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Robust adaptive backstepping control for piezoelectric nano-manipulating systems ☆

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ABSTRACT

In this paper we present a systematic modeling and control approach for nano-manipulations of a two-dimensional PZT (piezoelectric transducer) actuated servo stage. The major control challenges associated with piezoelectric nano-manipulators typically include the nonlinear dynamics of hysteresis, model uncertainties, and various disturbances. The adverse effects of these complications will result in significant performance loss, unless effectively eliminated. The primary goal of the paper is on the ultra high precision control of such systems by handling various model uncertainties and disturbances simultaneously. To this end, a novel robust adaptive backstepping-like control approach is developed such that parametric uncertainties can be estimated adaptively while the nonlinear dynamics and external disturbances are treated as bounded disturbances for robust elimination. Meanwhile, the L_2-gain of the closed-loop system is considered, and an H_∞ optimization problem is formulated to improve the tracking accuracy. Numerical simulations and real time experiments are finally conducted, which significantly outperform conventional PID methods and achieve around 1% tracking error for circular contouring tasks.

1. Introduction

With the rapid development of nanoscience and nanotechnology, PZT actuated servo stages have been successfully applied to many emerging industrial areas to achieve nano-scale manipulations [1–3]. Representative applications include atomic force microscopes (AFM), electron beam direct-write lithography, computer Hard Disk Drives, and fast tool servo in computer numerical control (CNC) machines, all of which require very high-bandwidth tracking accuracy as well as good disturbance rejection capability. A typical PZT actuated nano-manipulating system consists of four major components: a flexure-hinge-based mechanism, displacement sensors, a PZT driving circuit, and piezoelectric ceramic actuators (PCA). Compared with conventional mechatronic systems, the nano-manipulator has many advantages [4] such as: (1) motions are generated through elastic deformation without frictions; (2) the actuators can tolerate large loads; (3) very high resolution and fast response. However, the PZT actuators also have some challenging dynamical behaviors which complicate the

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control design, such as hysteresis and saturation nonlinearities, multiple low damped resonant modes, and creeping phenomenon [4–6]. Furthermore, various external disturbances, such as vibration and measurement noise, have significant adverse effects on system precision at nano-scale. Therefore it is quite a challenging task to develop a general control architecture for PZT nano servo stages to handle system uncertainties and nonlinearities, as well as disturbance rejections [7].

Note that the complicated dynamics in PCA nano stages, including the hysteresis, unmodeled dynamics and other perturbations, can be merged into the disturbances. Disturbance rejection control approaches have attracted significant research efforts for both linear systems and nonlinear systems. Some representative methods [8] include active disturbance rejection control (ADRC), disturbance observer based control (DOBC) and composite hierarchical anti-disturbance control (CHADC), among the abundant results in the literature.

The early ADRC concept was proposed in [9], and received more and more attentions due to its applicability to engineering problems, such as vibration suppression [10], voice coil motor-driven fast tool servo systems [11], permanent magnet synchronous motors [12] and so on. However, the rigorous theoretical analysis of its stability, as well as performance specifications, is generally difficult due to the nature of ADRC control structure [13]. Alternatively DOBC approaches are well studied for anti-disturbance control and widely used in various system designs [14–21]. Particularly the DOBC approaches have been explored for piezoelectric actuators in micro/nano servo systems. For example, a disturbance observer was introduced in [14] to estimate and compensate the hysteresis nonlinearity. and a DOBC framework was utilized to deal with the hysteresis compensation error in [20,21]. However, DOBC methods require accurate system model (or sufficient information about the disturbance dynamics) to construct the disturbance observer, which limits their applications for real engineering problems, particularly for the cases with nonlinear observers.

Considering the application limitations of existing methods, we propose a novel robust adaptive backstepping-like control (RABC) structure based on H_∞-control design method with disturbance attenuation for ultra high precision control of an X-Y PZT actuated nano-manipulator, such that various model uncertainties and disturbances can be handled simultaneously. The nonlinear hysteresis effect of the nano-stage is also analyzed using a backlash-like hysteresis model [22], and is further considered as part of the bounded disturbances.

The rest of this paper is organized as follows. Section 2 begins with a brief description of the piezoelectric positioning stage, and various aspects of the system modeling are discussed. A novel robust adaptive backstepping-like controller is proposed in Sections 3. The simulation results are given by Section 4, followed by real time control experiments and comparisons on the X-Y piezoelectric nano-stage in Section 5. Conclusion remarking are finally collected in Section 6.

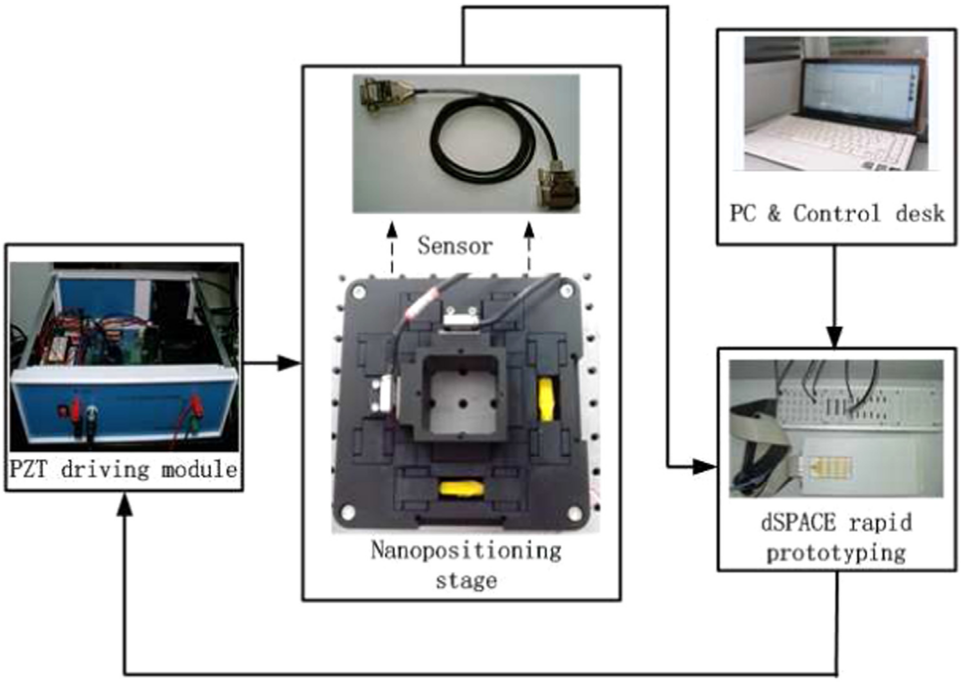

Fig. 1. Architecture of a piezoelectric positioning system.

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