MOBILE MICROROBOTICS

Intelligent Robotics and Autonomous Agents

Edited by Ronald C. Arkin

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MOBILE MICROROBOTICS

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To the beautiful memories of my beloved sister, brain surgeon, İlkay Sitti whom we lost so young and so unexpectedly

Acknowledgments

This book could never be possible without the love and support of my beloved wife Seyhan and daughters, Ada and Doğa. They have made my life always more beautiful and meaningful. In addition to them, I have been so lucky and happy that my parents and two sisters have loved and supported me unconditionally all the time. My father has been a role model for me as a person and an intellectual with many ideals.

I created and taught my first Micro/Nano-Robotics course at UC Berkeley in 2002 as a lecturer with 43 PhD and 2 undergraduate students. It was an amazing first-time teaching experience, and I continued teaching it at Carnegie Mellon University for 11 years as a professor. The content of the course evolved and changed each time, and this book represents its latest version with a focus on mobile microrobotics mainly. I hope it will help any professor who wants to teach such course or anybody who wants to learn about or start working on microrobotics.

I have been lucky and privileged to conduct exciting high-impact research, mentor, and have fun socially with so many great post-docs and PhD, MSc, and undergraduate students since 2002. For this book, I specially thank my previous student Eric Diller, who wrote a tutorial on microrobotics with me in 2013, which formed a starting point for this book. I also thank my previous or current students or post-docs Chytra Pawashe, Steven Floyd, Rika Wright Carlsen, Jiang Zhuang, Slava Arabagi, Bahareh Behkam, Uyiosa Abusonwan, Burak Aksak, Bilsay Sümer, Çağdaş Önal, Michael Murphy, Yiğit Mengüç, Onur Özcan, Yun Seong Song, Zhou Ye, Joshua Giltinan, Hakan Ceylan, Ceren Garip, Lindsey Hines, Guo Zhan Lum, Xiaoguang Dong, and Shuhei Miyashita, whose works and papers have enabled some portions of the book. Moreover, I would like to thank Hakan Ceylan, Byungwook Park, and Ahmet Fatih Tabak for providing some text and references for a sub-section; Wendong Wang, Wenqi Yu, and Sukho Song for providing specific information for a table; and Lindsey Hines, Kirstin Petersen, Thomas Endlein, Massimo Mastrangeli, Byungwook Park, Rika Wright Carlsen, and Wendong Wang for reviewing and giving feedback for some chapters. Finally, I thank my assistant Janina Sieber for her help and Alejandro Posada for drawing many figures in this book.

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1 Introduction

Significant progress in micro/nanoscale science and technology in last two decades has created increasing demand and hope for new microsystems for high-impact applications in healthcare, biotechnology, manufacturing, and mobile sensor networks. Such microsystems should be able to access small enclosed spaces such as inside the human body and microfluidic devices non-invasively and manipulate or interact with micro/nanoscale entities directly. Because human or macroscale robot sensing, precision, and size are not capable of achieving such desired characteristics, microrobotics has emerged as a new robotics field to extend our interaction and exploration capabilities to sub-millimeter scales. Moreover, mobile microrobots could be manufactured cost-effectively in large numbers, where a dense network of microrobots could enable new massively parallel, self-organizing, reconfigurable, swarm, or distributed systems. For these purposes, many groups have proposed various untethered mobile microrobotic systems in the past decade. Such untethered microrobots could enable many new applications, such as minimally invasive diagnosis and treatment inside the human body, biological studies or bioengineering applications inside microfluidic devices, desktop micromanufacturing, and mobile sensor networks for environmental and health monitoring.

1.1 Definition of Different Size Scale Miniature Mobile Robots

A typical macroscale mobile robot is a self-contained, untethered, and reprogrammable machine that can perceive, move, and learn in a given environment to realize a given task. But when can a mobile robot be called a mobile microrobot? Unfortunately, there is not yet a standardized definition of the term *microrobot*. Let us attempt to create a definition to classify different miniature robots in the literature. First, let us define two unique characteristics of a mobile microrobot [65]:

- *Overall size*: A mobile microrobot must be able to access small (less than 1 mm in all dimensions) spaces directly with minimal invasion, which entails untethered operation and all dimensions of the mobile robot being smaller than 1 mm.
- *Scaling effects on robot mechanics*: Locomotion mechanics and physical interactions of a mobile microrobot in a given environment are dominated by microscale physical forces and effects. Thus, volume-based forces such

as inertial forces, gravity, and buoyancy become almost negligible or comparable to surface area- and perimeter-based forces such as viscous forces, drag, friction, surface tension, and adhesion.

To incorporate these unique characteristics, we will define a mobile microrobot as *a mobile robotic system where its untethered mobile component has all dimensions less than 1 mm and larger than 1 μm and its mechanics is dominated by microscale physical forces and effects*. Thus, for microrobots, bulk forces are negligible or comparable to surface area- and perimeter-related forces. Also, viscous forces are much larger than inertial forces for a swimming microrobot, resulting in Reynolds number, which is the ratio of the inertial to viscous forces, less than 1. At the micron scale, fluid flows are mostly steady, and we are mostly in the Stokes flow regime. Brownian (stochastic) motion of microrobots in water resulting from their random collision with the water molecules at room temperature is negligible. Moreover, microrobots are made of sub-millimeter scale components, such as microactuators, microsensors, and micromechanisms, and are fabricated by microfabrication methods, which are different from conventional macroscale machining techniques. Finally, they have specific functions for a given task such as manipulation, sensing, cargo transport and delivery, and local heating.

There are currently two main approaches to designing, building, and controlling mobile microrobots in the literature depending on the given application:

- *On-board approach*: Similar to a typical macroscale mobile robot, the microrobot is self-contained and untethered, with all robot dimensions being less than 1 mm. Here, all on-board robot components, such as mechanisms, tools, actuators, sensors, power source, electronics, computation, and wireless communication, must be miniaturized down to few micrometers scale.
- *Off-board approach*: The mobile, untethered component of the microrobotic system is remotely (off-board) actuated, sensed, controlled, or powered and has all dimensions less than 1 mm while the overall system size could be very large.

The on-board approach is technically much more difficult to realize due to miniaturization challenges of all on-board components. However, it enables mobile microrobots navigating in large workspaces, e.g., in outdoors, which is required for mobile sensor network applications for environment monitoring and exploration. On the other hand, the off-board approach is easier to

Table 1.1

Definition of different size scale miniature mobile robots (Reynolds number is the ratio of inertial forces to viscous forces, which dictates the fluid dynamics regime.)

Mobile Robot Type	Overall Size	Dominant Forces Acting on Robot
Millirobots	1 mm to 10 cm	Macroscale volume-related forces; Reynolds number $\gg 1$
Microrobots	1 μm to 1 mm	Microscale surface area- or perimeter-related forces; Negligible Brownian motion; Reynolds number ~ 1 or $\ll 1$
Nanorobots	< 1 μm	Nanoscale physical and chemical forces; Non-negligible stochastic Brownian motion

implement due to fewer miniaturization challenges when operating in confined workspaces, such as the human body and microfluidic chips. Such limited workspace would not be an issue for potential microrobot applications in healthcare, bioengineering, microfluidics, and desktop micromanufacturing. Thus, almost all of the current mobile microrobotics studies in the literature have been using the off-board approach, and therefore our microrobotics definition also covers such studies.

In addition to the above on-board and off-board approaches, microrobots can also be classified as *synthetic* and *bio-hybrid*. In the former case, the microrobot is made of fully synthetic materials, such as polymers, magnetic materials, silicon, silicon oxide, metal alloys, composites, elastomers, and metals, while the latter is made of both biological and synthetic materials. Bio-hybrid microrobots are typically integrated with single or many cells, such as cardiac or skeletal muscle cells, or microorganisms, such as bacteria, algae, spermatozoids, and protozoa, and powered by the chemical energy inside the cell or in the environment. They harvest the efficient and robust propulsion, sensing, and control capabilities of biological cells at the microscale. Such cells could propel the robot in a given physiologically compatible environment, and sense environmental stimuli to control the robot motion by diverse mechanisms, such as chemotaxis, magnetotaxis, galvanotaxis, phototaxis, thermotaxis, and aerotaxis.

Reported miniature mobile robot sizes range from sub-micron to centimeter scale. We can classify such different length scale miniature robots as *millirobots*, *microrobots*, and *nanorobots* as given in Table 1.1. These small-scale robots have different dominant physical forces and effects. For the on-board approach case, their on-board components must have overall sizes much

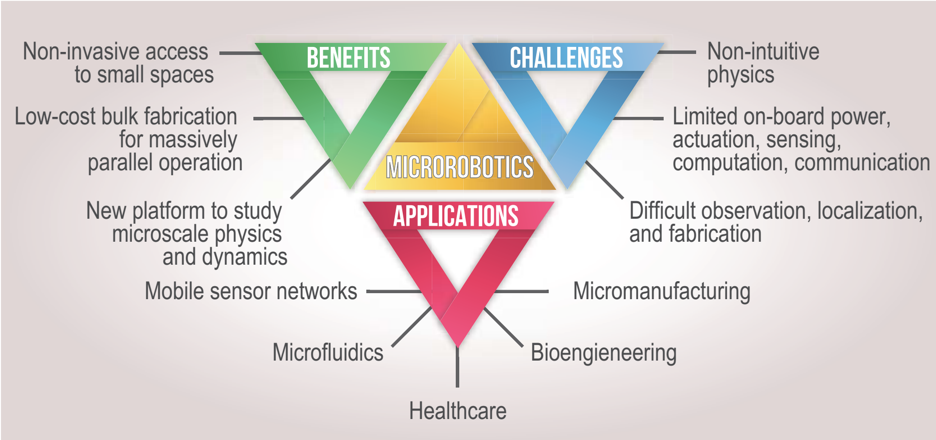

Figure 1.1
Diagram showing the benefits, challenges, and potential applications of mobile microrobots.

smaller than the given robot overall size. For millirobots, macroscale forces such as bulk forces dominate the robot mechanics instead of microscale forces and effects. The fluid dynamics is unsteady and even starts to be periodically turbulent when the Reynolds number is much larger than 1. For nanorobots, assumptions of continuum mechanics may not be valid at the sub-micron scale, and effects such as Brownian motion and chemical interactions create highly stochastic robot behavior. The fluid dynamics for nanorobots are no longer described accurately by the Navier-Stokes equation, so the Reynolds number is not relevant.

The size scale range in Table 1.1 presents significant new challenges in fabrication, actuation, locomotion mechanisms, and power supply not seen in macroscale mobile robotics. Microscale robots are particularly interesting because new physical principles begin to dominate the robot behavior. Changes in fluid mechanics, stochastic motions, and shorter time scales also challenge natural engineering notions as to how robotic elements move and interact. These physical effects must be taken into account when designing and operating robots at the small scale.

The benefits, challenges, and potential applications of mobile microrobots are overviewed in Figure 1.1. Here, we see that microrobots promise to access small spaces in a non-invasive manner as a new platform for microscale physics and dynamics. Compared with other robotic systems, they can be fabricated

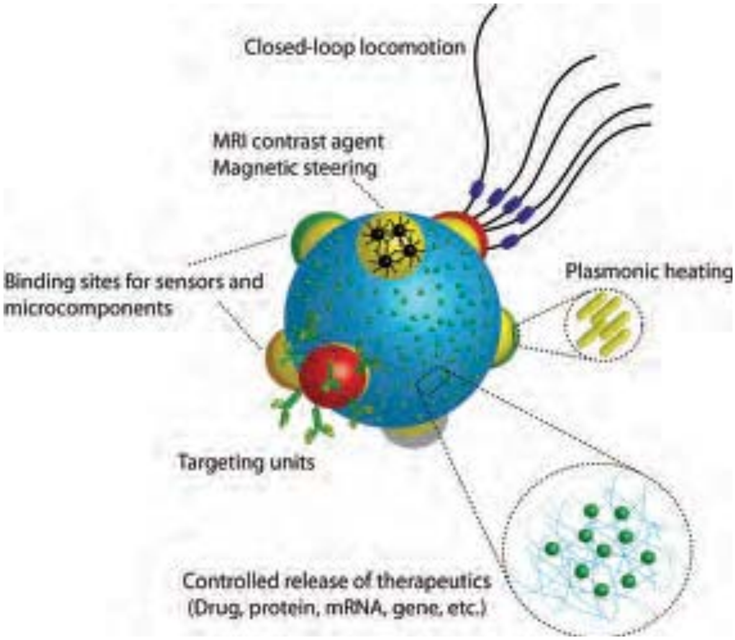

Figure 1.2

A conceptual sketch of an example future mobile microrobot with spatio-selective surface functionalization for potential medical applications. Each functional component could be assembled on a main body. The main body further could serve as a large depot for therapeutics to launch controlled release at the site of action. A closed-loop autonomous locomotion (e.g., a bio-hybrid design) could couple environmental signals to motility. Targeting units could enable reaching and localization at the intended body site. Medical imaging, e.g., magnetic resonance imaging (MRI), contrast agents loaded on the microrobot could enable visualization as well as remote steering on demand. Metallic nanorods could enable remote plasmonic or RF heating to decompose a tumor tissue by hypothermia.

inexpensively in bulk for potential massively parallel applications. However, several challenges arise in the design and control of microscale robots, such as non-intuitive attractive/repulsive and contact/non-contact physical forces, limited options for power and actuation, significant fabrication constraints, and difficulty in localizing such tiny robots. The field of microrobotics is particularly exciting due to the potential applications in healthcare, bioengineering, microfluidics, mobile sensor networks, and desktop microfactories. A conceptual sketch of an example mobile microrobot for medical applications is shown in Figure 1.2 with its possible components and functions.

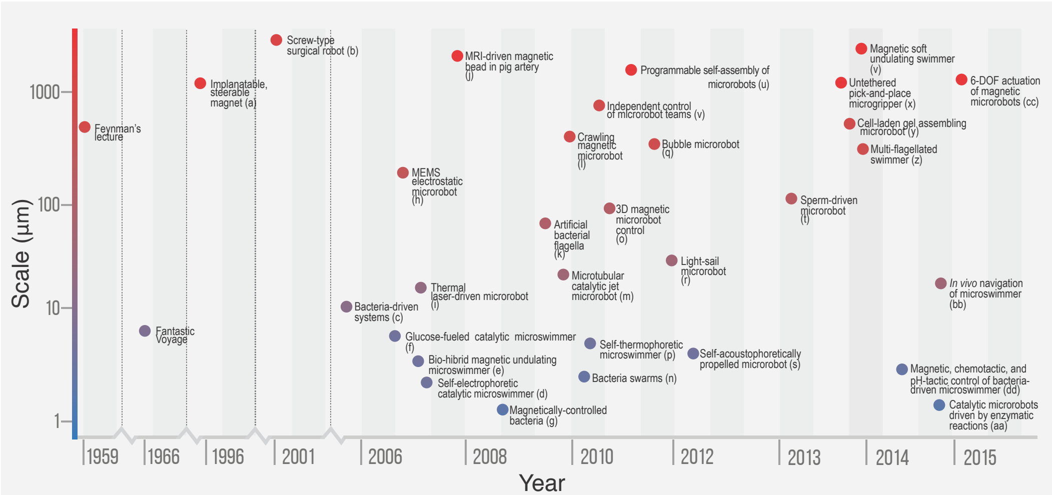

Figure 1.3

Approximate timeline showing the emerging new microrobot systems with their given overall size scale as significant milestones. (a) Implantable tiny permanent magnet steered by external electromagnetic coils [1]. (b) Screw-type surgical millirobot [2]. (c) Bacteria-driven biohybrid microrobots [3]. (d) Self-electrophoretic catalytic microswimmer [4]. (e) Bio-hybrid magnetic undulating microswimmer [5]. (f) Glucose-fueled catalytic microswimmer [6]. (g) Magnetically controlled bacteria [7]. (h) MEMS electrostatic microrobot [8]. (i) Thermal laser-driven microrobot [9]. (j) Magnetic bead driven by an MRI device in pig artery [10]. (k) Magnetic microswimmer with rigid helical flagellum inspired by bacterial flagella [11, 12]. (l) Crawling magnetic microrobot [13]. (m) Microtubular catalytic jet microrobot [14]. (n) Bacteria swarms as microrobotic manipulation systems [15]. (o) 3D magnetic microrobot control [16]. (p) Self-thermophoretic microswimmer [17]. (q) Bubble microrobot [18]. (r) Light-sail microrobot [19]. (s) Self-acoustophoretically propelled microrobot [20]. (t) Sperm-driven bio-hybrid microrobot [21]. (u) Magnetic, chemotactic, and pH-tactic control of bacteria-driven microswimmers [22–24]. (v) Magnetic soft undulating swimmer [25]. (x) Untethered pick-and-place microgripper [26]. (y) Cell-laden microgel assembling microrobot [27]. (z) Catalytic micromotors driven by enzymatic reactions [28]. (aa) In vivo navigation of microswimmers [29, 30]. (bb) 6-degrees-of-freedom (6-DOF) actuation of magnetic microrobots [31].

1.2 Brief History of Microrobotics

Advances in and increased use of microelectromechanical systems (MEMS) since the 1990s have driven the development of untethered microrobots. MEMS fabrication methods allow for precise features to be made from a wide range of materials, which can be useful for functionalized microrobots. There has been a surge in microrobotics work in the past few years, and the field is relatively new and growing fast [55, 66–68]. Figure 1.3 presents an overview of a few of the new microrobotic technologies which have been published, along with their approximate overall size scale.

The first miniature machines were conceived by Feynman in his lecture on "There's Plenty of Room at the Bottom" in 1959. In popular culture, the field of microrobotics is familiar to many due to the 1966 sci-fi movie Fantastic Voyage, and later the 1987 movie *Innerspace*. In these films, miniaturized submarine crews are injected inside the human body and perform non-invasive surgery. The first studies in untethered robots using principles which would develop into microrobot actuation principles were only made recently, such as a magnetic stereotaxis system [1] to guide a tiny permanent magnet inside the human body and a magnetically driven screw which moved through tissue [2]. Other significant milestone studies in untethered microrobotics include a study on bacteria-inspired swimming propulsion [69], bacteria-propelled beads [3, 70], steerable electrostatic crawling microrobots [8], laser-powered microwalkers [9], magnetic resonance imaging (MRI) device-driven magnetic beads [10], and magnetically driven milliscale nickel robots [71]. These first studies have been followed by other novel actuation methods, such as helical propulsion [11, 12], stick-slip crawling microrobots [13], magnetotactic bacteria swarms as microrobots [72], optically driven "bubble" microrobots [18], and microrobots driven directly by the transfer of momentum from a directed laser spot [19], among others. Figures 1.4 and 1.5 show a number of the existing approaches to microrobot mobility in the literature for motion in two dimensions and three dimensions. Most of these methods belong to the off-board (remote) microrobot actuation and control approach, and will be discussed in detail later. It is immediately clear that actual microrobots do not resemble the devices shrunk down in popular microrobotics depictions.

As an additional driving force for the development of mobile microrobots, the Mobile Microrobotics Competition began in 2007 as the "nanogram" league of the popular Robocup robot soccer competition [73]. This yearly event has since moved to the IEEE International Conference on Robotics and Automation and challenges teams to accomplish various mobility and manipulation tasks with an untethered microrobot smaller than 500 μm on a side. The competition has spurred several research groups to begin research in microrobotics, and has helped define the challenges most pressing to the microrobotics research field.

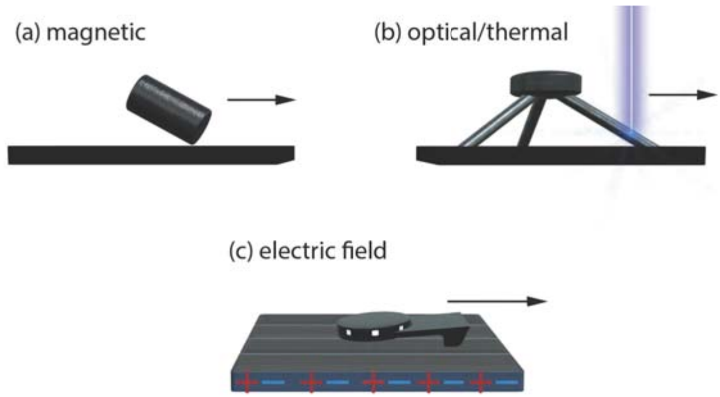

Figure 1.4

Some existing remote (off-board) approaches to mobile microrobot actuation and control in 2D. (a) Magnetically driven crawling robots include the Mag-μBot [13], the Mag-Mite magnetic crawling microrobot [32], the magnetic microtransporter [33], the rolling magnetic microrobot [34], the diamagnetically levitating milliscale robot [35], the self-assembled surface swimmer [36], and the magnetic thin-film microrobot [37]. (b) Thermally driven microrobots include the laser-activated crawling microrobot [9], the micro-light sailboat [19], and the optically controlled bubble microrobot [18]. (c) Electrically driven microrobots include the electrostatic scratch-drive microrobot [38] and the electrostatic microbiorobot [39]. Other microrobots which operate in 2D include the piezoelectric-magnetic microrobot MagPieR [40] and the electrowetting droplet microrobot [41].

1.3 Outline of the Book

This book introduces the reader to the newly emerging robotics field of mobile microrobotics. Chapter 2 covers the scaling laws that can be used to determine the dominant forces and effects at the micron scale. Such laws would also give us a significant physical intuition when we design and analyze different microrobots. Moreover, such scaling laws can be used to design and build scaled-up robots to understand the design and control principles for microrobotic systems, which are much harder to study experimentally at the micron scale directly.

In Chapter 3, forces acting on microrobots such as surface forces, adhesion, friction, and viscous drag are given and analytically modeled for simple spherical microrobot and flat surface interaction cases. Significant surface forces in air are typically van der Waals, capillary, and electrostatic forces for microsystems. In liquids, van der Waals forces still exist, but many other surface forces

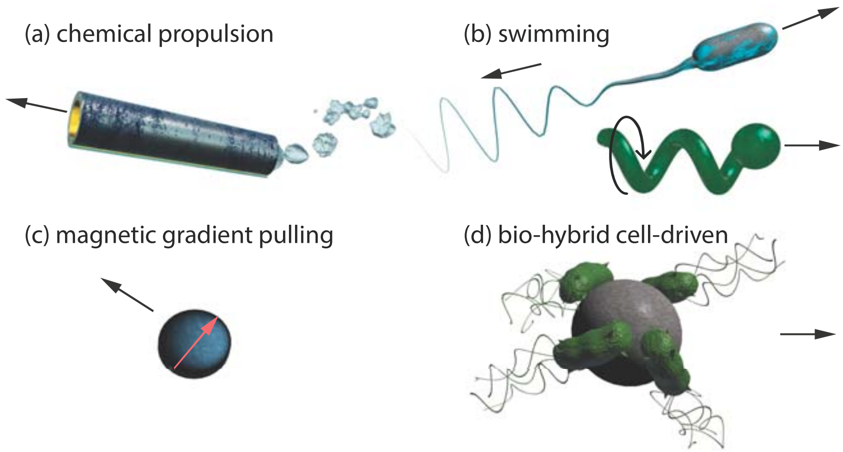

Figure 1.5

(a) Chemically propelled designs include microtubular jet microrobots [14], catalytic micro/-nanomotors [42], and electro-osmotic microswimmers [43]. (b) Swimming microrobots include the colloidal magnetic swimmer [5], the magnetic thin-film helical swimmer [44], the microscale magnetic helix fabricated by glancing angle deposition [12], the helical microrobot with cargo carrying cage fabricated by direct laser writing [45], and the helical microrobot with magnetic head fabricated as thin-film and rolled using residual stress [46]. (c) Microrobots pulled in 3D using magnetic field gradients include the nickel microrobot capable of 5-DOF motion in 3D using the OctoMag system [16] and the MRI-powered and imaged magnetic bead [47]. (d) Cell-actuated bio-hybrid approaches include the artificially magnetotactic bacteria [48], the cardiomyocyte-driven microswimmers [49], the chemotactic steering of bacteria-propelled microbeads [24], the sperm-driven and magnetically steered microrobots [21], and the magnetotactic bacteria swarm manipulating microscale bricks [15].

(such as double layer, hydration, and hydrophobic forces) also become important. When the microrobot contacts surfaces or other robots, surface forces induce adhesion, which is function of interfacial physical properties, contact geometry, and load. For elastic and viscoelastic materials, such adhesive forces and surface deformation are modeled using micro/nanoscale contact mechanics models. When the robot moves and inserts shear force on another solid surface it is in contact with, micro/nanoscale friction becomes crucial to model and understand. Sliding, rolling, and spinning types of frictional forces are modeled approximately. Inside fluids, microfluidic forces such as viscous drag and drag torque are important to model while having possible wall effects (i.e., changes in fluidic flows and forces due to the nearby walls) in the given operation environment. Finally, measurement techniques that can be used to characterize such micron scale force parameters are described so that the force models could use real empirical parameter values towards realistic robot behavior prediction.

Chapter 4 describes possible microfabrication techniques for microrobots, which are photo-lithography, bulk micromachining, surface micromachining, LIGA process, deep-reactive ion etching, laser micromachining, two-photon lithography, electro-discharge machining, micromilling, and so on. Each method's capabilities and limitations are studied so that the proper microfabrication method for a given microrobot design can be determined optimally. Especially, two-photon lithography is a recent exciting fabrication tool that could create a wide range of complex 3D microrobots with specific surface patterning and functionalization.

Chapter 5 includes possible on-board and remote sensing methods for microrobots. Tiny cameras and piezoresistive, capacitive, and piezoelectric microsensors could be potentially integrated to microrobots with proper size reduction, signal conditioning, and powering. However, such on-board sensors are not available for sub-mm scale robots, but remote magnetoelastic and optical sensing methods are more feasible for microrobots at the moment.

Microrobots can be actuated using on-board microactuators, self-propelled using physical or chemical interactions with their operation medium or biological cells attached to them, or remotely actuated. Chapter 6 studies possible on-board microactuators such as piezoelectric, shape memory alloy, conductive polymer, ionic polymer-metal composite, dielectric elastomer, MEMS electrostatic or thermal, and magneto- and electrorheological fluid actuators. Some of these actuators can be scaled down to micron scale as thin-film or unimorph/bimorph bending-type actuators integrated to robot structures directly while their on-board driving, control, and powering are still challenging for sub-mm scale robots. Chapter 7 describes self-propulsion methods that can use self-generated local gradients and fields or biological cells as the actuation source in proper liquid environments. Such catalytic (e.g., self-electrophoretic, self-diffusiophoretic, self-generated microbubbles-based, self-acoustophoretic, self-thermophoretic, and self-generated Marangoni flows based propulsion) or biological (bacteria, muscle cell, and algae-driven microswimmers) actuation approaches do not require any on-board electrical power source, electronics, processor, and control circuitry, which make them promising for mobile microrobots down to few microns and even submicron scale. Such self-propelling microswimmers are all stochastic and can be controlled by tactic stimuli in the environment. Chapter 8 covers the commonly used remote microrobot actuation methods. Remotely generated physical forces and torques can be used to actuate microrobots operating in a limited workspace, such as inside the human body or a microfluidic device. Main remote actuation methods based on magnetic, electrostatic, optical, and ultrasonic forces or pressures are explained. These actuation methods are currently the most common untethered mobile microrobot actuation method in addition to catalytic microswimming methods.

All current mobile microrobots have no on-board powering capability, therefore they are typically actuated remotely or self-propelled by the fuels in the operation environment with no on-board functions such as sensing, processing, communication, and computing yet. Only in the specific case of some biohybrid microrobot designs, the chemical energy inside the cells can power the biomotors and thus the locomotion of microswimmers. Such on-board functions are indispensable for future medical and other microrobot applications with more advanced capabilities. Therefore, Chapter 9 covers the possible onboard powering methods for microrobots: we can integrate an on-board energy/power source, transfer power wirelessly, and scavenge power from the operation environment.

Chapter 10 includes the typical locomotion methods for microrobots on surfaces, in liquids, in air, and on fluid-air interfaces. Microrobots can have many different locomotion modes, such as surface locomotion in 2D (crawling, rolling, sliding, walking, and jumping), swimming in 3D (flagellar propulsion, pulling, chemical propulsion, body/tail undulation, jet propulsion, and floating), locomotion at the air-fluid interface in 2D (walking, jumping, climbing, sliding, and floating), and flying in the air in 2D or 3D (flapping wings, rotary wings, and levitated near-surface motion). We study each locomotion mode with its given physical conditions, possible actuation methods, power consumption, and challenges. We also give example relevant biological counterparts for each locomotion mode.

In Chapter 11, microrobot localization and control methods are studied. Determining the location of untethered microrobots in a space is a major challenge, depending on the operational environment. Optical, magnetic (electromagnetic and MRI-based), x-ray, and ultrasound tracking methods are described with their given resolution, speed, penetration depth, and potential health and technical issues. Next, control, vision, planning, and learning issues for microrobots are briefly described. Controlling teams/swarms of microrobots is a significant challenge for future applications, and various multi-robot control methods are studied for the case of magnetic microrobots especially.

Potential current and future applications of microrobots are covered in Chapter 12. Biological and synthetic micropart manipulation using contact and non-contact methods, healthcare, environment remediation, microfactory, reconfigurable microsystems, and scientific tool applications are described with given challenges.

Chapter 13 summarizes and describes the key near-future challenges to solve in the microrobotics field.

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