Nanomagnetic Encoding of Shape-morphing Micromachines

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Shape-morphing systems, which can perform complex tasks through morphological transformations, are of high interest for future applications in minimally invasive medicine^{1,2}, soft robotics³⁻⁶, active metamaterials⁷, and smart surfaces⁸. With current fabrication methods, shape-morphing configurations have been embedded into structural design, for example by spatially distributing heterogeneous materials⁹⁻¹⁴, which cannot be altered once fabricated. The systems are therefore restricted to a single type of transformation that is predetermined by their geometry. In this work, we have developed a strategy to encode multiple shape-morphing information into a micromachine by programming the magnetic configurations of arrays of single-domain nanomagnets on connected panels. By tailoring the switching fields of the nanomagnets, the magnetic configurations can be programmed using a specific sequence of magnetizing fields and, with customised micromachine designs, these magnetic configurations result in specific shape transformations in an applied magnetic field. Using this concept, we have built an assembly of modular units that can be programmed to morph into alphabetic letters, and we have constructed a microscale ‘bird’ capable of complex behaviours, including ‘flapping’, ‘hovering’, ‘turning’ and ‘side-slipping’. This establishes a route for the creation of future intelligent microsystems that are reconfigurable and reprogrammable *in situ*, and can therefore adapt to complex situations.

It has been a longstanding goal to create intelligent machines that are untethered and can execute tasks at small scales. Magnetic actuation is of particular interest for the control of these machines, since it comes with the advantage of being able to perform tasks in confined and enclosed spaces¹⁵. For magnetic shape-morphing systems, a mechanical torque is generated when the magnetization of a magnetic media is not in line with the applied magnetic field¹⁶. Previous programming of the magnetic configurations could be achieved by reorienting permanent magnetic microparticles in millimetre-sized devices^{10,17,18}. For micrometre-sized devices, programming methods such as aligning superparamagnetic nanoparticles^{12,19} (region (i) in Fig. 1a) and selective coating of soft magnetic thin films²⁰ (region (iii) in Fig. 1a) have been demonstrated. In this work, we employed stadium-shaped single-domain nanomagnets to encode shape-morphing information into micromachines. Utilizing nanomagnets with lateral dimensions in an intermediate range between 100 and 500 nm (region (ii) in Fig. 1a), means they are single domain with a stable remanent magnetization and have a tunable magnetic anisotropy at room temperature.^{21,22} As a result of the magnetic shape

anisotropy, the magnetization is parallel to the long axis of the magnets, pointing in one of the two directions. By implementing arrays of these nanomagnets in a micromachine, the magnetic configuration can be remotely programmed by applying a sequence of magnetizing fields to store the shape-morphing information.

Inspired by origami²³, the art of paper folding, the micromachine is designed with two types of functional components; *rigid panels*, some of which are made functional with arrays of single-domain nanomagnets covering the panel surface; and *structured ‘soft’ spring hinges* as the connecting creases. In the micromachine design shown in Fig. 1b, there are four panels patterned with 60 nm-thick nanomagnets that can be remotely encoded and manipulated, and one central passive panel (see Extended Data Fig. 1 for SEM image). Arrays of nanomagnets with different magnetic switching fields are fabricated on opposite panels, e.g., Panel I and Panel II in Fig. 1b. The switching fields of the nanomagnets were engineered by varying the aspect ratios of the nanomagnets while maintaining the same volume (See “The geometric design and the switching behaviour of the stadium-shaped nanomagnets” in Methods and Extended Data Fig. 2). As given by the magnetic hysteresis loops in Fig. 1c (see Magnetic Characterization in Methods), the coercive fields B_c required to switch the magnets range from ≈ 30 mT for low aspect ratio ‘wide’ nanomagnets (300 nm x 110 nm, nanomagnet Type IV), to ≈ 140 mT for high aspect ratio ‘narrow’ nanomagnets (520 nm x 60 nm, nanomagnet Type I). The square shape of the loops indicates that they are fully magnetized at remanence. Arrays of Type I and II nanomagnets are patterned on the opposite panels of the four-panel micromachine and have switching fields of $B_c(I) \approx 140$ mT and $B_c(II) \approx 90$ mT, respectively. Type III and IV nanomagnets with $B_c(III) \approx 70$ mT and $B_c(IV) \approx 30$ mT are employed later in this work.

The micromachine can then be encoded by a series of magnetizing fields shown schematically in Fig. 1d. By applying a magnetic field $B_1 > B_c(I)$ along the x-direction, both Type I and II nanomagnets are magnetized with full remanent magnetization. A second lower magnetic field $B_c(I) > B_2 > B_c(II)$ is then applied in the opposite direction to remagnetize the Type II magnets in the opposite direction, so that the magnetization of the arrays on the two panels point head-to-head along the x-direction (orange and light blue horizontal arrows in Fig. 1d). Similarly, applying B_1 and B_2 fields sequentially along the y-direction gives head-to-head magnetization for the other two panels, so that the device has all four panels magnetized towards the centre. Furthermore, using magnetizing field protocols with different combinations of B_1 and B_2 fields, the same micromachine can be magnetized into different magnetic configurations and, since each panel can be magnetized in one of two opposite directions, there are a total of $2^4 = 16$ magnetic configurations for the same micromachine.

After programming the magnetic configurations, the micromachine is released from the substrate (see Sample Fabrication in Methods) and actuated with an applied magnetic field providing a magnetic torque $\tau = \mathbf{m} \times \mathbf{B}$ on the panels. All of the panels patterned with nanomagnets try to align with the applied magnetic field direction, which is counterbalanced with the mechanical torque from the deformed hinge springs (See “Hinge spring design, mechanical properties of a two-panel fold, and maximum force estimations” in Methods and Extended Data Fig. 3 for spring designs and mechanical calculations). When actuated by the controlling field, the four types of magnetic configurations give four distinct conformations, as shown in Fig. 1e and Supplementary Video 1. The transformations of our micromachines require actuation fields < 15 mT that are smaller than the switching fields, which are in the range 30 - 140 mT for the Type I - IV nanomagnets. The complete set of shape transformations for all sixteen magnetic configurations for this four-pad micromachine are

shown in Extended Data Fig. 4. There are the four distinct conformations due to the four-fold rotational symmetry of this particular micromachine. Nevertheless, the full programmability is given by the sixteen different magnetic configurations, which can give additional conformations when assembling the micromachines into multicomponent devices or when using an asymmetric machine design. We have therefore demonstrated that, by encoding magnetic configurations through magnetizing field protocols, micromachines of the same structural design can be programmed with different shape-morphing behaviours.

Multicomponent shape-morphing micromachines can be constructed by assembling modular units such as the four-panel devices shown in Fig. 1e. We first built a micromachine by assembling the same modular units into a 3×3 array, which provides four distinct conformations (see Extended Data Fig. 5 and Supplementary Video 2). Furthermore, multiple tailored conformations can be attained by customizing the individual units and encoding their magnetic configurations. To demonstrate this, we engineered a micromachine that can transform to two distinct alphabet letters, 'P' and 'X', based on different nanomagnetic encoding, as shown in Fig. 2. For this, we first selected a 4×4 assembly of the four-panel units (Fig. 2a) and, when applying the controlling magnetic field, each of the units moves either 'up' (magnetization on all four panels point inwards, represented by a '1' state), or 'down' (magnetization on all four panels point outwards, represented by a '0' state), with the set of '1'-state units representing a letter. Building both mode 'P' and mode 'X' into a single machine, gives four distinct *coding states* $(P, X) = (0, 0), (1, 1), (1, 0)$ or $(0, 1)$ for each unit, where the first digit is associated with the 'P' mode and the second digit is associated with the 'X' mode. We created four types of assembly units, each having one of the four coding states, which was achieved using different combinations of arrays of the four types of nanomagnets I – IV (Fig. 2b). The micromachine was then constructed from these four assembly units, corresponding to the arrangement of the coding states shown in Fig. 2a. The micromachine is then encoded so that one set of magnetic configurations of the units represents 'P' and the other represents 'X' (Fig. 2c). After releasing the encoded devices from the substrate, the micromachines display shape morphing into 'P' and 'X' patterns when actuated by an applied controlling field (see Fig. 2d and Supplementary Video 3). In addition to these two patterns, this micromachine design also has '9' and '0' modes, which are conjugate modes of 'P' and 'X' modes, respectively (see Extended Data Fig. 6). This modular design concept can therefore be used to create complex shape-morphing systems with tailored 3D transformations by customizing the design and layout of the functional units.

More advanced folding behaviours, such as the bending and twisting shown in Fig. 3a, can be achieved by programming the rigid panels of the shape-morphing micromachines with arbitrary magnetic configurations. The magnetic moment of the panels can be tuned by including arrays of nanomagnets with different aspect ratios and orientations (see "Designing the nanomagnet arrays to give a specific magnetization of the micromachine panels" in Methods). In the example shown in Fig. 3b, with four types of nanomagnets I - IV oriented along both the x- and y-directions, there are $2^4 \times 2^4 = 2^8$ magnetic configurations on a single panel. By adjusting the quantities n_x and n_y of each type of nanomagnet along the x- and y-directions, it is possible to assign each panel with a total magnetic moment with almost arbitrary magnitude and direction. As a demonstration, we have engineered an origami-like microscale bird to mimic the different flying modes of a real bird (see Fig. 3c). This is achieved with specific arrangements of the nanomagnet arrays of the five body parts consisting of a head, neck, body, tail, and a pair of wings. For the tips and joints of the bird's wings, there are four

arrays of nanomagnets on each panel with different orientations and switching fields. Therefore the total magnetization on these panels has eight possible directions and one demagnetized state (see Extended Data Fig. 7). By encoding the nanomagnets on the microscale bird with different magnetic configurations, we demonstrate four distinct morphological transformations – ‘flapping’, ‘hovering’, ‘turning’ and ‘side-slipping’ (see Fig. 3d and Supplementary Videos 4-7), achieved by varying magnetic fields as indicated in the Fig. 3d. Here, advanced folding behaviours are demonstrated; for the ‘hovering’ mode, the left and right wings ‘twist’ relative to the body, and in the ‘side-slipping’ mode, the right wing tip ‘bends and twists’ relative to the right wing joint. Methods to achieve additional transformations are discussed in “Use of out-of-plane anisotropy magnets to achieve additional transformations” in Methods.

For future applications, our micromachines have a wide range of tunability in terms of size, ranging from sub-micrometre-sized panels with a single nanomagnet, up to millimetre-sized devices, which is limited only by the fabrication methods available. The nanomagnet arrays can be further engineered to have temperature-dependent magnetic properties²⁴, and they can be modulated using radio frequency magnetic fields²⁵ and light²⁶. This possibility for control with several different stimuli provides further functionality of the micromachines in many different environments. Nanoscale magnets switch in only a few nanoseconds²⁵, which is much faster than the mechanical response of the micromachines that occurs at the millisecond timescale¹⁵. Therefore, the micromachines can be reprogrammed in situ using a magnetic field pulse with a pulse length in the nanosecond to millisecond range. With the ability to precisely control transformations at the micrometre scale, our micromachines also offer a platform to construct 3D magnetic metamaterials²⁷ such as a 3D realization of artificial spin ice²⁸, and photonic metamaterials²⁹ where optical properties, such as the polarisation of transmitted light, can be tuned by magnetically actuated transformations. This concept can also be applied in flexible electronics with morphable 3D structures having multistable states³⁰. By encoding the nanomagnets, the devices can be readily switched between these states using an applied magnetic field.

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Author contributions: J.C., T.-Y.H., L.J.H. and B.J.N. conceived the project. J.C., Z.L., P.T. and X.-Z.C. developed the fabrication process. T.-Y.H., J.C., Z.L. and H.G. developed the design strategy of nanomagnetic encoding. T.-Y.H., J.C. and X.-Z.C. tested the shape-morphing performance. J.C., T.-Y.H. and L.J.H. worked on the manuscript together. All authors contributed to the discussion of the results and the manuscript revision.

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References

1. Nelson, B. J., Kaliakatsos, I. K. & Abbott, J. J. Microrobots for Minimally Invasive Medicine. *Annu. Rev. Biomed. Eng.* **12**, 55–85 (2010).
2. Li, J., Esteban Fernández De Ávila, B., Gao, W., Zhang, L. & Wang, J. Micro/nanorobots for Biomedicine: Delivery, surgery, sensing, and detoxification. *Science Robotics* **2**, eaam6431 (2017).
3. Rus, D. & Tolley, M. T. Design, fabrication and control of soft robots. *Nature* **521**, 467–475 (2015).
4. Rich, S. I., Wood, R. J. & Majidi, C. Untethered soft robotics. *Nat. Electron.* **1**, 102–112 (2018).
5. Palagi, S. & Fischer, P. Bioinspired microrobots. *Nat. Rev. Mater.* **3**, 113–124 (2018).
6. Hu, C., Pané, S. & Nelson, B. J. Soft Micro- and Nanorobotics. *Annu. Rev. Control. Robot. Auton. Syst.* **1**, 53–75 (2018).
7. Zheludev, N. I. & Kivshar, Y. S. From metamaterials to metadevices. *Nat. Mater.* **11**, 917–924 (2012).

8. Xia, F. & Jiang, L. Bio-inspired, smart, multiscale interfacial materials. *Adv. Mater.* **20**, 2842–2858 (2008).
9. Miskin, M. Z. *et al.* Graphene-based bimorphs for micron-sized, autonomous origami machines. *Proc. Natl. Acad. Sci.* **115**, 466–470 (2018).
10. Kim, Y., Yuk, H., Zhao, R., Chester, S. A. & Zhao, X. Printing ferromagnetic domains for untethered fast-transforming soft materials. *Nature* **558**, 274–279 (2018).
11. Sydney Gladman, A., Matsumoto, E. A., Mahadevan, L., Nuzzo, R. G. & Lewis, J. A. Biomimetic 4D printing. *Nat. Mater.* **15**, 413–418 (2016).
12. Huang, H.-W., Sakar, M. S., Petruska, A. J., Pane, S. & Nelson, B. J. Soft micromachines with programmable motility and morphology. *Nat. Commun.* **7**, 1–10 (2016).
13. Magdanz, V., Guix, M., Hebenstreit, F. & Schmidt, O. G. Dynamic Polymeric Microtubes for the Remote-Controlled Capture, Guidance, and Release of Sperm Cells. *Adv. Mater.* **28**, 4084–4089 (2016).
14. Jin, D. *et al.* Four-dimensional direct laser writing of reconfigurable compound micromachines. *Mater. Today* (2019). doi:10.1016/j.mattod.2019.06.002
15. Peyer, K. E., Zhang, L. & Nelson, B. J. Bio-inspired magnetic swimming microrobots for biomedical applications. *Nanoscale* **5**, 1259–1272 (2013).
16. Erb, R. M., Martin, J. J., Soheilian, R., Pan, C. & Barber, J. R. Actuating Soft Matter with Magnetic Torque. *Adv. Funct. Mater.* **26**, 3859–3880 (2016).
17. Hu, W., Lum, G. Z., Mastrangeli, M. & Sitti, M. Small-scale soft-bodied robot with multimodal locomotion. *Nature* **554**, 81–85 (2018).
18. Xu, T., Zhang, J., Salehizadeh, M., Onaizah, O. & Diller, E. Millimeter-scale flexible robots with programmable three-dimensional magnetization and motions. *Sci. Robot.* **4**, eaav4494 (2019).
19. Kim, J. *et al.* Programming magnetic anisotropy in polymeric microactuators. *Nat. Mater.* **10**, 747–52 (2011).
20. Huang, T. Y. *et al.* 3D Printed Microtransporters: Compound Micromachines for Spatiotemporally Controlled Delivery of Therapeutic Agents. *Adv. Mater.* **27**, 6644–6650 (2015).
21. Cowburn, R. P., Koltsov, D. K., Adeyeye, A. O. & Welland, M. E. Single-Domain Circular Nanomagnets. *Phys. Rev. Lett.* **83**, 1042–1045 (1999).
22. Cowburn, R. P. Property variation with shape in magnetic nanoelements. *J. Phys. D: Appl. Phys.* **33**, R1–R16 (1999).
23. Rus, D. & Tolley, M. T. Design, fabrication and control of origami robots. *Nat. Rev. Mater.* **3**, 101–112 (2018).
24. Gliga, S. *et al.* Emergent dynamic chirality in a thermally driven artificial spin ratchet. *Nat. Mater.* **16**, 1106–1112 (2017).
25. Barros, N., Rassam, M., Jirari, H. & Kachkachi, H. Optimal switching of a nanomagnet assisted by microwaves. *Phys. Rev. B - Condens. Matter Mater. Phys.* **83**, 144418 (2011).

26. Lambert, C. H. *et al.* All-optical control of ferromagnetic thin films and nanostructures. *Science* **345**, 1337–1340 (2014).
27. Fernández-Pacheco, A. *et al.* Three-dimensional nanomagnetism. *Nat. Commun.* **8**, 15756 (2017).
28. Heyderman, L. J. & Stamps, R. L. Artificial ferroic systems: novel functionality from structure, interactions and dynamics. *J. Phys. Condens. Matter* **25**, 363201 (2013).
29. Gansel, J. K. *et al.* Gold helix photonic metamaterial as broadband circular polarizer. *Science* **325**, 1513–1515 (2009).
30. Fu, H. *et al.* Morphable 3D mesostructures and microelectronic devices by multistable buckling mechanics. *Nat. Mater.* **17**, 268–276 (2018).

Fig. 1 | Basic design of shape-morphing micromachine. **a**, Schematic diagram of the magnetic states found in magnets with increasing size: (i) superparamagnetic, (ii) stable single domain at room temperature and (iii) multidomain state. **b**, Four-panel micromachine with array of 520 nm x 60 nm (Type I) nanomagnets on Panel I and 398 nm x 80 nm (Type II) nanomagnets on Panel II, and corresponding SEM images of the nanomagnetic arrays. The zig-zag hinge spring has six turns. Scale bar is 500 nm. **c**, Magneto-optical Kerr effect hysteresis loops of single-domain nanomagnets with the same volume but with six different aspect ratios. The lateral dimensions are indicated to the right of the vertical axis in nanometres. The coercive fields of the Type I – IV nanomagnets are $B_c(I) \approx 140$ mT, $B_c(II) \approx 90$ mT, $B_c(III) \approx 70$ mT and $B_c(IV) \approx 30$ mT. **d**, Schematic of the encoding of the micromachine using two fields $B_1 > B_c(I)$ (large enough to switch Type I and II nanomagnets) and $B_c(I) > B_2 > B_c(II)$ (large enough to switch Type II, but not Type I, nanomagnets) applied in orthogonal directions. **e**, Schematics of the magnetic configurations (with Type I and II nanomagnets) and micromachine folding behaviour on application of the controlling magnetic field $B = 15$ mT, with optical microscope images showing the different conformations of the fabricated devices. Scale bar is 10 μ m.

Fig. 2 | Encoding alphabet letters into a shape-morphing micromachine assembled from an array of 4×4 four-panel units. a, Conceptual design of a micromachine with 16 four-panel units that can be encoded to transform into letters 'P' and 'X'. Each box in the schematic represents a four-panel unit, where the magnetization of all panels in a given unit can be encoded to point either outwards or inwards. Consequently, the central panel will move down or up when an out-of-plane controlling field B is applied and we assign these to be the '0' state or the '1' state, respectively. In order to combine mode 'P' and mode 'X' into a single micromachine, each unit is assigned one of four possible coding states given by $(P, X) = (0, 0), (1, 1), (1, 0)$ or $(0, 1)$. **b**, Design of the four different four-panel units with the four different coding states. Each panel contains an array of identical magnets whose orientation is given by the coloured bar on the panels. The colour of the bars corresponds to the colour of the hysteresis loops for the four different types of nanomagnets, I – IV, shown in Fig. 1c. **c**, Encoding the magnetization in the arrays of nanomagnets of the micromachine for the 'P' and 'X' shape morphing. The magnetization directions are given by the arrows which are coloured according to the four types of nanomagnets. **d**, Schematics and corresponding optical microscope images of the fabricated devices encoded for 'P' and 'X' shape morphing. The devices are actuated with $B = 15$ mT. Scale bars are 20 μ m.

Fig.3 | Origami-like microscale bird with multiple shape-morphing modes. **a**, Schematic of the folding behaviours of two-panel devices when actuated using an applied out-of-plane magnetic field. These are achieved by setting the magnetization perpendicular, parallel or at an angle to the folding crease as indicated by the red arrows on the panels. **b**, Schematic of the panel design using Type I – IV nanomagnets with the magnet long axis oriented along x- and y-directions and the colour of the nanomagnets corresponding to the colours of the magnetic hysteresis loops in Fig. 1c. **c**, Scanning electron microscope image of the microscale bird. The coloured bars indicate the location of the arrays of Type I – IV nanomagnets and the orientation of the nanomagnets. Scale bar is 15 μm . **d**, Schematic and optical images of a microscale bird mimicking four flying modes, ‘flapping’, ‘hovering’, ‘turning’, and ‘side-slipping’. From left to right in each row: encoded magnetization direction (coloured arrows) of the Type I – IV nanomagnets with the colours corresponding to the colours of the magnetic hysteresis loops in Fig. 1c, schematic of a flat microscale bird with the total magnetization direction for each panel indicated with red arrows, schematic of the folding of the microscale bird under the indicated controlling field, and the optical microscope images of the experimental demonstrations. The red dashed arrows in the optical images of ‘turning’ and ‘side-slipping’ modes highlight the corresponding motion of the microscale bird. The controlling fields for each of the modes are: ‘flapping’, slow increase to 15 mT; ‘hovering’, 1.5 mT, 1 Hz; ‘turning’, 11.6 mT, 24.5 Hz; and ‘side-slipping’, 6.2 mT, 19.5 Hz. Scale bars are 30 μm .

Methods

Sample fabrication. A schematic of the fabrication process can be found in Extended Data Fig. 8. The samples were fabricated on a 50 nm-thick low-stress silicon nitride membrane (Silson Ltd, England) supported by a rigid silicon frame. First, the nanomagnets were fabricated on the membrane with electron beam lithography using an electron beam writer (Vistec EBP 5000PlusES) to pattern a spin-coated 50k Poly(methyl methacrylate) (PMMA)/ 950k PMMA double-layer. A magnetic film of 5 nm Ti (adhesion layer)/60 nm Co/3 nm Al (capping layer) was thermally evaporated at a base pressure of $\approx 1 \times 10^{-6}$ mbar onto the patterned resist, which was followed by a lift-off process in acetone. Then the panels were fabricated by spin-coating a 950k PMMA layer on the front of the silicon nitride membrane, which was then patterned using electron beam lithography in order to define the geometry of the rigid panels and hinge springs of the micromachines. After coating a second 950k PMMA layer on the back of the membrane, reactive ion etching (RIE, Oxford PlasmaPro 100) was performed on the front side to etch through the 50 nm-thick silicon nitride membrane. After the RIE process, the fabricated micromachines were only supported by the free-standing PMMA layer coated on the back of the membrane. The devices were then magnetized by a sequence of the magnetic fields and released in an organic solvent, Propylene glycol monomethyl ether acetate (PGMEA). A further discussion on this release process and possible operation of the micromachines in other media can be found in “Release and operation of the micromachines in organic solvents, water and air” in Methods. The scanning electron microscopy (Zeiss Supra VP55) images were taken with 3 - 10 kV acceleration voltage.

Magnetic characterization and magnetizing process. The nanomagnets were characterized with magnetic optical Kerr effect (MOKE) measurements using a commercial setup (NanoMOKE, Durham Magneto Optics Ltd.) in the longitudinal mode with a focused laser spot with a diameter $\approx 10 \mu\text{m}$. Each hysteresis loop was obtained by averaging ten single-shot measurements. The nanomagnet arrays were encoded using the magnetizing field from the electromagnet in the NanoMOKE setup. The electromagnet was equipped with a manual rotation stage to hold the sample between the electromagnet iron poles. By rotating the sample on this stage, a magnetic field of up to 400 mT could be applied in any direction in the sample plane.

Magnetic Manipulation. After the sample fabrication and the magnetic field encoding, the sample was released in an organic solvent (PGMEA), which was observed with an optical microscope incorporating three pairs of Helmholtz coils in an orthogonal configuration. A computer was used to simultaneously control the electric currents in the three-pair Helmholtz coils to produce a magnetic field vector in arbitrary 3D directions. A magnetic field with a maximum magnitude of 15 mT was generated to manipulate the released micromachines. The observed folding behaviour and motion were captured with a video camera (Grasshopper GRAS-03K2C, Point Grey Research) on the microscope. The tested micromachines were actuated reversibly with a dynamic field more than 18,000 times (30 Hz, 10 minutes) with no significant signs of plastic deformation or breaking.

The geometric design and the switching behaviour of the stadium-shaped nanomagnets. The magnetic domain state of an element made of a soft polycrystalline ferromagnetic material (typically Fe, Ni, and Co) is dictated by the competition between quantum mechanical exchange energy and the stray field energy that is size- and shape-dependent³¹. By varying the lateral size and shape, it is possible to create single-domain nanomagnets.

The nanomagnets are designed with a stadium shape, comprising a rectangle with two semi-circles at each end, with the width of the rectangle matching the semi-circle diameter, as shown in Extended Data Fig. 2a. This shape ensures that the remanent magnetization is parallel to the long axis of the magnets, pointing in one of the two directions. The volume of the stadium-shaped nanomagnet is given by

$$V = \left[d(L - d) + \pi \left(\frac{d}{2} \right)^2 \right] t \quad (1.1)$$

When $L = 300$ nm, $d = 110$ nm and $t = 60$ nm, the volume of the nanomagnet is $V_0 = 1.82 \times 10^{-21}$ m³. The total magnetic moment of a nanomagnet is given by $m = MV$, where M is the saturation magnetization of the magnetic material. In this work, 60 nm-thick cobalt nanomagnets are employed, and the saturation magnetization of the thermally evaporated Co thin film is $M_s = 1153$ kA/m, measured using a superconducting quantum interference device - vibrating sample magnetometer (SQUID VSM) at room temperature.

Nanomagnets with different aspect ratios, L/d , display different magnetic coercivities, as shown in Fig. 1 of the main text. Here we keep the same nanomagnet volume V_0 and thickness $t_0 = 60$ nm for all nanomagnets regardless of the aspect ratio. Therefore, they have the same magnetic moment $m_0 = MV_0$ and Equation 1.1 can be modified to

$$V_0 = \left[d(L - d) + \pi \left(\frac{d}{2} \right)^2 \right] t_0 \quad (1.2)$$

So that the relation between L and d is given by

$$L = d + \frac{\frac{V_0}{t_0} - \pi \left(\frac{d}{2} \right)^2}{d} \quad (1.3)$$

A plot of d against L , determined using Equation 1.3, is shown in Extended Data Fig. 2c. In this figure, the nanomagnets with the same volume V_0 but with six different aspect ratios are selected, i.e., with lateral dimensions of 520 nm × 60 nm, 450 nm × 70 nm, 398 nm × 80 nm, 358 nm × 90 nm and 326 nm × 100 nm and 300 nm × 110 nm. The layout of the nanomagnet arrays is schematically shown in Extended Data Fig. 2b with a spacing of $d/2$ in the x-direction. In this layout, the dipolar coupling between the nanomagnets supports parallel alignment of the magnetization between neighbouring magnets. In the y-direction, neighbouring nanomagnets are separated by a distance $s = 40$ nm for all nanomagnetic arrays.

SEM images of the fabricated arrays are given in Extended Data Fig. 2e. The MOKE magnetic characterization is shown in Fig. 1 of the manuscript, with the square shapes of the hysteresis loops confirming the single-domain magnetic state of the nanomagnets. Since all nanomagnets investigated in this study have same magnetic moment of $m_0 = 2.10 \times 10^{-15}$ A·m², the total magnetic moment of the nanomagnets arrays on an individual panel (when all magnetization are aligned in the same direction) is

$$m_{total} = n_{magnets} m_0 \quad (1.4)$$

where $n_{magnets}$ is the number of nanomagnets on the panel. For the device demonstrated in Fig. 1, a total of 1040 nanomagnets are fabricated on each panel, with $m_{total} = 2.18 \times 10^{-12}$ A·m² pointing parallel to the long axis of the nanomagnets.

The square shapes of the hysteresis loops measured using the magneto-optical Kerr effect (MOKE) in Fig. 1c indicate that all the six types of designed nanomagnets are fully magnetized at remanence. As shown by the MOKE curves in Extended Data Fig. 2d, the magnetic switching occurs

over a relatively small field range of 5 – 20 mT. Since the six transition regions do not overlap, all six types of nanomagnets can be individually programmed, even for a micromachine containing arrays of all six nanomagnets oriented in the same direction.

Hinge spring design, mechanical properties of a two-panel fold, and maximum force estimations.

Inspired by the art of origami, we have designed rigid panels carrying single-domain nanomagnets, connected by structured hinge springs as folding creases. The hinge spring layout needs to be designed so that there is a significant folding behaviour on the application of a small magnetic field $B < 15$ mT.

We first derive the relationship between applied magnetic field B and panel rotation angle θ . Neglecting the bending of the short sections of the spring, the twisting of the zig-zag spring can be determined by considering a long and slender beam of equivalent length that can twist subject to an applied torque.

Considering first the twist of an isolated beam with uniform cross-section along its length (see Extended Data Fig. 3a), the angle of twist in radians is given by, $\theta = \frac{\tau L}{GJ}$, where τ is the applied torque, L is the beam length, and G and J are the shear modulus and torsional constant of the material, respectively.

For a beam with a rectangular section, the torsional constant is given by

$$J = \frac{wt(w^2 + t^2)}{12} \quad (2.1)$$

where w and t are the side lengths³². For a homogeneous isotropic material,

$$G = \frac{E}{2(1+\nu)} \quad (2.2)$$

where E is Young's modulus and ν is the Poisson ratio. Hence the panel rotation angle is given by

$$\theta = \frac{24(1+\nu)L}{Ewt(w^2 + t^2)} \tau. \quad (2.3)$$

The applied torque is given by, $\tau = k\theta$, so that the magnitude of the torsional spring constant, k , is given by

$$k = \frac{Ewt(w^2 + t^2)}{24(1+\nu)L} \quad (2.4)$$

For the current design, the total length of such a beam is $L = nl$, where l is the length of each of the beam sections, and n is the total number of the beam sections. Therefore, for each spring,

$$k_s = \frac{Ewt(w^2 + t^2)}{24(1+\nu)nl} \quad (2.5)$$

Since two springs are used and they are in a parallel configuration,

$$k_{total} = k_s + k_s = \frac{Ewt(w^2 + t^2)}{12(1+\nu)nl} \quad (2.6)$$

Taking into account that the direction of panel rotation θ is opposite to the mechanical torque direction induced on the spring, the total torque on the spring is given by

$$\tau_{spring} = -k_{total}\theta \quad (2.7)$$

We now determine the extent of the folding in a magnetic field for hinge designs with different numbers of turns in our micromachines. For this, we have fabricated simple two-panel devices to investigate the relationship between the applied magnetic field and the panel rotation angle. An SEM image of an eight-turn two-panel device is shown in Extended Data Fig. 3b. The fabricated devices had identical arrays of nanomagnets (398 nm x 80 nm nanomagnets on the left panel, and 520 x 60nm

nanomagnets on the right panel) but the number of turns in the hinge spring was varied with $q = 2, 4, 6$ and 8 , see Extended Data Fig. 3c. The total length of each of the spring is therefore $L = nl = (2q + 1)l$, where $l = 5 \mu\text{m}$ is the length of each section of the spring.

According to the illustration in Extended Data Fig. 3d, the magnetic-field-induced torque on the device is $\tau_B = \mathbf{m} \times \mathbf{B}$ and its magnitude

$$\tau_B = mB \sin(90^\circ - \theta) = mB \cos(\theta) \quad (2.8)$$

At equilibrium,

$$\tau_B + \tau_{\text{spring}} = 0 \quad (2.9)$$

Introducing Equations 2.7 and 2.8 into 2.9 gives

$$\begin{aligned} mB \cos(\theta) - k_{\text{total}}\theta &= 0 \\ \frac{\theta}{\cos(\theta)} &= \frac{m}{k_{\text{total}}}B \end{aligned} \quad (2.10)$$

Introducing Equations 1.4 and 2.6 into Equation 2.10, we obtain

$$\frac{\theta}{\cos(\theta)} = \frac{n_{\text{magnets}} m_0 \cdot 12(1+\nu)nl}{Ewt(w^2+t^2)} B \quad (2.11)$$

This equation is the relation between applied magnetic field H and panel rotation angle θ , which can be numerically solved. Here $n_{\text{magnets}} = 1175$, $n = [5, 9, 13, 17]$ for devices with 2-, 4-, 6- and 8-turn hinges, and lateral dimensions $w = 100 \text{ nm}$, $t = 50 \text{ nm}$ and $l = 5 \mu\text{m}$, as used in the experimental micromachines. From Equation 1.4, the total magnetic moment on each panel is $m_{\text{total}} = 2.47 \times 10^{-12} \text{ A}\cdot\text{m}^2$. Shown in Extended Data Fig. 3e are optical microscope images of the panel rotation angles for hinged spring designs with different number of turns following actuation in the same field $B = 5 \text{ mT}$. The experimental demonstrations and computational results are plotted in Extended Data Fig. 3f and g, respectively, and follow the similar trends. The panel rotation angle is larger in the experiment, which may be partly due to over-etching in the final nanofabrication step leading to hinged springs that are narrower than in the original design. For the devices shown in Figs. 1-3, hinge springs with $q = 6$ turns were used. With the current possibilities for the magnetic field control with field steps of 0.1 mT , we can orient the panels to within ≈ 0.1 to 1° , depending on the panel rotation angle in an applied magnetic field.

We now estimate the magnitude of the largest torque and force that can be generated from the panels patterned with nanomagnets. The induced mechanical torque on the panels τ has a linear relationship with the magnitude of the applied magnetic field B since $\tau = \mathbf{m} \times \mathbf{B}$. However, on increasing B , the mechanical torque τ cannot be infinitely high, since the applied magnetic field may switch the nanomagnets. For example, if the magnetic field is applied along the long axis of the magnets, then it will alter the magnetization if it is larger than the switching field, which is 30 mT for the Type IV nanomagnets.

For a given micromachine, there are several panels in different orientations that change as the magnetic field is applied. We therefore assume that we can safely operate a machine with an upper limit to the field given by the coercive field B_c , i.e. the switching field of the magnets when applying a field parallel to the magnet long axis.

We calculate the torque and force that can be generated by a panel patterned with Type IV nanomagnets. For the four-panel devices and their modular assemblies in Figs. 1 and 2, there are in total 1040 nanomagnets on each $10 \mu\text{m} \times 10 \mu\text{m}$ panel, with $m_{\text{total}} = 2.18 \times 10^{-12} \text{ A}\cdot\text{m}^2$ pointing along the long axis of the nanomagnets. In this case, for a 30 mT operation field, the highest generated

magnetic torque is $\tau = 2.18 \times 10^{-12} \text{ A} \cdot \text{m}^2 \cdot 30 \text{ mT} \cdot \sin(90^\circ) = 6.54 \times 10^{-14} \text{ N} \cdot \text{m}$. Assuming one edge of the panel is hinged, then the highest generated force is $f = 6.54 \times 10^{-14} \text{ N} \cdot \text{m} / 10 \text{ } \mu\text{m} = 6.54 \times 10^{-9} \text{ N} = 6.54 \text{ nN}$.

Similarly, for a $10 \text{ } \mu\text{m} \times 10 \text{ } \mu\text{m}$ panel patterned with Type I nanomagnets, which have a switching field of 140 mT, the highest generated mechanical torque is $\tau = 3.05 \times 10^{-13} \text{ N} \cdot \text{m}$, and the highest generated force is $f = 30.5 \text{ nN}$.

It has been shown previously that microrobots can be used to move cells by pushing them with forces in pN range³³. For moving even larger objects, such as a $100 \text{ } \mu\text{m} \times 10 \text{ } \mu\text{m} \times 8 \text{ } \mu\text{m}$ microbar, it has been shown that $\approx 200 \text{ pN}$ of force is needed³⁴. Therefore, since our machines can supply forces up to several nN, they are capable of manipulating biological objects such as cells.

Designing the nanomagnet arrays to give a specific magnetization of the micromachine panels. We engineer the orientation and magnitude of the magnetic moment of the arrays of nanomagnets. Here, we can consider a panel consisting of nanomagnets with p different aspect ratios, each with different switching fields $B_{c,i}$ and magnetic moments $m_i = M_i V_i$, where $i = 1, 2, \dots, p$. M_i is the magnetization of the magnetic material and V_i is the volume of the nanomagnet. The nanomagnets with magnetic moment m_i can be fabricated with several different arbitrary orientations $\varphi_{i,j}$ on a panel. Here, $j = 1, 2, \dots, k_i$, where k_i denotes the total number of different orientations for the nanomagnets with magnetic moment m_i . Therefore, we obtain the total magnetic moment m_{total} for all arrays of nanomagnets on a given panel

$$m_{total} = \sum_{i=1}^p \sum_{j=1}^{k_i} n_{i,j} \cdot m_i \cdot (\cos \varphi_{i,j} + i \sin \varphi_{i,j}) \quad (3.1)$$

where $n_{i,j}$ is the quantity of the nanomagnets with magnetic moment m_i and orientation $\varphi_{i,j}$. This total magnetic moment m_{total} of nanomagnets on a single panel can be programmed with arbitrary magnitude and direction by careful adjustment of the magnetic moment $m_i = M_i V_i$, orientations $\varphi_{i,j}$ and quantities $n_{i,j}$ of the nanomagnets.

In our micromachines, both the magnetization M_i and the volume V_i of the nanomagnets are the same for nanomagnets with different switching fields, so we can assume that magnitude of the magnetic moment $m_i = M_i V_i$ of all magnets in the array are the same, i.e. $m_i = M_i V_i = M_0 V_0 = m_0$. Therefore, Equation 3.1 can be simplified to

$$m_{total} = m_0 \cdot \sum_{i=1}^p \sum_{j=1}^{k_i} n_{i,j} \cdot (\cos \varphi_{i,j} + i \sin \varphi_{i,j}) \quad (3.2)$$

In our systems, we only have nanomagnets in two orientations, which are orthogonal to each other. This means that the magnets in the two orthogonal arrays can be magnetized independently by applying a field parallel to the long axes of the nanomagnets in one of the arrays. To be specific, in our design, each the long axis of each magnet is aligned along one of two orientations, i.e., parallel to one of the two coordinate axes (x- or y-axis, so $k_i = 2$). Therefore, the magnetization can point along one of four cardinal directions (North, South, East and West) so that the orientation of the total magnetic moment is given by

$$\varphi = \tan^{-1} \frac{\sin \varphi_{i,y} \cdot \sum_{i=1}^p n_{i,y}}{\cos \varphi_{i,x} \cdot \sum_{i=1}^p n_{i,x}} \quad (3.3)$$

where $n_{i,x}$, $n_{i,y}$ are the number of i types of nanomagnets with a given switching field with the long axis along the x- and y-axis, respectively, so that $\varphi_{i,x} = 0, \pi$ and $\varphi_{i,y} = \pm \frac{\pi}{2}$ depending on the direction of magnetization in the nanomagnets. According to Equation 3.3, by changing the number of magnets

with a given orientation, i.e. $n_{i,x}$, $n_{i,y}$, it is possible to obtain an arbitrary orientation φ of the total magnetic moment m_{total} .

For each panel, there are nanomagnets with p_x and p_y different switching fields along the x- and y-axis, respectively. It is therefore possible to program $2^{p_x} \times 2^{p_y}$ magnetic configurations, which give a total magnetic moment with a particular magnitude and orientation. In order to encode a panel with two or more different types of nanomagnets, one starts by magnetizing the highest coercivity magnet, so that all magnets on the panel will be magnetized in the direction of the field. If required, the lower coercivity magnets can be oppositely magnetized using a magnetic field applied in the reverse direction that is sufficiently low to leave the higher coercivity nanomagnets unaffected.

Use of out-of-plane anisotropy magnets to achieve additional transformations. In this paper, the transformations are inspired by origami, and the micromachines are constructed with rigid panels and structured soft creases. The rigid panels carry the programmed nanomagnet arrays, which provide the mechanical torque for transformations when an external magnetic field is applied. Here, the nanomagnets are designed to be stadium-shaped with the remanent magnetization pointing in the plane of the rigid panel along the geometric long axis of the magnets as a result of the magnetic shape anisotropy.

The current concept has limitations, where folding into particular shapes is not straightforward. For example, the four-panel devices shown in Fig. 1, which have all four side panels magnetized towards or away from the centre, can achieve folding into an “uncovered box”. Shutting the lid to give a “closed” box with an additional panel is not possible with the arrangement of nanomagnets used in this work. Instead, the magnetization of the nanomagnets on the lid needs to point out of the plane of the lid. This requires nanomagnets with out-of-plane magnetic anisotropy, which can be achieved with, for example, a Co/Pt multilayer system³⁵.

Release and operation of the micromachines in organic solvents, water and air. We used organic solutions, such as PGMEA and acetone, to dissolve the PMMA supporting layer and release the micromachines from the silicon substrate in the final step of the fabrication process. We chose PGMEA because it does not evaporate as fast as acetone and, in order to keep the experimental processes simple, we directly actuated the micromachines in the PGMEA solvent after the release. Nevertheless, the micromachines can also be operated in other working environments such as water and air and, since the nanomagnets have a 3 nm Al capping layer, they will not be easily oxidized. This 3 nm Al layer also ensures the biocompatibility of the micromachines. Here, we suggest three approaches to transfer and operate the structures in a water environment:

Approach 1. Instead of using a PMMA support layer coated on the back of the membrane (step 3-4 in Extended Data Fig. 8), water-soluble coatings, such as Poly(acrylic acid) or Dextran³⁶, can be used. These are compatible with microfabrication techniques and, after the RIE etching, the structures can be directly released and operated in water.

Approach 2. After the fabrication and the release of the structures in an organic solvent, the structures can be fished out and transferred to a water environment using a micromanipulator tip. This is a standard procedure for micro- and nano-robotic manipulation, and has been widely reported²⁰.

Approach 3. After the fabrication and the release of the structures in an organic solvent, water substitution can be performed, for example, in a petri dish containing the solvent and the micromachines. This technique is widely used in soft or shape-morphing microrobotics¹⁴. It should be

noted that PGMEA has limited miscibility with water. Therefore, if PGMEA is used to dissolve the PMMA for device release, acetone or IPA (fully miscible with PGMEA) can be used to substitute PGMEA first, and then a water substitution can be performed to replace acetone or IPA. An alternative approach is to directly use acetone to dissolve PMMA for device release, followed by a water substitution.

Using Approach 3 with acetone to dissolve the PMMA, we have demonstrated the four-panel device operation in water (See Extended Data Fig. 9a-b). In addition, we have demonstrated the manipulation of 6 μm diameter Polystyrene microbeads (Polybead 15714-5, Polysciences, Inc.) in a water environment in Extended Data Figure 9c-d and Supplementary Video 8.

We have also demonstrated the operation of the micromachines in air. For this, we have fabricated single panels with one end attached by a hinge spring connection to a fixed silicon nitride membrane frame. In this case, both the PMMA support layer and the device release in PGMEA are not required, and the device is free to be manipulated in a magnetic field immediately after the reactive ion etching process. As shown in Extended Data Fig. 10 and Supplementary Video 9, on increasing an applied out-of-plane magnetic field, the panels fold upwards or downwards depending on the programmed magnetization direction of the nanomagnet arrays on each panel.

It is worth noting that, even without suspension in a solvent, the micromachines will not collapse due to the gravitational force. For the four-panel micromachine shown in Fig. 1, the weight is the combined weight of the silicon nitride membrane and the nanomagnets, which is approximately given by $7.8 \times 10^{-13} \text{ N}$ (silicon nitride density, $\rho = 3.17 \text{ g/cm}^3$) + $6.6 \times 10^{-13} \text{ N}$ (cobalt density, $\rho = 8.9 \text{ g/cm}^3$) = $1.44 \times 10^{-12} \text{ N} = 1.44 \text{ pN}$. In comparison, the magnetic actuation force and the elastic force from the hinge springs (see “Hinge spring design, mechanical properties of a two-panel fold, and maximum force estimations” in Methods) is three orders of magnitude higher than the gravitational loads. Therefore the devices can be manipulated in air without structural collapse due to gravity.

Reference

31. O’Handley, R. C. *Modern Magnetic Materials: Principles and Applications*. (Wiley, 1999).
32. Timošenko, S. P. & Goodier, J. N. *Theory of elasticity*. (McGraw-Hill, 1961).
33. Steager, E. B. *et al.* Automated biomanipulation of single cells using magnetic microrobots. *Int. J. Rob. Res.* **32**, 346–359 (2013).
34. Huang, T. Y. *et al.* Cooperative manipulation and transport of microobjects using multiple helical microcarriers. *RSC Adv.* **4**, 26771–26776 (2014).
35. Luo, Z. *et al.* Chirally coupled nanomagnets. *Science* **363**, 1435–1439 (2019).
36. Linder, V., Gates, B. D., Ryan, D., Parviz, B. A. & Whitesides, G. M. Water-soluble sacrificial layers for surface micromachining. *Small* **1**, 730–736 (2005).

Extended Data Fig. 1|Scanning electron microscopy images of a four-panel micromachine. a, Overview. **b,** Enlarged image corresponding to the dashed box in **a** with arrays of 520 nm $\times$ 60 nm nanomagnets and 398 nm $\times$ 80 nm nanomagnets. Scale bars are 4 μ m in **a**, and 2 μ m in **b**.

Extended Data Fig. 2 | The geometric design and the switching behaviour of the nanomagnets. **a**, Schematic of a stadium-shaped nanomagnet with length, L , width, d , and thickness, t . **b**, Schematic of the layout of nanomagnetic arrays with vertical separation, s , and horizontal separation given by $d/2$. **c**, Relationship between d and L for nanomagnets with the same volume V_0 and thickness $t = 60$ nm. Six arrays of nanomagnets with the same volume but different aspect ratios are indicated on the curve. The colour of the points corresponds to colour of the hysteresis loops in Fig. 1c. **d**, Magneto-optical Kerr effect curves of the six types of nanomagnets in the field region where they switch (top panel) and the derivative with the switching region highlighted with shaded boxes (bottom panel). As the six switching regions do not overlap, all six nanomagnets can be individually programmed. **e**, SEM images of fabricated arrays of nanomagnets with lateral dimensions given in nanometres corresponding to those associated with the six highlighted points in **c**. Nanomagnets with lateral dimensions 520 nm $\times$ 60 nm (Type I), 398 nm $\times$ 80 nm (Type II), 358 nm $\times$ 90 nm (Type III) and 300 nm $\times$ 110 nm (Type IV) are used in this work. Scale bar is 1 μ m.

Extended Data Fig. 3 | Hinge spring design. **a**, Schematic of a single section of a spring. **b**, SEM image of a two-panel device with an 8-turn spring. **c**, Schematic of two-panel devices with 2-, 4-, 6-, and 8-turn spring designs. **d**, Schematic of two-panel device that folds when applying a controlling magnetic field. **e**, Optical microscope images of four fabricated devices with the different numbers of turns in the spring design on application of a 5 mT controlling field. Scale bar is 5 μm . **f**, Predicted panel rotating angle versus applied magnetic field based on theoretical calculations of the two-panel devices with different numbers of turns. **g**, Measured panel rotating angle versus applied magnetic field of the fabricated devices with different numbers of turns. Each data point corresponds to the average of three measurements of the angle using image analysis software with the error bar given by the standard deviation.

Extended Data Fig. 4 | Sixteen magnetization configurations of a four-panel micromachine and their corresponding shape transformation after applying a vertical controlling field. The four background colours highlight the family of four distinct conformations demonstrated in the Fig. 1c.

Extended Data Fig. 5 | Four conformations of a micromachine consisting of a 3×3 assembly of four-panel modular units. Shown in the middle and right panels are schematics and experimental demonstrations of the actuated micromachines. The units in a given micromachine all have the same conformation (left panel) corresponding to one of the 16 different magnetization configurations. Scale bars are $30\ \mu\text{m}$ in the optical microscope images.

Extended Data Fig. 7 | Possibilities for the total magnetic moments of the wing tip in the microscale bird. **a**, Scanning electron microscope image of the wing tip of the microscale bird. Light blue vertical bar, Type II nanomagnets (398 nm x 80 nm); dark blue horizontal bar, Type III nanomagnets (358 nm x 90 nm); purple bar (horizontal and vertical), Type IV nanomagnets (300 nm x 110 nm). Each of the arrays has the same number of magnets (1040) with the same magnetic moment m . Scale bar is 4 μm . **b**, Nine possible total magnetic moment magnitudes and directions. **c**, Schematics of sixteen possible magnetic configurations of the wing tip. Each of the arrays of different types of nanomagnets (Types II, III and IV) have different switching fields, and there are two out of the four arrays that have the same Type IV magnets but with orthogonal orientation. Therefore, with the orientation of the nanomagnets in two of the arrays along the x-direction and in the two other arrays along the y-direction, there are in total $2^2 \times 2^2 = 16$ possible magnetic configurations that can be encoded into the wing tip. **d**, Schematics showing the magnitudes and directions of the total magnetic moment of the wing tip, corresponding to the sixteen magnetic configurations shown in c.

Extended Data Fig. 8 | Schematic of the steps used to fabricate the micromachines. The nanomagnets are fabricated using electron beam lithography including patterning of a spin-coated polymer resist, thermal evaporation of a cobalt thin film and lift off. See Sample Fabrication in the Methods in the main manuscript for more details about the individual steps.

Extended Data Fig. 9|Optical microscope images of a four-panel micromachine, demonstrating operation in water and manipulation of $\approx 6\ \mu\text{m}$ diameter Polystyrene microbeads. The micromachine is released in acetone and then a water substitution is performed. The magnetization of all four panels points towards the centre. **a**, Micromachine in water without a magnetic field. **b**, The micromachine panels fold up in an applied out-of-plane magnetic field of 10 mT. **c and d**, On application of a rotating magnetic field (10 mT, 5 Hz), the micromachine rolls across the surface and the rolling motion generates a vortex in the water surrounding it (highlighted with blue arrows). Polystyrene microbeads of $6\ \mu\text{m}$ diameter (highlighted with red arrows) are trapped in the vortex and are transported to a new location. Two snapshots of the motion, separated by a time interval of 14 seconds, are shown. Scale bars are $40\ \mu\text{m}$.

Extended Data Fig. 10|Optical microscope images of single-panel micromachines that can be operated in air. The panels are $10\ \mu\text{m} \times 10\ \mu\text{m}$ in size and are connected to the silicon nitride membrane frame on the left side by hinge springs (2 turns). **a**, After fabrication, the panels are somewhat out-of-focus. This is because they are tilted above the plane of the in-focus silicon nitride frame, which may be due to the residual stress in the hinge springs. The white arrows indicate the magnetization direction of the single-panel micromachines pointing left (top row) and right (bottom row). **b and c**, When the applied out-of-plane magnetic field is increased to 35 mT, the panels with magnetization pointing to the left (top row) bend downwards, so that they are first sharper (**b**) and then become more out-of-focus until finally almost disappearing, with a tilt close to 90° at 35 mT (**c**). The panels with magnetization direction pointing to the right (bottom row) bend upwards in the applied magnetic field, becoming increasingly out-of-focus as the field increases, with a tilt close to 90° at 35 mT. Scale bar is $20\ \mu\text{m}$.