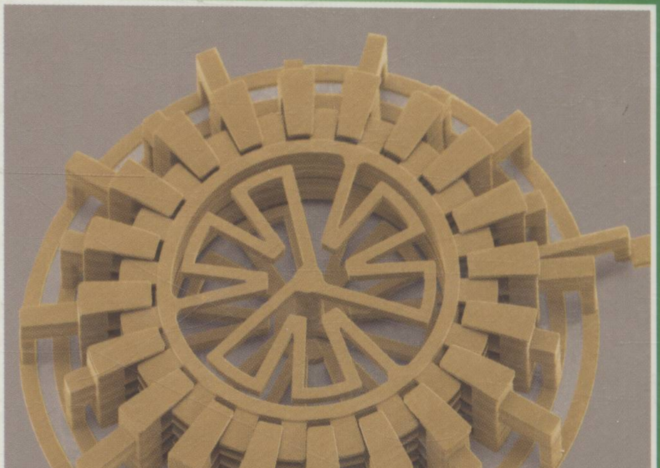
The MEMS Handbook Second Edition

MEMS

Introduction and Fundamentals



Edited by
Mohamed Gad-el-Hak

CRC Taylor & Francis
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Boca Raton London New York

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Foreground: A 24-layer rotary varactor fabricated in nickel using the Electrochemical Fabrication (EFAB®) technology. See Chapter 6, *MEMS: Design and Fabrication*, for details of the EFAB® technology. Scanning electron micrograph courtesy of Adam L. Cohen, Microfabrica Incorporated (www.microfabrica.com), U.S.A.

Background: A two-layer surface macromachined, vibrating gyroscope. The overall size of the integrated circuitry is 4.5 × 4.5 mm. Sandia National Laboratories' emblem in the lower right-hand corner is 700 microns wide. The four silver rectangles in the center are the gyroscope's proof masses, each 240 × 310 × 2.25 microns. See Chapter 4, *MEMS: Applications* (0-8493-9139-3), for design and fabrication details. Photograph courtesy of Andrew D. Oliver, Sandia National Laboratories.

Published in 2006 by
CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-9137-7 (Hardcover)
International Standard Book Number-13: 978-0-8493-9137-8 (Hardcover)
Library of Congress Card Number 2005050111

Library of Congress Cataloging-in-Publication Data

MEMS : introduction and fundamentals / edited by Mohamed Gad-El-Hak.
p. cm. -- (Mechanical engineering series)
Includes bibliographical references and index.
ISBN 0-8493-9137-7 (alk. paper)
1. Microelectronics. 2. Nanotechnology. I. Gad-el-Hak, M. II. Mechanical engineering series (Boca Raton, Fla.)

TK7874.M3762 2005
621.381--dc22 2005050111

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Introduction and Fundamentals

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Preface

In a little time I felt something alive moving on my left leg, which advancing gently forward over my breast, came almost up to my chin; when bending my eyes downward as much as I could, I perceived it to be a human creature not six inches high, with a bow and arrow in his hands, and a quiver at his back. ... I had the fortune to break the strings, and wrench out the pegs that fastened my left arm to the ground; for, by lifting it up to my face, I discovered the methods they had taken to bind me, and at the same time with a violent pull, which gave me excessive pain, I a little loosened the strings that tied down my hair on the left side, so that I was just able to turn my head about two inches. ... These people are most excellent mathematicians, and arrived to a great perfection in mechanics by the countenance and encouragement of the emperor, who is a renowned patron of learning. This prince has several machines fixed on wheels, for the carriage of trees and other great weights.

(From *Gulliver's Travels—A Voyage to Lilliput*, by Jonathan Swift, 1726.)

In the Nevada desert, an experiment has gone horribly wrong. A cloud of nanoparticles — micro-robots — has escaped from the laboratory. This cloud is self-sustaining and self-reproducing. It is intelligent and learns from experience. For all practical purposes, it is alive.

It has been programmed as a predator. It is evolving swiftly, becoming more deadly with each passing hour.

Every attempt to destroy it has failed.

And we are the prey.

(From Michael Crichton's techno-thriller *Prey*, HarperCollins Publishers, 2002.)

Almost three centuries apart, the imaginative novelists quoted above contemplated the astonishing, at times frightening possibilities of living beings much bigger or much smaller than us. In 1959, the physicist Richard Feynman envisioned the fabrication of machines much smaller than their makers. The length scale of man, at slightly more than 10^0 m, amazingly fits right in the middle of the smallest subatomic particle, which is approximately 10^{-26} m, and the extent of the observable universe, which is of the order of 10^{26} m. Toolmaking has always differentiated our species from all others on Earth. Close to 400,000 years ago, archaic *Homo sapiens* carved aerodynamically correct wooden spears. Man builds things consistent with his size, typically in the range of two orders of magnitude larger or smaller than himself. But humans have always striven to explore, build, and control the extremes of length and time scales. In the voyages to Lilliput and Brobdingnag in *Gulliver's Travels*, Jonathan Swift speculates on the remarkable possibilities which diminution or magnification of physical dimensions provides. The Great Pyramid of Khufu was originally 147 m high when completed around 2600 B.C., while the Empire State Building constructed in 1931 is presently 449 m high. At the other end of the spectrum of manmade artifacts, a dime is slightly less than 2 cm in diameter. Watchmakers have practiced the art of miniaturization since the 13th century. The invention of the microscope in the 17th century opened the way for direct observation of microbes and plant and animal cells. Smaller things were manmade in the latter half of the 20th century. The transistor in today's integrated circuits has a size of 0.18 micron in production and approaches 10 nanometers in research laboratories.

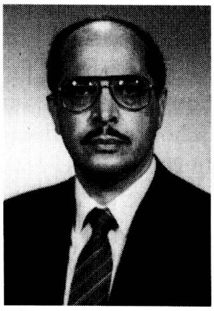
Microelectromechanical systems (MEMS) refer to devices that have characteristic length of less than 1 mm but more than 1 micron, that combine electrical and mechanical components, and that are fabricated using integrated circuit batch-processing technologies. Current manufacturing techniques for MEMS include surface silicon micromachining; bulk silicon micromachining; lithography, electrodeposition, and plastic molding; and electrodischarge machining. The multidisciplinary field has witnessed explosive growth during the last decade and the technology is progressing at a rate that far exceeds that of our understanding of the physics involved. Electrostatic, magnetic, electromagnetic, pneumatic and thermal actuators, motors, valves, gears, cantilevers, diaphragms, and tweezers of less than 100 micron size have been fabricated. These have been used as sensors for pressure, temperature, mass flow, velocity, sound and chemical composition, as actuators for linear and angular motions, and as simple components for complex systems such as robots, lab-on-a-chip, micro heat engines and micro heat pumps. The lab-on-a-chip in particular is promising to automate biology and chemistry to the same extent the integrated circuit has allowed large-scale automation of computation. Global funding for micro- and nanotechnology research and development quintupled from $432 million in 1997 to $2.2 billion in 2002. In 2004, the U.S. National Nanotechnology Initiative had a budget of close to $1 billion, and the worldwide investment in nanotechnology exceeded $3.5 billion. In 10 to 15 years, it is estimated that micro- and nanotechnology markets will represent $340 billion per year in materials, $300 billion per year in electronics, and $180 billion per year in pharmaceuticals.

The three-book *MEMS set* covers several aspects of microelectromechanical systems, or more broadly, the art and science of electromechanical miniaturization. MEMS design, fabrication, and application as well as the physical modeling of their materials, transport phenomena, and operations are all discussed. Chapters on the electrical, structural, fluidic, transport and control aspects of MEMS are included in the books. Other chapters cover existing and potential applications of microdevices in a variety of fields, including instrumentation and distributed control. Up-to-date new chapters in the areas of microscale hydrodynamics, lattice Boltzmann simulations, polymeric-based sensors and actuators, diagnostic tools, microactuators, nonlinear electrokinetic devices, and molecular self-assembly are included in the three books constituting the second edition of *The MEMS Handbook*. The 16 chapters in *MEMS: Introduction and Fundamentals* provide background and physical considerations, the 14 chapters in *MEMS: Design and Fabrication* discuss the design and fabrication of microdevices, and the 15 chapters in *MEMS: Applications* review some of the applications of micro-sensors and microactuators.

There are a total of 45 chapters written by the world's foremost authorities in this multidisciplinary subject. The 71 contributing authors come from Canada, China (Hong Kong), India, Israel, Italy, Korea, Sweden, Taiwan, and the United States, and are affiliated with academia, government, and industry. Without compromising rigorousness, the present text is designed for maximum readability by a broad audience having engineering or science background. As expected when several authors are involved, and despite the editor's best effort, the chapters of each book vary in length, depth, breadth, and writing style. These books should be useful as references to scientists and engineers already experienced in the field or as primers to researchers and graduate students just getting started in the art and science of electromechanical miniaturization. The Editor-in-Chief is very grateful to all the contributing authors for their dedication to this endeavor and selfless, generous giving of their time with no material reward other than the knowledge that their hard work may one day make the difference in someone else's life. The talent, enthusiasm, and indefatigability of Taylor & Francis Group's Cindy Renee Carelli (acquisition editor), Jessica Vakili (production coordinator), N. S. Pandian and the rest of the editorial team at Macmillan India Limited, Mimi Williams and Tao Woolfe (project editors) were highly contagious and percolated throughout the entire endeavor.

Mohamed Gad-el-Hak

Editor-in-Chief



Mohamed Gad-el-Hak received his B.Sc. (summa cum laude) in mechanical engineering from Ain Shams University in 1966 and his Ph.D. in fluid mechanics from the Johns Hopkins University in 1973, where he worked with Professor Stanley Corrsin. Gad-el-Hak has since taught and conducted research at the University of Southern California, University of Virginia, University of Notre Dame, Institut National Polytechnique de Grenoble, Université de Poitiers, Friedrich-Alexander-Universität Erlangen-Nürnberg, Technische Universität München, and Technische Universität Berlin, and has lectured extensively at seminars in the United States and overseas. Dr. Gad-el-Hak is currently the Inez Caudill Eminent Professor of Biomedical Engineering and chair of mechanical engineering at Virginia Commonwealth University in Richmond. Prior to his Notre Dame appointment as professor of aerospace and mechanical engineering, Gad-el-Hak was senior research scientist and program manager at Flow Research Company in Seattle, Washington, where he managed a variety of aerodynamic and hydrodynamic research projects.

Professor Gad-el-Hak is world renowned for advancing several novel diagnostic tools for turbulent flows, including the laser-induced fluorescence (LIF) technique for flow visualization; for discovering the efficient mechanism via which a turbulent region rapidly grows by destabilizing a surrounding laminar flow; for conducting the seminal experiments which detailed the fluid–compliant surface interactions in turbulent boundary layers; for introducing the concept of targeted control to achieve drag reduction, lift enhancement and mixing augmentation in wall-bounded flows; and for developing a novel viscous pump suited for microelectromechanical systems (MEMS) applications. Gad-el-Hak's work on Reynolds number effects in turbulent boundary layers, published in 1994, marked a significant paradigm shift in the subject. His 1999 paper on the fluid mechanics of microdevices established the fledgling field on firm physical grounds and is one of the most cited articles of the 1990s.

Gad-el-Hak holds two patents: one for a drag-reducing method for airplanes and underwater vehicles and the other for a lift-control device for delta wings. Dr. Gad-el-Hak has published over 450 articles, authored/edited 14 books and conference proceedings, and presented 250 invited lectures in the basic and applied research areas of isotropic turbulence, boundary layer flows, stratified flows, fluid–structure interactions, compliant coatings, unsteady aerodynamics, biological flows, non-Newtonian fluids, hard and soft computing including genetic algorithms, flow control, and microelectromechanical systems. Gad-el-Hak's papers have been cited well over 1000 times in the technical literature. He is the author of the book "*Flow Control: Passive, Active, and Reactive Flow Management*," and editor of the books "*Frontiers in Experimental Fluid Mechanics*," "*Advances in Fluid Mechanics Measurements*," "*Flow Control: Fundamentals and Practices*," "*The MEMS Handbook*," and "*Transition and Turbulence Control*."

Professor Gad-el-Hak is a fellow of the American Academy of Mechanics, a fellow and life member of the American Physical Society, a fellow of the American Society of Mechanical Engineers, an associate fellow of the American Institute of Aeronautics and Astronautics, and a member of the European Mechanics

Society. He has recently been inducted as an eminent engineer in Tau Beta Pi, an honorary member in Sigma Gamma Tau and Pi Tau Sigma, and a member-at-large in Sigma Xi. From 1988 to 1991, Dr. Gad-el-Hak served as Associate Editor for *AIAA Journal*. He is currently serving as Editor-in-Chief for *e-MicroNano.com*, Associate Editor for *Applied Mechanics Reviews* and *e-Fluids*, as well as Contributing Editor for Springer-Verlag's *Lecture Notes in Engineering* and *Lecture Notes in Physics*, for McGraw-Hill's Year Book of Science and Technology, and for CRC Press' *Mechanical Engineering Series*.

Dr. Gad-el-Hak serves as consultant to the governments of Egypt, France, Germany, Italy, Poland, Singapore, Sweden, United Kingdom and the United States, the United Nations, and numerous industrial organizations. Professor Gad-el-Hak has been a member of several advisory panels for DOD, DOE, NASA and NSF. During the 1991/1992 academic year, he was a visiting professor at Institut de Mécanique de Grenoble, France. During the summers of 1993, 1994 and 1997, Dr. Gad-el-Hak was, respectively, a distinguished faculty fellow at Naval Undersea Warfare Center, Newport, Rhode Island, a visiting exceptional professor at Université de Poitiers, France, and a Gastwissenschaftler (guest scientist) at Forschungszentrum Rossendorf, Dresden, Germany. In 1998, Professor Gad-el-Hak was named the Fourteenth ASME Freeman Scholar. In 1999, Gad-el-Hak was awarded the prestigious Alexander von Humboldt Prize — Germany's highest research award for senior U.S. scientists and scholars in all disciplines — as well as the Japanese Government Research Award for Foreign Scholars. In 2002, Gad-el-Hak was named ASME Distinguished Lecturer, as well as inducted into the Johns Hopkins University Society of Scholars.

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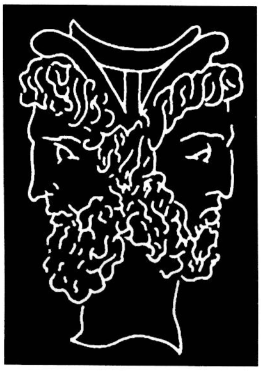
The farther backward you can look,
the farther forward you are likely to see.

(Sir Winston Leonard Spencer Churchill, 1874–1965)

Janus, Roman god of gates, doorways and all beginnings, gazing both forward and backward.



As for the future, your task is not to foresee, but to enable it.

(Antoine-Marie-Roger de Saint-Exupéry, 1900–1944,
in Citadelle [*The Wisdom of the Sands*])

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1

Introduction

Mohamed Gad-el-Hak
Virginia Commonwealth University

How many times when you are working on something frustratingly tiny, like your wife's wrist watch, have you said to yourself, "If I could only train an ant to do this!" What I would like to suggest is the possibility of training an ant to train a mite to do this. What are the possibilities of small but movable machines? They may or may not be useful, but they surely would be fun to make.

(From the talk "There's Plenty of Room at the Bottom," delivered by Richard P. Feynman at the annual meeting of the American Physical Society, Pasadena, California, December 1959.)

Toolmaking has always differentiated our species from all others on Earth. Aerodynamically correct wooden spears were carved by archaic *Homo sapiens* close to 400,000 years ago. Man builds things consistent with his size, typically in the range of two orders of magnitude larger or smaller than himself, as indicated in Figure 1.1. Though the extremes of length-scale are outside the range of this figure, man, at slightly more than 10^0 m, amazingly fits right in the middle of the smallest subatomic particle, which is

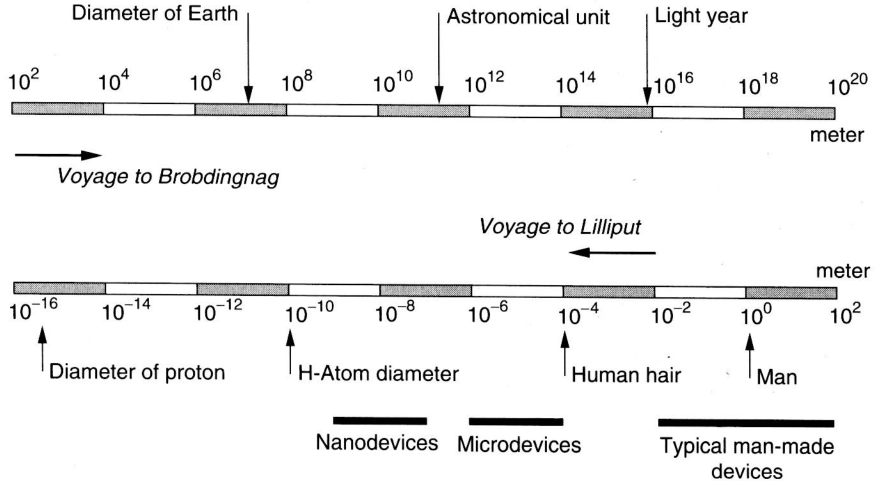

FIGURE 1.1 Scale of things, in meters. Lower scale continues in the upper bar from left to right. One meter is 10^6 microns, 10^9 nanometers, or 10^{10} Angstroms.

approximately 10^{-26} m, and the extent of the observable universe, which is of the order of 10^{26} m (15 billion light years); neither geocentric nor heliocentric, but rather egocentric universe. But humans have always striven to explore, build, and control the extremes of length and time scales. In the voyages to Lilliput and Brobdingnag of *Gulliver's Travels*, Jonathan Swift (1726) speculates on the remarkable possibilities which diminution or magnification of physical dimensions provides.[1] The Great Pyramid of Khufu was originally 147 m high when completed around 2600 B.C., while the Empire State Building constructed in 1931 is presently — after the addition of a television antenna mast in 1950 — 449 m high. At the other end of the spectrum of manmade artifacts, a dime is slightly less than 2 cm in diameter. Watchmakers have practiced the art of miniaturization since the 13th century. The invention of the microscope in the 17th century opened the way for direct observation of microbes and plant and animal cells. Smaller things were manmade in the latter half of the 20th century. The transistor — invented in 1947 — in today's integrated circuits has a size[2] of 0.18 micron (180 nanometers) in production and approaches 10 nm in research laboratories using electron beams. But what about the miniaturization of mechanical parts — machines — envisioned by Feynman (1961) in his legendary speech quoted above?

Manufacturing processes that can create extremely small machines have been developed in recent years (Angell et al., 1983; Gabriel et al., 1988, 1992; O'Connor, 1992; Gravesen et al., 1993; Bryzek et al., 1994; Gabriel, 1995; Ashley, 1996; Ho and Tai, 1996, 1998; Hogan, 1996; Ouellette, 1996, 2003; Paula, 1996; Robinson et al., 1996a, 1996b; Tien, 1997; Amato, 1998; Busch-Vishniac, 1998; Kovacs, 1998; Knight, 1999; Epstein, 2000; O'Connor and Hutchinson, 2000; Goldin et al., 2000; Chalmers, 2001; Tang and Lee, 2001; Nguyen and Wereley, 2002; Karniadakis and Beskok, 2002; Madou, 2002; DeGaspari, 2003; Ehrenman, 2004; Sharke, 2004; Stone et al., 2004; Squires and Quake, 2005). Electrostatic, magnetic, electromagnetic, pneumatic and thermal actuators, motors, valves, gears, cantilevers, diaphragms, and tweezers of less than 100 μm size have been fabricated. These have been used as sensors for pressure, temperature, mass flow, velocity, sound, and chemical composition, as actuators for linear and angular motions, and as simple components for complex systems, such as lab-on-a-chip, robots, micro-heat-engines and micro heat pumps (Lipkin, 1993; Garcia and Sniegowski, 1993, 1995; Sniegowski and Garcia, 1996; Epstein and Senturia, 1997; Epstein et al., 1997; Pekola et al., 2004; Squires and Quake, 2005).

Microelectromechanical systems (MEMS) refer to devices that have characteristic length of less than 1 mm but more than 1 micron, that combine electrical and mechanical components, and that are fabricated using integrated circuit batch-processing technologies. The books by Kovacs (1998) and Madou (2002) provide excellent sources for microfabrication technology. Current manufacturing techniques for MEMS include surface silicon micromachining; bulk silicon micromachining; lithography, electrodeposition, and plastic molding (or, in its original German, *Lithographie Galvanoformung Abformung, LIGA*); and electrodischarge machining (EDM). As indicated in Figure 1.1, MEMS are more than four orders of magnitude larger than the diameter of the hydrogen atom, but about four orders of magnitude smaller than the traditional manmade artifacts. Microdevices can have characteristic lengths smaller than the diameter of a human hair. Nanodevices (some say NEMS) further push the envelope of electromechanical miniaturization (Roco, 2001; Lemay et al., 2001; Feder, 2004).

The famed physicist Richard P. Feynman delivered a mere two, albeit profound, lectures[3] on electromechanical miniaturization: "There's Plenty of Room at the Bottom," quoted above, and "Infinitesimal Machinery," presented at the Jet Propulsion Laboratory on February 23, 1983. He could not see a lot of use for micromachines, lamenting in 1959 that "(small but movable machines) may or may not be useful, but they surely would be fun to make," and 24 years later said, "There is no use for these machines, so I still don't

[1]*Gulliver's Travels* were originally designed to form part of a satire on the abuse of human learning. At the heart of the story is a radical critique of human nature in which subtle ironic techniques work to part the reader from any comfortable preconceptions and challenge him to rethink from first principles his notions of man.

[2]The smallest feature on a microchip is defined by its smallest linewidth, which in turn is related to the wavelength of light employed in the basic lithographic process used to create the chip.

[3]Both talks have been reprinted in the *Journal of Microelectromechanical Systems*, vol. 1, no. 1, pp. 60–66, 1992, and vol. 2, no. 1, pp. 4–14, 1993.

understand why I'm fascinated by the question of making small machines with movable and controllable parts." Despite Feynman's demurring regarding the usefulness of small machines, MEMS are finding increased applications in a variety of industrial and medical fields with a potential worldwide market in the billions of dollars.

Accelerometers for automobile airbags, keyless entry systems, dense arrays of micromirrors for high-definition optical displays, scanning electron microscope tips to image single atoms, micro heat exchangers for cooling of electronic circuits, reactors for separating biological cells, blood analyzers, and pressure sensors for catheter tips are but a few of the current usages. Microducts are used in infrared detectors, diode lasers, miniature gas chromatographs, and high-frequency fluidic control systems. Micropumps are used for ink jet printing, environmental testing, and electronic cooling. Potential medical applications for small pumps include controlled delivery and monitoring of minute amount of medication, manufacturing of nanoliters of chemicals, and development of artificial pancreas. The much sought-after lab-on-a-chip is promising to automate biology and chemistry to the same extent the integrated circuit has allowed large-scale automation of computation. Global funding for micro- and nanotechnology research and development quintupled from $432 million in 1997 to $2.2 billion in 2002. In 2004, the U.S. National Nanotechnology Initiative had a budget of close to $1 billion, and the worldwide investment in nanotechnology exceeded $3.5 billion. In 10 to 15 years, it is estimated that micro- and nanotechnology markets will represent $340 billion per year in materials, $300 billion per year in electronics, and $180 billion per year in pharmaceuticals.

The multidisciplinary field has witnessed explosive growth during the past decade. Several new journals are dedicated to the science and technology of MEMS; for example *Journal of Microelectromechanical Systems, Journal of Micromechanics and Microengineering, Microscale Thermophysical Engineering, Microfluidics and Nanofluidics Journal, Nanotechnology Journal*, and *Journal of Nanoscience and Nanotechnology*. Numerous professional meetings are devoted to micromachines; for example Solid-State Sensor and Actuator Workshop, International Conference on Solid-State Sensors and Actuators (Transducers), Micro Electro Mechanical Systems Workshop, Micro Total Analysis Systems, and Eurosensors. Several web portals are dedicated to micro- and nanotechnology; for example, <http://www.smalltimes.com>, <http://www.emicronano.com>, <http://www.nanotechweb.org/>, and <http://www.peterindia.net/NanoTechnologyResources.html>.

The three-book *MEMS set* covers several aspects of microelectromechanical systems, or more broadly, the art and science of electromechanical miniaturization. MEMS design, fabrication, and application as well as the physical modeling of their materials, transport phenomena, and operations are all discussed. Chapters on the electrical, structural, fluidic, transport and control aspects of MEMS are included in the books. Other chapters cover existing and potential applications of microdevices in a variety of fields, including instrumentation and distributed control. Up-to-date new chapters in the areas of microscale hydrodynamics, lattice Boltzmann simulations, polymeric-based sensors and actuators, diagnostic tools, microactuators, nonlinear electrokinetic devices, and molecular self-assembly are included in the three books constituting the second edition of *The MEMS Handbook*. The 16 chapters in *MEMS: Introduction and Fundamentals* provide background and physical considerations, the 14 chapters in *MEMS: Design and Fabrication* discuss the design and fabrication of microdevices, and the 15 chapters in *MEMS: Applications* review some of the applications of microsensors and microactuators.

There are a total of 45 chapters written by the world's foremost authorities in this multidisciplinary subject. The 71 contributing authors come from Canada, China (Hong Kong), India, Israel, Italy, Korea, Sweden, Taiwan, and the United States, and are affiliated with academia, government, and industry. Without compromising rigorousness, the present text is designed for maximum readability by a broad audience having engineering or science background. As expected when several authors are involved, and despite the editor's best effort, the chapters of each book vary in length, depth, breadth, and writing style. The nature of the books — being handbooks and not encyclopedias — and the size limitation dictate the noninclusion of several important topics in the MEMS area of research and development.

Our objective is to provide a current overview of the fledgling discipline and its future developments for the benefit of working professionals and researchers. The three books will be useful guides and references to the explosive literature on MEMS and should provide the definitive word for the fundamentals and applications of microfabrication and microdevices. Glancing at each table of contents, the reader may rightly sense an overemphasis on the physics of microdevices. This is consistent with the strong conviction of the Editor-in-Chief that the MEMS technology is moving too fast relative to our understanding of the unconventional physics involved. This technology can certainly benefit from a solid foundation of the underlying fundamentals. If the physics is better understood, less expensive, and more efficient, microdevices can be designed, built, and operated for a variety of existing and yet-to-be-dreamed applications. Consistent with this philosophy, chapters on control theory, distributed control, and soft computing are included as the backbone of the futuristic idea of using colossal numbers of microsensors and microactuators in reactive control strategies aimed at taming turbulent flows to achieve substantial energy savings and performance improvements of vehicles and other manmade devices.

I shall leave you now for the many wonders of the small world you are about to encounter when navigating through the various chapters of these volumes. May your voyage to Lilliput be as exhilarating, enchanting, and enlightening as Lemuel Gulliver's travels into "Several Remote Nations of the World." *Hekinah degul!* Jonathan Swift may not have been a good biologist and his scaling laws were not as good as those of William Trimmer (see Chapter 2 of *MEMS: Introduction and Fundamentals*), but Swift most certainly was a magnificent storyteller. *Hnuy illa nyha majah Yahoo!*

References

Amato, I. (1998) "Formenting a Revolution, in Miniature," *Science* **282**, no. 5388, 16 October, pp. 402–405.

Angell, J.B., Terry, S.C., and Barth, P.W. (1983) "Silicon Micromechanical Devices," *Faraday Transactions I* **68**, pp. 744–748.

Ashley, S. (1996) "Getting a Microgrip in the Operating Room," *Mech. Eng.* **118**, September, pp. 91–93.

Bryzek, J., Peterson, K., and McCulley, W. (1994) "Micromachines on the March," *IEEE Spectrum* **31**, May, pp. 20–31.

Busch-Vishniac, I.J. (1998) "Trends in Electromechanical Transduction," *Phys. Today* **51**, July, pp. 28–34.

Chalmers, P. (2001) "Relay Races," *Mech. Eng.* **123**, January, pp. 66–68.

DeGaspari, J. (2003) "Mixing It Up," *Mech. Eng.* **125**, August, pp. 34–38.

Ehrenman, G. (2004) "Shrinking the Lab Down to Size," *Mech. Eng.* **126**, May, pp. 26–29.

Epstein, A.H. (2000) "The Inevitability of Small," *Aerospace Am.* **38**, March, pp. 30–37.

Epstein, A.H., and Senturia, S.D. (1997) "Macro Power from Micro Machinery," *Science* **276**, 23 May, p. 1211.

Epstein, A.H., Senturia, S.D., Al-Midani, O., Anathasuresh, G., Ayon, A., Breuer, K., Chen, K.-S., Ehrich, F.F., Esteve, E., Frechette, L., Gauba, G., Ghodssi, R., Groshenry, C., Jacobson, S.A., Kerrebrock, J.L., Lang, J.H., Lin, C.-C., London, A., Lopata, J., Mehra, A., Mur Miranda, J.O., Nagle, S., Orr, D.J., Piekos, E., Schmidt, M.A., Shirley, G., Spearing, S.M., Tan, C.S., Tzeng, Y.-S., and Waitz, I.A. (1997) "Micro-Heat Engines, Gas Turbines, and Rocket Engines — The MIT Microengine Project," AIAA Paper No. 97-1773, AIAA, Reston, Virginia.

Feder, T. (2004) "Scholars Probe Nanotechnology's Promise and Its Potential Problems," *Phys. Today* **57**, June, pp. 30–33.

Feynman, R.P. (1961) "There's Plenty of Room at the Bottom," in *Miniaturization*, H.D. Gilbert, ed., pp. 282–296, Reinhold Publishing, New York.

Gabriel, K.J. (1995) "Engineering Microscopic Machines," *Sci. Am.* **260**, September, pp. 150–153.

Gabriel, K.J., Jarvis, J., and Trimmer, W., eds. (1988) *Small Machines, Large Opportunities: A Report on the Emerging Field of Microdynamics, National Science Foundation*, published by AT&T Bell Laboratories, Murray Hill, New Jersey.

Gabriel, K.J., Tabata, O., Shimaoka, K., Sugiyama, S., and Fujita, H. (1992) "Surface-Normal Electrostatic/Pneumatic Actuator," in *Proc. IEEE Micro Electro Mechanical Systems '92*, pp. 128–131, 4–7 February, Travemünde, Germany.