-point nanometric positioning performance was demonstrated over the entire motion range. However, nonlinearities associated with the actuator as well as the driver resulted in inadequate tracking performance in response to dynamic commands. In this paper, design and implementation of a classical feedback controller along with an iterative learning controller is presented to overcome these nonlinearities in order to achieve nanometric tracking performance for dynamic commands over a large motion range. In Section 2, the physical system is described along with its open-loop characterization. Next, in Section 3, it is shown that a linear feedback and feedforward controller by itself offers inadequate performance. This is because of the limited sensitivity reduction that is possible by employing a feedback loop, given actuator saturation and low open-loop bandwidth of the system. For scanning-type applications, in which the command is a periodic signal, the deterministic part of the error arising due to nonlinearities also repeats every period. This provides the motivation to employ iterative learning control (ILC) to reduce the repeating portion of the tracking error. Since its inception in early 1980s, ILC has seen tremendous applications in the fields of robotics [30] and motion systems [31,32]. Some of the advantages of ILC include its linear formulation, minimal knowledge of plant dynamics, simple design and implementation, and that fact that it can be applied to any existing feedback control system [30]. A brief introduction to ILC is presented in Section 4 followed by the design and implementation of a lead type ILC in conjunction with the existing feedback and feedforward controller. Experimental results, reported in Section 5, demonstrate more than two orders of magnitude reduction in the tracking error while following dynamic commands, when compared to the performance obtained with a linear feedback and feedforward controller only. Concluding remarks are presented in Section 6.

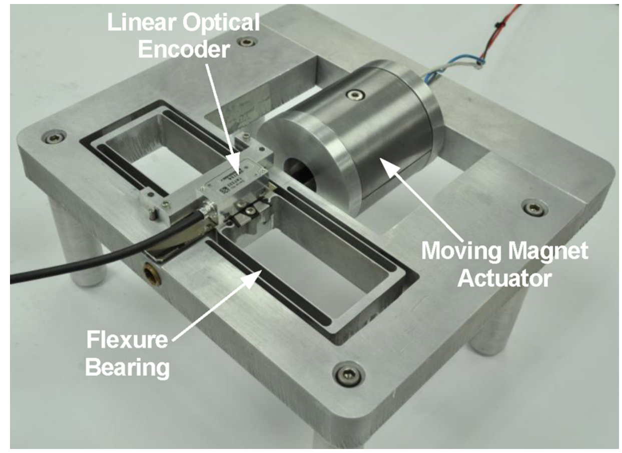

Fig. 1. Single-axis nanopositioning system.

2. Physical system description

The single-axis nanopositioning system prototype used in this work is shown in Fig. 1. This setup consists of a symmetric double parallelogram flexure bearing and a moving magnet actuator (MMA). A linear optical encoder (RELM scale, Si-HN-4000 read-head, and SIGNUM Interface from Renishaw) with 5 nm quantization steps is used for position measurement and feedback. The encoder read-head is mounted on the local ground of the flexure bearing and the scale is mounted on the motion stage. Hence, the sensor output is the relative displacement of the motion stage with respect to the local flexure ground. The physical construction of the system provides frictionless and backlash-free motion over a motion range of 8 mm. The detailed design and fabrication of the experimental setup can be found in [29]. A custom-made voltage amplifier (based on the MP111 power-OpAmp from Cirrus Logic) with a gain of 5 V/V and a bandwidth of 10 kHz is used to drive the MMA. The control system is implemented on a real-time hardware (DS1103 from DSpace) equipped with 16-bit digital-to-analog converter. While the sampling frequency and the loop rate are fixed at 10 kHz, all the measurements shown in this paper are taken at a bandwidth of 1 kHz.

In order to design a linear feedback controller, a linearized frequency domain model of the system is needed. Although, as mentioned later in this paper, there are known sources of nonlinearities in the system, they can be neglected for the purpose of obtaining a linearized plant model. The open-loop frequency response of the nanopositioning system was found experimentally via broadband FFT-based system identification technique. For this purpose, a chirp signal with a frequency content of 1–1000 Hz was sent as the input to the amplifier. The amplitude of the chirp signal was chosen to restrict the maximum displacement of the stage to be <10 μm. Next, the Matlab function *invfreqs* was used to fit a continuous-time stable transfer function, $P(s)$, to the open-loop frequency response,