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Foreground: The first walking microrobot with a Swedish wasp relishing a ride on its back. The out-of-plane rotation of the eight legs is obtained by thermal shrinkage of polyimide in V-grooves (PVG). Leg movements are effected by sending heating pulses via integrated heaters causing the polyimide joints to expand. The size of the silicon legs is $1000 \times 600 \times 30 \ \mu m$, and the overall chip size of the robot is $15 \times 5 \times 0.5 \ mm$. The walking speed is $6 \ mm/s$ and the robot can carry 50 times its own weight. (Photograph by Per Westergård, Vetenskapsjournalisterna, Sweden, courtesy of Thorbjörn Ebefors, Royal Institute of Technology, Sweden.)

Background: A 12-layer microchain fabricated in nickel using the Electrochemical Fabrication (EFAB) technology. Overall height of the chain is approximately $100 \ \mu m$ and the width of a chain link is about $290 \ \mu m$. All horizontal links are free to move, while the vertical links are attached to the substrate. By simply including a sacrificial layer beneath the links, the entire chain can be released from the substrate. The microchain is fabricated in a pre-assembled state, without the need for actual assembly. A humble, picnic-loving ant would tower over the microchain shown here. (The two scanning electron micrographs courtesy of Adam L. Cohen, MEMGen Corporation, Torrance, California.)
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.)

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. 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. But humans have always strived 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 speculates on the remarkable possibilities that 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 449 m tall. 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 µm in production and approaches 10 nm in research laboratories.

Microelectromechanical systems (MEMS) refer to devices that have a characteristic length of less than 1 mm but more than 1 µm, 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 electrodisharge 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-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 robots, micro heat engines and micro heat pumps. Worldwide market projections for MEMS devices tend to be optimistic, reaching $30 billion by the year 2004.

This handbook 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. Other chapters cover existing and potential applications of microdevices in a variety of fields including instrumentation and distributed control. The book is divided into four parts: Part I provides background and physical considerations, Part II discusses the design and fabrication of microdevices, Part III reviews a few of the applications of microsensors and microactuators, and Part IV ponders the future of the field. There are 36 chapters written by the world's foremost authorities on this multidisciplinary subject. The contributing authors come from the U.S., China (Hong Kong), Israel, Korea, Sweden and Taiwan and are affiliated with academia, government and industry. Without compromising rigorousness, the text is designed for maximum readability by a broad audience having an engineering or science background. As expected when several authors are involved, and despite the editor's best effort, the different chapters vary in length, depth, breadth and writing style.

The Handbook of MEMS should be useful as a reference book to scientists and engineers already experienced in the field or as a primer 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. Ms. Cindy Renee Carelli has been our acquisition editor and lifeline to CRC Press. Cindy's talent, enthusiasm and indefatigability were highly contagious and percolated throughout the entire endeavor.

Mohamed Gad-el-Hak
Notre Dame, Indiana
1 January 2001
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. Dr. Gad-el-Hak has since taught and conducted research at the University of Southern California, University of Virginia, Institut National Polytechnique de Grenoble, Université de Poitiers and Friedrich-Alexander-Universität Erlangen-Nürnberg and has lectured extensively at seminars in the U.S. and overseas. Dr. Gad-el-Hak is currently Professor of Aerospace and Mechanical Engineering at the University of Notre Dame. Prior to that, he was a Senior Research Scientist and Program Manager at Flow Research Company in Seattle, WA, where he managed a variety of aerodynamic and hydrodynamic research projects.

Dr. 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 introducing the concept of targeted control to achieve drag reduction, lift enhancement and mixing augmentation in boundary-layer 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. He 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 340 articles, authored/edited eight books and conference proceedings, and presented 195 invited lectures. 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*, and *Flow Control: Fundamentals and Practices*.

Dr. Gad-el-Hak is 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, a member of the American Academy of Mechanics, a research fellow of the American Biographical Institute and a member of the European Mechanics Society. From 1988 to 1991, Dr. Gad-el-Hak served as Associate Editor for AIAA Journal. He is currently serving as Associate Editor for *Applied Mechanics Reviews* 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, Sweden and the U.S., the United Nations, and numerous industrial organizations. 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, RI; 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.
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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, 
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I

Background and Fundamentals

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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, CA, December 29, 1959.)

Tool making 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 the 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 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 an 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 currently—after the addition of a television antenna mast in 1950—449 m high. At the other end of the spectrum of man-made 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 man-made 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 µm (180 nm) 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?

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$^1$Gulliver’s Travels was 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.
FIGURE 1.1  Scale of things, in meters. Lower scale continues in the upper bar from left to right. One meter is $10^6 \mu m$, $10^9$ nm or $10^{10}$ Å.
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; Ouelette, 1996; Paula, 1996; Robinson et al., 1996a; 1996b; Madou, 1997; Tien, 1997; Amato, 1998; Busch-Vishniac, 1998; Kovacs, 1998; Knight, 1999; Epstein, 2000; Goldin et al., 2000; O’Connor and Hutchinson, 2000; Chalmers, 2001; Tang and Lee, 2001]. Electrostatic, magnetic, electromagnetic, pneumatic and thermal actuators, motors, valves, gears, cantilevers, diaphragms and tweezers less than 100 µm in 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, 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].

Microelectromechanical systems (MEMS) refer to devices that have a characteristic length of less than 1 mm but more than 1 µm, that combine electrical and mechanical components and that are fabricated using integrated circuit batch-processing technologies. The books by Madou (1997) and Kovacs (1998) 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 galvanof ormung 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 man-made 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].

The famed physicist Richard P. Feynman delivered a mere two, but profound, lectures 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: “[Small but movable machines] may or may not be useful, but they surely would be fun to make,” and, 24 years later, “There is no use for these machines, so I still don’t 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 ($30 billion by 2004). 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 in current use. 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 amounts of medication, manufacturing of nanoliters of chemicals and development of an artificial pancreas.

This multidisciplinary field has witnessed explosive growth during the last decade. Several new journals are dedicated to the science and technology of MEMS—for example, Journal of Microelectromechanical Systems, Journal of Micromechanics and Microengineering and Microscale Thermophysical Engineering. 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, Eurosensors, etc.

This handbook 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 discussed. Chapters on

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the electrical, structural, fluidic, transport and control aspects of MEMS are included. Other chapters cover existing and potential applications of microdevices in a variety of fields including instrumentation and distributed control. Physical understanding of the different phenomena unique to micromachines is emphasized throughout this book. The handbook is divided into four parts: Part I provides background and physical considerations, Part II discusses the design and fabrication of microdevices, Part III reviews a few of the applications of microsensors and microactuators, and Part IV ponders the future of the field. The 36 chapters are written by the world’s foremost authorities on this multidisciplinary subject. The contributing authors come from academia, government and industry. Without compromising rigorosity, the text is designed for maximum readability by a broad audience having an engineering or science background. The nature of the book—being a handbook and not an encyclopedia—and its size limitation dictate the exclusion 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 handbook will be a useful guide and reference to the explosive literature on MEMS and should provide the definitive word for the fundamentals and applications of microfabrication and microdevices. Glancing at the 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, better, 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 man-made 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 that follow. 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 this book), but Swift most certainly was a magnificent storyteller. *Hnuy illa nyha majah Yahoo!*

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1 Chapter 1 Introduction


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Chapter 2 Scaling of Micromechanical Devices


3 Chapter 3 Mechanical Properties of MEMS Materials


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4 Chapter 4 Flow Physics


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5 Chapter 5 Integrated Simulation for MEMS


University of California, Berkeley.


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Chapter 11 Bubble/Drop Transport in Microchannels


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The standard textbooks for geometric nonlinear control are Isidori (1996) and Nijmeijer and van der Schaft (1990). Additional material concerning the mathematical basis for differential geometry is found in Abraham et al. (1988) and Boothby (1986). Sastry (2000) provides an overview of differential geometric techniques but also considers Lyapunov-based methods and nonlinear dynamical systems in general.

Khalil (1996) focuses primarily on Lyapunov methods and
includes a chapter on differential geometric techniques.
13 Chapter 13 Model-Based Flow Control for Distributed Architectures


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For Further Information

For neural networks, the monographs by Schalkoff (1997) and Haykin (1999) are very good for beginners.

to specific areas. For genetic algorithms, the books by Goldberg (1989), Michalewicz (1992) and Mitchell (1997) are recommended for beginners. There are many excellent fuzzy control texts; however, the authors found Kosko (1997) and Passino and Yurkovich (1998) particularly clear and useful. Texts with indepth and complete developments of fuzzy logic include Klir and Yuan (1995) and Jang et al. (1997).
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16 Chapter 16 MEMS Fabrication


FIGURE 16.112 SEM micrograph of the stepping slider (top) and scanned image (bottom). (From Akiyama, T., J. Microelectromech. Syst., 2, 106-110, 1993. With permission.)

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Information on VLSI X-ray lithography with some DXRL subject matter is covered by the international conference on Electron, Ion and Photon Beam Technology and Nanofabrication (EIPBN), with papers published in the Journal of Vacuum Science and Technology B.

Book chapters devoted to the topic of LIGA may be found in Fundamentals of Microfabrication (M. Madou, CRC Press, 1997) and Handbook of Microlithography, Micromachining, and Microfabrication,

Many LIGA-related journal articles may be found in the IoP Journal of Micromechanics and Microengineering: Structures, Devices, and Systems.

Web sites where additional information on LIGA may be found include: http://www.fzk.de/imt/elmt.htm; http://www.imm.uni-mainz.de/; http://daytona.ca.sandia.gov/LIGA/; http://mems.engr.wisc.edu/liga.html.
Chapter 19 Electrochemical Fabrication (EFABTM)


For Further Information
The University of California/Information Sciences Institute has a Web site for EFAB at www.isi.edu/efab.

The site includes links to some SFF companies that can provide more information on SFF. Readers may also visit MEMGen Corporation’s Web site at www.memgen.com.

EFAB, Instant Masking, Instant Mask and Layerize are trademarks of MEMGen Corporation. Windows is a registered trademark of Microsoft Corporation.
Chapter 20 Fabrication and Characterization of Single-Crystal Silicon Carbide MEMS


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22 Chapter 22 Microfabricated Chemical Sensors for Aerospace Applications


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Chapter 27 Surface-Micromachined Mechanisms


For Further Reading

Among the several excellent sources of information on surface-micromachining and surface-micromachined devices are the recommended books by Madou (1997) and Kovacs (1998). Many conferences—for example, IEEE Micro Electro Mechanical Systems Conferences, biannual conferences on Solid State Sensors and Actuators (Transducers)—are mainly focused on device fabrication. Actuators are also good sources for some good device and mechanism papers. SPIE and ASME also sponsor MEMS conferences or workshops.

Some of the heavily read journals in the field of MEMS include Sensors and Actuators and the Journal of
Microelectromechanical Systems (J. MEMS). Of the two, J. MEMS is the better source for surface-micro
machined mechanism papers. For information on designing and building surface micromachines, both
Cronos and Sandia provide information about their processes. The internet address for Cronos is
http://www.memsrus.com/; for Sandia, the address is http://www.mdl.sandia.gov/Micromachine/. Good
[Shigley and Mischke, 1989] and the Mechanisms and Mechanical Devices Sourcebook [Chironis and
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microrobots as well as different aspects of the definition of microrobots is found in the paper, “Review—Microactuators for Microrobots: A Critical Survey,” by Dario et al. and published in IOP Journal of Micromechanics and Microengineering (JMM), Vol. 2, pp. 141-157, 1992. Proceedings from the “Microrobotics and Micromanipulation” conference have been published annually by SPIE (the Inter national Society for Optical Engineering) since 1995. These proceedings document the latest development in the field of microrobotics each year.
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