Supplementary Materials for

Untethered small-scale magnetic soft robot with programmable magnetization and integrated multifunctional modules

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The PDF file includes:

- Texts S1 and S2
- Figs. S1 to S19
- Legends for movies S1 to S7

Other Supplementary Material for this manuscript includes the following:

- Movies S1 to S7
**Supplementary text 1**

The reason that some simulation images are different from the experimental images can be explained from three factors:

(1) The spatially nonuniform magnetic field generated by a magnet, which induces magnetic force and magnetic torque acting on the soft robots. The coupled interaction of magnetic force and torque give rise to the structural changes of soft robots. However, the magnetic field used in the simulation is uniform.

(2) The assembling process. We have manually assembled the soft robots, which is a labor-intensive and approximate process. Thus, the assembled soft robots have certain uncontrollable differences in structure when compared with the theoretical design. However, the simulation has been conducted in the structures of theoretical design.

(3) The imperfect and discontinuous magnetization profiles in the simulated models. We have divided the curved deformation into discrete segments when rendering the magnetization profiles for simulation. This will result in an approximation of the curved deformation that will not be in exact agreement with the experimental result. This can be potentially addressed with a more detailed and finer discretization, which would make the magnetization profiles more representative of the continuous distribution and allow the simulation results to be in closer agreement with the real deformation.
Supplementary text 2

The areal mass density of NdFeB particles (The mass of NdFeB microparticles adhered onto per square centimeter of tape) has a major influence on the magnetic force. We measured the areal mass density of NdFeB microparticles with different average sizes of 38.0, 75.0, and 150.0 μm to be 6.837 mg cm$^{-2}$, 7.991 mg cm$^{-2}$, and 9.791 mg cm$^{-2}$, respectively. The areal mass density increases with increasing NdFeB particle sizes.

According to the equation:

$$f_m = \int_{V_m} (m \cdot \nabla) B \, dV_m$$

where $f_m$ is the magnetic force, $V_m$ is the volume of the NdFeB microparticles, $B$ is the flux density of the applied field, and $m$ is the magnetization of the NdFeB microparticles. These NdFeB microparticles with different sizes we purchased have the same type (LW-N), so their magnetization has the identical value at the same magnetizing condition. Thus, at the same applied field, larger mass of NdFeB particles with larger volume will produce larger magnetic force.
**Fig. S1.** The magnetization of NdFeB patterns. The relationship between the shape of templates and the magnetization profiles of all NdFeB patterns in Figure 2, Figure 3, and Figure 4. (the inset images in Figure 3H (1-3) and Figure 3I (1-6) are the schematic images of the template and magnetization ways)
Fig. S2. The formation process of NdFeB patterns on PEI tape. (A) The adhesion of NdFeB microparticles onto the PEI tape for the formation of NdFeB patterns; (B) Wax removal after soaking by ethyl acetate and slightly shaking; (C) No NdFeB microparticles can be found by attracting the residual solution with a strong magnetic.
Fig. S3. The fabrication accuracy of NdFeB stripes. (A) The super-resolution optical image and (B) magneto-optical microscope image of NdFeB stripes with different widths.
**Fig. S4. SEM images of NdFeB microparticles.** The scanning electron microscope (SEM) images of NdFeB microparticles with different average sizes of (A) 150 μm, (B) 75 μm, and (C) 38 μm.
Fig. S5. Demonstration of the transfer of NdFeB patterns. (A) The schematic diagram of NdFeB microparticles transfer from PEI tape to the double-sided tape; (B) The optical images of NdFeB patterns on PEI and double-sided tape after two transfer processes.
Fig. S6. Demonstration of magnetic properties of NdFeB microparticles. (A) The magnetic field strength of NdFeB microparticles with different sizes; (B) The height changes and (C) the curvature changes of rectangular NdFeB patterns with in-plane magnetization incorporated in the double-sided tapes with different thicknesses (the NdFeB patterns are composed of NdFeB microparticles with different sizes)
**Fig. S7. Optical images of NdFeB microparticles in double-sided tape.** The optical images of magnetized and unmagnetized NdFeB microparticles with different sizes (38.0, 75.0 and 150.0 μm) in the double-sided tapes with different thicknesses (0.3 (Tape I), 0.5 (tape II), and 1.0 mm (Tape III))
Fig. S8. SEM images of NdFeB microparticles in the double-sided tape. The SEM images of NdFeB microparticles with different sizes (38.0, 75.0, and 150.0 μm) in the double-sided tapes with different thicknesses (0.3 mm, 1.0 mm)
Fig. S9. The stability of NdFeB patterns in different fluids and treatments. (A-H) the stability and (I-J) weight changes of NdFeB pattern in double-sided tape after (A) ultrasonic in water for 1 h and magnetic stimulation in (B) HCl solution, (C) NaOH solution, (D) ethanol, (E) gastric fluids, (F) blood, (G) saliva, and (H) urine for 2 h.
Fig. S10. The planar geometrical parameters of all soft robots
Fig. S11. Assembly process of soft robots. (A-F) The selected assembly process of all soft robots (red patterns with black arrows (magnetization profiles) printed onto A4 paper are used to guarantee assembly accuracy)
Fig. S12. The magnetic properties of applied magnets. (A) The magnetic field distribution of a permanent disc-shaped magnet (80 mm diameter and 10 mm thickness) in 3D space; (B) The change of magnetic field strength with increasing vertical distance from the surface center of the disc-shaped magnet; (C) The magnetic field distribution of a permanent cuboid magnet (40 mm length, 40 mm width, and 10 mm thickness) in 3D space; (D) The change of magnetic field strength with increasing vertical distance from the surface center of the cuboid magnet.
Fig. S13. The demonstration of good stickiness of the double-sided tape. The loading weight is thousands of times the weight of assembled soft robots.
Fig. S14. The demonstration and self-adhesive spraying of functional modules. (A) The color changes of temperature sensing power out of and in double-sided tape at the temperature of 25 ℃ and 65 ℃; (B) The color changes of UV light sensing power out of and in double-sided tape when the UV light is turned off and on; (C) The formation of a layer of self-adhesive on pH sensing module (pH testing paper) and oil sensing modules (PDMS foam) by spraying.
**Fig S15. The magnetic actuation styles for different locomotion of multifunctional multi-legged soft (MFMLS) robot.** (A) The crawling on land and in water is achieved by moving the permanent magnet up and down in the “xz” plane along the yellow dotted line. The magnet is below the MFMLS-robot. (B) Swimming on water is achieved by moving permanent magnet upper and down in the “xz” plane along the yellow dotted line with small increments. The magnet is above the MFMLS-robot. (C) Diving is achieved by approaching the magnet to the MFMLS-robot from its bottom. (D) Swimming to the water is achieved by moving the permanent magnet up and down in the “xz” plane along the yellow dotted line with relatively large increments. The magnet is above the MFMLS-robot.
Fig. S16. The measurement of contact angle. The optical image of water droplet on the (A) double-sided tape and (B) NdFeB incorporated double-sided tape; Photos of water droplet contact angle for (C) double-sided tape and (D) NdFeB incorporated double-sided tape; The optical image of (E) water droplet and oil on the PDMS foam and (F-G) their corresponding photos of contact angle.
Fig. S17. Temporary circuit connecting in the apparent channel. (A-B) The total process; The lateral view of (C) approaching and (D) connecting.
Fig. S18. Six actuation styles demonstrated by five structures (original, O-shaped, M-shaped, W-shaped, and semi-curved structures) when moving inside an ex vivo pig stomach controlled by a magnet manually. (A) Curling: the magnet first approaches the soft robot from its bottom, and then rotates at the fixed position to achieve magnetic torque-induced curling. (B) Rolling: the magnet rotates and moves along the x-axis at the bottom of the soft robot. The magnetic torque and magnetic force collectively determine the rolling. (C) Unfolding: the magnet first rotates to the reverse side, then approaches the soft robot, and finally rotates to another side to achieve unfolding. The magnetic torque mainly determines the unfolding. (D) Climbing: the magnet first approaches the soft robot to induce W-shaped deformation, then the soft robot is pulled by magnet to straddle the fold of the stomach, next the position of magnet is adjusted down, and further pull the soft robot to partially pass through the fold. By repeating these operations, the magnet rotates again when a large part of soft robot pass through the fold. The magnetic force and magnetic torque collectively determine the climbing. (E) Turning over: the soft robot first achieves Semi-curved deformation by rotating a magnet half a circle at the bottom of the soft robot and then approaching the soft robot. Then, the magnet is quickly rotated to the reverse side to achieve turning over. The magnetic torque mainly determines the turning over. (F) Slipping: the magnet first approaches the soft robot to induce W-shaped deformation, and then the soft robot is pulled by a movable magnet to achieving slipping. The magnetic force mainly determines the slipping.
Fig. S19. The detailed processes in the transfer and return process of therapy patch on the pig stomach.
Supplementary movie captions:

Movie S1. The fabrication and transfer of NdFeB patterns
Movie S2. The assembly of soft robots with roll-to-roll device
Movie S3. The structural changes of soft robots with uniform and nonuniform magnetization and 2D and 3D geometries stimulated by a magnet
Movie S4. Multidirectional temperature and UV sensing
Movie S5. Temporary circuit connecting in a narrow and hard-to-reach space
Movie S6. Multimodal locomotion and environmental detection
Movie S7. Therapy patch transfer and return process on the pig stomach