Programmable Magnetoelastic Energy Landscapes for Autonomous Microscopic Machines

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Primary CNF Tools Used: Oxford 81/82 etcher, YES EcoClean Asher, ASML DUV stepper, Gamma Automatic Coat-Develop Tool, JEOL 9500 EBL, SC 4500 odd-hour evaporator, AJA Sputter Deposition, Heidelberg DWL2000, PT770 ICP etcher (left side), Unaxis 770 Deep Silicon Etcher, Oxford FlexAL, Plasma-Therm Takachi HDP-CVD, Zeiss SEM, Veeco AFM.

Abstract:

The function of many microscopic machines is determined not only by their structure, but by conformational, dynamic changes in the shape of a device or molecule. Developing design paradigms for these microscopic machines requires the development of novel experimental platforms with controlled energy landscapes, and the ability to drive transitions between energy minima. Here, we introduce such a platform based on panels covered with programmable nanomagnetic domains, connected by flexible elastic hinges. We show that the combination of magnetic and elastic parameters gives rise to tunable energy minima, which can be accessed by applying an external magnetic field. Structuring the elastic or magnetic degrees of freedom of the device leads to the creation of multiple stable states, and as a first step we demonstrate a basic paradigm for three-state work cycles. We combine these principles to produce conformation-dependent locomotion via a magnetic walker with bistable energy landscape.

Research Summary:

The function of many biological and synthetic micromachines is realized by targeted conformational changes (1). Such functions include catalysis, sensing, force and torque generation creating concentration gradients, fluid pumping, light steering, and locomotion. However, the rational design of microscopic machines that undergo conformational change and transduce energy into mechanical work remains an outstanding goal. A key obstacle is the difficulty of modeling and designing the entire energy landscape of systems driven by electrostatic and chemical interactions, and furthermore to perform mechanical work by controllably actuating transitions between local energy minima (2).

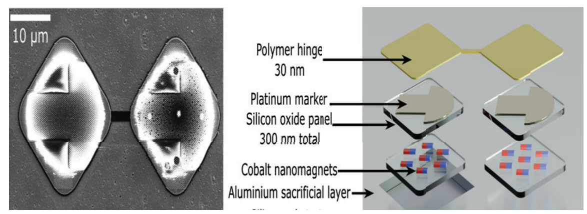

Figure 1: Scanning electron microscope image of the device, with schematic showing the device layer structure.

Here, we present a new experimental platform for programmable energy landscapes based on microscale magneto- elastic structures (Figure 1) (3,4,5). Competing elastic and magnetic interactions allow for the design and construction of energy landscapes with many potential minima, whose depth is controlled by device parameters. At the same time, transitions between these constructed energy minima can be actuated by applying directed torques in the form of external magnetic fields.

Combining magnetic and elastic design degrees-of-freedom allows for the construction of a two-state bistable shutter. Such a bistable shutter toggles between two states, here an “open" and a “closed" state, which can differentially control light transmission at the location of the free panel. In order to actuate transitions between local energy minima, we use an external magnetic field to apply a torque to the free panel. Once the panels are close enough, magnetic interactions between the panels stabilize the “closed state”. To re-access the “open” state, we apply an increasing magnetic field, so that the stable state of the system switches to being aligned with the external magnetic field (Figure 2). This two-panel, one elastic degree-of- freedom device thus provides a minimal example of a bistable energy landscape with controlled minima depth, with a single actuated transition between the two stable states.

In addition to controlling an on/off state, many

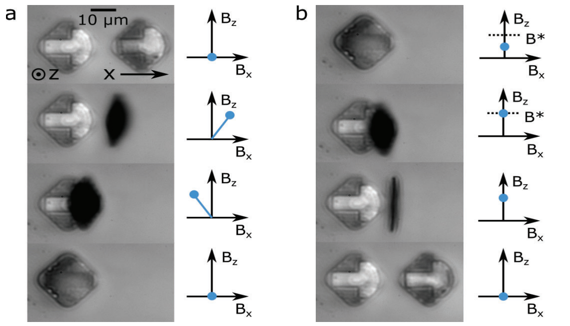

Figure 2: Using external magnetic fields to actuate a bistable shutter. (a) Sequence of images and accompany magnetic field magnitudes for closing a magnetic shutter. Magnetic interactions stabilize the closed position when the magnetic field is turned off. (b) Sequence of images showing the shutter re-opening upon the application of a finite magnetic field.

microscopic machines perform some work on the environment, such as pumping fluid, which requires a nonreciprocal cycle through configuration space. We construct such a nonreciprocal cycle by twisting the flexible elastic hinge to access a third stable state in the energy landscape (Figure 3). Each cycle of the machine pumps fluid in a rotational motion. This pumping is enabled by the difference in cross-sectional drag between the first and second steps of the work cycle, where the energy stored in the system by bending the hinge in-plane is released out-of-plane and transferred into rotational fluid flow.

The work generated (in the form of fluid flow) by this three-state device is realized by navigating between minima in an energy landscape. Such navigation requires a relatively complex control sequence in order to guide the free panel through the correct sequence of motions. In contrast, molecular motors convert a scalar energy input (ATP) to translate along a symmetry-broken direction. Similarly, we utilize a unidirectional magnetic field as our scalar energy input, and break the symmetry of the locomotion direction by bistability in the energy landscape of the magnetic device. In this case, devices operate within an energy landscape with multiple basins, where the initial condition of a device determines the basin about which it operates. The unidirectional magnetic field then serves as an energy source to drive work cycles within each basin, which translate to motion in opposite directions (Figure 4).

References:

[1] Alzgool, M., Tian, Y., Davaji, B., and Towfighian, S. (2023). Self-powered triboelectric MEMS accelerometer. Nano Energy, 109, 108282.

[2] M. Baroncini, L. Casimiro, C. De Vet, J. Groppi, S. Silvi, and A. Credi, Making and operating molecular machines: a multidisciplinary challenge, ChemistryOpen 7, 169 (2018).

[3] J. Cui, T.-Y. Huang, Z. Luo, P. Testa, H. Gu, X.-Z. Chen,B. J. Nelson, and L. J. Heyderman, Nanomagnetic encoding of shape-morphing micromachines, Nature 575, 164 (2019)

[4] C. L. Smart, T. G. Pearson, Z. Liang, M. X. Lim, M. I. Abdelrahman, F. Monticone, I. Cohen, and P. L. McEuen, Magnetically programmed diffractive robotics, Science 386, 1031 (2024).

[5] K. J. Dorsey, T. G. Pearson, E. Esposito, S. Russell, B. Bircan, Y. Han, M. Z. Miskin, D. A. Muller, I. Cohen, and P. L. McEuen, Atomic layer deposition for membranes, metamaterials, and mechanisms, Advanced Materials 31, 1901944 (2019).

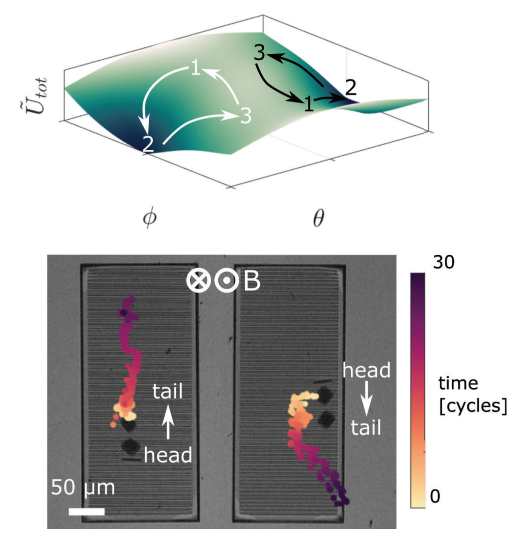

Figure 4: (a) Energy landscape with two minima, allowing for two independent work cycles, (b) Center-of-mass motion of two magnetic walkers with tails facing opposite directions, under the same magnetic actuation, with the time indicated by the shared color scale on the right.

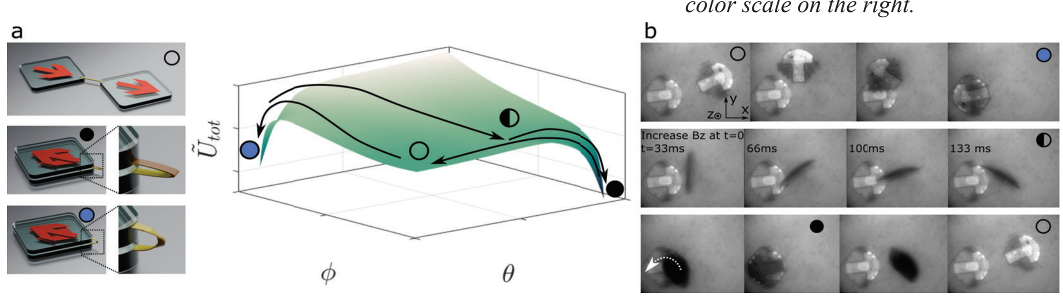

Figure 3: Creating a microfluidic rotary pump by navigating a multi-stable energy landscape. Diagram of the stable states of the system, together with the predicted energy landscape. (b) Series of optical microscope images showing a three-state work cycle, marked by symbols corresponding to the illustrations in (a).