Guest Editorial
Introduction to the Special Issue on Dynamics and Control of Micro- and Nanoscale Systems

OVER the past two decades, we have observed an explosive growth in the field of nanotechnology, the science of understanding and controlling matter at dimensions of 100 nm or fewer. Nanotechnology involves imaging, measuring, modeling, and manipulating matter at this level of precision. The essential properties of materials at the nanoscale level differ in fundamental ways from the properties of bulk matter. Research in nanotechnology is aimed at understanding and creating improved materials, devices, and systems that exploit these new properties.

It is highly likely that nanotechnology will have a profound impact on the economy of the early 21st century, in a manner similar to the continuing influence of information technology and biotechnology on the creation of wealth in modern economies. The engineering research in nanotechnology is expected to lead to breakthroughs in areas such as health care and medicine, advanced materials, electronics, manufacturing, biotechnology, IT, and defense. As such, there is a strong belief that nanotechnology has the potential to bring about the next industrial revolution for humankind. Being one of the most exciting and important technologies to emerge out of the 20th century, control is a key enabling technology for this rapidly growing field.

The ability to manipulate materials and devices at micro- and nanoscale levels is essential to successful progress of this field. Owing to the continuing demand for greater bandwidth, resolution, and robustness, feedback control has moved from an optional consideration to a necessity in micro- and nanoscale systems. This trend is set to continue and will pose numerous interesting and rewarding challenges to control engineers and researchers. The purpose of this Special Issue on Dynamics and Control of Micro- and Nanoscale Systems is to reveal some of these challenges to the control community—in the hope that this will lead to a more proactive participation from a community that has a lot to offer to further progress in nanotechnology.

This special issue consists of nine regular papers and five brief papers, which cover important research topics of current interest. All manuscripts submitted for possible publication in this Special Issue were rigorously reviewed according to the Transaction's guidelines. A brief overview of this Special Issue follows.

This Special Issue begins with a review paper coauthored by the three Guest Editors, entitled "A Survey of Control Issues in Nanopositioning." Nanopositioning is an important aspect of nanotechnology research which involves precision control and manipulation of materials and devices at a nanoscale. This review paper presents an overview of the available nanopositioning systems and explains the role of advanced control techniques in improving precision, accuracy, and speed of operation of nanopositioning devices. The paper starts by introducing two systems for which nanopositioning is crucial: scanning probe microscopes and dual-stage hard-disk drives. It then goes on to discuss a variety of actuators and sensors utilized in nanopositioning systems. Piezoelectric actuators, possibly the most popular actuating mechanism in ultra-high precision systems, are studied in detail. Moreover, also the most widely used control design methodologies for nanopositionig are discussed, and the paper is concluded by introducing a number of emerging nanopositioning systems and their associated control design challenges.

The paper by Pantazi, *et al.*, entitled "Control of MEMS-Based Scanning-Probe Data-Storage Devices" explains a new approach to data storage and studies some of the control problems associated with this new technology. Probe-based data storage is an alternative approach to conventional data-storage technologies such as magnetic recording. The prototype MEMS-based scanning-probe data-storage device described in the paper utilizes nanometer-sharp tips such as those often used in atomic force microscopes (AFM) for imaging and investigating the structure of materials down to the atomic scale. In this system, a MEMS-based microscanner is used to position the storage medium, in two dimensions, with respect to an array of READ/WRITE probes. Digital information is stored by making indentations on a thin polymer film using tips of AFM microcantilevers. The paper describes track-seeking and track-following problems associated with this system and reports the successful implementation of a number of controllers that satisfy the required specifications.

In the paper, "Visual Servoing-Based Autonomous 2–D Manipulation of Microparticles Using a Nanoprobe," Onal and Sitti describe how microparticles, as small as 4.5 μm, can be manipulated under an optical microscope using an AFM probe tip. They describe how microparticles can be autonomously formed into specific patterns, using an image-processing procedure for their real-time detection from the image and an iterative sliding mode parameter estimator, which determines the real-world position of a microparticle from the image. The manipulation procedure involves pushing and pulling of the particles using a scanning probe microscope.

The paper by Bhikkaji *et al.*, entitled "High-Performance Control of Piezoelectric Tube Scanners," deals with control of piezoelectric tube actuators for fast nanoscale positioning applications. These actuators are extensively used in the scanning stage of scanning probe microscopes. One of the characteristics of piezoelectric tube scanners is a low-frequency resonant mode which significantly reduces the scanning speed of such devices. The paper describes a controller design approach for attenuating the actuator's resonance using the strain signal

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measured at one of the collocated electrodes on the outside surface of the tube.

In "Robust Multiple Frequency Trajectory Tracking Control of Piezoelectrically Driven Micro/Nanopositioning Systems," Bashash and Jalili describe a controller design approach for piezoelectric actuators used in micro- and nanopositioning systems. They develop a nonlinear model of the piezoelectric actuator to capture its hysteretic behavior. Then the model is augmented with a second-order linear system to capture the linear vibratory nature of the device. To deal with uncertainties present in the dynamics of the system, they design and implement a sliding mode controller. The paper contains experimental results illustrating that the proposed controller can track multiple frequency trajectories.

In the paper "Design, Modeling, and Control of Piezoelectric Actuators for Intracytoplasmic Sperm Injection (ICSI)," Putra *et al.* describe the development of an interesting device that uses piezoelectric actuators for controlled injection of a sperm into an oocyte. The sperm is injected into an oocyte using a pipette whose movements are controlled by a piezoelectric actuator. The authors report an overall success rate of over 77%, which is higher than the 57% success rate achieved by an operator.

In "H_∞ Loop-Shaping Bilateral Controller for a Two-Fingered Telemicromanipulation System," Boukhnifer and Ferreira describe control challenges associated with remote operation of a two-fingered mircrogripper over a communication channel. The microgripper is equipped with force feedback and is capable of handling micrometer-sized objects. The inevitable transmission delay complicates the task of stabilizing the closed-loop system. The authors propose a loop-shaping H_∞ controller that, *inter alia*, allows a tradeoff between robustness and a prespecified time delay. They report successful implementation of a controller in the laboratory.

The paper "Design and Modeling of a High-Speed AFM-Scanner" by Schitter *et al.* is concerned with designing, modeling, and controlling a prototype scanner for atomic force microscopes. The scanner is designed to move in three coordinates over a range of several micrometers. The mechanical design of the scanner is such that its first resonance is above 22 kHz, which, the authors explain, enables faster scanning than with most comparable devices. A proportional–integral (PI) controller is designed and implemented on the scanner and the system is used to develop images of a biological sample with a resolution of 256×256 pixels.

In "An Integrator-Backstepping-Based Dynamic Surface Control Method for a Two-Axis Piezoelectric Micropositioning Stage" Shieh and Hsu discuss the design and implementation of an integrator backstepping controller for a two-axis positioning platform. Such piezoelectric stack-driven, flexure-based positioning systems are becoming increasingly popular in micro- and nanopositioning applications owing to the low cross-coupling between the various axes. The authors develop a dynamic model of the system that incorporates the nonlinear effects of hysteresis associated with the piezoelectric stack actuators. This model lends itself to backstepping controller design methodology, which is used to generate a tracking controller that is then implemented on the platform and experimentally validated.

This Special Issue also contains a number of brief papers. The first brief, "Feedback-Linearized Inverse Feedforward for Creep, Hysteresis, and Vibration Compensation in Piezoactuators," by Leang and Devasia, studies a combined feedback and feedforward control approach for reducing hysteresis, creep, and vibration in piezoelectric actuators. They illustrate that their proposed approach can enable a considerable reduction of scanning error at relatively higher frequencies when implemented on an atomic force microscope.

The second brief by Wu and Zou, "Iterative Control Approach to Compensate for the Hysteresis and the Vibrational Dynamics Effects of Piezo Actuators," explains how the inversion-based iterative control approach can be used to compensate for the effect of hysteresis and scan-induced vibrations during high-speed positioning of a piezoelectric actuator. They experimentally illustrate the performance of their controller on an atomic force microscope.

The third brief, "Multiscale Control for Nanoprecision Positioning Systems With Large Throughput" by Shakir and Kim, discusses control design challenges associated with a maglev-based macro/nanopositioning system with six-degrees-of-freedom. They describe how a controller can be designed to satisfy prespecified micro- and nanoscale performance criteria. As it is an inherently unstable system, the authors utilize closed-loop system identification to develop a model of the system, and experimentally verify the closed-loop performance of their controller.

In the fourth brief "A Review of the Systems Approach to the Analysis of Dynamic-Mode Atomic Force Microscopy," Sebastian *et al.* describe how systems and control concepts can be utilized to analyze dynamic-mode operation of atomic force microscopes (AFMs). They develop a nonlinear model for tip sample interaction in AFMs, describe how a piecewise-linear model can be obtained to capture this, and report experimental data to validate their analysis.

In the last brief, "Development of Human-Robot-Shared Controlled Teletweezing System," Hwang *et al.* propose a telemanipulation system with a haptic interface, operated over a communication channel with its inevitable delays, for dexterous manipulation of biological objects. They describe the system architecture, design and implement a controller, and experimentally illustrate successful operation of the system in performing tasks such as pick-and-place using multiple micromanipulators.

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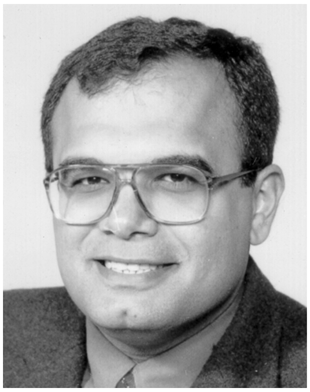

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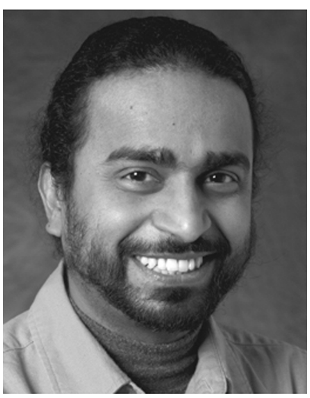

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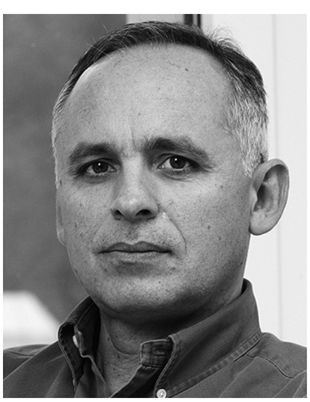

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