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A Robotic Micro-assembly Process Inspired by the Construction of the Ancient Pyramids and Relying on Several Thousand Flagellated Bacteria Acting as Micro-workers

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Fig. 1. Photograph of the Djoser Step pyramid known as an important, initial milestone in the history of man-made structures. This pyramid has inspired the new micro-assembly method proposed here where several thousand human workers of the ancient Egypt have been replaced by several thousand micro-workers represented by flagellated magnetotactic bacteria of type MC-1, each having a diameter of approximately 2 micrometers.

BACTERIA can be used as computer-controlled bio-actuators and means of propulsion for microrobots and other micro-scaled entities to accomplish precise operations as first proposed by our research group in [1] and demonstrated later experimentally in [2]. The last reference confirmed that the propulsion force provided by the flagella being connected to molecular motors embedded in the bacterial cell, could be exploited to replace more conventional technologies being presently used in robotics but which could not be implemented at such a scale. In a coherent effort, our group also pioneered a method of not only harnessing instead of mimicking nature by using flagellated bacteria and more specifically Magnetotactic Bacteria (MTB) for propulsion and transport, but also for the controlled steering or computerized directional swimming control of bacterial micro- nanorobots [3].

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 [4] is comprised of two elements: 1. Nanometer-scaled ferromagnetic particles called magnetosomes which orientate bacterial cells along the earth's magnetic field and 2. Two flagella bundles (in the case of the MC-1 cell) that propel each bacterium like a biological motor along the magnetic field.

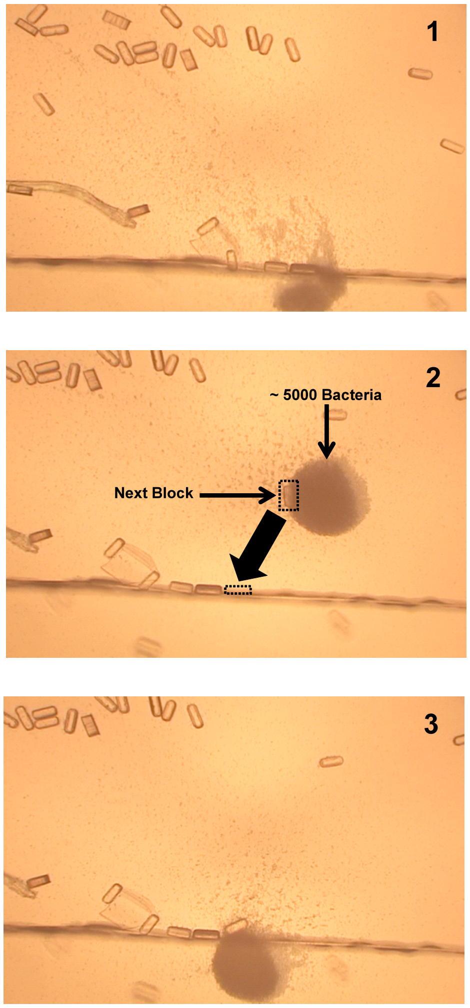
The polar magnetotactic bacteria of strain MC-1 have been identified by our research group as excellent candidates to implement and validate our new concept of bacterial micro- nanorobots and bacterial micro-assembly.

The experiment validating the concept of bacterial micro-assembly was observed using a Zeiss AxioImager Z1 microscope with dark field illumination. A special configuration of electromagnets acting under computer control has been installed at 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. This experimental setup forced the bacteria to accumulate in the center of the microscope image. While all electromagnets were controlled by a computer, a CCD camera was used to acquire the images.

The images of the video depicted in Figs. 2 and 3 show the aggregate of approximately 5000 MC-1 bacteria being controlled to transport and assemble blocks to build a Step pyramid somewhat similar to the one shown in Fig. 1. In this example, the pyramidal structure was built one block at a time with each block having a maximum length of 80 micrometers. This size has been chosen arbitrary to show the possibility of moving not only small objects but also larger objects that could not be moved using other approaches such as photon trapping. Depending on the characteristics of objects, other experiments showed that objects of a few hundred micrometers could also be transported by scaling appropriately the number of flagellated bacteria involved.

These images show not only the first structure being constructed by bacteria, but it also prove that the force provided by flagellated bacterial cells can be exploited to accomplish relatively complex micro-manipulation and micro-assembly tasks.

The final Step pyramid shown in Fig. 4 and which was built initially with only 6 blocks may not look at good as the human-made Step pyramid depicted in Fig. 1 in 2500 B.C., but unlike the latter which took many years to complete, the one depicted in Fig. 4 only took approximately 15 minutes using blocks with overall sizes and weight witch were much more difficult to work with when compared with the size and weight of each individual workers.



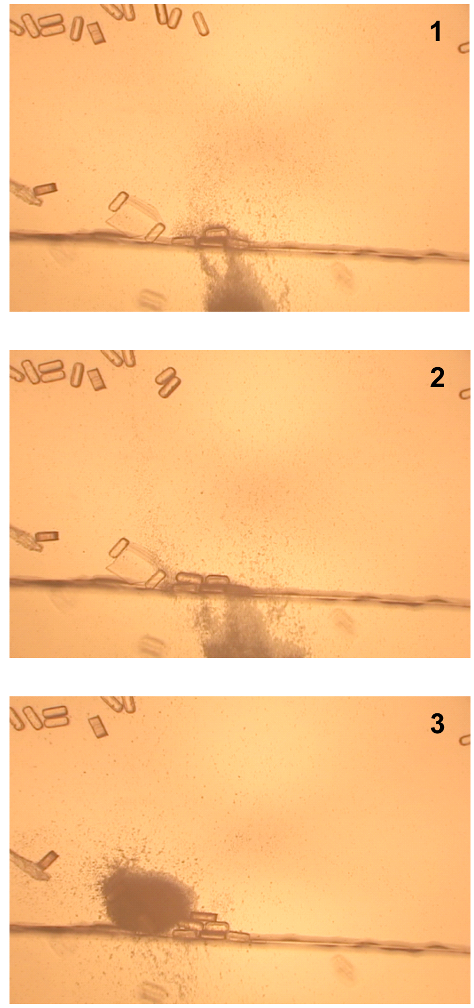


Fig. 2. Images taken under an optical microscope showing the initial micro-assembly process performed by the bacteria to construct the base of the Step pyramid. In the first image, the second block of the base of the pyramid has been placed next to the first block. In the second image, another block (surrounded by a dotted square and indicated by an arrow) to complete the base of the pyramid is being transported by the aggregate of approximately 5000 flagellated magnetotactic bacteria of type MC-1. The thick arrow in the second image points to the planned location where the last block of the base of the pyramid must be placed. In the third image, the base of the Step pyramid is almost completed. In the same image, the last block is being placed and adjusted to be positioned in the right location.

Fig. 3. Completion of the first Step pyramid built with bacteria. In the first image, the first block of the second level is placed on top of the base. In the second image, the second level is completed with the placement of another block. Finally in the last image, the Step pyramid is completed. In the last image, the size of the aggregate of approximately 5000 bacteria is seen with respect to the size of the pyramid.

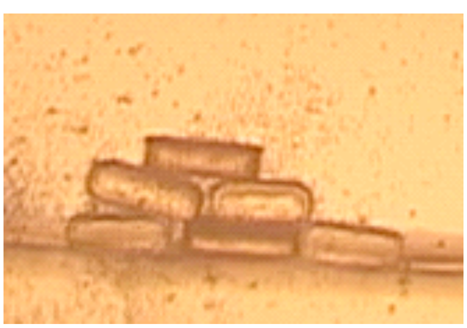


Fig. 4. The final Step pyramid. This is a first-proof-of-concept proving the feasibility of using bacteria for micro-manipulation and micro-assembly.

ACKNOWLEDGMENT

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