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Micro-Scale Mobile Robotics

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Abstract

The field of microrobotics has seen tremendous advances in recent years. The principles governing the design of such submillimeter scale robots rely on an understanding of microscale physics, fabrication, and novel control strategies. This monograph provides a tutorial on the relevant physical phenomena governing the operation and design of microrobots, as well as a survey of existing approaches to microrobot design and control. It also provides a detailed practical overview of actuation and control methods that are commonly used to remotely power these designs, as well as a discussion of possible future research directions. Potential high-impact applications of untethered microrobots such as minimally invasive diagnosis and treatment inside the human body, biological studies or bioengineering, microfluidics, desktop micromanufacturing, and mobile sensor networks for environmental and health monitoring are reported.

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1

Introduction

Due to recent advances in micro- and nanoscale science and technology and increasing demand for new microsystems for applications in medicine, biotechnology, manufacturing, and mobile sensor networks, creating tiny mobile robots that could access enclosed small spaces down to the micron scale such as inside the human body and microfluidic devices and could manipulate and interact with micro/nanoscale entities has become a critical issue. Since human or macroscale robot sensing, precision, and size are not sufficient to interact with such tiny objects and access such tiny spaces directly, microrobotics has emerged as a new robotics field to extend our interaction and exploration capabilities to submillimeter scales. Moreover, mobile microrobots could be manufactured cost-effectively in large numbers where a large number of microrobots could enable new massively parallel, self-organizing, reconfigurable, swarm, or distributed systems. For these purposes, many groups have been proposing 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 channels, desktop micromanufacturing, and mobile sensor networks for environmental and health monitoring.

There is no standardized definition of the term *microrobot*. In fact, reported microrobots range in size from single μms to the cm scale. However, one common approach defines a microrobot as existing in the size range of hundreds of nm to 1 mm. In some cases, *component size scale* being micron scale is taken as the crucial aspect, which could then include millimeter or centimeter-scale mobile robots as microrobots. In other cases, *overall size scale* being micron scale is emphasized where mobile robots able to fit in spaces smaller than a millimeter are considered as microrobots. In this monograph, the latter is used to define microrobots since the overall size dictates the environment in which the robots are capable of accessing, and also tells us something about their capabilities. On the other hand, a more relevant definition when studying novel wireless locomotion schemes might involve the types of *physical interactions* which dominate the motion and interaction of the robot. Large or centi/milli-scale robots are dominated by inertial and other bulk forces, while the motion of microrobots is dominated by surface area-related forces, including friction, adhesion, drag, and viscous forces at the micro-scale. The lower-bound of microrobots could likewise be when assumptions of the continuity of matter are no longer valid. At sizes below tens of μm, effects such as Brownian motion and chemical interactions could lead to stochastic descriptions of motion behavior. This is the realm of *nanorobots*, and will not be addressed in this survey. Thus, we define microrobots as being roughly in the size range single to hundreds of μm, and being dominated by micro-scale physical forces and effects.

This size range presents significant new challenges in fabrication, actuation, and power supply not seen in larger traditional robotics. This size scale is particularly interesting because new physical principles begin to dominate the behavior. As we go smaller, the balance of different forces changes dramatically, and we see increases in friction and adhesion while the influence of weight and inertia is markedly reduced. Other 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.

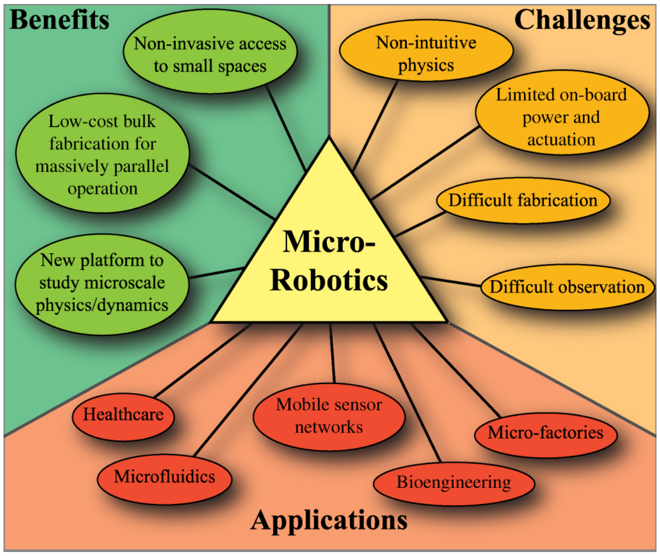

Fig. 1.1 Diagram showing the benefits, challenges, and potential applications of micro-scale mobile robots.

The benefits, challenges, and potential applications of micro-scale mobile robots 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/dynamics. Compared with other robotic systems, they can be fabricated inexpensively in bulk for potential massively parallel applications. However, several challenges arise in the design and control of micro-scale robots such as nonintuitive 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 in micro-factories.

1.1 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

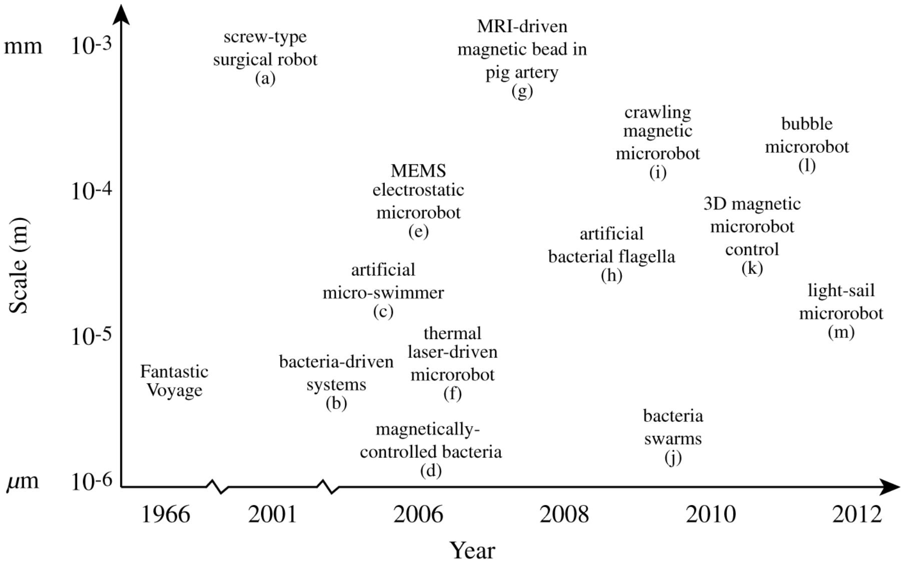

Fig. 1.2 Approximate timeline showing the emerging new microrobot systems as significant milestones. (a) Screw-type surgical robot [100]. (b) Bacteria-driven systems [40]. (c) Artificial micro-swimmer [53]. (d) Magnetically controlled bacteria [133]. (e) MEMS electrostatic microrobot [50]. (f) Thermal laser-driven microrobot [201]. (g) MRI-driven magnetic bead in pig artery [132]. (h) Artificial bacterial flagella [236]. (i) Crawling magnetic microrobot [155]. (j) Bacteria swarms [134]. (k) 3D magnetic microrobot control [115]. (l) Bubble microrobot [96]. (m) Light-sail microrobot [27].

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 is growing fast [186]. Figure 1.2 overviews a few of the new microrobotic technologies which have been published, along with their approximate size scale.

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 noninvasive surgery. The first studies in untethered robots using principles which would develop into microrobot actuation principles were only made recently, such as a magnetically driven screw which moved through tissue [100]. Other significant milestone studies in untethered microrobotics include a study on bacteria-inspired swimming propulsion [55], bacteria-propelled beads [14, 40], steerable electrostatic crawling microrobots [50], laser-powered micro-walkers [201], magnetic resonance imaging (MRI) device-driven magnetic beads [132], and magnetically driven mm-scale nickel robots [231]. These first studies have been followed by other novel actuation methods such as helical propulsion [75, 236], stick-slip crawling microrobots [155], magnetotactic bacteria swarms as microrobots [135], optically driven "bubble" microrobots [96], and microrobots driven directly by the transfer of momentum from a directed laser spot [27], among others. Figures 1.3 and 1.4 show a number of the existing approaches to microrobot mobility in the literature for motion in 2D/3D. These methods will be discussed in detail in Section 3. 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 sponsored and run by the National Institute of Standards and Technology (NIST) began in

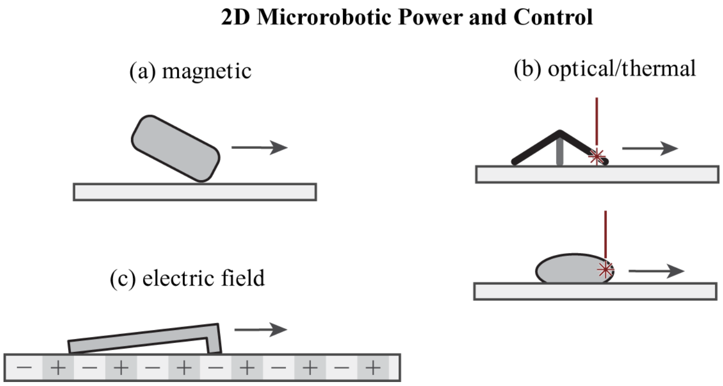

Fig. 1.3 Some existing approaches to mobile microrobot power and control in 2D. (a) Magnetically-driven crawling robots include the Mag-μBot [155], the Mag-Mite magnetic crawling microrobot [71], the magnetic microtransporter [173], rolling magnetic microrobot [105], the diamagnetically-levitating mm-scale robot [157], the self-assembled surface swimmer [192], and the magnetic thin-film microrobot [106]. (b) Thermally-driven microrobots include the laser-activated crawling microrobot [201], micro light sailboat [27], and the optically controlled bubble microrobot [96]. (c) Electrically-driven microrobots include the electrostatic scratch-drive microrobot [52] and the electrostatic microbiorobot [174]. Other microrobots which operate in 2D include the piezoelectric-magnetic microrobot MagPieR [28] and the electrowetting droplet microrobot [176].

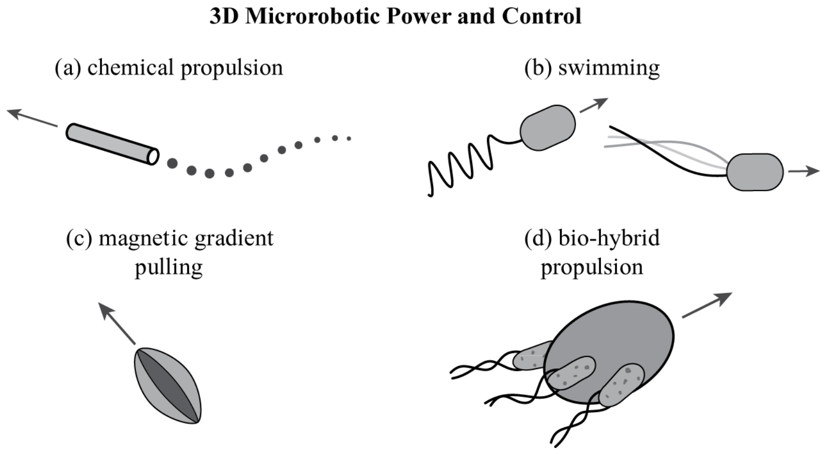

Fig. 1.4 Some existing approaches to mobile microrobot power and control in 3D. (a) Chemically-propelled designs include the microtubular jet microrobot [193] and the electro-osmotic swimmer [98]. (b) Swimming microrobots include the colloidal magnetic swimmer [53], the magnetic thin-film helical swimmer [226], the micron-scale magnetic helix fabricated by glancing angle deposition [75], the micro-helix microrobot with cargo carrying cage, fabricated by direct laser writing [208] and the micro-helix microrobot with magnetic head, fabricated as thin-film and rolled using residual stress [237]. (c) Microrobots pulled in 3D using magnetic field gradients include the nickel microrobot capable of 5 DOF motion in 3D using the OctoMag system [115] and the MRI-powered and imaged magnetic bead [131]. (d) Bio-hybrid approaches include the artificially-magnetotactic bacteria [99], the chemotactic steering of bacteria-propelled microbeads [110] and the bacteria swarm manipulating micron-scale bricks [134].

2007 as the “nanogram” league of the popular Robocup robot soccer competition [82]. This yearly event has moved to the International Conference on Robotics and Automation (ICRA), and challenges teams to accomplish 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.

This monograph introduces the reader to micro-scale robotics in the context of the relevant micro-scale physical effects which govern their operation. It begins with an overview of the most commonly encountered physical effects in Section 2, followed by a review of some of the microrobot actuation methods used in Section 3. The monograph concludes with a discussion of potential application areas in Section 4 and a summary of the current status of the field, along with a list of important open challenges in Section 5. A list of nomenclature used throughout the monograph is also given at the end.

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