Controlled Propulsion of Artificial Magnetic Nanostructured Propellers
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Recommended with a commentary by Thomas R. Powers, Brown University

Some three hundred years ago, Antoni van Leeuwenhoek used small glass beads to reveal a world of swimming microorganisms. Leeuwenhoek likely used molten glass fibers to make beads of high magnifying power [1]. In a modern twist, Ghosh and Fischer have cleverly used glass fibers to make artificial controllable microscopic swimmers (Fig. 1, left panel) [2]. Each swimmer is a helix with a head; a coating of cobalt on one side of the swimmer provides a magnetic moment perpendicular to the axis of the helix. By applying a rotating homogeneous magnetic field, the experimentalists can apply a torque along the axis of the helix and cause it to move along this axis, with a direction that depends on the handedness of the helix.

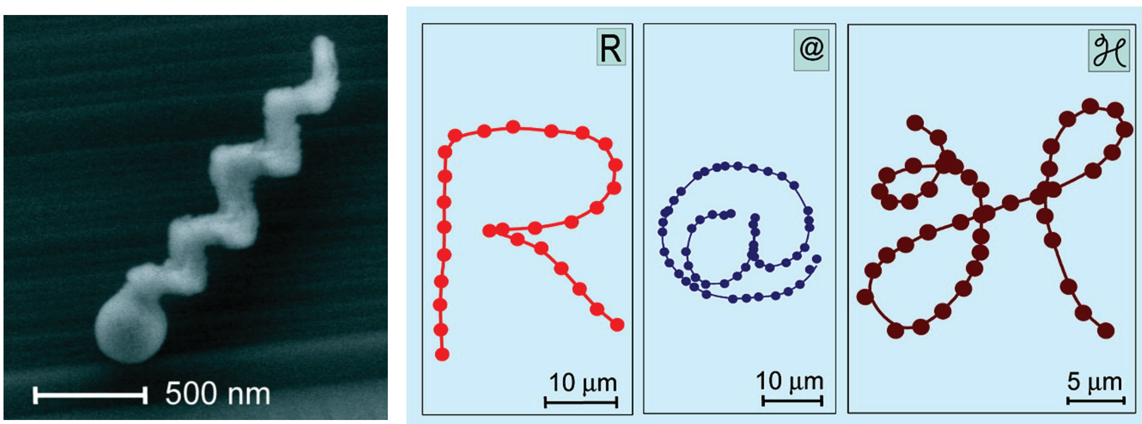

Figure 1: Left panel: a helical swimmer made from silicon dioxide. Right panel: programmed (lines) and actual (dots) trajectories of helical swimmers. From [2].

This means of propulsion is reminiscent of the way that the bacterium *Escherichia coli* swims. *E. coli* has helical flagellar filaments about $10\,\mu$m long and about 20 nm in diameter. These filaments are rotated by motors embedded in the cell wall of the bacterium [3]. Both the bacteria and the artificial swimmers must contend with hydrodynamics at low Reynolds number: the characteristic length and velocity scales of these swimmers is such that inertial effects are negligible relative to viscous forces. In other words, we demand that the both total force and torque acting on the swimmer vanishes, since the viscous forces are extremely large compared to the product of mass and typical acceleration[1]. In this regime, swimming strategies

[1]Note that Ghosh and Fischer's helices are not true swimmers, since they are subject to external torque. However, they are certainly not towed by an external force.

based on coasting or imparting momentum to the liquid do not work. In particular, a swimming stroke which is reciprocal, like the waving of a rigid oar, leads to no net motion [4]. Biological organisms have come up with various non-reciprocal swimming strokes, such as the propagation of bending waves down the length of a flagellum in spermatozoa, or the rotation of helical filaments in bacteria. People have recently built artificial versions of these swimmers, such as a chain of μm-sized magnetic beads driven by an oscillating magnetic field to form a propagating wave that propels a red blood cell along [5]. Other groups have also created small helices that are driven by rotating magnetic fields [6, 7, 8]. The key advance of Ghosh and Fischer is the ability to control the trajectory of the swimmers with μm-scale precision (Fig. 1, right panel), a crucial property for any of the imagined applications for microscopic swimmers. Since large populations of such swimmers are readily made and controlled by the external field, these swimmers should prove to be ideal models for the study of hydrodynamic interactions and the collective behavior of swarming microorganisms.

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