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An adaptive integral sliding mode control approach for piezoelectric nano-manipulation with optimal transient performance☆

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ABSTRACT

This paper presents a control framework supporting high precision tracking of a piezoelectric nano-manipulating system with guaranteed transient performance, where a modified dynamic model describing the hysteresis behavior is also proposed. To achieve the desired optimal transient performance, a dynamic hysteresis compensation based control approach is developed by employing robust adaptive integral sliding mode control technique to accommodate both hysteresis nonlinearities and model uncertainties. An adaptive law is designed to estimate the gain of the integral sliding mode controller such that the chattering behavior is alleviated and the upper bound of uncertainties is no longer required a priori. In particular, it can be proved that the tracking error converges to zero in a finite time. The proposed control architecture is applied to a PZT actuated nano-manipulating stage, where real time implementations demonstrate excellent tracking performance with tracking error around 4.6‰for multi-frequency trajectory tracking experiments. Comparisons with existing results are also given, where significant improvements are achieved in various tracking scenarios.

1. Introduction

Piezoelectric nano-manipulating systems play a key role in various emerging areas [1] such as micro-/nanomanipulation [2–4], atomic force microscope (AFM) [5], high precision machining [6], and three dimensional printing [7]. Advanced applications of nano-manipulators, such as AFM scanning, require ultra high dynamical performance during tracking motions, which poses major challenges for control design to achieve the desired transient performance and robustness in the presence of hysteresis nonlinearities and system uncertainties [8,9].

Motivated by these open challenges, significant effort has been made to seek appropriate control strategies based on the modeling of hysteresis for compensation purposes, where some representative hysteresis models include Preisach model [10], Bouc–Wen model [11], Prandtl-Ishlinskii model [12–14], and hysteresis friction model [15–17,23,26]. However, the former three models with a complex mathematical structure usually require significant computation during control implementations and may result in performance degradation [18]. By comparison, hysteresis friction model is simpler for implementation, because its parameters can be retrieved easily.

Given a hysteresis model, various control schemes have been studied to compensate the impact of hysteresis and improve the control performance. To better handle the compensation errors, significant research efforts have been given with some representative results such as disturbance observer-based backstepping control [19], adaptive control [20,21], and sliding mode control [14,22]. Among these techniques, sliding mode control has been proved to be effective for dealing with system nonlinearities [23]. However, the existing sliding mode control such as [14,22] with a fixed discontinuous control gain may result in undesirable output chattering, which would deteriorate the robustness of the closed loop control system. Moreover, optimal transient performance (which is critical for nano-manipulations) is seldom discussed in the above literatures.

In this paper, a modified dynamic hysteresis model based on the hysteresis friction model is proposed to compensate the hysteresis nonlinearities of the piezoelectric nano-manipulator, where a dual-observer structure is also designed to estimate the unmeasurable state of the proposed dynamic hysteresis model. To overcome the shortcomings of existing results such as [14,22], a robust adaptive integral sliding mode control approach is introduced to improve the system robustness and alleviate the chattering phenomenon. Based on the prescribed performance index, an optimal control method is also incorporated to

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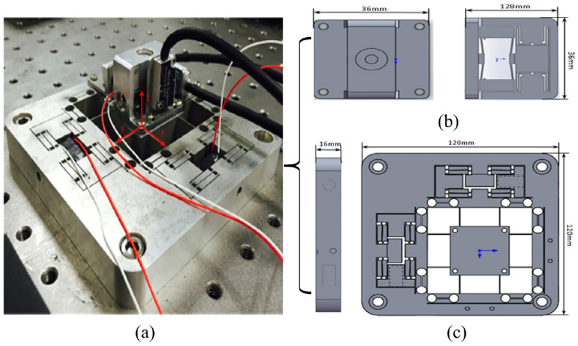

Fig. 1. (a) Prototype of a piezoelectric nano-manipulator. (b) Z nano-stage. (c) XY nano-stage.

guarantee the finite-time convergence of the tracking error to zero. Finally, a piezoelectric nano-manipulation platform is established, where real time implementations of the proposed control architecture are successfully deployed, demonstrating excellent tracking performance with significant improvement over representative results in the literature.

2. Modeling of a piezoelectric nano-manipulator

In this section, a piezoelectric nano-manipulator (as depicted in Fig. 1) is considered, where a general dynamic model will be established accordingly.

2.1. Description of the piezoelectric nano-manipulator

As shown in Fig. 1, the piezoelectric nano-manipulator consists of a parallel XY nano-stage and a Z nano-stage mounted on top of the XY platform. Three identical piezoelectric ceramics with a free stroke of 25.7 μm at 150 V and a stiffness of 80 N/μm are utilized to drive the nano-stage. The corresponding three driving modules are designed to provide 20 times amplified voltages for the piezoelectric ceramics. To achieve large travel stroke, a bridge type displacement amplification mechanism is employed to amplify the output displacement of the piezoelectric ceramics. The central motion platform is connected to the fixed frame through four leaf springs, where the leaf springs act as the guiding mechanism. A prototype of the piezoelectric nano-manipulating stage is monolithically machined by AL 7075-T6 using the wire electric discharge machining (WEDM) method.

2.2. Dynamics of the piezoelectric nano-manipulator

The model of a piezoelectric nano-manipulating system includes both the electrical and mechanical aspects. In particular, the linear capacitance in parallel with the electromechanical transformer having a ratio of T_{El} and the hysteresis effect caused by the piezoelectric actuators are considered in the electrical part. And the mechanical part is regarded as a mass-spring-damper system in X, Y, and Z directions.

The general form of the electromechanical model for piezoelectric actuated servo stages can be referred to [24]. In this particular case, the dynamical model of the three-dimensional piezoelectric nano-manipulating stage can be represented by the following equation:

$$m_l\ddot{x}_l + b_l\dot{x}_l + k_lx_l = T_{El}k_{aml}u_l - F_{Hl} + d_l, \tag{1}$$

where the index l=X, Y, or Z (X, Y, and Z denote the three-dimension coordinates). The variable m_l denotes the effective mass of the moving plate of the nano stage, x_l, $\dot{x}_l$, and $\ddot{x}_l$ denote the displacement, velocity, and acceleration, respectively. The variables b_l and k_l are the damping and stiffness of the nano stage, respectively, k_{aml} represents a fixed amplification gain, and F_{Hl} denotes the hysteresis friction force which will be determined later. Meanwhile d_l represents the unmodeled lumped dynamics such as high-frequency vibrational modes and cross-coupling effects with $|d_l| \le D_l$.

A large number of experiments demonstrate that the piezoelectric nano-manipulating stages inevitably exhibit strong asymmetric and rate-dependent hysteresis phenomena [25,26]. In this paper, a modified differential equation-based model is used to represent the hysteresis behavior, resulting from the combined effect of the nonlinear flexibility of the compliant mechanism and the equivalent friction. Note that the output displacement x_l depends not only on the current hysteresis friction force but also all the preceding hysteresis friction force. Motivated by [27], the equivalent friction model can be expressed as

$$F_{fl} = \beta_{0l}z_l + \beta_{1l}\dot{z}_l + \beta_{2l}\dot{x}_l, \tag{2}$$

$$\dot{z}_l = \sigma_{0l}\dot{x}_l - \sigma_{1l}|\dot{x}_l|z_l, \tag{3}$$

where F_{fl} denotes the equivalent friction force function, z_l denotes the internal friction state, β_{0l}, β_{1l}, and β_{2l} are the bristle stiffness, bristle damping, and viscous damping-coefficient, respectively. Meanwhile σ_{0l} and σ_{1l} represent the static friction parameters. To demonstrate the effectiveness of the model given by (2) and (3), both the sinusoidal input $u_X = 1 - \sin(10\pi t + \pi/2)$V and the multi-frequency input $u_X = 3 - 1.8\sin(40\pi t + \pi/2) - 1.2\sin(32\pi t + \pi/2)$ are used to drive the piezoelectric nano-manipulating stage in X-axis. The parameters of the model (2) and (3) are chosen as $\sigma_{0X} = 30, 500, \sigma_{1X} = 20, 500, \beta_{0X} = 1250$, $\beta_{1X} = 15$, and $\beta_{2X} = 1005$ for the sinusoidal excitation. For the case of the multi-frequency excitation, the model parameters are given by $\sigma_{0X} = 1 \times 10^{-3}$, $\sigma_{1X} = 2 \times 10^{-5}$, $\beta_{0X} = 1.06 \times 10^4$, $\beta_{1X} = 52.5$, and $\beta_{2X} = 1.15 \times 10^{-4}$. As depicted in Figs. 2 and 3, the equivalent friction model can well represent the hysteresis effect of the piezoelectric nano-manipulator. The cases in both Y-axis and Z-axis are quite similar and thus omitted here.

On the other hand, the relationship between the hysteresis friction force F_{Hl} and the corresponding displacement x_l, across the compliant mechanism, are usually determined by a nonlinear function $\Psi_{sl}(x_l)$, where Ψ_{sl} is the stiffness curve depending on the characteristics of the compliant mechanism [25,28]. As a result, the hysteresis friction model can be derived in the following:

$$F_{Hl} = \Psi_{sl}(x_l) + F_{fl}, \tag{4}$$

where the corrective term $\Psi_{sl}(x_l)$ is an analytical odd polynomial function. Substituting (2) and (3) into (4), we have

$$F_{Hl} = \Psi_{sl}(x_l) + \beta_{0l}z_l - \beta_{1l}\sigma_{1l}|\dot{x}_l|z_l + (\beta_{1l}\sigma_{0l} + \beta_{2l})\dot{x}_l. \tag{5}$$

Using (5), we can rewrite Eq. (1) as

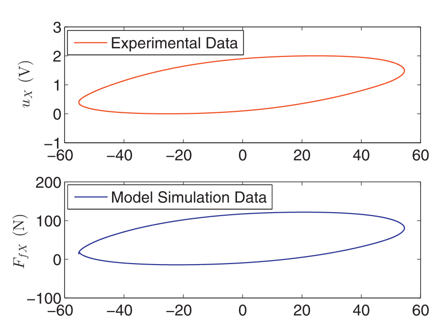

Fig. 2. Comparisons of the hysteresis loops between the experimental result and the model simulation result for the sinusoidal excitation.