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A disturbance observer-based adaptive control approach for flexure beam nano manipulators

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A B S T R A C T

This paper presents a systematic modeling and control methodology for a two-dimensional flexure beam-based servo stage supporting micro/nano manipulations. Compared with conventional mechatronic systems, such systems have major control challenges including cross-axis coupling, dynamical uncertainties, as well as input saturations, which may have adverse effects on system performance unless effectively eliminated. A novel disturbance observer-based adaptive backstepping-like control approach is developed for high precision servo manipulation purposes, which effectively accommodates model uncertainties and coupling dynamics. An auxiliary system is also introduced, on top of the proposed control scheme, to compensate the input saturations. The proposed control architecture is deployed on a customized-designed nano manipulating system featured with a flexure beam structure and voice coil actuators (VCA). Real time experiments on various manipulating tasks, such as trajectory/contour tracking, demonstrate precision errors of less than 1%.

1. Introduction

The design and control of micro/nano manipulators has become one of the key enabling technologies in many emerging industry areas with ultra-high precision requirements. Some successful applications include the lithography and fabrication equipments [1], the scanning probe microscopy [2] and the atomic force microscope [3], to name just a few.

Some advanced designs of nano manipulators are based on the structure of flexure hinges driven by piezoelectric stack actuators (PSA). However, the PSA based systems have general difficulties to deliver strokes of more than 1 mm, even if the lever transmission mechanisms are used to amplify the output displacement [4,5]. In order to achieve larger strokes without significant sacrifice of precision, some recent results discussed the design of flexure beam based structure driven by voice coil actuators (VCAs) [6,7]. Such servo stages have many merits: (1) a large motion stroke (up to 1.5 mm); (2) reduction of various nonlinear dynamics such as hysteresis and creeping behavior [8,9]; (3) motions are generated through elastic deformation without frictions.

For two dimensional *XY* micro/nano servo systems, some dynamical behaviors inherited from mechanical designs are challenging from control perspectives. In particular, the existence of cross-axis coupling, model uncertainties, as well as nonlinearities such as input saturations has significant impact on system precisions, and complicates controller designs. For example the effects of cross-axis coupling are discussed for multi-axis compliant mechanisms supporting micro/nano manipulation [10–12]. The presence of cross-axis coupling increases the complexity in modeling and control of such systems [13]. Furthermore, large cross-axis coupling can damage the VCAs [14–16]. Considering the adverse impact of this issue, many recent research works focus on innovations from the aspect of mechanical designs. In [17], the cross-coupling is eliminated by building serial mechanisms. Nevertheless, this strategy results in a non-uniform performance. In [15,16,18,19], parallel kinematic chains are used to improve cross-axis coupling. However, cross-axis coupling cannot be fully eliminated. Therefore, it is still necessary to resolve the problem by controller designs.

Note that the complicated dynamical behaviors of *XY* micro/nano manipulators, including cross-axis coupling, parametric uncertainties, can be practically treated as disturbances, where the linear portion of the dynamics is used as a nominal plant. Some representative disturbance rejection approaches include active disturbance rejection control (ADRC) and disturbance observer

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based control (DOBC). The ADRC methods simplify the controller design by employing extended state observers (ESO) to estimate disturbances and high order dynamics, which received more and more attentions due to its applicability to engineering problems. For example, the ADRC scheme was used to ensure the performance of vibration suppression in [20]. In [21], a linear ADRC controller was developed for the non-circular machining problem with estimation and compensation of parameter uncertainties and cutting load variations. For solving the tracking problem for permanent magnet synchronous motors, a novel ADRC-based method was proposed in [22]. Note that, however, the rigorous theoretical analysis of the ADRC based feedback control systems is generally difficult. Alternatively, DOBC strategies have been well studied for anti-disturbance control and widely used in both linear systems and nonlinear systems. For example, LMI-based DOBC algorithms were considered to deal with the disturbance rejection problem for a class of nonlinear systems [23]. In [24], the DOBC method was extended to solving the problem of multiple disturbances for Markovian jump systems. By integrating DOBC with $\mathcal{H}_\infty$ and terminal sliding mode controls, the composite control laws were presented in [25,26]. In [27], a novel nonlinear disturbance observer was developed to estimate the disturbances generated by an exogenous system. Meanwhile, the DOBC approaches have been applied in robotic manipulators [28,29].

In this paper, a disturbance observer-based adaptive backstepping-like control (DOABC) methodology is proposed for a flexure beam-based *XY* servo stage supporting micro/nano precision manipulation tasks. In the proposed control architecture, a new disturbance observer is developed to estimate the cross-axis coupling, parametric uncertainties, and other disturbances. By combining the disturbance observer with adaptive backstepping-like control, the DOABC algorithm is constructed for ultra high precision servo manipulations. Considering the limited actuator stroke of the servo stage, an auxiliary control structure is also introduced to compensate the input saturation nonlinearity. Finally, the numerical simulations and real time experiments demonstrate the effectiveness of the proposed control scheme.

The rest of this paper is organized as follows. Section 2 briefly describes the modeling of the flexure beam-based *XY* servo stage. In Section 3, the DOABC algorithm is proposed, and the stability of the closed-loop system is discussed. The simulation results are given in Section 4, followed by real time control experiments on the flexure beam-based *XY* nano-manipulator in Section 5. Finally, some conclusions are collected in Section 6.

2. Modeling of a flexure beam-based *XY* micro/nano servo stage

2.1. Description of a flexure beam-based XY micro/nano servo stage

The experimental setup of this study is a bi-axial micro/nano positioning stage (as shown in Fig. 1). To achieve large stroke and high precision motions in *X* and *Y* directions, the mechanical design of the motion stage employs a novel compact flexure mechanism consisting of Z-shaped and Π-shaped flexures as well as 4-bar supporting flexures, to reduce the error motions and motion coupling behaviors (as depicted in Fig. 2). A prototype of the motion stage is monolithically machined by Al 7075-T6 by means of the Wire Electric Discharge Machining (WEDM).

Based on the proposed motion stage, a nano-manipulating servo system is generated. Two identical voice coil actuators are instrumented delivering a stroke of 12.7 mm on each direction. The VCAs are driven by high bandwidth current amplifiers. Two linear encoders with a resolution of 5 nm are used to generate real time displacement feedback for control purpose. Meanwhile a RENISHAW laser interferometer is also implemented to provide a stand-alone measurement of the output displacement with a range up to 1.5 mm × 1.5 mm. Real time control of the servo system is achieved by using the dSPACE-R1103 rapid prototyping system and Matlab/Simulink. It is worth mentioning that the *XY* flexure beam-based micro/nano stage has the identical dynamical model in *X* and *Y* directions, thanks to the design of the symmetric structure.

2.2. Electromechanical modeling

The overall dynamics of the servo stage consists of mechanical and electrical parts, where as the power amplifier is designed with a very high bandwidth of 20 kHz, it can be assumed that the dynamics from the controlled voltage input to the amplified current is a constant gain. For the mechanical part, with reasonable assumptions and simplifications, its dynamic model can be considered as a 5-DOF mass–spring system shown in Fig. 3. According to Newton's laws, the dynamical equation from thrust force to the output displacement, in any direction, can be described as

$$m\ddot{x}(t)+c_z\dot{x}(t)+k_zx(t)=F_A, \tag{1}$$

where F_A denotes the transduced force from the electrical domain, and the parameters m, c_z, and k_z represent the equivalent mass, damping

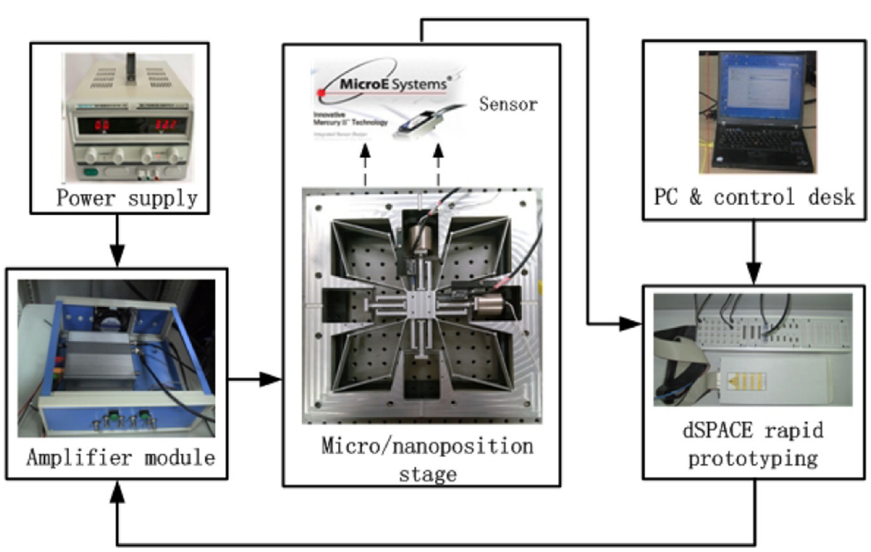

Fig. 1. Architecture of a flexure beam-based *XY* micro/nano servo stage.