Supplementary Information

Magnetically-Powered Flexible Metal Nanowire Motors

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Captions:

SI Scheme 1. Preparation and propulsion of the nanowire magnetic swimmer. (A) Electrochemical preparation of the Au/Ag/Ni nanowire swimmer: a) Sequential template deposition of gold, silver and nickel segments on the sputtered silver layer of the alumina membrane template; b) removal of the sputtered silver layer and dissolution of the alumina template in 3 M NaOH; c) partial dissolution of the silver segment in a 8% H_2O_2 solution for one min. (B) Propulsion of magnetic nanowires with a flexible Ag segment in the rotating magnetic field. The magnetic field is provided by a rotating magnet (Magnet A) and static magnetic (Magnet B). To eliminate the whole body rotation (in the perpendicular direction), a static magnet B is used to compensate the rotation torque, making the nanowire become stable and generate a cone-shaped rotation of the Ni segment, which breaks the symmetry and facilitates movement along the nanowire axis.

SI Figure 1. Backscattered SEM images of the nanowire swimmer. A) the nanowire swimmer moving 'forward' before dissolving silver, B) the nanowire swimmer moving 'backward' before dissolving silver.

SI Figure 2. The SEM image of the flexible central silver segment following one minute immersion in a 8% H_2O_2 solution.

SI Figure 3. Dependence of the speed of the 'backward' moving motor upon the frequency of the rotating magnetic field (B=5 Gauss, f= 0~15 Hz). The lengths of Au, Ag and Ni segments are 2, 3.5 and 1 μm, respectively.

SI Figure 4. Effect of the salt concentration upon the 'backward' movement of the nanowire swimmer. Track-lines of the nanowire swimmer in pure water (a), 30 μM (b) and 30 mM (c) KCl solution under 5 Gauss rotating magnetic field with a 10 Hz frequency.

SI Video 1. Partial dissolution of the central Ag segment in 8% H_2O_2 to form a flexible joint between the Ni and Au segments.

SI Video 2. Comparison of the 'forward' and 'backward' movement of the rigid Au/Ag/Ni and flexible Au/Ag_{flex}/Ni nanowires under a rotating magnetic field over a 15 s period before and after partially dissolving the silver segment (in 8% H_2O_2).

SI Video 3. On-Demand 'Stop-and-Go' operation of 'forward' and 'backward' moving Au/Ag_{flex}/Ni nanomotors under the rotating magnetic field.

SI Video 4. Comparison of the movement of the flexible Au/Ag_{flex}/Ni nanowire in the absence of salt and in 30 μM and 30 mM KCl solutions.

SI Video 5. Motion of the magnetic Au/Ag_{flex}/Ni nanowire swimmer in urine under the rotating magnetic field.

Experimental Section

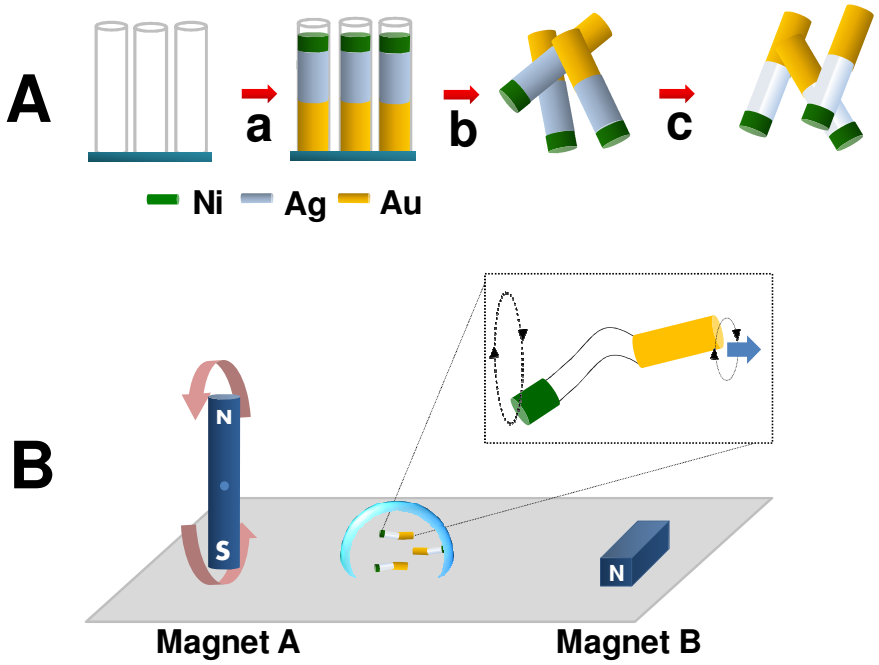
***Synthesis of the flexible gold/silver/nickel magnetic nanowires*:** The gold/silver/ nickel magnetic nanowires were prepared using common template-directed electrodeposition protocols. A silver film was first sputtered on one side of the porous alumina membrane template containing 200 nm diameter cylindrical pores and 25 mm diameter (Catalog No 6809-7022; Whatman, Maidstone, U. K.) to serve as a working electrode. The membrane was then assembled in a plating cell with an aluminum foil serving as a contact for the sputtered silver. Copper was electrodeposited in the branch area from a 1 M $CuSO_4 \cdot 5H_2O$ solution, using a charge of 8 C and a potential of -0.9 V (vs. Ag/AgCl reference), along with a Pt-wire counter electrode; subsequently, gold was plated from the commercial gold-plating solution (Orotemp 24 RTU RACK; Technic Inc.) at -1.0 V (vs. Ag/AgCl), using a charge of 4 C or 3 C (for 'forward' or 'backward' motions, respectively), silver was plated at -0.9 V (vs. Ag/AgCl) for a total charge of 3 C (for forward) or 3.5 C (for backward) using a commercial silver plating solution (1025 RTU @ 4.5 Troy/gallon; Technic Inc., Anaheim, CA); finally, Ni was plated from a nickel plating solution containing 20 g L^{-1} $NiCl_2 \cdot 6H_2O$, 515 g L^{-1} $Ni(H_2NSO_3)_2 \cdot 4H_2O$, and 20 g L^{-1} H_3BO_3 at -1.0 V (vs. Ag/AgCl) for 2 C (for 'forward') or 3 C (for 'backward'). The sputtered silver layer and copper sacrificial layer were mechanically removed from the membrane by polishing with 3-4 μm alumina slurry using a grinder/polisher (model 900, South Bay Technology Inc., San Clemente, CA). The membrane was then dissolved in a 3 M NaOH solution for 30 min to completely release the nanowires. The nanowires were collected by centrifugation at 6000 rpm for 5 min and were washed repeatedly with nanopure water (18.2 MΩ·cm) until a neutral pH was achieved. All nanowire solutions were stored in nanopure

water at room temperature. The flexible thinner joint of central silver segment is prepared by its partial dissolution accomplished by mixing 10 µl of diluted Au-Ag-Ni nanowire solution with 10 µl of a 16% hydrogen peroxide solution for 1 min (SI Video 1). The nanowires were then washed under optical microscope using nanopure water (18.2 MΩ·cm) until a neutral pH was achieved. The preparation yield of backward moving wires is higher compared to the forward moving ones. Most work thus employed backward moving motors. The nanowire sample was used for SEM imaging of the partially dissolved Ag segment, in connection to a 1 min immersion in hydrogen peroxide on the glass slide, followed by immediate wash with nanopure water on the glass slide, then dried. For clarity, and avoiding magnetic aggregation, the Ni segment was replaced with an Au one.

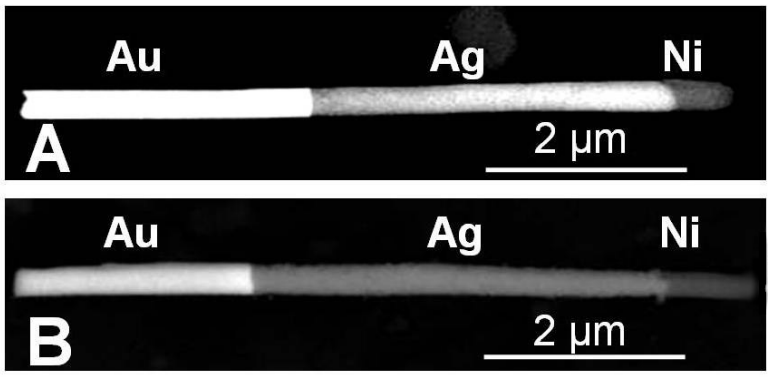
Magnetic driven movement: Movement studies were performed by using alternating magnetic field with 5 Gauss Magnetic Induction) was provided by a rotating magnet (Magnet A: Cole-Parmer magnetic stirrer EW-84000-00) at a specific speed (0~15 Hz) and static magnet (Magnet B). The static magnet stabilizes the nanowire swimmer by eliminating the whole body rotation (in the perpendicular direction). The magnetic induction was measured by a Gaussmeter (Lake Shore Model 475 DSP Gaussmeter). The exact positions of the magnet are shown in Scheme 1B. The locomotion of nanoswimmers in high salt and urine samples (collected from a healthy volunteer) was carried out by mixing directly with the nanomotor solution (1:1 mixing). Note that, due to electrostatic effects, some of the nanowires adhere to the during high-salt experiment.

Equipment: Electrochemical deposition of nanowires was carried out with a CHI 621A potentiostat (CH Instruments, Austin, TX). Scanning electron microscopy (SEM) images were obtained with Phillips XL30 ESEM instrument using an acceleration potential of 20 kV. An inverted optical microscope (Nikon Instrument Inc. Ti-S/L100), coupled with a 40x objective, a Photometrics QuantEM 512/SC camera (Roper Scientific, Duluth, GA) and a MetaMorph 7.6 software (Molecular Devices, Sunnyvale, CA) were used for capturing movies at a frame rate of 30 frames per second. The speed of the nanomotors was tracked using a Metamorph tracking module and the results were statistically analyzed using Origin software.

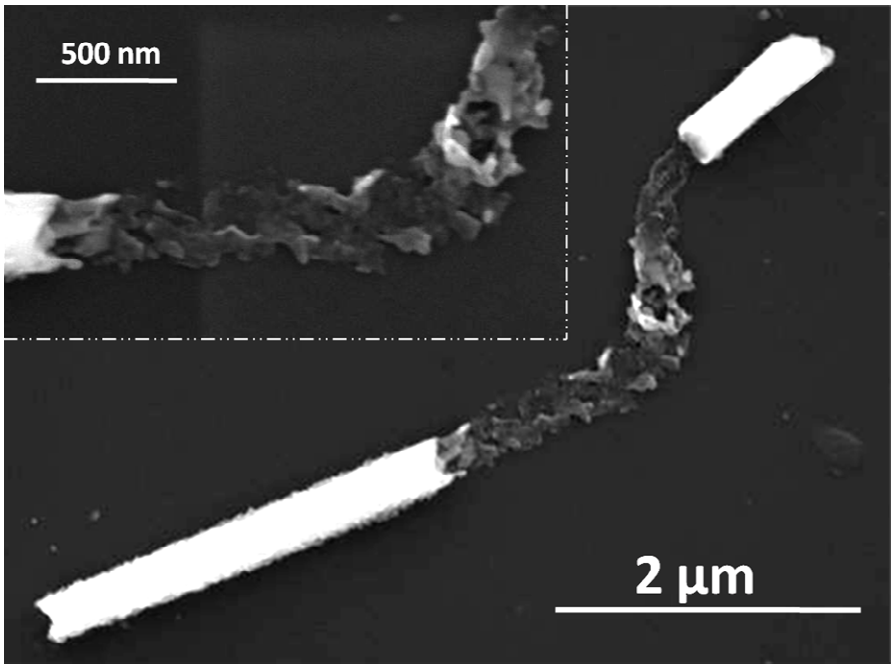
SI Scheme 1



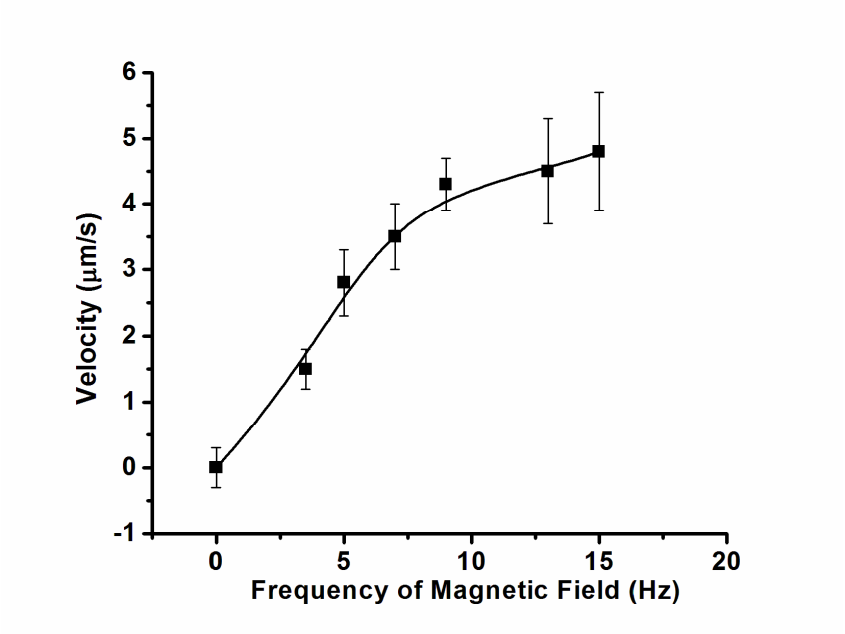
SI Figure 1



SI Figure 2



SI Figure 3



SI Figure 4