Reprogrammable shape morphing of magnetic soft machines

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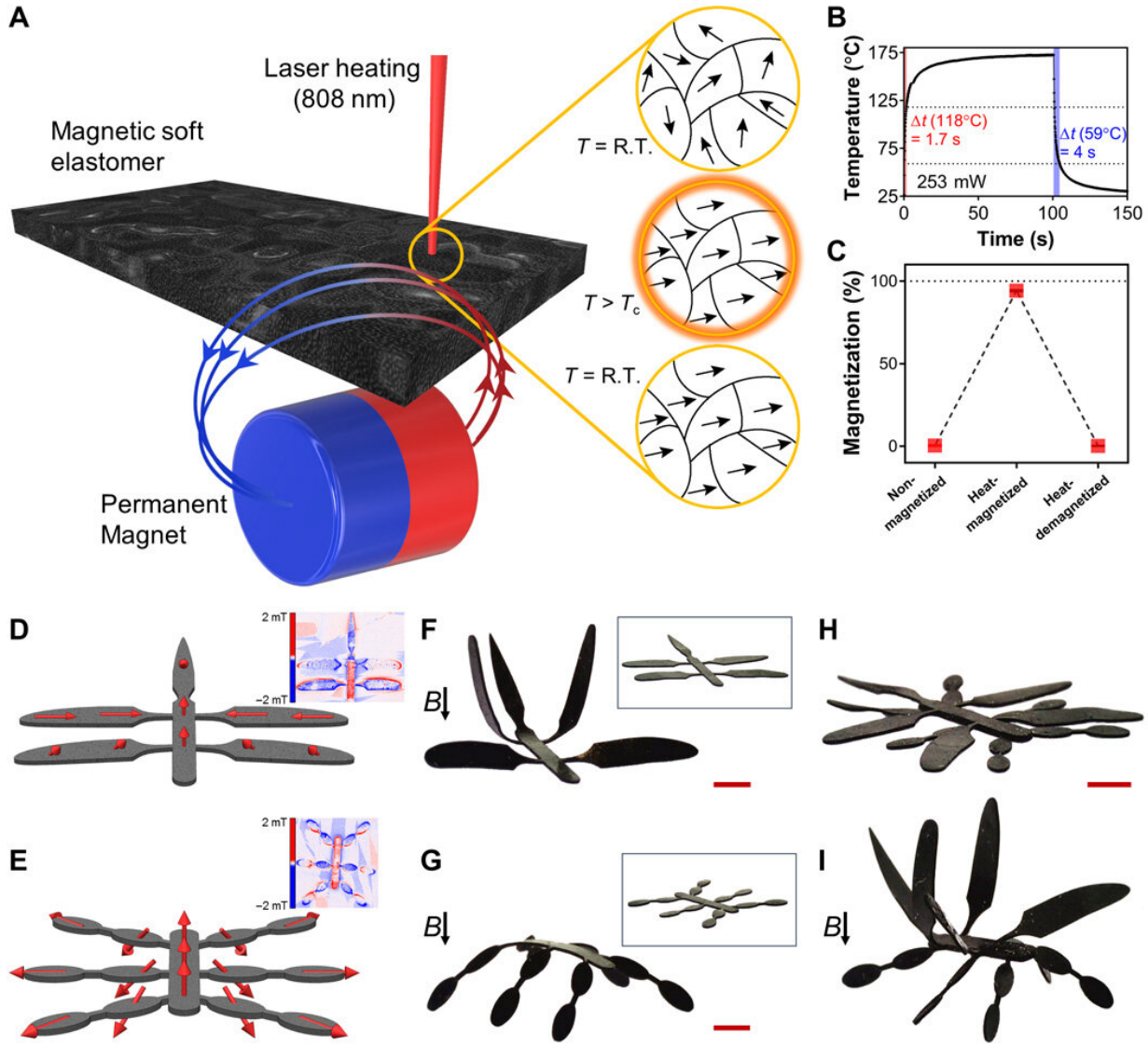


Heat-assisted 3D magnetic programming of magnetic soft machines. (A) A magnetic soft elastomer, composed of magnetic CrO2 particles embedded in

PDMS, is locally heated above the Curie temperature of the particles via a laser. Above the Curie temperature, the particles lose their permanent magnetization, and their magnetization direction is reoriented by applying an external magnetic field during cooling. R.T., room temperature. (B) The magnetic soft elastomer is heated above the Curie temperature of the CrO2 particles (118°C) in 1.7 s and cooled down to half of this temperature in 4 s. (C) The magnetic soft elastomer is magnetized with 90% efficiency by heat-assisted magnetization and demagnetized by only heating above the Curie temperature without any external magnetic field. Error bars represent the SD of the mean. (D to G) Examples of the magnetic soft elastomer cut into the shapes of a body with a tail and wings (D) and a six-legged body (E) with corresponding magnetization directions (indicated by red arrows) and out-of-plane magnetic flux profile measurements. Color bars indicate magnetic flux density strength. (F and G) Upon magnetic actuation, individual parts underwent shape change in accordance with their programmed magnetization directions. Scale bars, 2 mm. Insets show the initial shape of the structures in the absence of magnetic fields. (H and I) Bodies with wings and legs are stacked to generate a 3D hierarchical dragonfly structure upon magnetic actuation. Scale bar, 2 mm. Actuation of the structures is performed by applying magnetic fields of 60 mT in the directions indicated with the black arrows. Credit: Science Advances, doi: 10.1126/sciadv.abc6414

Shape-morphing magnetic soft machines have diverse applications in minimally invasive medicine, wearable devices and soft robotics. However, most magnetic programming approaches are inherently coupled to the fabrication processes, therefore they prevent reprogrammability of the machines. In a new report in *Science Advances*, Yunus Alapan and a multidisciplinary research team in Germany, Turkey, Switzerland and the U.S. described a high-throughput, magnetic programming strategy. To accomplish this, they heated magnetic soft materials containing embedded ferromagnetic particles above the Curie temperature of the embedded particles and reoriented their magnetic domains by applying external magnetic fields during cooling. The team demonstrated discrete, three-dimensional (3-D) and reprogrammable

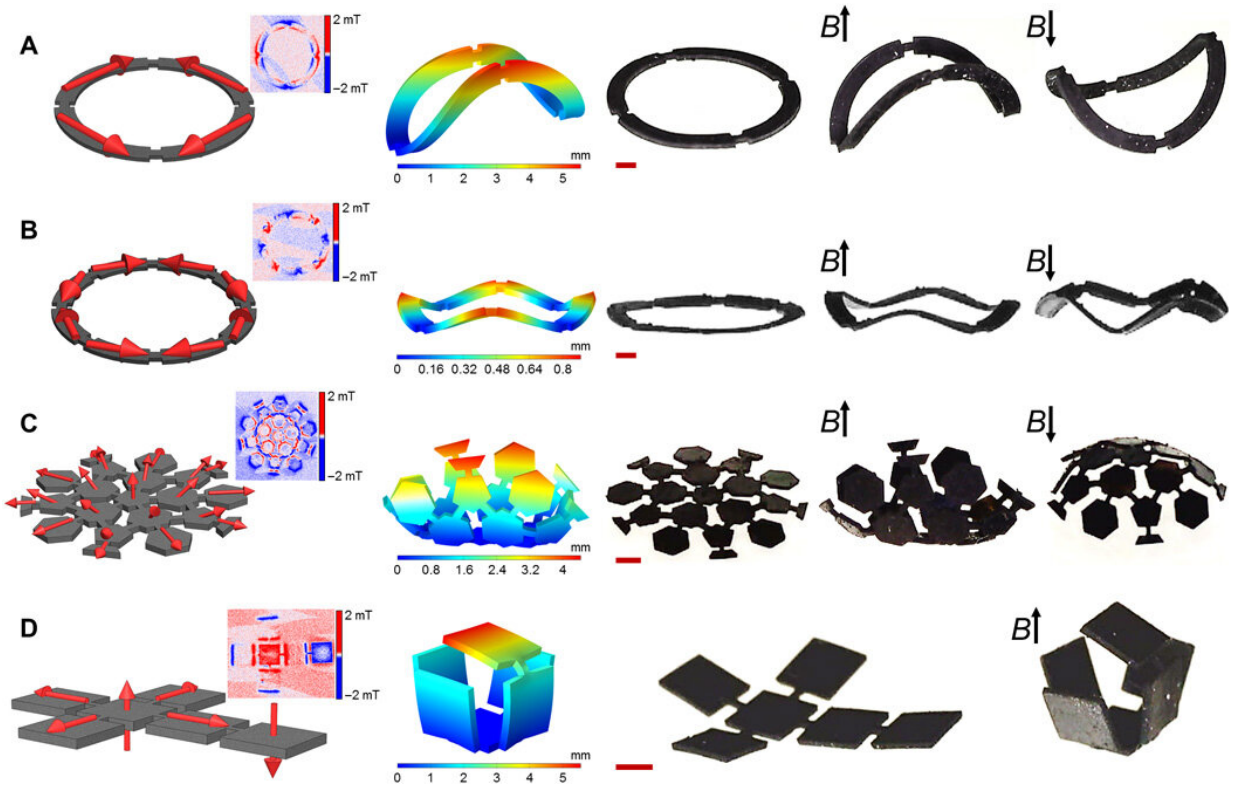
magnetization with high spatial resolution. Then, using the reprogrammable capacity, they configured the mechanical behavior of three objects—an auxetic metamaterial structure, tunable locomotion of a surface-walking robot and adaptive grasping of a soft gripper. The approach facilitated high-throughput magnetic programming to establish a rich design space and mass manufacturing potential to develop multiscale, reprogrammable soft robots.

Shape-morphing materials and developing magnetic soft machines

External stimuli including light, temperature, humidity, pH and acoustic or electromagnetic fields can control shape-morphing materials to form miniature microrobots for important futuristic applications across multidisciplinary research fields. Magnetically soft materials contain programmable shape deformation for fast, reversible and complex morphing. Applied magnetic fields can generate torque on magnetic soft materials to align the magnetization direction of all domains with the direction of the field. As a result, researchers can create spatial distribution of magnetization in a magnetic soft machine to develop programmable shape deformation under magnetic fields. In this work, Alapan et al. introduced a versatile strategy to encode programmable shape-morphing instructions into magnetic soft machines using chromium dioxide (CrO_2) nanoparticles embedded in polydimethylsiloxane (PDMS) elastomer.

Chromium dioxide is a ferromagnetic material with a Curie temperature of 118 degrees Celsius that allowed heat-assisted magnetic reprogramming within the functional temperature range of most elastomers. The team prepared the CrO_2/PDMS magnetic elastomer composite sheet to obtain a resulting magneto-elastic film and heated the material surface using a collimated near-infrared (NIR) laser with

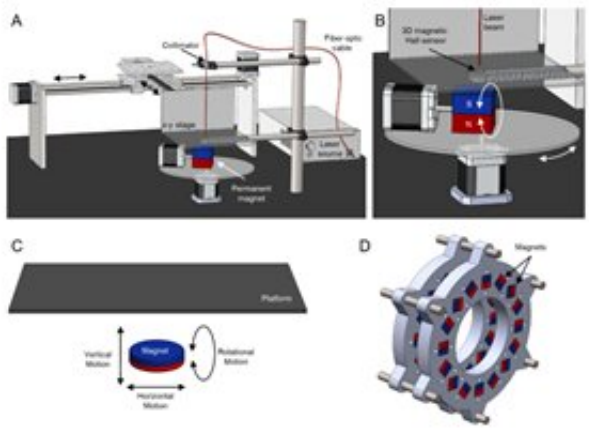
tunable power. The shortest heating-cooling cycle was 5.7 seconds under a 1.3 mm-diameter heated spot. The team could reverse the process and de-magnetize the material locally or fully by heating above the Curie temperature of CrO_2 particles in the absence of a magnetic field for non-invasive magnetic programming and reprogramming effects.



Discrete and 3D magnetization of magnetic soft structures. (A to D) Distributed 3D magnetizations, out-of-plane magnetic flux density profile measurements, finite element simulations, and experimental shape changes upon magnetic actuation of a four-segment ring (A), eight-segment ring (B), a half-sphere (C), and a cube structure (D). Scale bars, 1 mm. Actuation was performed by applying a magnetic field of 60 mT in the directions indicated with the black arrows. Credit: Science Advances, doi: 10.1126/sciadv.abc6414

Proof-of-Concept soft robots

As an experimental model, Alapan et al. developed a planar magnetic soft elastomer film in the shape of a six-legged body with wings and a tail, and discretely magnetized the structure by varying 3-D directions to form a 3-D "dragonfly" under magnetic control. The 3-D magnetic profiles could transform into complex 3-D forms under magnetic fields. Using a computational model, the team therefore produced complex 3-D shape transformations with designated profiles of magnetization. They then magnetically reprogrammed soft machines to optimize their multifunctionality. For example, the scientists developed a heat-assisted magnetization strategy to program soft structures on demand, and in this instance, they presented a "stick man" figure with a 3-D magnetization encoded body, shoulders, arms and head to undergo complex transformation under magnetic actuation. Alapan et al. also reprogrammed the magnetization profile of the stick man structure to reconfigure its head and arms. They then locally reprogrammed the internal material behavior to facilitate the design and optimization of advanced active metamaterials. The reprogramming technique allowed them to control individual units and the accompanying mechanical behavior. The scientists highlighted the importance of simple programming to demonstrate flexible robots. The examples highlighted the accurate use of remote and non-invasive reprogramming to optimize material behavior during the development of soft robots.

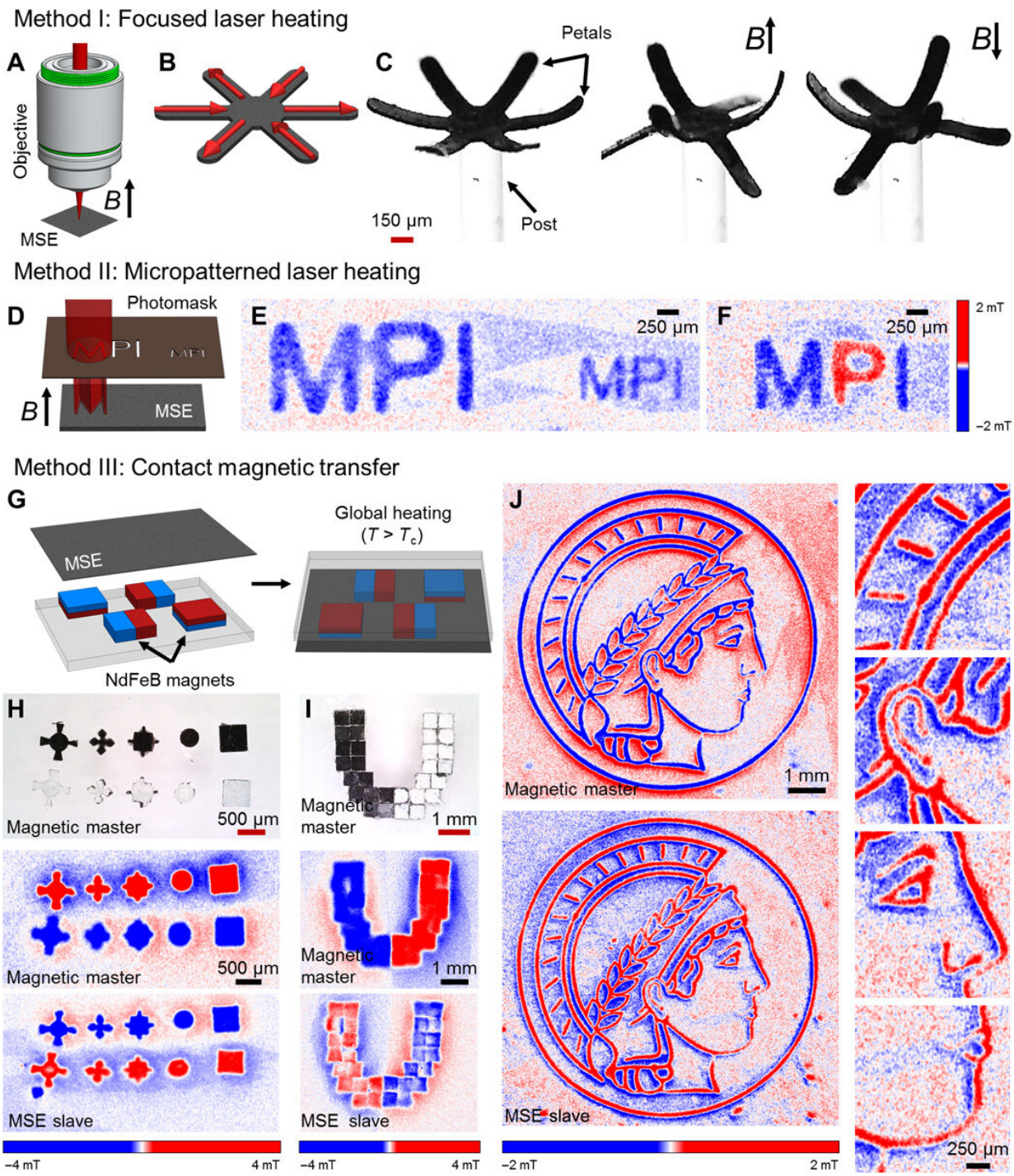


Heat-assisted magnetization and magnetic actuation setups. (A, B) Magnetization setup consists of a motorized stage, a NdFeB permanent magnet that can rotate in 360°, a 3D magnetic hall-effect sensor, and a power-adjustable fiber-coupled NIR laser with a collimator. (C) For magnetic actuation, a disc shaped magnet (60 mm diameter and 10 mm thick) was moved in vertical or horizontal directions or rotated underneath an actuation platform. (D) A Halbach array, composed of 16 permanent magnets (10 mm x10 mm x 10 mm) arranged as shown, was used for generation of the uniform magnetic field for magnetic actuation. Credit: Science Advances, doi: 10.1126/sciadv.abc6414

Microscale robotic applications

The foundation of microscale robots and machines developed in this work will have multiple applications that range from bioengineering to minimally invasive medicine. The magnetically programmed shape deformation can establish a new class of microsystems for advanced locomotion and control. Alapan et al. scaled down the heat-assisted magnetization approach to program microstructures by focusing the NIR laser beam size below 200 μm through a microscope objective. Using focused laser heating, they could magnetize a soft structure with six petals to generate synchronized petal deformation. Thereafter, they further programmed photomask-enabled micropatterned laser heating to

generate specific letters of interest. The team additionally realized magnetic programming by generating the desired magnetic pattern near the soft elastomers and heating the system for one-shot magnetization of the entire sample.



Heat-assisted magnetic programming of soft materials at the microscale. (A) Scanning a focused laser spot on a magnetic soft elastomer (MSE), which creates a precisely controlled local heating, in a desired pattern is used to program the magnetization profile on that material. (B and C) An example soft structure with six petals (150-μm width, 500-μm length, and 30-μm thickness) is placed on a micropost. Red arrows indicate the magnetization directions of the petals. Magnetic actuation (60 mT) resulted in deformation of petals in reverse directions. (D) A collimated laser can heat a desired shape on a target magnetic soft elastomer in one shot through a mask containing the micropattern of this desired shape. (E and F) Magnetic flux density measurements of example magnetically programmed samples by this micropatterned laser heating. The smallest magnetic pattern is 80 μm in width. Scale bars, 250 μm. (G) Contact transfer of desired magnetic profiles in one shot via global heating. The magnetic soft elastomer is placed in direct contact with NdFeB magnets, with a greater Curie temperature, arranged in different configurations and heated above the Curie temperature of the CrO2. Magnetization directions of the NdFeB magnets are transferred to the magnetic soft elastomer during cooling. (H and I) Magnetic flux density measurements of the NdFeB masters of different example shapes and configurations and the magnetic soft elastomer slaves. Scale bars, 500 μm and 1 mm, respectively. (J) Contact transfer of a complex magnetization profile in the geometric pattern of Minerva. Insets show closeup views of the magnetic flux density profile of the magnetic soft elastomer slave. The smallest magnetic pattern is 38 μm in width. Color bars indicate magnetic flux density strength. Scale bars, 1 mm and 250 μm, respectively. Credit: Science Advances, doi: 10.1126/sciadv.abc6414

In this way, Yunus Alapan and colleagues established heat-assisted programming to non-invasively program shape deformations at high spatial resolution. The team used discrete 3-D magnetization to develop a variety of magnetic soft machines from undulating swimmers and crawlers to multi-armed grippers. The scientists showed how the

behavior of 3-D magnetic metamaterials with programmed domains underwent complex shape changes under external magnetic fields. Since laser-based heating is not feasible for magnetic soft machine reprogramming in the human body, Alapan et al. aim to incorporate the 3-D magnetization approach for high throughput programming applications in minimally invasive medical applications. The scientists can also achieve remote and selective heating via remote power transfer on to receiver coils stationed on elastomers that constitute the soft robot. The new soft machines with reprogrammable complex shape transformations will benefit diverse applications from medical robots to wearable health monitoring devices and bioinspired microrobots.

Reprogrammable magnetization of flexible and 3D structures. Credit: Science Advances, doi: 10.1126/sciadv.abc6414

More information: Yunus Alapan et al. Reprogrammable shape morphing of magnetic soft machines, *Science Advances* (2020). DOI: 10.1126/sciadv.abc6414

Yoonho Kim et al. Ferromagnetic soft continuum robots, *Science Robotics* (2019). DOI: 10.1126/scirobotics.aax7329

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