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Supporting Information

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Cargo-Towing Fuel-Free Magnetic Nanoswimmers for Targeted Drug Delivery

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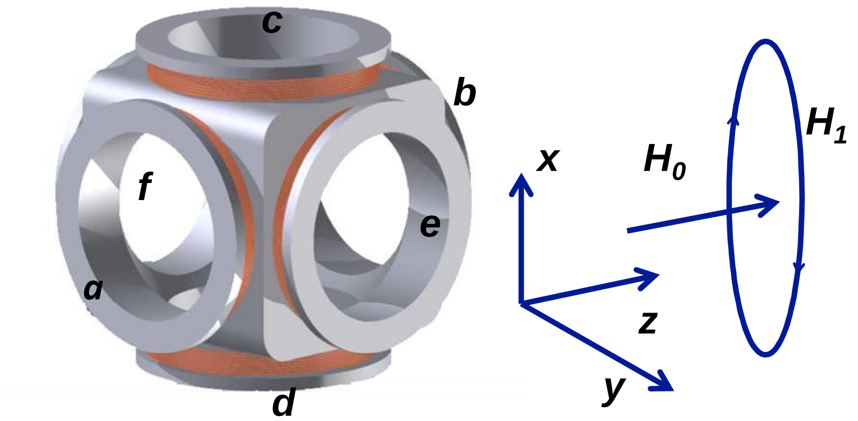
Supporting Videos description

Supporting Video S1. Slow motion of a magnetic nanowire motor with a 1.0 μm drug-loaded PLGA microparticle. Conditions, as in Figure 1.

Supporting Video S2. Pick-up of different sizes of drug-loaded PLGA microparticles using magnetic nanowire motors. Conditions, as in Figure 2.

Supporting Video S3. Microchannel drug delivery to HeLa cells using magnetic nanomotors in cell culture media. Conditions, as in Figure 5.

SI Figures



SI Figure 1. The magnetic field setup in the experiments. H_0 is a longitudinal constant component of the magnetic field generated by a Helmholtz pair: coils *a* & *b*, carrying an constant electrical current *I*; H_1 is a transverse rotating magnetic field generated by two Helmholtz pairs: coils *c & d and* coils *e* & *f*, carrying the sinusoidal currents I_1 and I_2, respectively. I_1 and I_2 have a 90 degree phase shift).

Elastohydrodynamics at low Reynolds number

In this supporting information, we briefly describe the derivation of the elastohydrodynamic equations in the main article (Equations 1 and 2). The calculation is an extension of our unloaded swimmer in Ref [16] in the main text. We model the fluid-body interaction by resistive force theory, which linearly relates the viscous force acting on a slender filament $\vec{f}_{\mathrm{vis}}$ to the local velocity of the filament $\vec{u}$ relative to any background flow,

$$\vec{f}_{\mathrm{vis}} = -\left[\xi_{//}\vec{t}\vec{t} + \xi_{\perp}\vec{n}\vec{n}\right]\cdot\vec{u}\,,$$

where the local tangent and normal vectors are denoted by $\vec{t}$ and $\vec{n}$ respectively, and $\xi_{//}$ and $\xi_{\perp}$ are the drag coefficients of a slender filament moving parallel and perpendicular to its axis respectively.

The elastic bending force of the filament is given by

$$\vec{f}_{\mathrm{elastic}} = -A\frac{\partial^4\vec{r}}{\partial s^4}\,,$$

where A is the bending stiffness of the filament, and $\vec{r}(s)$ is the position vector as a function of the arclength along the filament s.

In the microscopic fluidic environment, inertial forces are negligible and we have a simple force balance $\vec{f}_{\mathrm{vis}} + \vec{f}_{\mathrm{elastic}} = 0$, which leads to the equation governing the elastohydrodynamics of the filament

$$\left[\xi_{//}\vec{t}\vec{t} + \xi_{\perp}\vec{n}\vec{n}\right]\cdot\vec{u} = -A\frac{\partial^4\vec{r}}{\partial s^4}\,.$$

We are in the regime where the motion of the nanowire is synchronous with the rotating magnetic field. Therefore, we situate ourselves in a rotating reference frame where the magnetic field is fixed and the nanomotor has a non-changing shape in time. Therefore, we have $\vec{u} = \vec{U} - \vec{v}_b$, where $\vec{U}$ is the swimming velocity of the nanomotor and $\vec{v}_b$ is any background flow. Observing the motion in such a rotating reference frame induces a background flow given by $\vec{v}_R = \Omega(-y, x, 0)$, where Ω is the rotational frequency of the magnetic field. In our previous work[16], this is the only background flow present in the analysis, *i.e.* $\vec{v}_b = \vec{v}_R$. Here, we include another flow field $\vec{v}_S$ created by a spinning sphere of radius a_r centered at $z = L+a_r$, *i.e.* $\vec{v}_b = \vec{v}_R + \vec{v}_S$, where $\vec{v}_S = \Omega a_r^3 [x^2 + y^2 + (L + a_r - z)^2]^{-3/2} (y, -x, 0)$.

We nondimensionalized lengths and time by using the length of silver filament, L, and the inverse of the angular frequency, $1/\Omega$, respectively, and the dimensionless elastohydrodynamic equation is given by

$$\left[\gamma^{-1}\vec{t}\vec{t} + \vec{n}\vec{n}\right]\cdot \vec{u} = -\mathrm{Sp}^{-4}\frac{\partial^4 \vec{r}}{\partial s^4},$$

where $\gamma = \xi_\perp / \xi_{//}$, and $\mathrm{Sp} = L(\xi_\perp \Omega / A)^{1/4}$ is called the sperm number, a dimensionless parameter comparing the viscous to elastic forces. The same symbols are used for dimensionless variables for simplicity.

To make analytical progress, we consider small deformation, hence $z \approx s$, and we expand the transverse deformation $\vec{r}_\perp(z) = (x(z), y(z))$ and swimming speed in powers of h (ratio of the amplitude of the transverse and longitudinal magnetic field):

$$\vec{r}_\perp(z) = h\vec{r}_{\perp 1}(z) + h^2 \vec{r}_{\perp 2}(z) + \cdots$$

$$U = hU_1 + h^2 U_2 + \cdots$$

Integrating the $O(h)$ local viscous force in the z-direction over the entire swimmer yields $U_1 = 0$, and swimming occurs at $O(h^2)$. Therefore, the $O(h)$ local velocity of the filament relative to the background flow is given by

$$\vec{u}_1(z) = -\vec{v}_{b1} = -(\vec{v}_{R1} + \vec{v}_{S1}) = \left(\left[1 - \left(\frac{a}{1+a-z}\right)^3\right] y_1, -\left[1 - \left(\frac{a}{1+a-z}\right)^3\right] x_1, 0\right),$$

where $a = a_r / L$ is the dimensionless radius of the spinning sphere. Balancing the local viscous and elastic forces in the transverse directions leads to the equations governing the first order deformation $(x_1(z), y_1(z))$:

$$-y_1\left[1 - \left(\frac{a}{1+a-z}\right)^3\right] = \mathrm{Sp}^{-4}\frac{\partial^4 x_1}{\partial z^4}$$

$$x_1\left[1 - \left(\frac{a}{1+a-z}\right)^3\right] = \mathrm{Sp}^{-4}\frac{\partial^4 y_1}{\partial z^4},$$

where $a = a_r / L$ is the dimensionless radius of the spinning sphere. Note that when there is no background flow set up by the sphere ($a = 0$), the above equations reduce to those in Ref [16].

Upon solving the above equations for $(x_1(z), y_1(z))$ subject to different boundary conditions in the main text, we can obtain the dimensionless second order swimming speed[16] as

$$U_2 = \frac{1-\gamma}{\mathrm{Sp}^4(1+\alpha l_m)}\left[\frac{\partial x_1}{\partial z}\frac{\partial^3 x_1}{\partial z^3} - \frac{1}{2}\left(\frac{\partial^2 x_1}{\partial z^2}\right)^2 + \frac{\partial y_1}{\partial z}\frac{\partial^3 y_1}{\partial z^3} - \frac{1}{2}\left(\frac{\partial^2 y_1}{\partial z^2}\right)^2\right]_{z=1},$$

where $l_m = L_m / L$ is the dimensionless length of the nickel segment, and $\alpha = \xi_{m//} / \xi_{//}$ is the ratio of the drag coefficients of moving the nickel segment parallel to its axis to the same drag coefficeint of the silver segment.