Guest Editorial
Introduction to the Focused Section on Mechatronics for MEMS and NEMS

I. Introduction

THE advancement of emerging microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) requires comprehensive mechatronic-based (i.e., modeling, identification, control, and experimentation) analysis and investigation. One of the most challenging aspects of "micro- and nanoscale" mechatronic systems as compared to their "macroscale" versions is the added complexity of uncertainties and nonlinearities that are unique to micro- and nanoscale. This added complexity combined with the extra precision requirement calls for development of comprehensive modeling frameworks and controllers for these applications. Accordingly, in an effort to respond to such demanding needs for new applications of MEMS and NEMS, this "Focused Section on Mechatronics for MEMS and NEMS" brings together the current advances in this area that could stimulate future research directions in this field. This Focused Section particularly targets current research and development efforts in modeling, control, and applications of MEMS and NEMS including new sensing and actuation mechanisms at micro- and nanoscale, modeling and control of micro- and nanoscale sensors and actuators, and applications. In this editorial note, a brief overview of recent developments in this area of research is first presented, followed by an overview of the papers included in this Focused Section.

II. Highlights of Related Articles Published in the IEEE/ASME Transactions on Mechatronics

A. Pre-2000 Articles

Kota *et al.* [1] have presented a generalized methodology to design compliant mechanisms with a feasible configuration, size, and shape for MEMS and smart structures applications. The rationale behind this study is to establish a monolithic "solid-state" mechanical transmission system that consists of an unconventional compliant mechanism and an unconventional electrostatic actuator. Other examples based on other unconventional actuators such as shape memory alloy actuators and piezoelectric actuators are presented to demonstrate the efficacy of the design methodology.

Imamura *et al.* [2] have proposed a new MEMS-based integrated head/actuator/slider concept for hard disk drives. The slider body and an electrostatic microactuator are fabricated using a micromachining technology. Preliminary performance characterization results are provided for the slider and the electrostatic actuator assembly.

Favrat *et al.* [3] have reported on an integrated circuit to drive an electrostatic micromotor with a 1.5 V battery. The circuit is application specific and can output up to 80 V. The circuit was proposed for wearable systems.

Itoh [4] adopted a fuzzy control method based on an image processing method to control the motion of the protozoa for bio-MEMS. Negative galvanotaxes are employed to realize the motion control of the protozoa as a bio-inspired micromanipulator.

Dario and Fukuda [5] have reported on a teleoperated mobile microrobot activated by an electromagnetic wobble micromotor, which has a volume of 1 cm^3, provides a torque of 350 μN·m, and maximum speed of 180 r/min. The design, fabrication, and operation principle of the microactuator are presented. The mobile microrobot can achieve a maximum speed of 10 cm/s and climb a 15° slope.

Tendick *et al.* [6] reported on the significance of micromechatronic technologies for minimally invasive surgery (MIS). With reference to a millirobotic system for the MIS of the abdomen, key research and technological issues in the MIS are discussed and the need to enhance the surgeons ability to access confined regions are elaborated.

Dario *et al.* [7] have reported on numerous micromechatronics systems designed for medical applications and on open research problems in micromechatronics. The significance of miniaturizing mechatronic systems together with the development of novel design concepts and technologies is highlighted.

Reynaerts *et al.* [8] have proposed a mechatronic approach to the design of microsystems. Case studies including solid and wet drug delivery systems are used to demonstrate the efficacy of the concurrent design approach. The authors also proposed the electrodischarge machining of silicon parts as a complementary microfabrication technique to the conventional silicon micromachining techniques, hence paving the way toward the establishment of 3-D micromechanical sensors and actuators with embedded electronics.

Arai *et al.* [9] reported on the surface forces associated with handling microsized objects, and how to reduce them when a microgripper manipulates microsized objects. The authors proposed to create micropyramids on the microgripper surface using a micromachining technique. They also incorporated a force sensor into the contact surface of the microgripper to measure grasping force. Experimental results are presented to demonstrate the efficacy of the micropyramids to minimize the surface forces.

Horsley *et al.* [10] dwell on the design and control of an electrostatic microactuator producing sufficient propulsion force

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to articulate the picoslider of a disk drive above 2 kHz. The mathematical model of the actuator is experimentally validated. The prototype microactuator is controlled with a classical proportional–derivative (PD) controller, resulting in a 2.5-kHz closed-loop bandwidth. The actuator is proposed as a high-bandwidth secondary actuator for magnetic hard disk drives.

Suzumori *et al.* [11] reported on the development of a microinspection robot with 23 mm in diameter, 110 mm in length, and 16 g in weight to handle small objects in 1 in pipes. The components of the microrobot including a micro-charge-coupled device camera with a high resolution are specially designed to meet the stringent operation constraints. The performance of the robot was quantified experimentally.

Hirano *et al.* [12] reported on the design, fabrication, and performance quantification of a high-bandwidth, high-accuracy rotary microactuator for magnetic hard disk drives. The microactuator was fabricated using a new fabrication technique consisting of two processes—high-aspect-ratio polymer etching and thick metal electrodeposition. The microactuator, which has a bandwidth of 5 kHz, is controlled using a PID controller to improve its positioning tracking ability. Experimental results presented suggest that the microactuator can be used in a dual-stage servo system.

Suzumori *et al.* [13] developed a new, low-cost and fibreless (nonreinforced) flexible microactuator based on a finite-element analysis. The fibreless design approach was experimentally and theoretically demonstrated. The actuator can be mass fabricated.

B. Post-2000 Articles

Beccai *et al.* [14] reported on the establishment and experimental performance evaluation of a soft compliant tactile microsensor, which is a triaxis microforce sensor encapsulated with a compliant material. The robustness of the sensor impaired when its sensitivity increased. The sensor was tested to be suitable for artificial hands with enough sensitivity to slippage. The slippage was detected with a time delay ranging from 24.5 to 44 ms.

Chen *et al.* [15] have proposed a dynamic 3-D surface profilometer with 3–5 nm accuracy and a dynamic bandwidth of 1 MHz for MEMS characterization. It is based on the white light interferometric scanning principle with a stroboscopic LED light source. The profilometer was successfully employed to determine the resonant frequency of the cantilever probe of an atomic force microscope. The experimentally determined resonant frequencies were in agreement with theoretical results obtained using finite-element analysis.

Luo and Pan [16] reported on an intelligent mold with embedded MEMS-based microsensors, which are fabricated using MEMS technology. The embedded microsensors were able to measure global and local temperature distribution in the direct metallic rapid tooling mold during the injection, hold, and cooling processes.

Basset *et al.* [17] have reported asynchronous wireless powering and remote control of electrostatic microactuators in order to establish a wireless microrobot. While inductive coupling was applied to power an integrated circuit and MEMS components, the carrier amplitude was modulated by 25% to obtain the digital transmission. The demonstrator was tested to activate 1700 electrostatic microactuators under 100 V.

Huang *et al.* [18] have presented the design and analysis of MEMS actuators for a dual-stage servo system for hard disk drives. The servo system is designed using sensitivity decoupling approach and a multiobjective optimization. The microactuator has the first mode at 2.2 kHz and the second at 40 kHz.

Oboe *et al.* [19] reported on the control of a z-axis MEMS vibrational gyroscope operating in vacuum. An electrostatic actuator derives the gyroscope in the z-direction with a controlled speed. The controller was able to maintain the required speed under shock-type disturbances.

Platt *et al.* [20] have employed piezoelectric transduction for energy harvesting at low frequencies. The harvester is designed to satisfy many design considerations consisting of parameter identification, load matching, form factors, efficiency, longevity, energy conversion, and storage. The harvester was applied to generate electrical energy inside a prototype total knee replacement implant.

Zhou *et al.* [21] reported on three types of polymer-based MEMS underwater actuators, which generate a large deflection, but requires less power input than conventional MEMS actuators. Experimental characterization results are presented to demonstrate the suitability of these actuators for underwater applications.

Arai *et al.* [22] reported on a laser trapped microtool to manipulate a target microbe with minimum laser irradiation to the target. The microtool, which uses a pinpoint injection method, is installed inside a liquid-filled microchamber to transport the target microbe for separation.

Li and Horowitz [23] proposed a decoupled control design structure and a discrete-time pole placement method for MEMS-based dual-stage servo control of magnetic disk drives. The decoupled controller is based on three inner-loop controllers, voice motor controller, and microactuator inner and outer controllers. The control system design methodology can be applied to multiple-input–multiple-output (MIMO) and single-input–multiple-output (SIMO) microsystems.

Sitti [24] has proposed a four-bar mechanism with two flexible links to amplify the stroke of a micromechanical flying-insect robot. Piezoelectric actuators are employed to activate the four-bar mechanism, which is optimized from the kinematics and kinetics points of view. Laser micromachining and microfolding were applied to produce the four-bar mechanism. Experimental results in agreement with the theoretical results are presented to demonstrate the ability of the four-bar mechanism to generate a 90° flapping motion at 29 Hz resonant frequency.

Sitti and Hashimoto [25] proposed a teleoperated nanoscale touching system, consisting of a custom-designed 1-DOF haptic device, 3-D virtual reality graphics display, a nanorobot in the form of a piezoresistive nanoprobe with a sharp tip, and a force-reflecting servo-type controller. They conducted 1-D and 3-D touching experiments and virtual reality experiments. The results presented suggest that the proposed teleoperated system force feedback from nanosized surfaces in contact and noncontact modes.

Zhang *et al.* [26] have presented the establishment of a rotary–linear actuator based on piezoelectric translators, and experimental and theoretical performance characterization results. The results presented demonstrate the validity of the actuation principle and a dynamic model. The 2-DOF rotary–linear actuator, which requires a sawteeth-shaped input voltage, has an unlimited rotation range but a 40-mm linear range with a minimum step width of 26 nm.

Komori and Hirakawa [27] reported on the establishment of a magnetically driven linear microactuator consisting of a microplatform with permanent magnets and a stator with a large coil. The microplatform is fabricated using a conventional lithographic technique. Dynamics performance characteristics of the microplatform are presented.

Wong *et al.* [28] employed electrokinetics to manipulate micro- and nanosized biological species, and discussed importance of fundamental characteristics and limitations of electrokinetic forces for microdevices. The influence of the forces on fluid delivery, cell positioning, mixing, separation, and concentration of biomolecules in microdevices is presented.

Chen and Tan [29] have reported on a control-oriented and physics-based mathematical for ionic polymer metal composite (IPMC) actuators for applications typified by micro-/nanomanipulation and bio-inspired robotic devices. The model is validated experimentally and in real-time control design.

Alici and Huynh [30] have reported on modeling, performance characterization, and quantification of conducting polymer actuators and their application to articulating a two-finger microgripper. Experimental and theoretical results presented demonstrate that conducting polymer actuators offer many useful characteristics suitable to establishing functional microsized robotic devices.

Shen *et al.* [31] have reported on a microforce sensor based on a cantilevered composite beam structure with embedded piezoelectric actuation and sensing layers. The sensor is offered for fine micromanipulation and microassembly. Optimal control approach was implemented to increase the stiffness, and therefore the sensitivity of the sensor for high-accuracy motion control.

Park *et al.* [32] have reported on the design and control of a sensorized microgripper based on a voice coil motor and a flexure mechanism. Finite-element analysis is applied to improve the gripping sensitivity and optimize the gripper topology. Force and position control of the gripper were experimentally implemented.

Perez *et al.* [33] have reported on the modeling and fabrication performance characterization of a 2-DOF micromanipulation system articulated with piezoactuators. A model is proposed to minimize the hysteresis of the piezoactuators. Constant voltage control and constant charge control are implemented simultaneously to reduce the hysteresis by one order of magnitude. This is demonstrated experimentally.

Ferreira *et al.* [34] reported on the concept of the microrobot on chip. The concept is demonstrated on a 6-degree of freedom piezoelectrically activated micromanipulator. A model based position and force controller is proposed together with a hysteresis model implemented in an open-loop control manner.

Ferreira *et al.* [35] reported on a micromanipulation system for visually servoed teleoperated microassembly. A vision-based position control and force control are implemented for a pushing-based micromanipulation strategy. A typical microassembly scenario is implemented using millimeter-sized components.

Menciassi *et al.* [36] reported on the development of microinstruments to augment the performance of surgeons, especially their finger palpation capabilities in order to characterize tissue hardness and measure pulsating vessels. After describing potential applications of a minirobotic instrument consisting of a microfabricated gripper equipped with force sensors, the authors demonstrate that the mini-instrument can provide significant quantitative and qualitative information about skin samples and can detect pulsating fluid passing through microvessels.

Khamesee *et al.* [37] reported on the design and control of a remotely operated 3-DOF microrobot based on magnetic levitation. A PID controller was used to control the position of the robot under payloads. The microrobot, which weighs 8.1 g, can lift masses up to 1.5 g with a precision of 50 μm.

Ando *et al.* [38] proposed the development of a telemicromanipulation system with haptic feedback in order to create a more effective human interface for micromanipulation applications. A 6-DOF parallel manipulator is chosen as the slave micromanipulator and a 6-DOF haptic interface with force feedback as the master system. The master and slave systems are connected through Ethernet to perform teleoperation through the network. A model-referenced adaptive control was implemented to compensate for the frictional effects in the haptic interface. Experimental results characterizing the performance of the master and slave systems demonstrate that the proposed telemicromanipulation system can be used for micromanipulation.

Alici *et al.* [39] have reported on the characterization of the dynamic response of trilayer polypyrrole (PPy) type electroactive polymer sensors. The electroactive polymers offer many features such as being suitable to miniaturization and having embedded sensing and actuation abilities. After identifying experimental transfer functions of the polymer sensors, the dynamic sensing behavior of the sensors is characterized through impulse current and voltage responses. The voltage output is estimated using an energy balance approach, which has been successfully validated through a set of experimental results. Based on the novel experimental and analytical results, the electroactive polymers can be employed to make macro- and microsized mechanical sensors.

Grossard *et al.* [40] have proposed a topology optimization method to design a monolithic piezoelectrically driven microgripper. It is an evolutionary approach to optimize the truss-like planar structure of the microgripper made of piezoelectric material. Optimization criteria to improve the open-loop frequency response of the system are especially considered to optimize the controllability and observability of system design under consideration. Experimental and theoretical results demonstrating the efficacy of the optimization method are presented to suggest that the proposed method can be applied for the design of microactuators and microrobots.

Liu *et al.* [41] proposed a real-time fault detection and correction method to eradicate faulty display due to random drift, and modeling errors due to the uncertainties of the nanoenvironment in the virtual reality interface used for nanomanipulation applications. The method is based on the atomic force microscopy (AFM) probe employed as an end-effector and a force sensor during nanomanipulation. The force data provided by the AFM cantilever is used to improve visual feedback and detect faulty display. Experimental and theoretical results are presented to demonstrate the efficacy of the real-time fault detection and correction method when manipulating nanoparticles and nanorods.

Based on magnetic levitation technology, Shakir and Kim [42] proposed a path planning and control methodology for the nanofabrication applications typified by microstereolithography, dip-pen nanolithography, and nanoscanning applications. After determining motion trajectories, a hybrid control approach consisting of a lead-lag compensator and a linear quadratic regulator was implemented to demonstrate the efficacy of the proposed trajectory planning and control methodology. The position resolution of 5 nm and command tracking accuracy of 4.5 nm are achieved to suggest that the proposed methodology meets the stringent performance requirements of the nanofabrication techniques.

Sitti [43] has proposed two nanotribological characterization methods based on an atomic force microscope probe as a nanomanipulator in order to determine the friction parameters between micro- and nanosized objects and the substrate and their behavior in various media. The methods are modeled and experimental results are provided for 500-nm-radius gold-coated latex particles pushed on a silicon substrate. The nanopushing results suggest that sliding, rolling, and rotation can be observed, and shear stresses and frictional behavior can be evaluated using the proposed characterization method.

Li *et al.* [44] proposed an augmented reality system based on updating the atomic force microscope (AFM) image with real-time force data provided during operation to widen application areas of the AFM such as making nanoassembly more feasible and applicable. A haptic device was employed to provide real-time force feedback and command the AFM probe. The augmented system provides both real-time force feedback and real-time visual display. Experimental results are presented to demonstrate that the augmented system can help generate nanopatterns and manipulate nanoparticles accurately.

Verma *et al.* [45] reported on the design, control, and performance testing of a 6-DOF magnetically levitated system with nanometer positioning precision. It is a compact system articulated with six linear actuators consisting of permanent magnets and current-carrying coils. The position resolution, maximum velocity, and acceleration of the system are 5 nm, 0.5 m/s, and 30 m/s^2, respectively. Based on the experimental performance results, the magnetically levitated system is proposed for nanomanipulation, microassembly, and microfabrication applications.

Huang *et al.* [46] have reported on the design and analysis of a dual-stage servo system equipped with MEMS linear or rotary actuators, which show two resonant frequencies at 2.2 and 40 kHz. The servo system is designed using sensitivity coupling method and multiobjective optimization. It is demonstrated that the linear actuator offers better performance than the rotary one.

III. Highlights of This Focused Section

This Focused Section, consisting of seven papers, presents recent research in the general area of mechatronics for MEMS and NEMS from modeling and control to sensing/actuation and manipulation.

In the paper "Conditions for Image-Based Identification of SPM-Nanopositioner Dynamics," presented by Clayton and Devasia, conditions are developed for the image-based identification of scanning probe microscope (SPM) nanopositioner dynamics to increase the positioning speed. The main issue is to estimate the achieved position trajectory for a given input to the SPM nanopositioner. The authors identify the calibration sample and scan trajectory properties that are needed for image-based modeling of the SPM-nanopositioner dynamics. A trade-off between calibration sample and scan trajectory properties are discussed in the context of scanning tunneling microscope (STM). These conditions were applied to identify a dynamics model of an STM result using standard, highly oriented pyrolytic graphite (HOPG) calibration sample. Finally, comparative results between image-based and sensor-based models are discussed in the context of STM.

Lee *et al.* propose in their paper, "Fast Robust Nanopositioning—A Linear-Matrix-Inequalities-Based Optimal Control Approach," a novel 2-DOF robust optimal control design method for achieving multiple objectives of resolution, bandwidth, and robustness to modeling uncertainties in nanopositioning systems. To achieve these multiple objectives, the authors formulated a new 2-DOF problem as a linear-matrix-inequality (LMI)-based convex optimization problem. The controller is obtained by standard convex optimization tools. To demonstrate the main distinguishing feature of this approach, the authors carried out experiments on a nanopositioning system with limited performances. The experimental results demonstrate over 200% improvement in bandwidth over optimal 1-DOF designs and achieve specifications that are impossible in a 1-DOF framework.

The principle of phase feedback has been investigated for an oscillator circuit containing a nonlinear electrostatically actuated clamped-clamped beam microelectromechanical (MEM) resonator in the paper entitled "Phase Feedback for Nonlinear MEM Resonators in Oscillator Circuits" by Mestrom *et al.* The principle of the proposed approach is illustrated for a nonlinear Duffing resonator that is representative of many types of oscillators. The authors used frequency-phase curves and power-phase curves for selecting optimal operation points for the phase feedback in oscillator circuits. The intensive simulations carried out by the authors demonstrated that for their phase feedback approach, the control parameters amplifier phase and saturation value provide a means for tuning the frequency of oscillation as well as the output power of the simulator. Based on these interesting simulations, it is possible to select the optimal operation points for MEMS oscillator circuits incorporating a nonlinear resonator.

New technology for wireless micromanipulation of microsized objects is proposed by Khamesee *et al.* in the paper "Design and Implementation of a Micromanipulation System Using a Magnetically Levitated MEMS Robot" using magnetic levitation. An experimental microrobot setup has been designed and developed. The wireless microrobot, made of either NdFeB magnets or Co–Ni–Mn–P magnetic films, is controlled by external magnetic fields. It is equipped with a photothermal polymer microgripper that can be actuated remotely by laser focusing for microgripping operations. The authors experimentally demonstrated the 3-D motion capability to operate in a working space of $4 \times 4 \times 5$ cm^3. Micromanipulation experiments such as pick-and-place, pushing, and pulling were demonstrated using objects with 100 μm and 1 mm diameter. The operation of the microrobot is such that a closed chamber opens the path for micromanipulation of biological samples and hazardous items.

In the paper "On the Mode-Matched Control of MEMS Vibratory Gyroscope via Phase-Domain Analysis and Design," Sung *et al.* introduce a mode-matching approach to the controller design for the vibratory-rate MEMS gyroscope systems. The key idea and motivation is to improve the gyroscopic sensitivity to the Coriolis force by adjusting the resonant frequency of the sensing mode to that of the drive mode through tuning the electrostatic stiffness. In the design, the resonant characteristics of the driving axis serves as the reference mode while the phase difference between the sensing and driving modes at the resonant frequency of the drive mode is used to generate a control signal for phase error regulation. The results of experiments in a manufactured MEMS gyroscope prototype show that the desired performance can be achieved when there are phase errors.

Treating it as an external disturbance to a linear system, Chang *et al.* present an observer-based scheme to compensate for the hysteresis nonlinearity of PMN-PT piezoelectric actuators in the paper "Disturbance-Observer-Based Hysteresis Compensation for Piezoelectric Actuators." A disturbance observer (DOB) is used to estimate and compensate for the hysteresis nonlinearity. As a benefit, the exact knowledge of the hysteresis is not required, which makes the design easy to implement in practical applications. Experiments were performed to validate the proposed DOB approach on a piezoelectric cantilever actuator developed for a tip-based nanopower sintering process. The results of two experimental examples demonstrated that the system with the DOB compensation shows better tracking performance than the one without hysteresis compensation in terms of both overshoot and response speed.

Zhang and Meng investigate a very specific topic, i.e., the modeling issue of the gas-lubricated slider bearings of a micromotor in MEMS systems, in the paper "Property Analysis of the Rough Slider Bearings in Micromotors for MEMS Applications." A new slip model for gas-lubricated slider bearings is developed and a modified Reynolds equation is established based on the kinetic theory of gases. The presented slip model was compared with other similar models in a few different slider bearing configurations, and it is shown that the new model is more accurate in the prediction of lubrication characteristics. The analysis also reveal that the coupled effects of gas rarefaction and roughness are very important for designing the slider bearings of MEMS micromotors. The solutions obtained with the presented new slip model match well those obtained using the linearized Boltzmann equation.

IV. Future Trends

While the MEMSs have a characteristic length <1 mm but >100 nm, the NEMSs have a characteristic length >100 nm. Further, if the functional components of macroscale systems (with a characteristic length >1 mm) are on micro- or nanoscale, they may still be referred to as MEMS or NEMS, respectively. With these definitions in mind, some future trends outlined later are identified.

Novel materials with embedded actuation and sensing ability offer small footprint and allow further miniaturization, pushing the limits to functional nanodevices, and high actuation and sensing densities. There is an increasing demand to synthesize novel materials with small footprint, compatible with MEMS and NEMS from the operation and system integration points of view. The MEMS industry is currently hampered by the lack of suitable actuation systems that are robust, require low power, have small footprints, and can operate in a wide range of environments. The development of the next-generation MEMS products and future development of nanodevices (NEMS) relies on continued innovation in novel materials and the introduction of fabrication methods.

Novel fabrication and integration techniques are required to make functional micro-/nanostructures, from novel materials, to be integrated into MEMS/NEMS at component and system levels. These techniques are expected to be nonconventional fabrication approaches, different than photolithographic techniques. Template-based self-assembly techniques are expected to be used to make micro-/nanosized structures with useful characteristics, and micro-/nanointerconnects and contacts with minimum resistance.

Rather than extending analysis, design, optimization, control, characterization and operation principles, concepts, and methodologies of macrosized devices to MEMS and NEMS, there is indeed a great demand for new device concepts, methodologies, and operation principles for the next generation of MEMS and NEMS.

Another future trend is to create functional MEMS and NEMS for remote and *in situ* applications. They should be able to harvest their own energy from different sources, such as mechanical vibrations, bioprocesses, heat, and light, depending on their operation environment and principles.

Another future challenge is to establish MEMS/NEMS with figures of merit including high sensitivity, high reliability, high level of functional integration and modularity, reconfigurable actuator and sensor networks with fault-tolerant operation, and low power consumption for remote, hazardous, and *in situ* applications requiring autonomous MEMS and NEMS.

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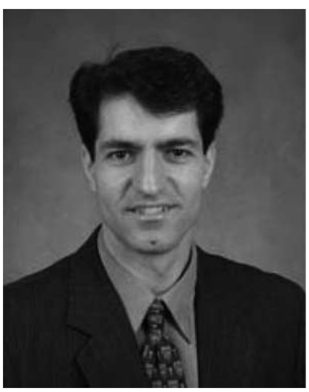

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