Microrobotics in Medicine

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Abstract: Recent progress in microrobotics is moving us closer to a future in which tiny intelligent machines will navigate throughout our bodies. These microrobots will aid medical professionals in the diagnosis and treatment of a number of human diseases. This talk will overview recent progress in this field and discuss near-term applications in ophthalmic therapies as well as longer term possibilities.

Keywords : **microrobotics, medical robotics**

I. Introduction

Since the 1980's, medicine has seen a dramatic shift towards the use of minimally invasive procedures because of the many advantages this technology presents. The next step in the evolution of medical procedures will be from minimally invasive approaches towards extremely targeted, localized and high precision endoluminal techniques performed by untethered microrobots. These new surgical tools capable of entering the human body through natural orifices or very small incisions and delivering drugs, performing diagnostic procedures, and even excising and repairing tissue will be developed. The procedures these devices will enable will not only result in even less trauma to the patient and faster recovery times, but will also enable new therapies that have yet been conceived.

Endoluminal operations performed by microrobots will potentially entail several different steps: a) processing previously acquired medical data (primarily images), simulation and planning of interventions; b) computer design of the optimal configuration of the microrobot customized for the specific patient anatomy and for the planned therapy at the target site; c) delivery of devices within the body to the desired site; d) extremely precise execution of the intervention; e) disassembly, recovery or biodegradation of the devices.

One enabling technology for medical microrobots is Micro-Electro-Mechanical-Systems (MEMS), now a commercial technology with various sub-fields and a large variety of application areas. The acceleration sensor that triggers your car's airbag or the microscopic deflecting mirrors that create the images from a digital projector are two examples of everyday MEMS. Usually, it is a combination of their low cost, low power consumption and small size that makes a MEMS based design the better choice compared to conventional technology. But MEMS can also be an enabling technology, opening new frontiers to science [100], one of which is the topic of this paper, the use of untethered microrobots for biomedical applications in the human body.

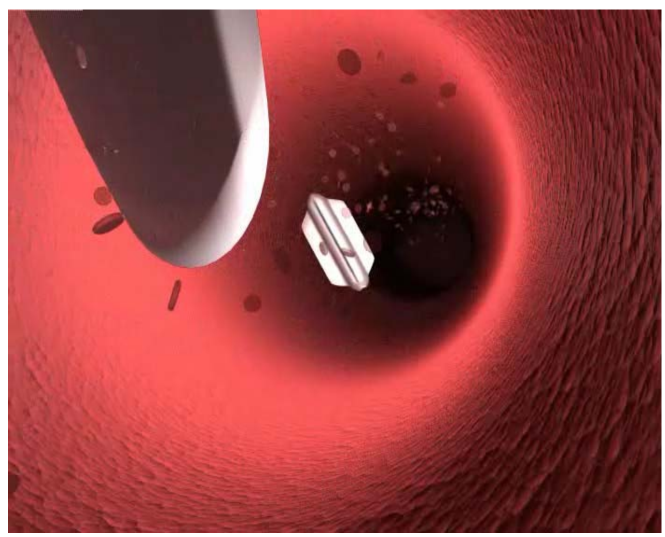

Fig. 1. Artist's rendering of a microrobot being released into the bloodstream through a needle.

Challenging design issues present themselves when envisioning a medical microrobot for in-vivo applications. Devices must be small, reliable and biocompatible. They must carry the necessary tools and subsystems on-board. They must be inserted into, steered inside and removed from the target area of the patient's body in a "non-invasive" way. It is difficult to resolve all these issues at once, also because much depends on the particular application.

II. APPLICATION AREAS

One application of small untethered robots that captured the attention of early researchers was in the gastro-intestinal (GI) tract. This passageway through the body, which can accommodate relatively large objects, is where the first commercial systems have been applied [12][13]. These untethered, endoscopic capsules are the size of a pill and are simply swallowed by the patient. They capture video images from the GI path with their imaging and illumination systems while naturally travelling through the path. Other researchers proposed robotic systems with locomotion and biopsy capabilities [2][8]. Typically, robots built for the GI path are miniaturized mechatronic systems with many components of conventional design.

It is in the more challenging parts of the human body where truly microscopic sized robots would be needed that MEMS technology provides the only solution. Robots swimming in the blood stream or inside the vitreous humor (a clear, gel-like substance that fills the posterior cavity of the eye) have been envisioned [9][16]. A reoccurring theme with such microrobots is the use of ex-vivo generated magnetic fields to transfer energy to the robot. Whereas MEMS and VLSI technologies have accomplished the miniaturization of structural and electronic components, a corresponding breakthrough in energy storage was not been achieved. This issue comes to center-stage with sub-mm sized microrobots for cardiovascular or ophthalmic applications.

III. WIRELESS ACTUATION

Magnetic actuation technology has been applied in biological systems for many years when wireless actuation is needed. A common application area is targeted drug delivery where magnetized carrier particles that are coated with various chemical agents are concentrated on specific target regions of the body using external magnetic fields [5][6]. A similar idea is used in magnetic cell separation where magnetized particles that are selectively attached to a targeted group of cells through their chemical composition are used to sort apart the cells [17]. Individual magnetic beads of a few microns diameter have also been steered inside cells for the study of their mechanical properties [1][11] as well as for the manipulation of individual DNA molecules [4]. These applications differ from drug targeting or cell separation in that precise and dynamic control of magnetic field vectors through real-time feedback is desired. Another area with similar requirements on field control is magnetically assisted stereotaxis to guide catherers inside the brain [3][14].

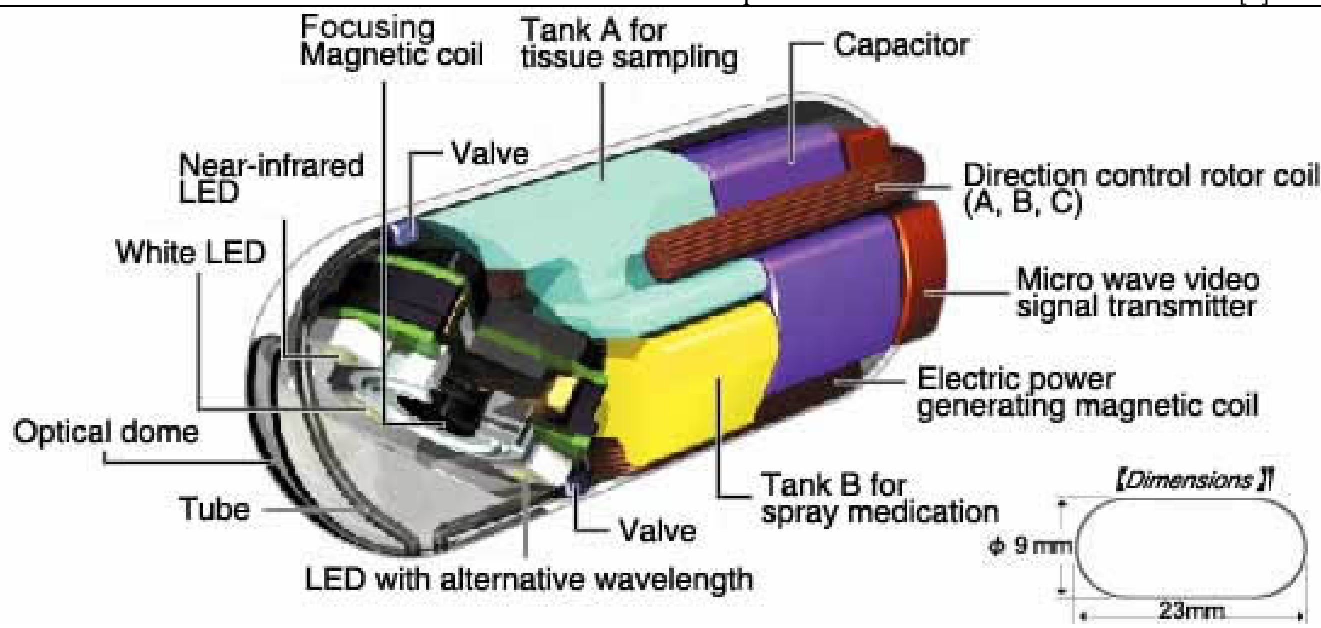

Fig. 2. Capsule endoscope system from RFNorika [11]

The basic equations describing magnetic interactions of matter give insight into the principle of magnetic steering and the consequences of miniaturization. The primary vectors that define the magnetostatic (i.e. when the magnetic fields are DC or of low frequency) field in magnetized matter are the (external) magnetic field strength, H (A/m), the resulting magnetization of the material $\mathbf{M}$ (A/m) and the net magnetic flux density $\mathbf{B}$ (Tesla). The relationship between these vectors is

$$\mathbf{B}=\mu_0(\mathbf{H}+\mathbf{M})$$

where μ_0 is the magnetic permeability of free space defined as $4\pi\times10^{-7}$ Tm/A. For the idealized case of linear, isotropic and homogeneous media the above relationship simplifies as

$$\mathbf{M}=\chi\mathbf{H}$$

$$\mathbf{B}=\mu_0(\mathbf{H}+\chi\mathbf{H})=\mu_0(1+\chi)\mathbf{H}=\mu_0\mu_r\mathbf{H}$$

where χ and μ_r are the susceptibility and relative permeability of the media, respectively. In general, these values are not constant but change with magnetization, putting a material dependent upper limit to the amount of magnetization known as the saturation magnetization $\mathbf{M}_s$. Within the saturation limits, the permeability can be thought as an amplification factor that creates a net magnetic field inside the matter through an external field.

The magnetic force and torque that are exerted on an object with uniform magnetization $\mathbf{M}$ in a magnetic field with flux density $\mathbf{B}$ are defined as

$$\mathbf{F}_m=V_m(\mathbf{M}\cdot\nabla)\mathbf{B}$$

$$\mathbf{T}_m=V_m\mathbf{M}\times\mathbf{B}$$

where V_m is the volume of the magnetized object. Notice that the magnetic torque is dependent on $\mathbf{B}$ whereas the magnetic force is dependent on the gradient of $\mathbf{B}$. These equations also indicate that magnetic forces are volumetric. Therefore, the required field and field gradient to exert a certain torque and force on a magnetized object increases rapidly as the object gets smaller. In contrast, the viscous drag forces from the body fluids are related to the surface area of the robot, therefore, there is a disadvantage in terms of the necessary external magnetic field strengths as the robot's size goes smaller.

IV HYBRID MEMS

Another design challenge for a sub-mm sized microrobot is the high degree of integration that is needed. Most MEMS devices are designed to be components that are inserted into larger sized electro-mechanical systems. Even the system-on-a-chip type devices with integrated mechanical and electronic components need to be physically interfaced for power supply and data I/O. In contrast, the sub-mm sized medical microrobot must be micro-manufactured to its final form. The emerging technology of Hybrid MEMS, where individual MEMS components are combined through a robotic microassembly process, promises a solution [15]. In a Hybrid MEMS design, different and incompatible manufacturing technologies (e.g. Lithography, LIGA, MOEMS, Nanosystems) can be used together. By separately manufacturing the sub-components using the optimal technique and parameters, increased yields can be achieved. Most importantly, with three dimensional manipulation and assembly, the flat, 2.5D shape limitations inherent in standard MEMS manufacturing methods can be overcome. With a 3D geometry, more efficient use of allowed robot volume is possible.

A biomedical microrobot with a Hybrid MEMS design is being developed at the ETH Institute of Robotics and Intelligent Systems. The first area of application of this robot will be ophthalmic operations on the retina. Figure 3 shows an early prototype microrobot with a three dimensional structure that was built to investigate hybrid MEMS assembly and magnetic steering concepts. The 50 µm thick nickel parts were manufactured using an electroplating process and bonded with UV activated glue. The "winged-ellipsoid" shape of the robot has an axis of symmetry along the long axis of the ellipsoid. An external magnetic field acts to align and pull the robot along this axis (i.e. magnetic torque and force) due to the shape anisotropy effect, much like a needle always becoming magnetized along its long axis. On the other hand, 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.

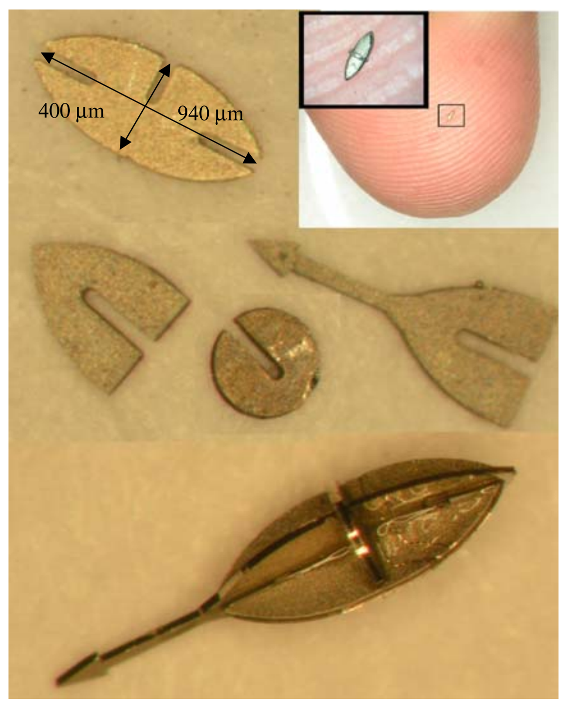

Fig. 3. Prototype magnetic microrobot with Hybrid MEMS design.

V MAGNETIC CONTROL

An important issue related to the control of a magnetic microrobot is the nonlinear nature of the field and field gradients that are created by electromagnet coils or by permanent magnets. The field from an air-core solenoid coil along its axis is roughly proportional to the inverse square of the distance to the solenoid. In this case the torque and force on the soft magnetic material are proportional to the fourth and fifth inverse power of the distance respectively. To appreciate the effect of this nonlinearity, one could try to levitate a small metallic object in a water filled cup by moving a permanent magnet close and afar. It is not possible to stabilize such a system without high bandwidth feedback and actuation. One way of reducing these nonlinearities is to create uniform magnetic fields and field gradients using various coil configurations [7]. For example, the Helmholtz coil configuration consists of two identical coils that are placed on the same axis and separated by a distance equal to the radius of the coils. This arrangement generates a uniform field close to the center of the coil pair when current passes in the same direction in both coils. A similarly configuration called the Maxwell coil can generate a uniform gradient near the center. Figure 4 shows a plot of the superimposed fields from Helmholtz and Maxwell coils. Both of these coil types are commonly used in MRI systems. The magnetic steering principle was demonstrated using a small scale system. The microrobot was put inside a plastic, maze-like structure with 1000 μm wide, water-filled channels. The maze was inserted at the center of a pair of concentric Maxwell and Helmholtz coils that were actuated to rotate around the maze. The current through the coils were regulated to control the force and torque (i.e. the forward thrust and orientation) on the robot independently. Numerous trials with the system confirmed that the independent orientation/thrust control principle was successful. Recent efforts at IRIS are towards applying this principle in a larger scale in combination with on-board magnetic actuators.

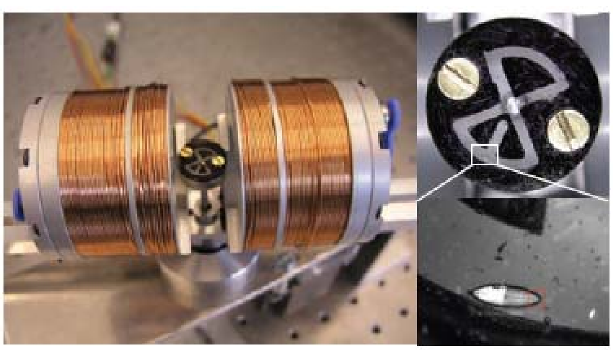

Fig. 4. 900 μm×400 μm assembled-MEMS microrobot navigating a fluid-filled maze. A motorized magnetic coil system provides computercontrolled field magnitude, orientation,

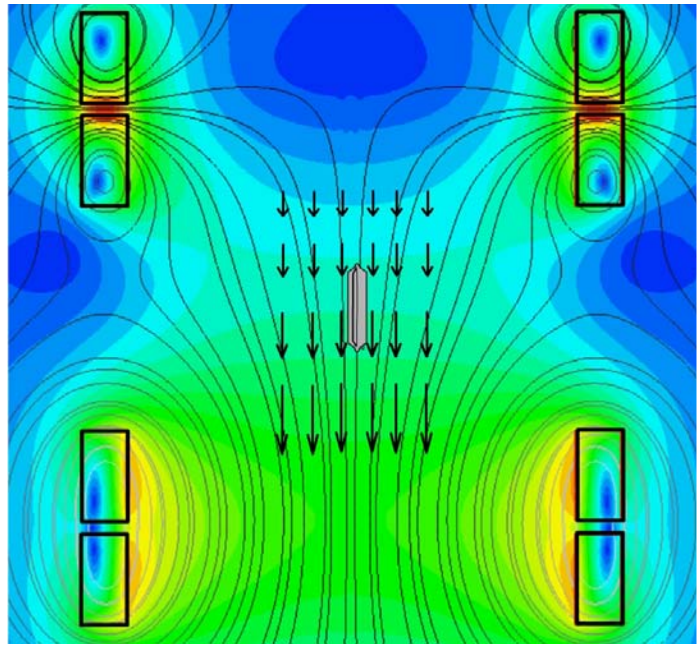

Fig. 5. Superimposed magnetic field generated by concentric Maxwell and Helmholtz coils. This configuration enables independent control of magnetic force (thrust) and torque (orientation) on the microrobot.

VI CONCLUSION

Biomedical microrobotics is one of the next major challenges in the field of robotics. It combines the established theory and techniques of robotics (e.g. motion control, path planning, remote operation or sensor fusion) with the exciting new tools enabled by MEMS technology in order to significantly improve the quality of our lives. International robotics research efforts are already shifting towards this direction. Effective collaboration between medical and robotics experts is an important key for the success of this technology of the future.

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