

EXTENDED ABSTRACT

Flagellated magnetotactic bacteria as controlled MRI-trackable propulsion and steering systems

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BACTERIA can be used as computer-controlled miniature propulsion system with accurate steering for microrobots to accomplish precise operations. The propulsion force provided by the flagella being connected to molecular motors embedded in the bacterial cell and the chain of nanoparticles referred to as magnetosomes acting as a miniature steering mechanism under the control of an external computer can be exploited to embed micro-systems that could not be implemented at the micro-scale due to technological constraints. This strategy relies on harnessing instead of mimicking nature to compensate for unavailable technologies. In this particular case, flagellated bacteria and more specifically Magnetotactic Bacteria (MTB) are used for not only propulsion and transport, but also for the controlled steering or computerized directional swimming control of bacterial micro- nanorobots, i.e. micro-nanorobots being propelled by bacteria. The latter aimed at embedding natural with artificial or synthetic components to construct what we refer to as hybrid micro- nanorobots.

Connecting artificial or synthetic components to a natural self-propelled entity that can be controlled by computer is a very powerful concept that opens new possibilities. For instance, antibodies can be used to attach functionalized polymeric nanoparticles containing therapeutic agents to the cell of each flagellated bacterium. A swarm of such hybrid microrobots operating under computer control can then be used for targeting tumoral lesions in the human body for the delivery of therapeutic agents while providing high thrust to cope with the blood flow velocity in the microvascular network. Indeed, it was shown that the flagellated molecular motors embedded in each MC-1 bacterium being propelled by two flagella bundles, provides a thrust force exceeding 4pN. This is significant since it means that these MTB or natural microscale robots are more suitable than any other technologies when operating in the microvasculature while being trackable in the human body using Magnetic Resonance Imaging (MRI).

Therefore, this general approach aims at replacing artificial microscale robots designed to operate in the human microvasculature that are still beyond what present and near future technology can achieve, with artificial microscale robots capable of performing some of the same tasks being

envisioned. As such, a natural microrobot is defined here as an entirely biological organism that can act and operate like an artificial robot. Unlike other types of microrobots, a natural microrobot is one that has been created by natural means. As such, natural microrobots have typically the advantage when submitted to proper conditions of being self-replicating. A photograph of the MC-1 cell that could be considered as a natural microrobot is depicted in Fig. 1. The figure shows some of the fundamental embedded functions that are somewhat equivalent to the ones found in some of the artificial microrobots namely, the propulsion (P) system with the engines or motors, the directional (D) or steering control system, the transmitter (T) for localization inside the human body using MRI, and various sensors (S) that can be exploited for any given tasks.

As shown also in the photograph of Fig. 1, the overall diameter of this spherical microrobot is at the lower end of the micrometer-scale with an overall diameter of the main body between 1 and 2 micrometers (μm). Although many would see this flagellated bacterium as a simple biological organism, others could see it as a sophisticated self-propulsion system that when interacting with an external computer system, can accomplish many of the collective tasks that could be envisioned by the artificial microrobots.

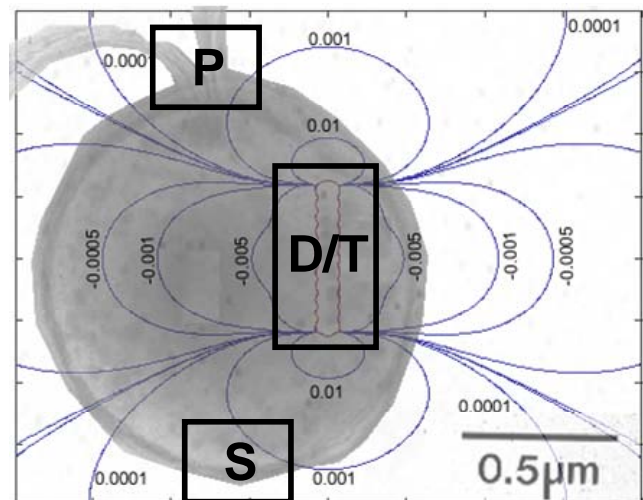


Figure 1 – A photograph of the MC-1 natural microrobot with some of the embedded functions identified as P: Propulsion; D/T: Directional control and Transmission; and S: Sensors (placed in front of the cell only for simplification).

The propulsion system embedded in the MC-1 bacterial microrobot consists of two flagella bundles. As depicted in Fig. 2, each flagellum acting as a propeller is activated by a molecular motor.

Although the design of the propeller of the bacterial microrobot as depicted in Fig. 2 is quite different when compared to the macroscale versions since it is conceived to interact directly with a different fluid environment being characterized by a low Reynolds regime, the design of the rotary motor used to activate the flagellum is on the other hand, surprisingly very similar to modern electrical rotary motors such as the one depicted in the lower left portion of Fig. 2. Indeed, although each molecular motor embedded in flagellated bacteria measures less than 300 hydrogen atoms across, as for modern engineered macroscale rotary motors, this miniature motor has a rotor that performs full rotations within a stator. By connecting each flagellum to a rotor, the collective force created by the two flagella bundles of each MC-1 bacterial microrobot results in a propulsion thrust force that is at least 10 times what is typically measured from other species of flagellated bacteria since the propulsion thrust force of the MC-1 cells exceeds 4pN. This means that this system can propel this type of 2µm microrobot in an aqueous medium at velocities exceeding 100 times its own body length per second (velocities exceeding 150 times its body length per second have also been recorded for the fastest MC-1 bacteria).

a scale is an important constraint and a major limiting factor in the level of miniaturization that can be achieved for the implementation of microrobots.

The chain of nanoparticles depicted in the cell acts like a miniature compass that can be used to control the swimming direction of the bacterium. The same nanoparticles can also be used to track the bacteria using MRI since each nanoparticle causes a local magnetic field inhomogeneity that can be detected with a large enough swarm of these bacteria. All these features make the MC-1 bacteria a unique and powerful alternative for microrobots aimed at navigating in the microvasculature that motivates us to continue its investigation for cancer therapy. More will be presented during the presentation at the workshop.

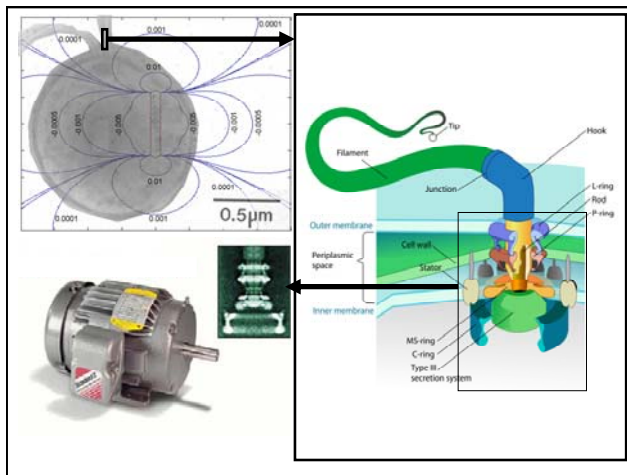


Figure 3 – Diagram of one of the flagella of the propulsion system being attached to a molecular motor embedded in the bacterium http://upload.wikimedia.org/wikipedia/commons/1/15/Flagellum_base_diagram_en.svg with a photograph of the real molecular motor next to a modern electrical motor.

Although much more can be said about this propulsion system, in this context it is important to note that this rotary nano-engine is composed of proteins and is powered by a flow of protons. The fact that proton flux is being used makes this propulsion system particularly attractive for microrobots especially self-propelled microrobots since as explained earlier, the availability of electrical power at such