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Initial Design of a Bacterial Actuated Microrobot for Operations in an Aqueous Medium

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Abstract—**The initial design of a 500 µm × 200 µm untethered microrobot for future operations in an aqueous medium is briefly described. Electrical energy requirement is minimized by exploiting the motility of magnetotactic bacteria embedded in special reservoirs and used to propel the microrobot. An embedded control microcircuit powered through photovoltaic cells is developed to control the swimming directions of the bacteria and hence, the direction of the robot. The work presented is an initial step towards the development of platforms capable of relatively complex tasks being executed by a swarm of such microrobots pre-programmed with various behaviors.**

Index Terms—**Microrobot, micromanipulation, photovoltaic cell, magnetotactic bacteria.**

I. Introduction

HERE, the initial development of an untethered microrobot is briefly introduced. Such robot could be part of a colony of interacting devices, providing the framework for the execution of many operations encountered in actual lab-on-chip systems [1-3] and µ-TAS [4]. Unlike present modern platforms, a high quantity of these robots could be simply injected with the samples on a microscope slide and operate from pre-programmed behaviors to achieve relatively complex tasks but without any external control and supervision.

The estimated overall dimension of the proposed fully autonomous microrobot is approximately 500 µm × 200 µm. Due to major power constraints at such a scale, mechanical actuation for controlled displacements of the microrobots will be provided by magnetotactic bacteria (MTB) [5, 6] integrated in micro-reservoirs embedded in each robot. The directional control can be achieved by inducing a torque on the chain of magnetosomes embedded in each bacterium from small electrical current flowing through a special conductor network embedded in each robot. The generation and routing decisions of the electrical current in the conductor network is provided by an embedded electronic system. Although the limit in power consumption and hence computing power calls for several microrobots with various pre-programmed behaviors to complete relatively simple tasks initially, the power delivery for such small untethered systems operating in a fluid, and the successful integration of all components at such a scale are still real technical challenges.

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II. Evaluation of Physical Parameters of the Autonomous Bacterial System

Prior to minimize the energy consumption, the internal circuit of this Autonomous Bacterial System (ABS) has been designed with the minimum electronics necessary to influence the swimming direction of the MTB.

In order to design the microrobot, preliminary estimations regarding the physical parameters of the system, such as the weight, the drag and the buoyancy force were carried out. The results, although based on some hypotheses, give a relatively good estimate of the feasibility of developing such a system.

A. Evaluation of the Weight of the Autonomous System

The specific weight of a silicon die per mm^2 is dependent upon the fabrication technology which is related to the thickness and the area of the die, and its value is equal to ≈ 11 µN/mm^2 for a 550 µm die thickness [7]. For 0.18µ technology, the thickness of the die is 250 µm [8] with a specific weight of 5 µN/mm^2. The evaluation of the weight of the microrobot is an important factor in this context and it is given by:

$$W = 5\times10^{-6}\frac{N}{mm^2}\times AT = 0.5\times10^{-6}N, \quad (1)$$

where AT = 0.1×10^{-6} m^2. Hence, the weight of the microrobot is estimated at 0.5µN.

Evaluation of the Buoyancy Force

The evaluation of the buoyancy force is:

$$FB=\gamma\times V, \quad (2)$$

where V is the volume of the submerged body and γ is the specific weight of the liquid where its value is given by:

$$\gamma=\rho\times g. \quad (3)$$

In Eq. 3, ρ is the density of the water (0.998 kg/m^3 at 20°C), and g (9.81 m/s^2) is the gravitational acceleration. From the values of ρ and g, the specific weight of the fluid is estimated at 9.79 kg/m^{3}s^2. With a submerged volume of 2.5×10^{-11} m^3, the buoyancy force is found to be 2.45×10^{-10} N.

Here, the buoyancy force is less than the weight of the system. The surface tension of the water is estimated at 34 µN which is greater than the weight of the microrobot. Therefore, by adjusting the weight of the microsystem, the depth of the microrobot in the aqueous medium can be predetermined.

B. Evaluation of the Drag Force

The drag force is given by:

$$D=\frac{1}{2}\rho v^2 A C_D, \qquad (4)$$

where A is the surface area moving against the liquid, ν is the speed of the liquid (water is considered here) referred to the microrobot, ρ is the density of water and C_D is the coefficient of drag. The drag force is estimated at 31 pN.

Previous experiments with some types of MTB have shown thrusts of approximately 0.6 pN per bacterium. Our group also estimated a thrust as high as approximately 4 pN for the MTB of type MC-1. Consequently, it seems conceivable to be able to integrate a group of MTB large enough to provide a force exceeding the drag force of 31 pN acting on the microrobot.

III. Global Architecture of the ABS

Each ABS has reservoirs containing the MTB, a control conductor network to influence the swimming direction and hence, the pushing force of the microrobot, a control microcircuit, and the photovoltaic cells for powering the microelectronic circuit in die form. The die will be covered with a thin layer of parylene with a thickness of approximately 200 nm in order to insulate the integrated circuit from the aqueous medium. Four bacterial reservoirs with porous walls will be incorporated onto the microrobot.

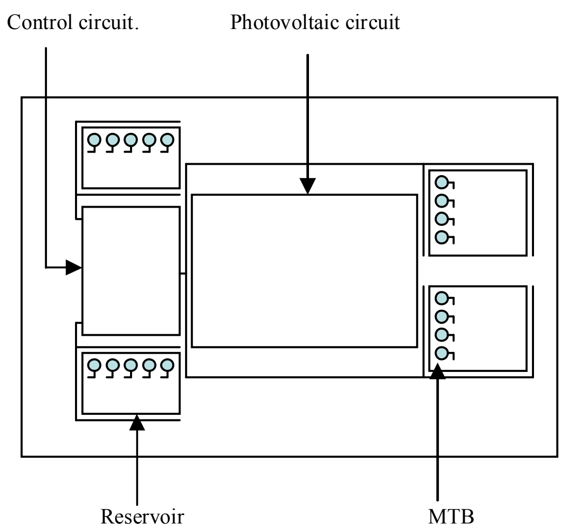

Fig. 1. Schematic (not to scale) of the global architecture of the ABS with an overall estimated size of 500 µm × 200 µm.

Figure 1 shows the global architecture of the ABS. There are two reservoirs on the left side of the microsystem acting as rudders in this particular implementation while the ones in the right are used for forward or backward movement of the microrobot.

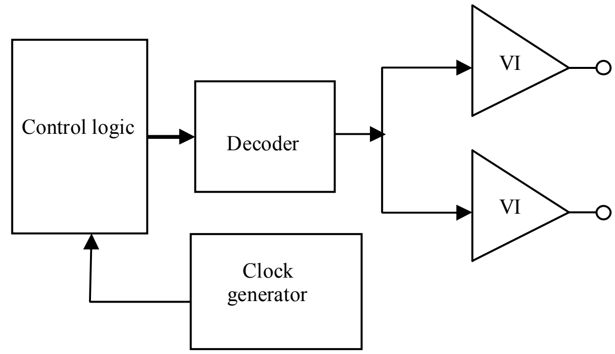

Fig. 2. Schematic of the internal architecture of the microelectronics embedded in each ABS. VI stands for voltage to current converter.

Figure 2 shows the control logic block based on a simple state machine inside the ABS providing the electrical current necessary to influence the swimming direction of the MTB. A minimum of 100 µA have been estimated for proper operation of the ABS. In order to power the microrobot, the design of a CMOS photovoltaic cell appeared to be the best alternative within the known constraints.

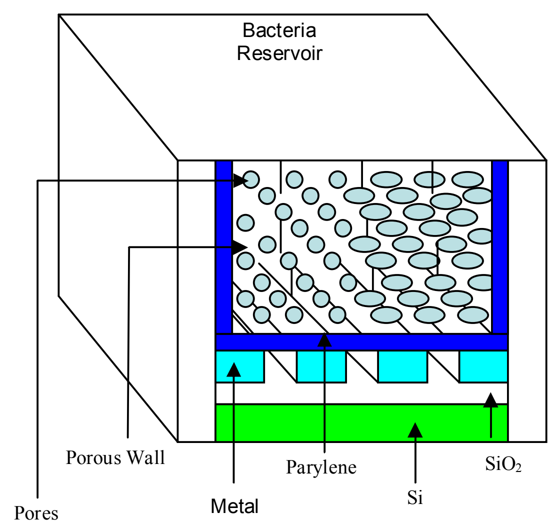

Fig. 3. Cross-section of a reservoir containing the MTB and acting as a "bacterial engine". Directional control is assured by inducing a torque on the chain of magnetosomes embedded in each bacterium by passing an electrical current in the metal conductors.

An optimal structure for the encapsulation of the MTB is an essential part of the system and relies on advanced microfabrication techniques. A simplified schematic of one reservoir is depicted in Fig. 3 where porous walls allow displacement of the microrobots while retaining all MTB in the reservoirs.

IV. Design of a Photovoltaic Cell

A special architecture of the photovoltaic cell is proposed to increase its quantum efficiency [9]. This architecture is based on an ensemble of concentric squares with alternate p and n type semiconductors. As a result, the number of pn junctions is increased and hence, the current provided by the photovoltaic cell is increased. The design of the photovoltaic cell was carried out with the software assistance Cadence layout Virtuoso and a netlist was extracted to carry out simulations of the cell for various values of light intensities. We have obtained an open circuit voltage of 0.58 Volt and a short current circuit of 100 µA which is sufficient to create the minimum local magnetic field to orient the bacteria. We have computed that a current of 100 µA injected into a conductor line will generate a magnetic field of 0.5 gauss within a distance of 400 nanometers (nm) which is also equal to the earth magnetic field. With 0.18µ CMOS technology, conductor wires of 230 nm of width are possible. Therefore, within a distance of 230 nm from the conductor wire, a magnetic field greater than the earth magnetic field can be produced to influence the trajectory of the MTB. Figure 4 shows the layout created with Cadence Virtuoso schematic of the power cell. The estimated power is depicted in Fig. 5 and Fig. 6.

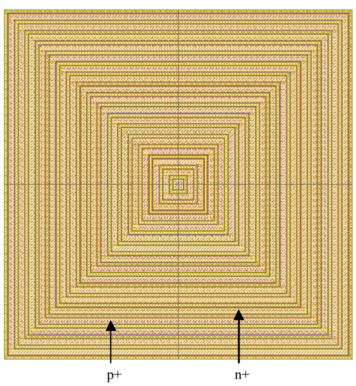

Fig. 4. View of the architecture of the cell from Cadence layout Virtuoso.

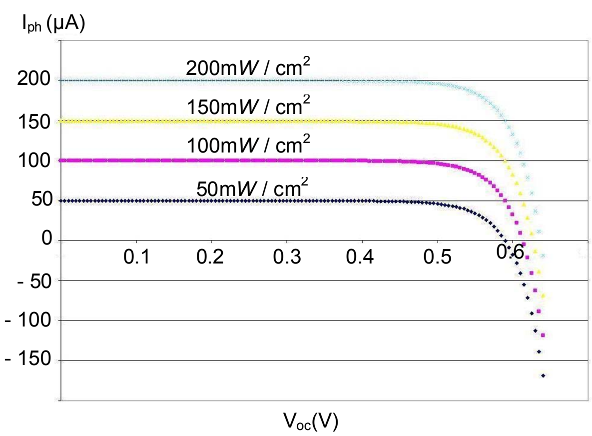

Fig. 5. Simulated I-V characteristics of the photocell for different green light intensities [9].

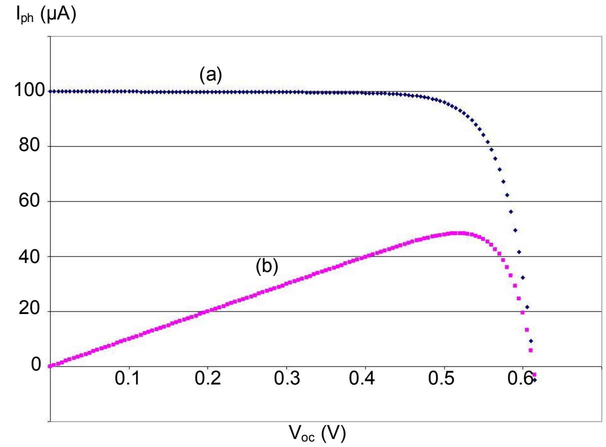

Fig. 6. (a) Simulated I-V characteristics of the photocell for 100m*W*/cm^2 green light intensity. (b) Simulated P-V characteristics of the photocell for different light intensities [9].

V. Conclusion

Preliminary results for the design of an autonomous bacterial microrobot that can be pre-programmed for a specific task have been briefly described. The long term goal is to build a fleet of such microrobots working autonomously towards relatively complex operations performed in a fluid sample. To minimize electrical power requirement, the motility of magnetotactic bacteria is exploited while a photovoltaic cell provides the minimum electrical power for the embedded control electronics. Preliminary estimates indicate that the 100 µA of current produced by the cells may be sufficient for influencing the swimming direction of the bacteria for controlled movements of the microrobot. This approach of combining synthetic and biological components has a great impact on the minimization of the power consumption of the microrobot, allowing the design of novel platforms that could play an important role for future laboratory tasks.

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