

Preface

Micro-/nano-positioning systems are positioning devices that are capable of producing displacement down to micro-/nano-meter resolution and accuracy. As typical ultrahigh-precision positioning devices, piezoelectric micro-/nano-positioning systems are driven by piezoelectric actuators (PEAs). They have found extensive applications in fields involving scanning probe microscopy, lithography manufacturing, and wafer alignment. In addition, these devices have also been applied in precision micro-/nano-manipulation and assembly domains.

Piezoelectric micro-/nano-positioning systems usually exhibit low damping, which causes the structural vibration problem. In addition, PEA introduces non-linearity into the system in terms of piezoelectric hysteresis and drift effects. The hysteresis is a nonlinear relationship between the applied voltage and output displacement of the PEA and induces a severe open-loop positioning error as high as 10–15 % of the travel range. Thus, the hysteresis has to be suppressed in high precision applications. Moreover, the nonlinearity poses a great challenge in combined position and force control of piezoelectric micro-/nano-positioning devices dedicated to micromanipulation tasks.

This book is focused on enabling technologies in the control implementation of piezoelectric micro-/nano-positioning systems. The book provides a collation of the state of the art of emerging techniques to precision motion control of micro-/nano-positioning systems actuated by PEAs. It covers both feedforward and feedback control strategies for positioning and tracking control of piezoelectric actuation micro-/nano-positioning systems. This book also demonstrates the joint position and force control of piezoelectric micro-/nano-positioning systems in micromanipulation applications. A comprehensive treatment of the subject matter is provided in a manner amenable to readers ranging from researchers to engineers, by providing detailed experimental verifications of the developed approaches.

The book begins with an introduction to piezoelectric micro-/nano-positioning system and provides a brief survey of its development and applications. According to different realizations of the control strategies, the remaining ten chapters are divided into four parts.

Part I consists of Chaps. 2 and 3, which addresses the hysteresis mode-based feedforward control technology. Chapter 2 extends least squares support vector machines (LSSVM) to the domain of rate-dependent piezoelectric hysteresis modeling and compensation. A LSSVM-based rate-dependent hysteresis model is proposed for a PEA by introducing the current input value and input variation rate as one data set to construct a one-to-one mapping. The adoption of the input variation rate allows the capture of the rate dependency of the hysteresis. For comparative studies, the widely used Bouc–Wen and modified Prandtl–Ishlinskii (MPI) hysteresis models are implemented. The hysteresis nonlinearity is suppressed by a hybrid control which employs an LSSVM inverse model-based feedforward controller combined with a proportional-integral-derivative (PID) feedback controller.

Chapter 3 addresses the identification and compensation of the rate-dependent piezoelectric hysteresis using an intelligent hysteresis model, while without modeling the hysteresis inverse. Generally, both a hysteresis model and an inverse hysteresis model are required for hysteresis identification and compensation purposes. In this chapter, an LSSVM-based hysteresis model is established and a feedforward compensator is developed based on a single model, which provides a computationally efficient way in hysteresis compensation.

Chapters 4 and 5 construct Part II, which presents the hysteresis mode-free, state observer-based control schemes. The merit of such schemes lies in that no hysteresis model is required. The unmodeled hysteresis is considered as an uncertainty or a disturbance to the nominal system, which is tolerated by an advanced robust or adaptive controller. Chapter 4 reports on a model predictive discrete-time sliding-mode control (MPDTSMC) to achieve the advantages of both model predictive control (MPC) and discrete-time sliding-mode control (DTSMC). It is shown that the proposed MPDTSMC with proportional-integral (PI) action drives the system state to slide in a vicinity of the sliding surface with a boundary layer of thickness $O(T^3)$ (T is the sampling time), which is much lower than a commonly designed DTSMC with $O(T)$ boundary layer in the sliding mode. In addition, the state tracking error of the order $O(T^2)$ is achieved with the presented control scheme. The theoretical analysis and effectiveness of the PI action in the control scheme are verified by experimental studies carried out on a nanopositioning platform.

Chapter 5 presents the design and implementation of a more desirable output-based DTSMC strategy, called model predictive output integral discrete-time sliding-mode control (MPOIDSMC), for micro-/nano-positioning applications. The presented strategy is capable of improving the system performance by integrating MPC, output integral discrete-time sliding-mode control (OIDSMC), and state observer techniques together. A sliding-mode observer is adopted to estimate the system state and to suppress the spillover effects. It is demonstrated that the integrated scheme eliminates the chattering effect by forcing the system trajectory to a vicinity of the sliding surface with a boundary layer of thickness $O(T^3)$ in an optimal manner, and achieves an output tracking error of the order $O(T^2)$. The theoretical analysis and effectiveness of the proposed strategy are validated by experimental studies.

Part III includes Chaps. 6–9, which addresses the strategy of hysteresis model-free, state observer-free digital feedback control. Generally, the DTSMC can be categorized into state-based and output-based methods. The implementation of either method usually requires the state feedback of the system. A state observer is indispensable for the practical realization of DTSMC, which complicates the control design procedure. In addition, an improperly designed state observer may cause instability of the system. Hence, it is desirable to eliminate the use of state observers. Chapter 6 proposes the design of a digital sliding-mode control (DSMC) for a piezoelectric micro-/nano-positioning system with a simple second-order plant model. The local stability of the closed-loop system is proved theoretically and the effectiveness of the proposed scheme is validated through experimental investigations.

Chapter 7 reports an input–output-based DSMC (IODSMC) algorithm for precision motion tracking of a class of piezoelectric micro-/nano-positioning systems, which can be described by a high-order linear model preceded by disturbances. Its implementation requires an input–output data-based model only, whereas neither a hysteresis model nor a state observer is needed.

Chapter 8 presents a digital sliding-mode prediction control (DSMPC) scheme for precision motion tracking of a class of piezoelectric micro-/nano-positioning systems, which can be represented by a high-order linear model preceded by disturbances. Its implementation does not require the knowledge of system states. The overall control action of the proposed DSMPC scheme involves equivalent control, switching control, and predictive control.

Chapter 9 devises a model-reference adaptive control (MRAC) scheme to compensate for the unmodeled hysteresis effect of a class of PEA-actuated systems which possess a second-order nominal model. By treating the uncertainties as a lumped perturbation to the nominal system, a scheme of MRAC with perturbation estimation (MRACPE) is developed and validated on a micropositioning system. Compared with the existing work, the presented scheme allows the predesign of the maximum tracking error. It is capable of estimating the unmodeled perturbation of the system.

Part IV is composed of Chaps. 10 and 11, which deal with the technique of position and force joint control for micromanipulation applications. As a typical micro-/nano-positioning device, microgripper is a crucial tool to realize the grasp–hold–release operation in micromanipulation tasks. To avoid damaging the grasped fragile microobjects and the microgripper itself, an interaction control is critical to regulate the desired position and contact force simultaneously. Chapter 10 presents an adaptive discrete-time sliding-mode generalized impedance control (ADSMGIC) to realize an interaction control of a piezoelectric microgripper dedicated to micromanipulation and microassembly. The control scheme regulates a desired dynamics relation between the position and contact force. The chattering phenomenon is suppressed by employing an adaptive law for the switching gain. The stability of the closed-loop system is proved theoretically and the effectiveness of the interaction control scheme is validated by conducting experimental studies on a piezo-bimorph microgripper system.

Chapter 11 reports on a scheme of position/force switching control to adjust the gripper tip position and gripping force in an alternate manner. An incremental control framework is developed to achieve a smooth transition between the position and force controls for the gripper system. Specifically, in the closing and opening phases, an incremental digital sliding-mode control is devised to cater for the position control. During the contact phase, an incremental-type digital PID force control is adopted. The proposed control algorithm is deployed to a field-programmable gate array (FPGA)-based digital control platform. The feasibility of the scheme is examined by a typical grasp–hold–release operation of a micro copper wire through experimental studies. Its superiority over the conventional approach is demonstrated through experimental comparisons.

This book provides the state-of-the-art coverage of the methodology and algorithms of precision motion control of piezoelectric micro-/nano-positioning systems in the context of control engineering and soft computing. The control approaches involve feedforward control based on intelligent hysteresis model, discrete-time sliding-mode control, model predictive control, and model-reference adaptive control. The book also touches on the combined position and force control in micromanipulation, which is a typical application of micro-/nano-positioning systems. Detailed examples of their implementations are provided. Readers can expect to learn how to design and apply new control approaches to precision motion control of piezoelectric micro-/nano-positioning systems.

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