Electronic Supplementary Information

Cooperative Manipulation and Transport of Microobjects Using Multiple Helical Microcarriers

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Supplementary Information

Fabrication of Microcarriers

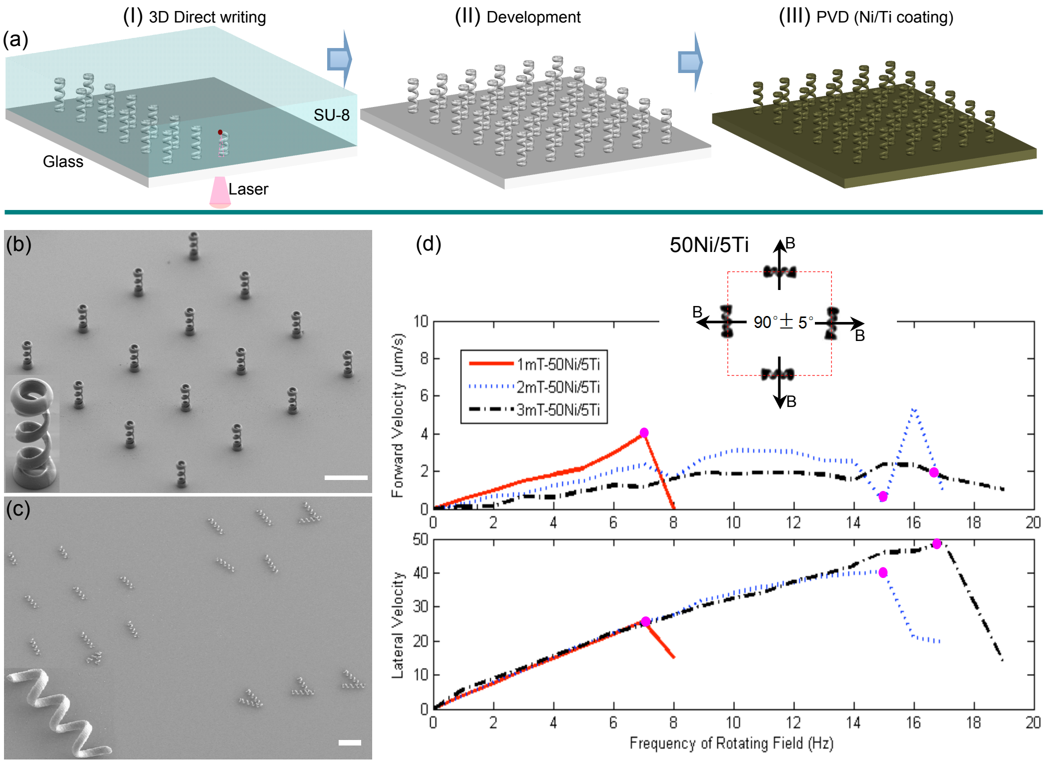

Figure S1. Fabrication of microcarriers and characterization of their swimming properties. (a) Schematic description of the fabrication process. The helical swimmers with (b) and without rings (c) generated with vertical writing. (d) The alignment of magnetization angle and swimming performance with rings. The scale bars are 50 μm .

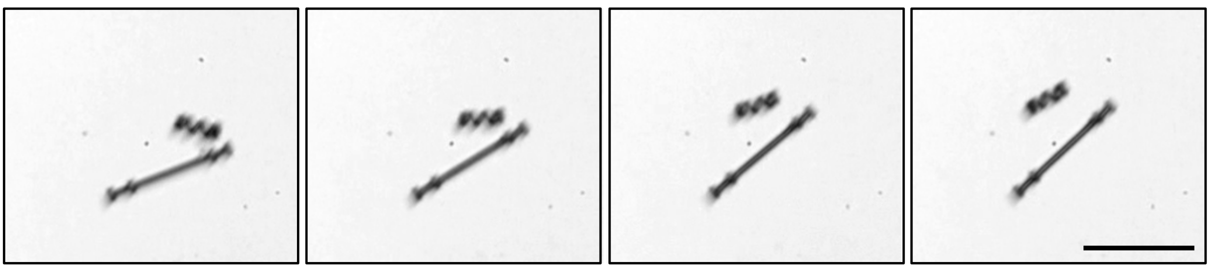

Figure S2 We utilized the low-pressure region around the carrier to pull microbars. The microbar was rotated due to the carrier motion. The scale bar is 100 μm .

Analytical model for drag

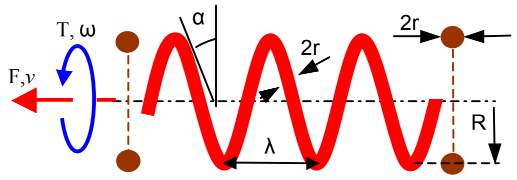

Figure S3. 1D model of the helical microcarrier.

Viscous forces dominate and inertia is negligible at low Reynolds numbers. As a result, a propulsion matrix (*PM*) linearly relates force F and torque T of the carrier with its forward velocity v and angular speed ω as

$$\begin{bmatrix} F^{helix} \\ T^{helix} \end{bmatrix} = PM \cdot \begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} A^{helix} & B^{helix} \\ B^{helix} & C^{helix} \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{2}$$

where the parameters in PM matrix are functions of turn numbers n, helical angle α, pitch λ, radius R, line width r, and the resistive force coefficients ξ_1 and ξ_2 parallel and perpendicular to the axis of helix (See Figure S3). The detailed parameters can be found in previous publications. [1,2] Furthermore, the drag force acting on each ring-shaped structure of a helical microcarrier can be approximated as a rotating torus with cross-sectional radius r and hole radius R-r in a uniform strokes stream with speed v. The toroidal coordinates are introduced by the relations $\varsigma = \kappa \dfrac{\sinh \tau}{\cosh \tau - \cos \sigma}$, $z = \kappa \dfrac{\sin \tau}{\cosh \tau - \cos \sigma}$ to describe the surface $\tau = \tau_0 > 0$ of a torus with circular cross-section of radius $r = \kappa \cdot \mathrm{cosech}\tau_0$ and hole of radius $R = \kappa \cdot \coth \tau_0$ where κ and τ_0 are uniquely determined with r and R prescribed.

Therefore, the translation and rotational drag coefficients in Stokes flow can be calculated as

$$A^{torus} = 4\sqrt{2}\pi\mu\kappa\sum_{n=0}^{\infty}[2nB_n - C_n] \tag{3}$$

$$C^{torus} = -16\mu\kappa^3\sum_{n=0}^{\infty}{}'(4n^2-1)\frac{Q^{(1)}_{n-1/2}(s_0)}{P^{(1)}_{n-1/2}(s_0)} \tag{4}$$

where $\sum{}'$ indicates that the term is multiplied by the factor 0.5 for n=0, and the parameters relating to geometric properties $B_n, C_n, Q^{(1)}_{n-1/2}$ and $P^{(1)}_{n-1/2}$ are obtained from literature.[3,4] The PM for the carriers can be rewritten as

$$\begin{bmatrix} A^{MC} & B^{MC} \\ B^{MC} & C^{MC} \end{bmatrix} = \begin{bmatrix} A^{helix} + 2A^{torus} & B^{helix} \\ B^{helix} & C^{helix} + 2C^{torus} \end{bmatrix} \tag{5}$$

Assuming that the microcarriers are sufficiently far away from each other and there is no interaction, we can estimate the non-fluidic force applied to the cargo during cooperative transport. The translational forces without and with load can be written as

$$F_{Assembly} = (\sum_{i=1}^{n} A_i^{MC})v + (\sum_{i=1}^{n} B_i^{MC})\omega \tag{6}$$

$$F'_{Assembly} = (A^{load} + \sum_{i=1}^{n} A_i^{MC})\hat{v} + (\sum_{i=1}^{n} B_i^{MC})\hat{\omega} \tag{7}$$

where A^{load} is the drag coefficients of load without rotation. If the rotational frequency of magnetic field is held constant at all times, that is $\omega = \hat{\omega}$, then according to (6) and (7) the drag force on the payload can be formulated as

$$F_{drag} = A^{load}\hat{v} = (\sum_{i=1}^{n} A_i^{MC})(v - \hat{v}) = A_{Assembly}(v - \hat{v}) \tag{8}$$

By measuring the forward velocity, we can estimate the drag force on the microbar during transport.

REFERENCES

(1) Peyer, K. E.; Zhang, L., Nelson, B. J. *Nanoscale* **2013**, 5, 1259.

(2) Frutiger, D. R.; Vollmers, K.; Kratochvil B. E.; Nelson, B. J. *Int. J. Robot. Res.* **2010**, 29, 613-636.

(3) Majumdar, S. R.; O'Neill, M. E. *JAMP*, **1977**, 28.

(4) Kanwal, R. P. *J. Fluid Mechanics*, **1961**, (10):17-24.

Supplementary Movies

Movie M1 shows erratic motion of swarms of the horizontal swimmers.

Movie M2 shows micromanipulation of micorbars with a single and multiple microcarriers.

Movie M3 shows cooperative manipulation of microbars with multiple microcarriers to assemble the letters of 'ETH'.