Controllable Bacterial Actuators for Nanorobots

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Abstract:
Magnetotactic bacteria (MTB) can be integrated in untethered devices such as micro- and nanorobots as a means of propulsion and steering being controllable by an electronic system. Here, we present experimental data that validate such new concept where these bacterial actuators prove to be efficient for directional and velocity control of nanorobots.

Keywords: Magnetotactic bacteria, nanorobots, bacterial actuators

Introduction

Depending upon the type of cells, the motility of bacteria can be influenced by several environmental signals. Among these signals there is the earth's magnetic field. In an aqueous environment, some bacteria such as Magnetotactic Bacteria (MTB) have a tendency to use the earth's magnetic field to navigate towards a depth corresponding to an optimum oxygen concentration. This phenomenon called magnetotaxis [1] is comprised of two elements: 1. Nanometer-scaled ferromagnetic particles called magnetosomes which orientate bacterial cell along the earth's magnetic field and 2. Two flagellums (in the case of MC-1 cell) that propel each bacterium like a biological motor along the magnetic field.
In an engineering point-of-view, MTB can be considered as sophisticated actuators with an embedded control interface. MTB that have been studied are motile by means of flagella and as such they could theoretically be considered for the implementation of actuation and propulsion systems for devices such as micro- or nanorobots [2]. In particular, the cell of the MC-1 bacterium is spherical in shape and measures approximately 2 micrometers (µm) in diameter [3]. Each cell has two flagella providing a thrust force exceeding 4 picoNewtons (pN). This value is relatively high compared to other flagellated bacteria where typical thrust forces in the range of 0.3-0.5pN have been recorded. Here we showed methods of directional and velocity controls and demonstrated that some behaviors and characteristics of the MTB can be altered.

Experimental setup

The main component of the experimental setup was a Zeiss AxioImager Z1 microscope with dark field illumination. Four electromagnets have been installed at each four corners of the microscope stage. Each electromagnet had a ferromagnetic core and could generate a magnetic field of 250 Gauss at each end of the visible field or field of view of the microscope. A fifth electromagnet has been installed under the field of view of the microscope. It consisted of a tip located in the proximity of the bottom of the microscope slide, the latter being motorized. This configuration forced the bacteria to accumulate in the center of the microscope image. All five electromagnets were controlled by a computer.
An AxioCamMR CCD camera was used to acquire the images. The camera directly attached to the microscope had a resolution of 1388 pixels × 1040 pixels with a dynamic range of 12 bits. To get stable results, the exposure time of the camera was fixed to 200ms and the gamma was set to linear.

Results and discussion

MC-1 bacteria swim in water at room temperature and without load at speeds often exceeding 200µm/s (see Fig. 1). This is a very high speed when we know that the swimming speeds of most flagellated bacteria in the same conditions are ~30µm/s. Maximum displacement speeds of ~300µm/s in water at room temperature and corresponding to ~150 times its cell's length for a relatively large proportion of the bacteria samples have also been recorded experimentally by our group.
The magnetic field's intensity has a direct effect on the bacteria's speed. In some conditions, with an intensity of 90 Gauss, the bacteria can be completely stopped and it will set off again as soon as the magnetic field's intensity is reduced (see Fig. 2A).
At higher temperatures, the bacteria are more sensitive to the magnetic field's intensity. By increasing the

temperature, a lower intensity can be used to slow down the bacteria (see Fig. 2B).

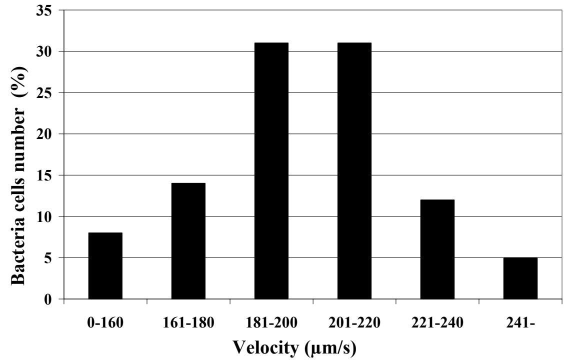

Fig.1: *Swimming speed distribution of MC-1 bacteria in a PBS buffer at room temperature. Strains of MC-1 bacteria were grown in liquid medium and approximately 500 cells were washed by suspending the cells in PBS-1X.*

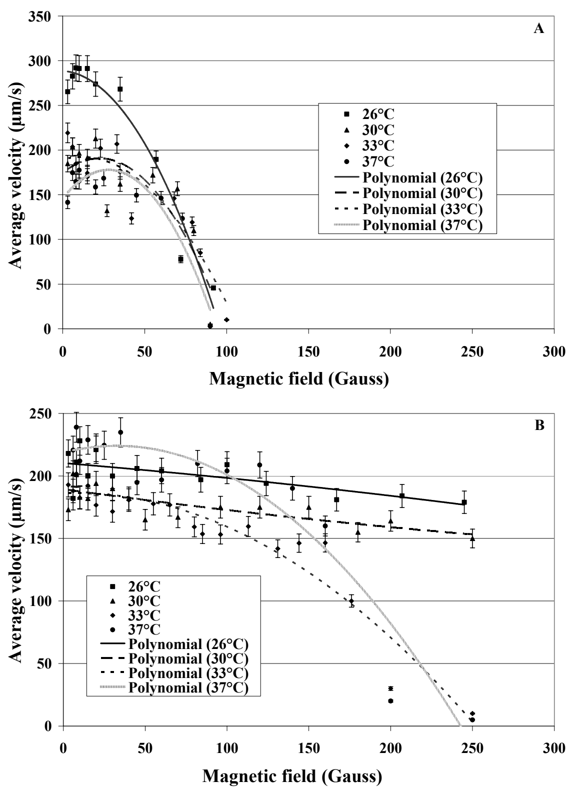

Fig. 2: *Swimming speeds of MC-1 bacteria versus the magnitudes of a DC magnetic field at different temperatures.* The *strain of MC-1 cells was grown in liquid medium and approximately 1000 cells were washed by suspending the cells in PBS-1X.* (A) *Bacteria have growth in medium containing 1% oxygen.* (B) *Bacteria have growth under anaerobic condition with only very small amounts of oxygen added daily.*

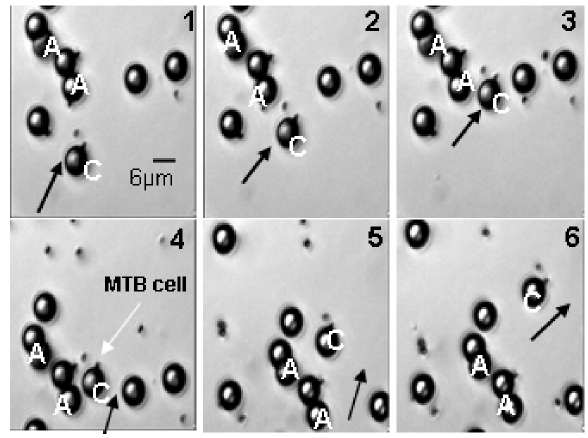

Fig. 3: *MC-1 cell attached to beads and controlled by magnetic field. Bacterial cells binding to anti-MC-1 antibody–coated beads were mounted on microscope slides. The bacterial mobility was controlled by magnetic field and monitored by optical microscopy using the following settings: magnetic field of 40 Gauss, objective LD Epiplan 40×, transmission-mode using Differential Interference Contrast (DIC).* ***A-*** *Static bead* ***C-*** *Bacterial cell attached to 6.4 µm bead and controlled by magnetic field during 18 min.,*
⟶ *Magnetic field direction*

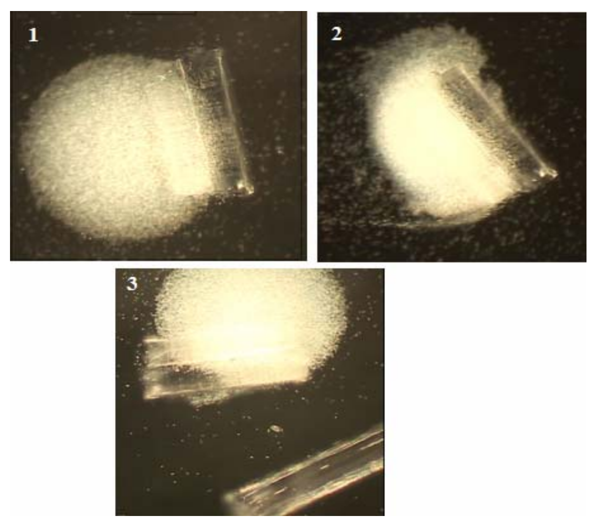

Fig. 4: *A population of MC-1 bacteria pushing a larger object under directional control for the implementation of a more powerful robot (approximately 5000 MC-1 cells have been used in this specific example).*

The bacterial cell can be used as a simple robot and be controlled individually (see Fig. 3). We can also use a population of cells to implement more powerful bacterial actuation for larger microrobots while

controlling the whole population like a unified organism (see Fig. 4).
The activity duration of the bacterial cells and the bacteria's behavior in time, are very important factors for the future use of these cells as biological robots. It has been proved that for temperatures between 27 and 30 degrees, the majority of the cells remain active for at least two hours (see Fig. 5).

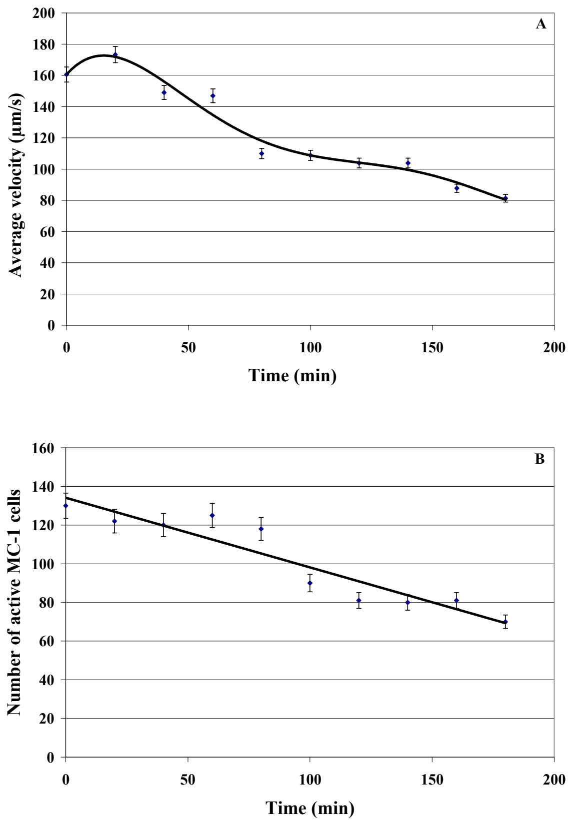

Fig5: *Bacteria's behavior (MC-1) over time. Bacteria have growth under anaerobic condition with only a very small amount of oxygen added daily. The cells were washed by suspending in PBS-1X. At 27º C, a magnetic field of 20 Gauss influences the bacteria (approx. 130 cells) to accumulate in the field of view of the microscope (291 µm × 218µm). We observed these 130 cells during 180 min. Bacteria speeds were measured (A) and the number of active bacteria (B) counted during 180 min.*

Conclusion

The data and methods provided in this paper allow us to create a biological robot which can be perfectly controllable. Unlike most bacteria that are based on chemotaxis to detect nutrient gradients and hence influence their motility, the direction of displacement of MTB with their chain of magnetosomes which are membrane based nanoparticles of a magnetic iron, although influenced by chemotaxis and aerotaxis, are also influenced by magnetotaxis. Using slightly higher magnetic fields than the earth's magnetic field of 0.5 Gauss, the directional motions of these MTB become mainly influenced by magnetotaxis and therefore fully controllable by electronics and computers. Here, we also showed the advantages of integrating magnetotactic bacteria for the development of hybrid nanorobots.

Acknowledgments

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References

[1] R. Blackmore, Science 190 (1975), 377-379

[2] S. Martel, C. Tremblay, S. Ngakeng, G. Langlois, Appl. Phys. Lett., 89 (2006), 233804-6

[3] R. B. Frankel, D. A. Bazylinski, M. S. Johnson, B. Taylor, Biophys. J., 73 (1997), 994–1000