MAKING MICROROBOTS MOVE

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Abstract: Our group has recently demonstrated three distinct types of microrobots of progressively smaller size that are wirelessly powered and controlled by magnetic fields. For larger scale microrobots, from 1mm to 500 µm, we microassemble three dimensional devices that precisely respond to torques and forces generated by magnetic fields and field gradients. In the 500 µm to 200 µm range, we have developed a process for microfabricating robots that harvest magnetic energy from an oscillating field using a resonance technique. At even smaller scales, down to micron dimensions, we have developed microrobots we call Artificial Bacterial Flagella (ABF) that are of a similar size and shape as natural bacterial flagella, and that swim using a similar low Reynolds number helical swimming strategy. ABF are made from a thin-film self-scrolling process. In this paper I describe why we want to do this, how each microrobot works, as well as the benefits of each strategy.

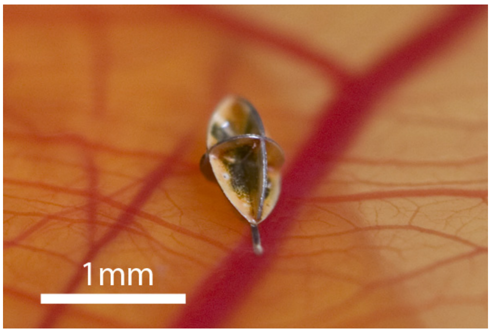
1 INTRODUCTION

Micro and nanorobotics have the potential to dramatically change many aspects of medicine by navigating bodily fluids to perform targeted diagnosis and therapy and by manipulating cells and molecules. In the past few years, we have developed three new approaches to wirelessly controlling microscale structures with high precision over long distances in liquid environments (Figure 1). Because the distance from which these structures can be controlled is relatively large, the structures can not only be used as tools for manipulating other micro and nanoscale structures, similar to particle trapping techniques, but can also serve as vehicles for targeted delivery to locations deep within the human body. The microrobots we have developed are non-spherical. Therefore, both their position and orientation can be precisely controlled, removing another limitation of particle trapping. Unprecedented control in multiple degrees of freedom has been achieved with field strengths as low as 1 mT.

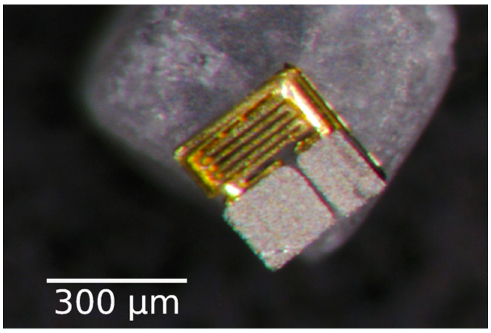
2 MEDICAL MICROROBOTS

Minimally invasive medical techniques are linked with a variety of patient oriented benefits ranging from reduction of recovery time, medical complications, infection risks, and post-operative pain, to lower hospitalization costs, shorter hospital stays, and increased quality of care [1-4]. Microrobotic devices have the potential for improved accessibility compared to current clinical tools, and medical tasks performed by them can even become practically noninvasive. They will perform tasks that are either difficult or impossible with current methods. Rather than acting as autonomous agents that navigate the body diagnosing and solving problems, microrobots will more likely act as new technical tools for clinicians, continuing to capitalize on the clinicians cognitive skill, which is their greatest asset.

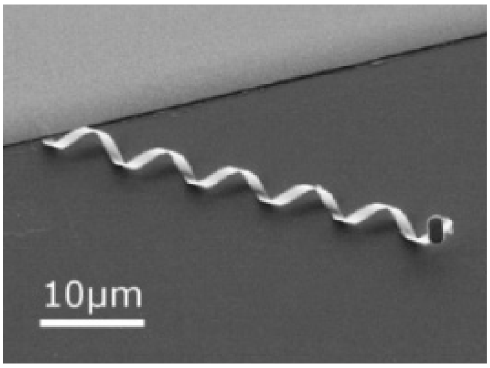
In recent years there has been significant progress on robot-assisted colonoscopy and on wireless miniature robots for use in the GI tract (Kazzim et al., 2006). Motivated by capsule endoscopes that are already in clinical use, a number of technologies have been explored to expand the capabilities of these devices, ranging from wireless GI pressure monitoring systems and lab-on-a-chip devices equipped with pH and temperature sensors (Johannessen et al., 2006) to the addition of legs and other mechanisms for controlled locomotion (Menciassi et al., 2007). The size of these devices approaches a few centimeters, capitalizing on the relatively large size of the GI tract. By further reducing device size and creating microrobots with a



(a) Octomag



(b) Magmite



(c) ABF

Figure 1: Three different types of microrobots at varying orders of magnitude. a) The Octomag robot (shown puncturing a small vein) is controlled using magnetic fields and field gradients. b) The Magmite (sitting on a grain of salt) is powered by oscillating magnetic fields that excite a spring mass system to resonance that harvests the impact energy. c) Artificial Bacterial Flagella (ABF) are propelled through fluid by rotating a magnetic field to generate torques on the magnetic metal head of the device.

maximum dimension of only a few millimeters or less, additional locations in the human body becomavailable for wireless intervention. Natural pathways such as the circulatory system, the urinary system, and the central nervous system become available, enabling intervention with minimal trauma.

As we downscale robots to submillimeter dimensions, the relative importance of physical effects changes (Wautelet, 2001). As device size is reduced, surface effects and fluid viscosity dominate over inertia and other volumetric effects, and power storage becomes a key issue. Furthermore, microrobots, like microorganisms, swim in a low-Reynolds-number regime, requiring swimming methods that differ from macroscale swimmers (Purcell, 1977). This places strong constraints on the development of medical microrobots. In traditional robotics, it is often easy to compartmentalize aspects of robot design such as kinematics, power, and control. In the design of wireless microrobots, fabrication is fundamentally limited by scaling issues, and power and control are often inextricably linked. Engineers must give up intuition gained from observing and designing in the macroscale physical world, and instead rely on analysis and simulation to explore microrobot design. Even then, only experimental results will demonstrate the efficacy of a given microrobot strategy, as the world experienced by the microrobot may be quite difficult to accurately model.

3 OCTOMAG MICROROBOTS

The Octomag microrobot (Yesin et al., 2006), shown in Figure 1, was the first microrobot we developed and is primarily intended for ophthalmic surgery. An external magnetic field acts to align the robot along the long (“easy”) axis, and a field gradient is generated to pull or push the microrobot. The winged shape acts to reduce the side-ways drift of the microrobot by increasing the fluid drag along the axes perpendicular to the long axis (Abbott et al., 2007). The relatively large size of the device is compatible with using gradient fields for propulsion at distances suitable for use within the body and is targeted at controlling the device in a viscous medium.

The robot is a three-dimensional structure built by microassembling individual parts, which allows for the combination of incompatible materials and processes for the integration of MEMS based sensors and actuators. The principle advantage of the hybrid design is that the individual parts of the assembly can be produced with standard MEMS manufacturing processes that create planar geometries. In this way, different subsystems of the robot can be manufactured using the most suitable process for the purpose. Robot parts have been made with electroplated nickel, single crystal silicon, polymer, and laser cut steel.

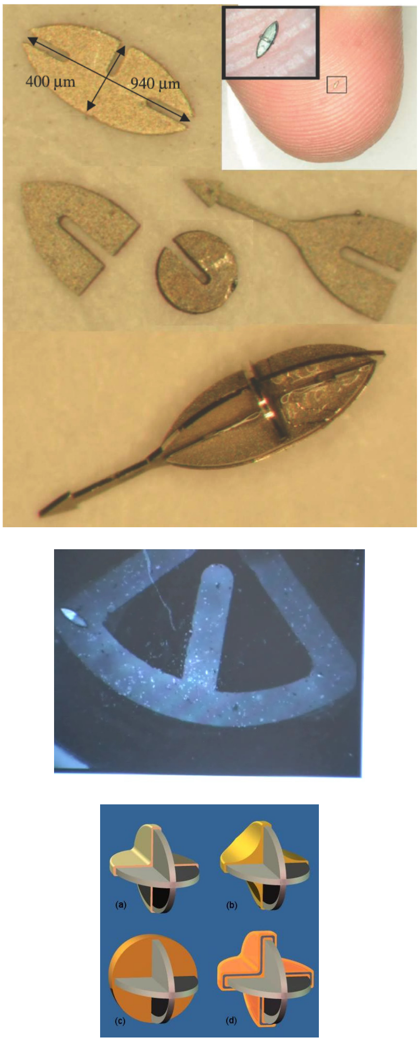


Figure 2: (a) Octomag microrobots are microassembled from 50µm thick electroplated nickel. (b) The sub-mm devices can be precisely controlled to navigate through tiny mazes, and (c) can be coated to ensure biocompatibility and for transport of cargo, such as drugs to be unloaded by diffusion (Yesin et al., 2006).

4 MAGMITES

With decreasing size, gradient propulsion becomes infeasible due to the force generated being related to the magnetic medium's volume, which decreases rapidly with size. To overcome this limitation, we have developed a second propulsion mechanism that harnesses the interactive forces between small magnetic bodies in a uniform magnetic field to drive a spring mechanism to resonance(Vollmers et al., 2008). This energy is then rectified to move the robot through its environment.

The resonant nature of the actuator enables the device to move with fields below 2 mT which is roughly 50x that of the Earth's magnetic field. This locomotion mechanism has been demonstrated on both structured and unstructured surfaces and is controllable enough to repeatedly and precisely follow trajectories. The frequency selectivity of the spring mass resonating structure allows multiple robotic agents to be used on the same substrate to perform tasks. Although this propulsion method was initially designed for operation in air, it has demonstrated its ability to perform in aqueous environments and manipulate glass microspheres on the order of 50 µm.

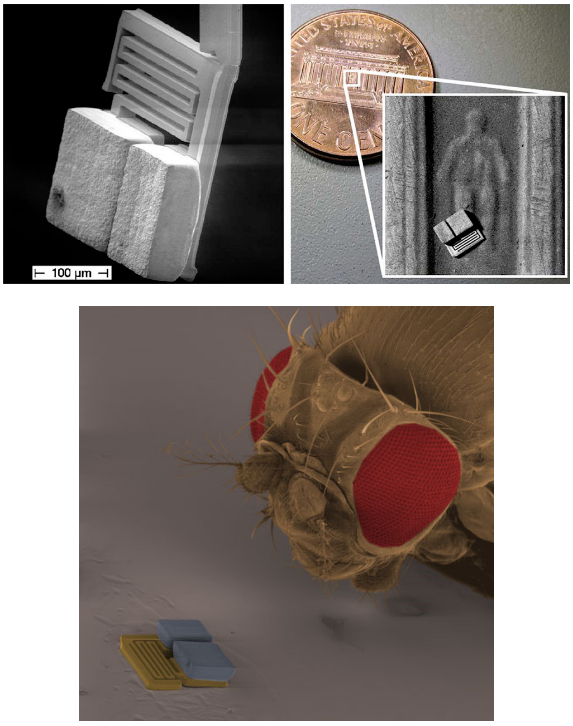


Figure 3: Magmite robots consist of two Ni masses separated by a gold spring. The robot shown measures 300µm square, 70µm thick, and is dwarfed by Drosophila melanogaster (Vollmers et al., 2008).

5 ARTIFICIAL BACTERIAL FLAGELLA

As sizes decrease further, the resonant frequencies of the mechanical structures required for the resonant magnetic actuator increase to tens of kHz and become difficult to generate at sufficient strength. At this scale, torque on the magnetic bodies becomes one of the predominant forces that can be generated.

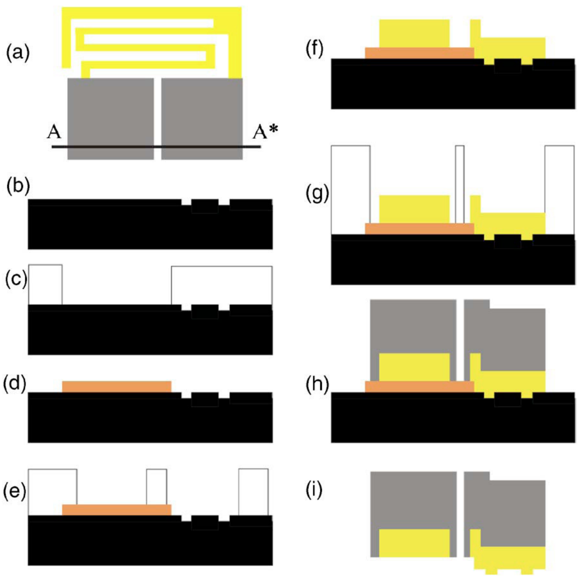


Figure 4: Fabrication sequence with cross section shown along line A-A* (a). Holes for dimples (b) are etched in a wafer before a Ti/Cu adhesion/seed layer is evaporated onto the surface. Photoresist is applied (c) to define thick electroplated copper islands (d). The springs and frame are defined (e) and plated (f) before a final layer of photoresist (g) defines the nickel bodies (h). The device is released from the wafer by etching the sacrificial copper layer (i).

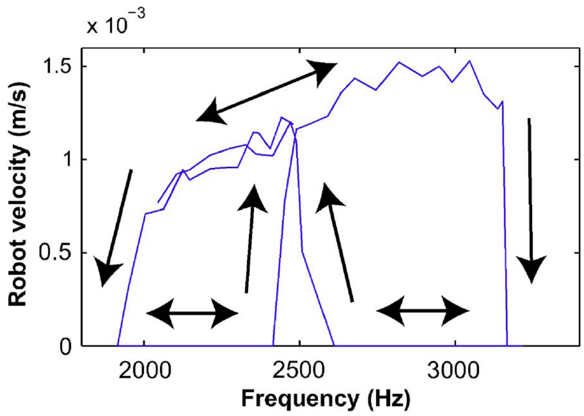


Figure 5: Robot velocity as a function of frequency with a driving field of 2.2 mT. When moving, the robot never comes to a complete rest to allow static friction can take effect. Driving with a frequency too far from resonance reduces the system energy and at some point the robot sticks to the substrate. Moving back toward resonance increases the absorbed energy, allowing the robot to begin moving again.

Taking inspiration from nature, this torque can be leveraged to create artificial bacterial flagella (Zhang et al., 2009).

The helical swimming robot consists of two parts: a helical tail and a magnetic metal head. The tails are 27 to 42 nm thick, less than 2 µm wide, and coil into diameters smaller than 3 µm. The robots are fabricated by a self-scrolling technique (Zhang et al., 2006). The helical swimming microrobots are propelled and steered precisely in water by a rotating magnetic field on the order of 1 to 2 mT. As the robot's principle dimensions approach those of individual cells, many of the experimental methods used with the robots parallel those used by their biological counterparts.

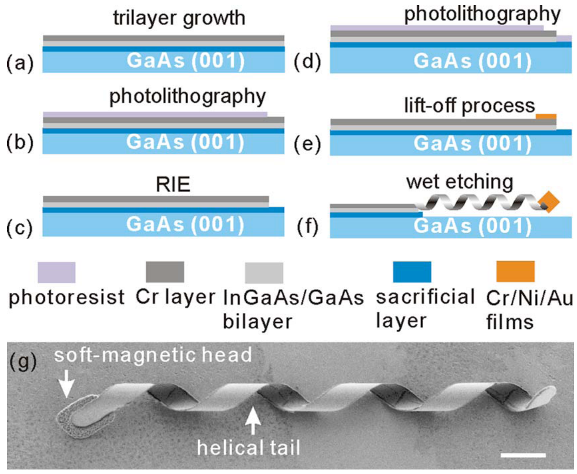


Figure 6: [(a)–(f)] Fabrication procedure of the ABF with InGaAs/GaAs/Cr helical tail. (g) FESEM image of an untethered ABF. The scale bar is 4 µm (Zhang et al., 2009).

6 SUMMARY

Recent advances in microbotics have demonstrated new capabilities in wirelessly controlling microscale structures with high precision over long distances in liquid environments. These breakthroughs make it possible to experimentally investigate the use of these microrobots for manipulating micro and nano size structures in as many as six degrees-of-freedom. Applications to nanomedicine in areas related to targeted medical therapies and molecular manipulation are clear, though many challenges must be addressed. To functionalize these devices and to improve their performance capabilities, fundamental issues in the role surface forces play must be addressed; biocompatibility must be ensured; loading and diffusion of biomolecules must be investigated; and interactions with and manipulation of tissue and macromolecules must be considered. There is a lot yet to do.

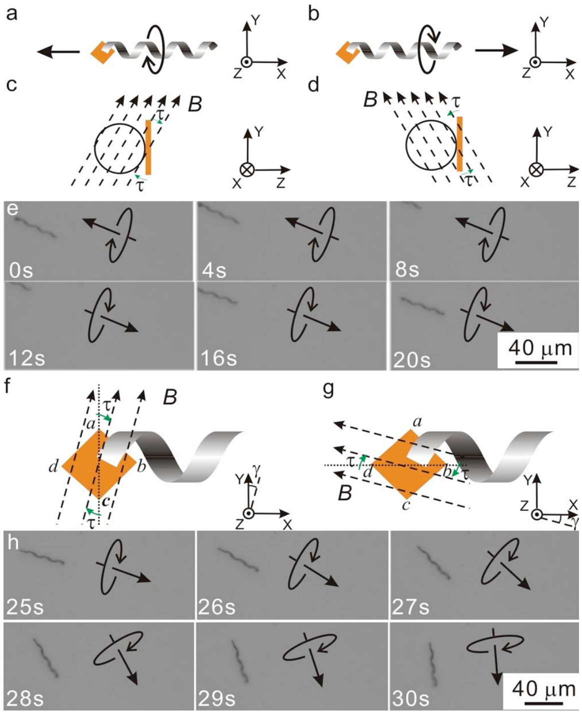


Figure 7: ABF swimming motion controlled by magnetic fields with field strength of 2.0 mT. [(a)-(d)] Schematic of a left-handed ABF swimming forward and backward. With the field B continuously rotating perpendicular to the X axis of the ABF, a misalignment angle between the field and the thin magnetic head will induce a magnetic torque (t) that attempts to align the ABF head with the field, resulting in rotation and propulsion of the ABF. (e) Optical microscope images of the forward/ backward motion of an ABF controlled by magnetic fields. The commanded translation and rotation directions of the ABF are indicated by the arrows. (f) If the field is rotated about the Z axis by an angle $|\gamma|<45°$ with respect to the easy axis ac of the head, then the ABF is steered as it is propelled, as the easy axis ac attempts to align with the field. This is the steering principle used during normal operation of the ABF. (g) If the field is rotated about the Z axis by an angle $|\gamma|<45°$ with respect to the easy axis bd, the ABF will instantaneously attempt to rotate perpendicular to the helix axis. However, steering using the bd easy axis is not possible simultaneously with forward/backward propulsion. (h) Optical microscope images of the turning motion of an ABF controlled by magnetic fields. The commanded translation and rotation directions of the ABF are indicated by the arrows.

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BRIEF BIOGRAPHY

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Prof. Nelson has been awarded a McKnight Land-Grant Professorship and is a recipient of the Office of Naval Research Young Investigator Award, the National Science Foundation Faculty Early Career Development (CAREER) Award, the McKnight Presidential Fellows Award, and the Bronze Tablet. He was elected as a Robotics and Automation Society Distinguished Lecturer in 2003 and 2008 and won Best Paper Awards at major robotics conferences and journals in 2004, 2005, 2006, 2007, 2008 and 2009. He was named to the 2005 “Scientific American 50,” Scientific American magazine’s annual list recognizing fifty outstanding acts of leadership in science and technology from the past year for his efforts in nanotube manufacturing. His laboratory won the 2007 and 2009 RoboCup Nanogram Competition, both times the event has been held. He serves on the editorial boards of several journals, has served as the head of the Department of Mechanical and Process Engineering from 2005–2007, and is currently the Chairman of the ETH Electron Microscopy Center (EMEZ).