Supplementary Information

Interactive and synergistic behaviours of multiple heterogenous microrobots

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Supplementary Note 1: Dynamical analysis of the micro-gear

Under the RMF,

$$\mathbf{B}(\mathrm{t}) = \mathrm{B}\left[\sin(\omega \mathrm{t})\, \mathbf{e}_\mathrm{x} + \cos(\omega \mathrm{t})\, \mathbf{e}_\mathrm{y}\right] \tag{1}$$

where, B and ω are the strength and angular frequency of the magnetic field, respectively, and $\mathbf{e}_\mathrm{x}$ and $\mathbf{e}_\mathrm{y}$ represent the unit vectors of different axes, the rotation of the micro-gear is manipulated by magnetic torque which can be expressed as:

$$\mathbf{T}_\mathrm{M} = \mathbf{m} \times \mathbf{B} \tag{2}$$

and the magnitude of the $\mathrm{T_M}$ is

$$\mathrm{T_M} = |\mathbf{m}||\mathbf{B}|\sin\left(\omega \mathrm{t} - \theta(\mathrm{t})\right) \tag{3}$$

Where $\mathbf{m}$ is the net magnetic moment of the micro-gear, $\omega \mathrm{t}$ is the rotation angle of the RFM and $\theta(\mathrm{t})$ is the phase angle of the micro-gear with respect to the initial position. When rotating in the water, the micro-gear also experiences the drag torque $\mathbf{T}_\mathrm{D}$ whose magnitude can be expressed as:

$$\mathrm{T_D} = \mathrm{C_R}\dot{\theta} \tag{4}$$

where $\mathrm{C_R}$ is the rotational damping coefficient and $\dot{\theta}$ is the angular velocity of the micro-gear. Since only the rotating motion of the micro-gear is studied, the motion equation can be expressed as follows:

$$\mathrm{T_M} - \mathrm{T_D} = \mathrm{I}\ddot{\theta} \tag{5}$$

where I and $\ddot{\theta}$ are the moment of inertia and the angular acceleration of micro-gear. Combining the abovementioned equations and simplifying, the dynamic equation of the rotating motion can be expressed as follows:

$$|\mathbf{m}||\mathbf{B}|\sin\big(\omega t-\theta(t)\big)-C_R\dot{\theta}=I\ddot{\theta}. \tag{6}$$

When the micro-gear rotates at a constant angular velocity, the magnetic toque is balanced by drag torque. Therefore, the angular velocity can be written as follows:

$$\dot{\theta}=\frac{|\mathbf{m}||\mathbf{B}|}{C_R}\sin\big(\omega t-\theta(t)\big). \tag{7}$$

According to the abovementioned equation, the critical frequency for the rotating locomotion occurs when $\sin\big(\omega t-\theta(t)\big)$=1.[1] Therefore, the net magnetic moment of the micro-gear and strength of RMF have a great influence on the c_f value of the micro-gear.

Supplementary Note 2: Finite element analysis of the rotating micro-gear

As shown in the two-dimensional virtual model in Fig. S7, COMSOL Multiphysics was used to simulate the rotating behaviour of the micro-gear, using the Rotating Machinery, Laminar Flow module. This simulation is based on the Navier-Stokes equation, which is applied to solve the flow field in the model. The model has a ring (outer diameter: 2002 µm, inner diameter: 2000 µm) with attached two rectangles (height: 200 µm, width: 5 µm) and the micro-gear with a dimeter of 400 µm is positioned at the center of the model. Area not occupied by the micro-gear was set to be equivalent to water (at room temperature). The boundary conditions at one sidewall of the two rectangles were set to free boundaries, allowing fluid to flow in and out, respectively. The micro-gear sidewall and other walls were set to no slip, assuming no relative fluid movement. The rotation domain consists of a difference set of another circle (diameter: 2000 µm) and the micro-gear, with the flow continuity condition applied to the boundary between the rotation domain and the stationary domain (everywhere else). In simulations of the rotating micro-gear, a free triangle mesh domain was used and the moving mesh domain had a maximum element size of 74.1 µm, a minimum element size of 0.25 µm, a maximum element growth rate of 1.25, a curvature factor of 0.25, and a resolution of narrow regions of 1.

Supplementary Figures:

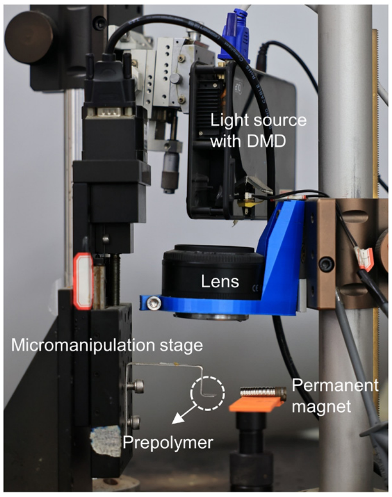

Fig. S1 DLP printing system.

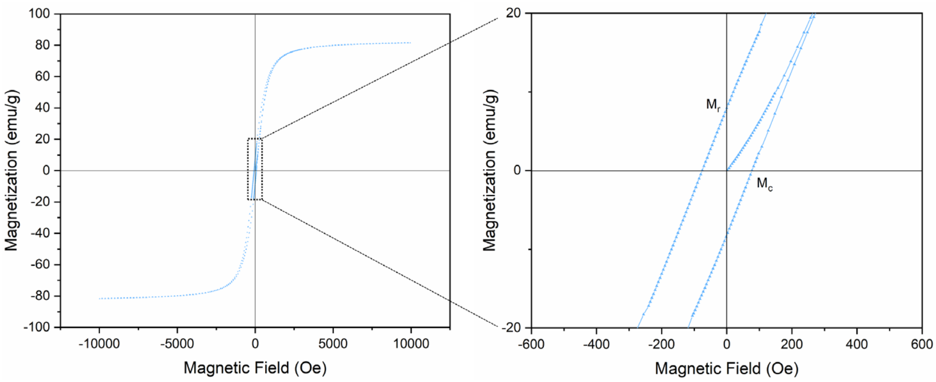

Fig. S2 Enlarged hysteresis curve of Fe_3O_4 particles (M_r: remanence, M_c: coercivity).

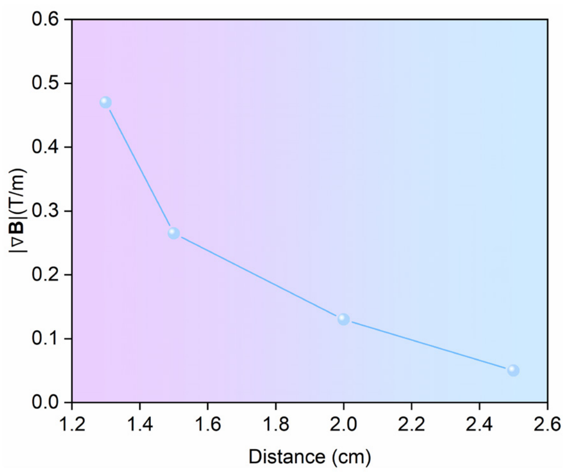

Fig. S3 Relationship between field gradient and different position of the permanent magnetic.

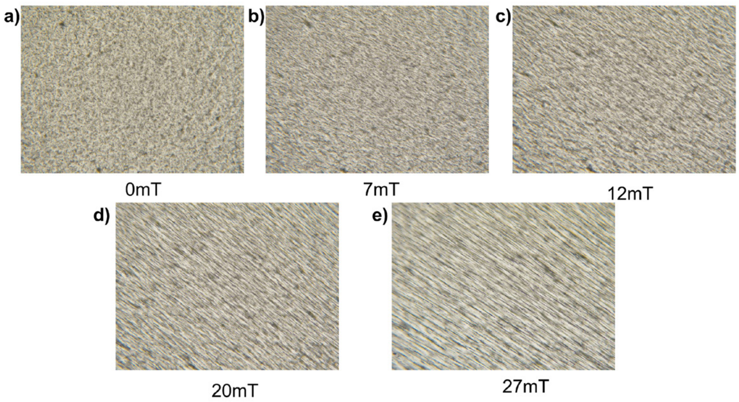

Fig. S4 Arrangements of MNPs in prepolymer solution under different external static magnetic fields before fabrication.

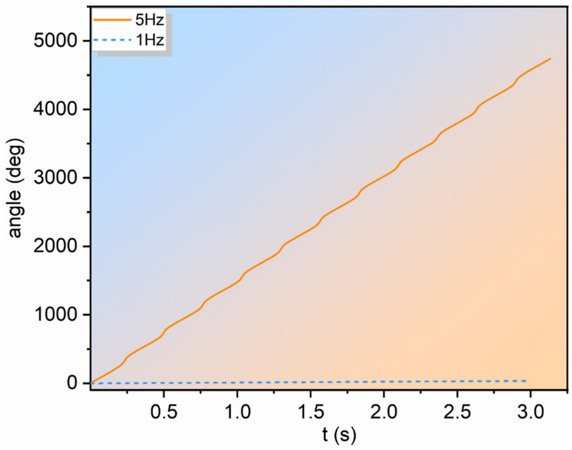

Fig. S5 The difference of the trajectory between the rotating field and the micro-gear at 1 Hz and 5 Hz, respectively. (The c_f value of the micro-gear is 3Hz.)

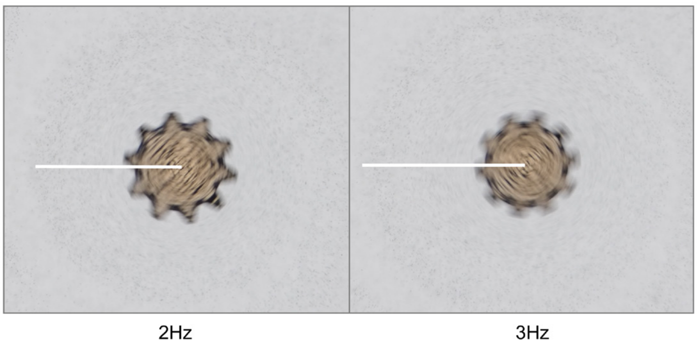

Fig. S6 Distribution of PS microbeads around rotating micro-gear at frequencies of 2 Hz and 3 Hz, respectively.

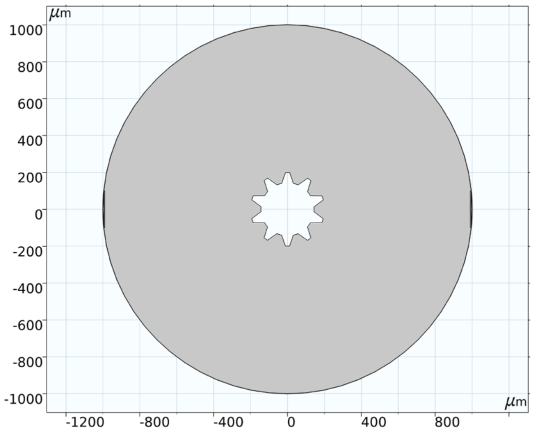

Fig. S7 Finite element model of the micro-gear.

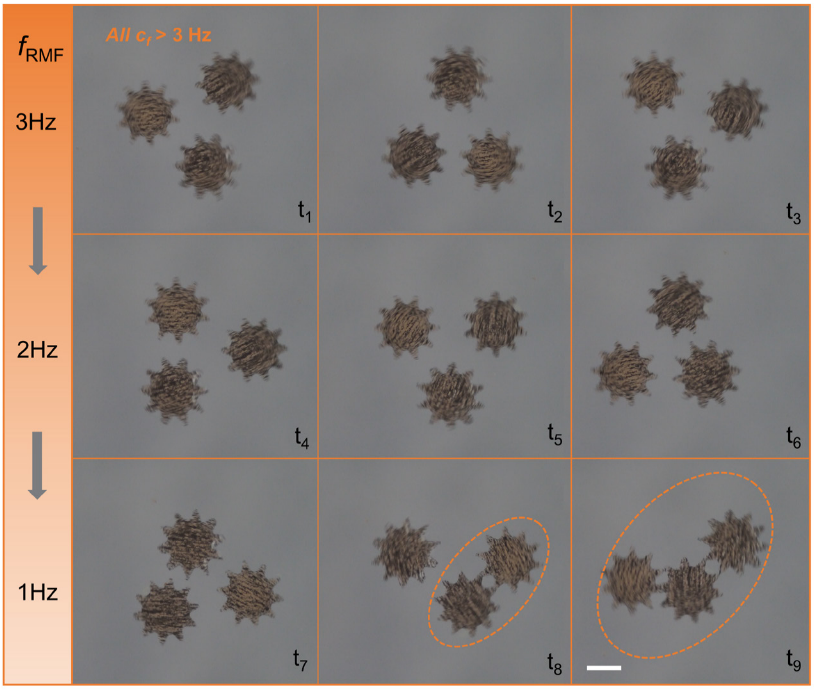

Fig. S8 Interactive and synergistic behaviour of three micro-gears with c_f values more than 3 Hz (Scalebar: 200 μm).

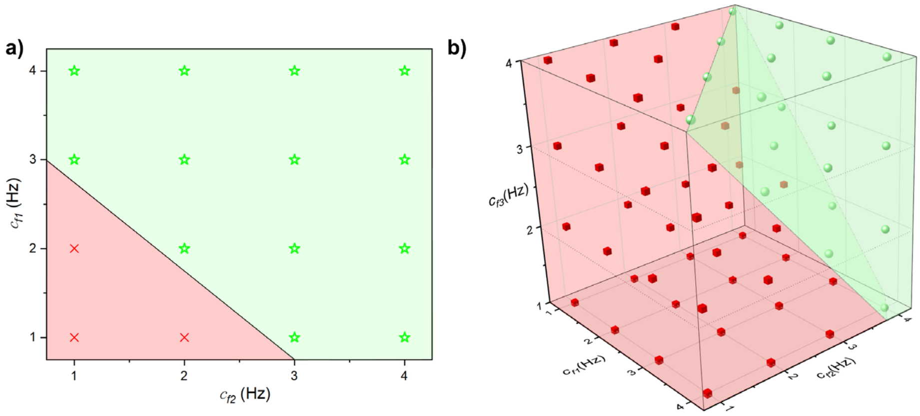

Fig. S9 a) Combinations of the cf values that the two micro-gears can (not) assemble to perform a synergistic rotation. (Red: failed, Green: successful) b) Combinations of the cf values that the three micro-gears can (not) assemble to perform a synergistic rotation. (Red: failed, Green: successful)

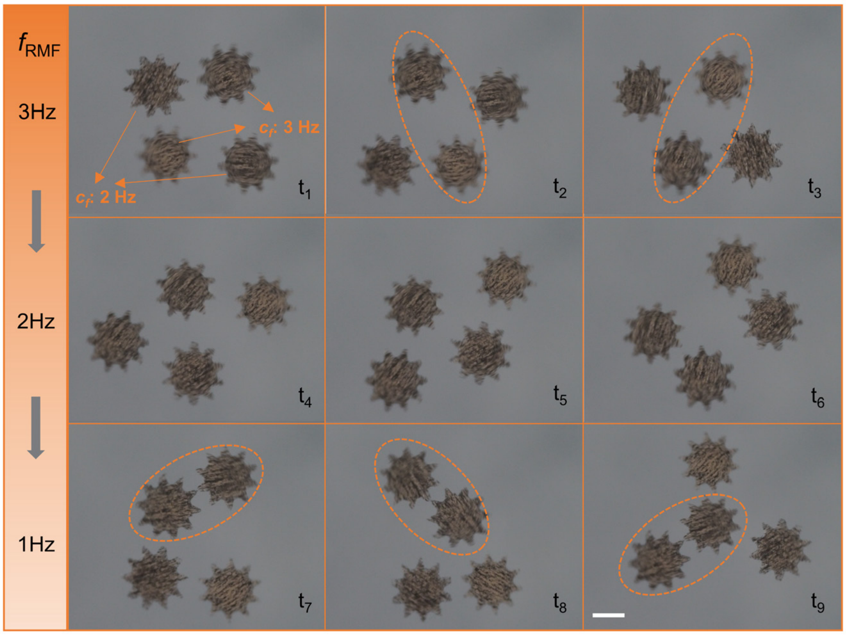

Fig. S10 Interactive and synergistic behaviours of four micro-gears with c_f values of 3, 3, 2, and 2 Hz, respectively (Scalebar: 200 μm).

1. T. T. Xu, Z. M. Hao, J. F. Yu, L. Zhang, X. Y. Wu and C. Huang, *IEEE-ASME Transactions on Mechatronics*, 2022, DOI: 10.1109/tmech.2022.3155806.