# Acting on Nanoparticles Embedded in Magnetotactic Bacteria to Implement Propulsion and Steering for Microrobots

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***Abstract*- A MEMS structure based on standard CMOS process is presented. It consists in the fabrication of micro-reservoirs in which will be embedded magnetotactic bacteria (MTB) to form a propulsion system for a 550 µm × 650 µm fully autonomous micro-robot to be operated in an aqueous medium. Due to magnetotaxis inherent in each bacterium, the motility of the MTB can be exploited. Furthermore, a directional magnetic field is used to orient their swimming direction. This magnetic field is produced by micro-coils embedded in each micro-reservoir. The operational power of the microrobot is collected through four photovoltaic cells which are able to provide a current of 65 µA and a low voltage of 400 mV to drive the micro-coils. Due to the size of the microrobot, the integration of the MTB into the micro-reservoirs is a complicated task. Here, a method to facilitate the integration of the MTB into such micro-reservoirs is proposed, which consists in the use of an external magnet placed iteratively at different locations with respect to the microrobot in order to gather the MTB near the micro-reservoir aperture consequently near the magnetic field lines generated inside of the micro-coils.**

## I. Introduction

The flagella motor which is found in many bacteria represents a very efficient biological micro-actuator that can be exploited [1, 2]. From previous experiments, we have demonstrated the controlled motion of a group of MC-1 MTB to move micro-objects [3] using magnetotaxis [4, 5]. When exploiting magnetotaxis, a directional torque can be induced on a chain of membrane composed of nanoparticles of magnetic minerals called magnetosomes embedded in each MTB, allowing us to control the swimming direction of the bacteria. Because there is no efficient micro-motor at this scale therefore the exploitation of the motility of the MTB offers a good avenue for the implementation of propulsion system for microrobots, where miniaturization and power minimization are to be considered.

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A sample of pre-selected bacteria has been considered to demonstrate that an average thrust force of approximately 4.0 pN can be achieved by each bacterium [3]. Therefore, by creating magnetic field lines, the swimming direction of the MTB can be controlled in order to form an agglomeration of MTB. This MTB agglomeration will act on a bacterial reservoir wall embedded in each aqueous microrobot (Fig. 1) in order to achieve a thrust force that can exceed the drag force acting on the microrobot for displacement.

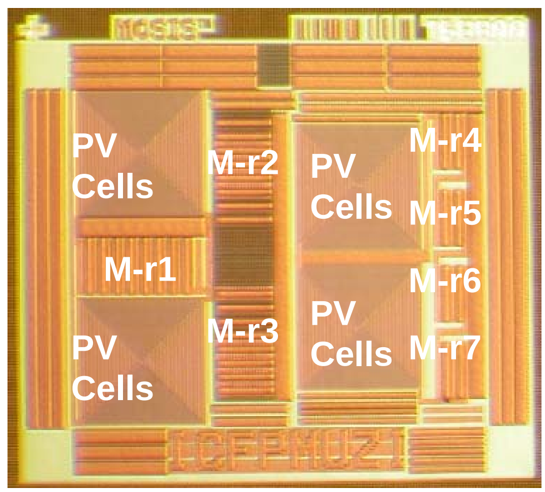


Fig. 1. Optical microscope image of the autonomous bacterial microrobot. (M-r: micro-reservoir)

Fig. 1 shows the first version of the autonomous microrobot, which contains four photovoltaic cells to provide the minimum operational power of the microrobot and bacterial reservoirs to shelter the MTB, which are numbered M-r1 to M-r7. The energy to operate the microrobot is collected from four standard CMOS photovoltaic cells embedded onto the microrobot. It is used to provide a minimum magnetic field of 0.6 Gauss required inside the micro-coils [7, 8] to influence the trajectory of the autonomous microrobot. However, encapsulation of bacteria into a CMOS integrated micro-reservoir has never been reported before. Here, we propose a technique taking advantage of the properties of the chain of nanoparticles embedded in each bacterium for the integration of the MTB into such reservoirs.

## II. Internal Architecture of the Microrobot

Here, a fully autonomous untethered microrobot for future operations in aqueous mediums is presented. Considering the small size of the robot, there is no efficient silicon or *MEMS* based micro-motor at such a scale capable of providing the minimum thrust required for the motion of the microrobot. Accordingly and prior to minimize the energy requirement of the microrobot, the molecular motors found in MTB have been exploited for mechanical motion. For the electrical power system, the photovoltaic effect has been considered because of wireless advantage.

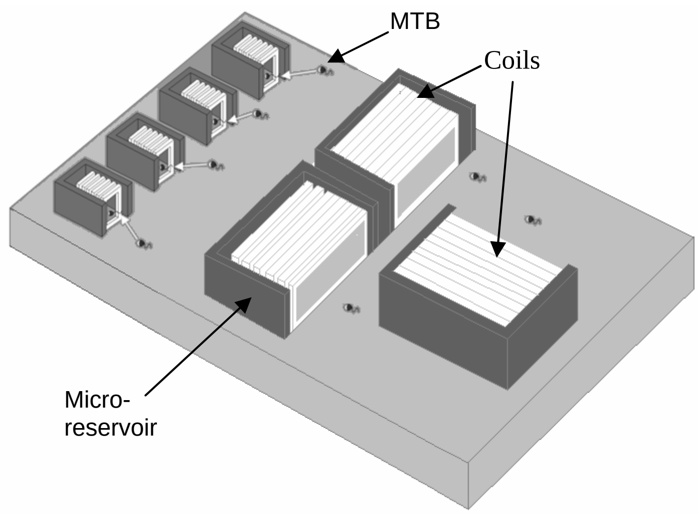


Fig. 2. Schematic (not to scale) of one version of the micro-robot with integrated micro-reservoirs to implement a propulsion and a steering system.

The 650 µm × 550 µm preprogrammed microrobot is fabricated using the 0.18 micron six metals CMOS process, which integrates embedded electronics and micro-reservoirs to shelter the MTB based propulsion system. Inside each bacterial reservoir, is located a 3D CMOS integrated micro-coil to generate a magnetic flux necessary to orient the MTB swimming direction. Since the MTB orient themselves to the earth magnetic field, we assume that a minimum magnetic field of 0.5 Gauss is required to exert a torque on the chains of magnetosomes found inside the bacterium cytoplasm, sufficient to influence its swimming direction. Therefore, from an agglomeration of magnetotactic bacteria pushing against the bacterial micro-reservoir walls, a pulling or a propelling motion of the microrobot can be achieved. The first version of the microrobot is depicted in Fig. 2.

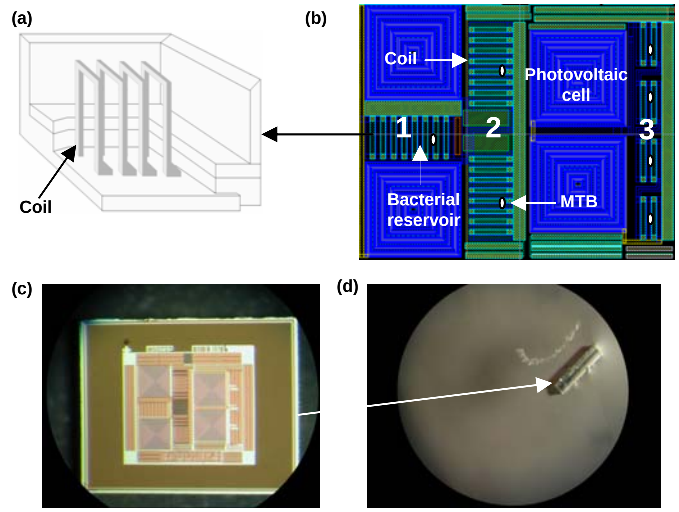


Fig. 3. (a) Cross-sectional view of the bacterial reservoir. (b) Schematic (not to scale) of the internal architecture of the microrobot from Cadence layout Virtuoso, showing the micro-reservoirs, and the photovoltaic cells. (c) Micro-photograph of the microrobot in die form after fabrication showing the micro-reservoirs and the photovoltaic cells. (d) Micro-photograph of the microrobot submerged at 90 degrees into an aqueous medium.

Figure 3(a) shows a schematic representation of the micro-coils inside the bacterial reservoirs. Figure 3(b) shows the internal architecture for one configuration of the microrobot designed using Cadence Layout Virtuoso. A minimum quantity of components necessary to preprogram a specific behavior is used in this specific architecture of the microrobot. In this configuration, the set of bacterial reservoirs mentioned in (2) is used as rudder; it enables the bacteria tom perform right or left turn; while the others are used to perform a forward or a backward motion of the microrobot. Accordingly, in order to achieve a displacement of the microrobot, an evaluation of the drag force has do be performed, and its value is found to be $0.38\times10^{-9}$ N. Since a single magnetotactic bacterium is able to generate a thrust force of 4.0 pN, an agglomeration of at least 80 MTBs pushing against the bacterial reservoirs walls would be sufficient to overcome the drag force acting on the microrobot. Figure 3(c) shows the photomicrography of the microrobot, while Fig. 3(d) shows the untethered microrobot submerged into an aqueous medium. By having an agglomeration of bacteria pushing on the bacterial reservoirs wall, a thrust force will be created to overcome the drag force, which will lead to the displacement of the microrobot. Since the bacterial reservoirs are located in specific directions, by orienting the swimming direction of the bacteria in specific set of micro-reservoirs, various degrees of freedom in motion can be achieved.

## III. Bacterial Reservoir and Integration method of the bacteria in to the micro-reservoirs

The micro-reservoirs are built in a 0.18 micron standard CMOS process, and its 3-D micro-coils structures will be obtained by etching SiO2 sacrificial layers. The Pad-etch has been considered to etch selectively the silicon dioxide (SiO2) without damaging the aluminum encountered in the design process [9] and at the same time will serve as a shield to isolate the micro-coils windings from the water, thus avoiding short cut circuit. The layout of the 3D square-shaped micro-coil embedded in each micro-reservoir has been designed with Cadence Layout Virtuoso, while the simulation is carried out with a lumped model of the micro-coil through Cadence schematic tool. Since, this design deals with an aqueous microrobot, a 100 nm layer of Parylene C will protect the microrobot internal control circuit from the medium. Matlab software has been used to study the magnetic field generated inside each micro-coil when a current of 65 µA is circulating through the coil. The results are presented in Fig. 5 showing the variation of the magnetic field in function of the location of the MTB inside the micro-coil. The rectangular coordinated (x, y) depicted in Fig. 5 is used to determine the impact of the magnetic field on the bacteria located at any (x, y) coordinates. According to the simulation results, an overall magnitude of 0.6 Gauss around the center of the coil is recorded in Fig. 3 respectively.

The expression of the magnetic field for the rectangular coil located at a point o(x, y) (Fig. 4) when coil segments of length *l* are driven by a current is [10]:

$$B = \frac{\lambda}{x}\left|\frac{1}{\sqrt{x^2+l^2}}\right|_{-y}^{l-y} + \frac{\lambda}{l-y}\left|\frac{1}{\sqrt{x^2+l^2}}\right|_{l-y}^{-x} + \frac{\lambda}{l-x}\left|\frac{1}{\sqrt{x^2+l^2}}\right|_{y-l}^{-y} + \frac{\lambda}{y}\left|\frac{1}{\sqrt{x^2+l^2}}\right|_{x-l}^{x} \quad (5)$$

with

$$\lambda = \frac{N\mu_c I}{4\pi} \quad (6)$$

where N is the number of coil turns, $\mu_c$ is the core permeability and *I* is the current.

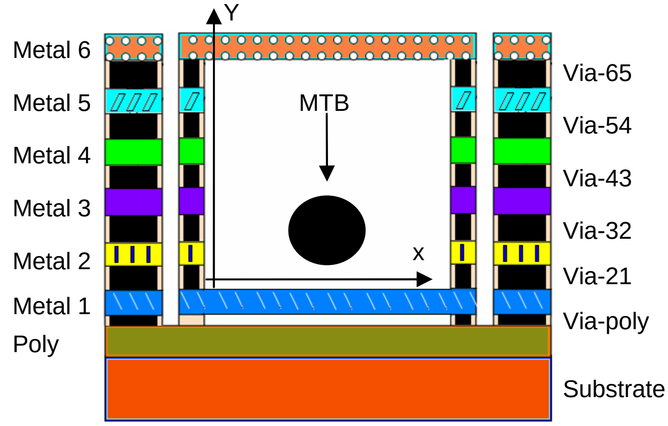


Fig. 4. Schematic showing the bacterial reservoir layout.

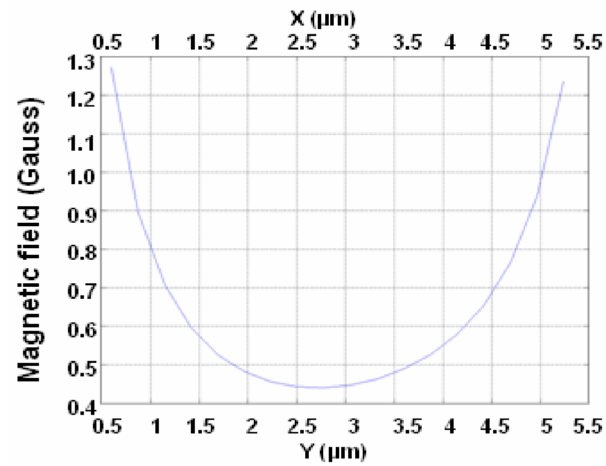


Fig. 5. Schematic showing the distribution of the magnetic field inside the micro-reservoirs.

The space between the coil windings is less than the diameter of the MTB in order to avoid them to escape from the reservoir. To prevent the MTB to escape from the back-end orifice of the reservoir, a constant magnetic field toward the reservoir wall is maintained. The integration of the MTB in the reservoirs will be achieved with the help of an external magnet exploiting magnetotaxis inherent in each MTB.

## IV. Conclusion

A new actuation method for microrobots and based on MTB have been briefly described. Due to the size of the microrobot, the integration of the MTB into the bacterial reservoir used as engines remains a challenge. The small power collected from the four photovoltaic cells was not meant to generate a high magnetic field to attract bacteria which are far away from the micro-reservoir. The magnetic field generated by the micro-coil located inside the micro-reservoir can attract only nearby bacteria. The use of an external magnet will bring the bacteria near the aperture of the micro-reservoir, and therefore will be attracted by the magnetic field lines generated by the micro-coil.

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