High-throughput 2D-to-4D fabrication of magneto-origami machines

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Article

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Abstract

Magneto-active soft machines capable of magnetically controllable shape-morphing and locomotion have diverse promising applications such as untethered biomedical robots. However, existing magneto-active soft machines often show simple structures and limited deformation range. These technologies also suffer because mass production of the magneto-active machines is unavailable. Here, we propose a direct 2D-to-4D fabrication strategy that transforms 2D magnetic sheets into 3D magneto-active soft machines with customized geometries by incorporating origami folding. The method can be easily adapted to roll-to-roll processing. This approach enables a variety of unique characteristics of magneto-origami machines, including large-magnitude deploying, sequential folding into predesigned shapes and multivariant actuation modes (e.g., contraction, bending, rotation and rolling locomotion). We leverage these abilities to demonstrate a few potential applications: an electronic robot capable of on-demand deploying and wireless charging, a mechanical 8-3 encoder, and a quadruped robot for cargo-release tasks. Our work paves a way for the high-throughput fabrication of magneto-active soft machines with multi-functionalities.

Introduction

Soft active machines capable of shape morphing and locomotion in response to external stimuli (e.g., temperature, pH, light, magnetic and electrical fields) hold great promise in diverse fields such as miniature surgical devices, actuators, soft robots, and flexible electronics. Among others, magnetic actuation has been widely adopted due to its untethered control, fast response, and large penetration range. Despite various strategies for fabricating magneto-active soft machines have been proposed (e.g., laser programming, 2D template molding, extrusion- and ultraviolet (UV) lithography-based 3D printing, existing fabrication methods suffer from limitations of the time-consuming process, low structural complexity, and limited shape-morphing capability (Table S1). For example, the laser programming method usually requires a relatively long time to encode magnetic polarity patterns in a large area. The extrusion-based approaches fail to construct complex structures due to the viscosity and the die swell of the magnetic composite ink. Therefore, mass and fast fabrication of magneto-active machines with customized architectures and advanced functionality is of great significance, yet remains an unresolved challenge.

Due to the excellent customizability, origami has been widely employed to construct three-dimensional (3D) structures. By harnessing the predesigned plastic folding, origami transforms a planar sheet into a 3D architecture, imparting the intrinsic shape-morphing capability with ease. Notably, origami is capable of complex folding and a large degree of recovery, manifesting superior shape programmability and shape-morphing capability. When integrating with stimuli-responsive property, origami structures have shown great potential in developing functional and autonomous systems, which offers a new window for designing magneto-active soft machines.
Here, we propose an origami-based 4D fabrication strategy that can fast construct 3D magneto-active soft machines by directly folding the 2D magnetic sheet (Fig. 1). The magnetization of the 2D sheet is enabled by coating a layer of magnetic composite (i.e., dispersing magnetic microparticles in the polymer matrix) on a piece of raw paper. The magnetic polarity patterns of 3D magneto-active machines can be readily programmed by magnetizing the folded 3D origami. When subjected to an actuation magnetic field, the magneto-origami machine can achieve on-demand shape morphing. We demonstrate a set of magneto-origami machines that can fold, bend, roll and walk with potential applications of deployment, object manipulation, and locomotion. Our approach allows for the high-throughput fabrication of magneto-active machines, paving the way to a variety of fielded applications in the future.

Results And Discussion

High-throughput 2D-to-4D fabrication of magneto-origami machines. The 2D magnetic sheet is prepared by coating and curing a layer of magnetic composite on a piece of raw paper (Fig. 1a, Fig. S1). The magnetic composite is made by uniformly dispersing NdFeB particles (average diameter ~30 μm) in the polymer resin (i.e., Ecoflex 00-10, Smooth-On) with a particle volume fraction of 25%. The designed 2D pattern is cut by a laser machine with uncut connections (Fig. S2) that allows for an easy tear off the sheet (Movie S1). Next, the torn pattern is folded into a desired 3D origami (Fig. 1b). Note that the folded origami has zero net magnetization owing to the random orientation of magnetic particles. To endow the magnetic response, the folded origami was then magnetized to saturation by an impulse magnetic field (H~ 3T), yielding a residual magnetization m with a strength of 170 kA m\(^{-1}\) due to the hard-magnetic nature of NdFeB particles (Fig. S3). Thereafter, the magnetizing field and folding forces are removed and the folded origami recovers partially to the rest state to form the magneto-origami machine. To avoid excessive recovery that impairs the construction of the magneto-origami machine, the thickness of the magnetic composite layer and the paper is selected as 100 μm and 90 μm, respectively (Fig. S4). When subjected to an actuation magnetic field, the magneto-origami machine is capable of controllable deformation and locomotion. This direct 2D-to-4D fabrication strategy allows for constructing magneto-origami machines by a roll-to-roll process (Fig. 1c).

To elucidate the magnetically controllable shape-morphing mechanism, a single-fold magneto-origami machine was constructed using the direct 2D-to-4D fabrication method. Here, we adopt a cuboid NdFeB magnet (dimension: 50 mm×25 mm×20 mm) as the magnetic actuation source (Fig. S5). By varying the distance between the magnet and the magneto-origami machine, the magnetic flux density B and its gradient \( \nabla B \) around the magneto-origami machine can be effectively tuned. Hence, the driving force, \( i.e., \) the magnetic torque \( T_m = m \times B \) and body force \( b_m = (\nabla B)m \) can be controlled to fold the magneto-origami machine to different degrees (fig. S6). When B reaches about 200 mT, the magneto-origami machine is completely folded. Upon removal of the actuation field, the magneto-origami machine rapidly recovers the rest state. This reversible folding and unfolding process is shown in Movie S2. Notably, our magneto-origami machine exhibits remarkable repeatability. In a cyclic test under a 200-mT magnetic
field, the magneto-origami machine shows negligible performance degradation after 1000 cycles of folding and unfolding (Fig. S7).

Next, we show folding the 2D sheet into a complex Miura origami in Fig. 1d. The folded Miura origami is then magnetized to be a Miura magneto-origami with complex magnetic polarity patterns (Fig. 1e). The Miura magneto-origami also exhibits magnetically controllable shape-morphing capability with excellent repeatability (Movie S1). This demonstration evidences that the direct 2D-to-4D fabrication method can construct complex magneto-origami machines with programmed magnetic polarity patterns that enable controllable shape-morphing with potential functionalities under magnetic actuation.

**Self-folding/unfolding of deployable magneto-origami machines.** By changing the size from folded to unfolding state or vice versa, deployable structures show great promise in applications such as medical devices (e.g., vascular stent) and solar panels for spacecraft. Here we present three deployable magneto-origami machines that can morph to different configurations by applying a magnetic field ($B \sim 200 \text{ mT}$) in Fig. 2 and Movie S3. First, a magneto-origami flower is constructed as shown in Fig. 2a. Upon application of the actuation field, the magneto-origami flower rapidly blossoms from the bud state. When the actuation field is removed, the open flower partially recovers. The opening and closing of the petals by tuning the magnetic field make it a potential candidate as a robotic gripper. Next, a deployable magneto-origami starshade is developed in reminiscence of the starshade that blocks the glare of stars for the space telescopes (Fig. 2b). Under the magnetic actuation, the magneto-origami starshade gradually expands while rotating around its center (shown by the red marker at the margin in Fig. 2b). After 7.5 s, the magneto-origami starshade quickly unfurls to a nearly flat sheet evidenced by the steep increase of its diagonal length $d$ (Fig. 2c). The entire unfolding process completes in a short time of 8 s, producing a twice area change of the magneto-origami starshade. We then present a square-twist origami machine with fourfold rotational symmetry in both structure and magnetic polarity patterns in Fig. 2d. The square-twist origami machine consists of alternating square and rhombus facets with tailored mountain and valley folds. Upon magnetic actuation, the square-twist origami machine first twists and folds slowly. Similar to the rapid expansion of the starshade in Fig. 2b, the square-twist machine also suddenly snaps into a self-locked state at 7.5 s. The diagonal length $\delta$ of the machine drops abruptly during the snap transition (Fig. 2e). Notably, the self-locked state is stable, suggesting that the machine can fix such a state even after the removal of actuating field.

**Sequential self-folding/unfolding of deployable magneto-origami machines.** The programmable sequence plays a key role in the self-assembly of 3D complex structures. Here, we present three tailored magneto-origami strips with sequential self-folding/unfolding ability via manipulating the actuation magnetic field. The 2D magnetic strip can be sequentially folded into a lamellar (Fig. 3a), triangle (Fig. 3b), and rectangle (Fig. 3c) origami, respectively. After being magnetized, they are imparted with alternating magnetization patterns. Different from the actuation mode in Fig. 2 where the magnet is placed at a fixed position during the entire deployment process, we move and rotate the magnet to realize the sequential folding and unfolding of the magneto-origami strips (Movie S4). Note that such a sequential folding and unfolding is fully reversible by manipulating the magnet in the reverse direction.
Taking the advantage of the sequential folding, we can encode different magnetization patterns into the magneto-origami strip. Here we demonstrate folding the magneto-origami strips into letters “b”, “m”, and “e” in Fig. 3d. The corresponding origami and magnetization pattern of each magneto-origami strip is shown on the right panel. The sequential folding and unfolding process is given in Movie S4.

The magneto-origami spring actuator. Tuning the position and orientation of the cuboid magnet, magneto-origami machines can be actuated in different modes. Here, we present a magneto-origami spring actuator with diverse actuation modes in Fig. 4 and Movie S5. First, the spring actuator can contract when the magnet is placed in its axial direction (Fig. 4a). Moving the magnet toward the spring actuator, i.e., increasing the magnetic field strength, the spring actuator undergoes a contraction ratio (defined by \((L_0 - L) / L_0\)) up to 50% as shown in Fig. 4b. Upon removal of the magnet, it recovers the normal length \(L_0\). Driven by the fast response of magnetic composite, the contraction and recovery process are realized within 0.3 and 0.25 s, respectively. Also, despite the multifold fabrication (Fig. S8), this spring actuator shows remarkable repeatability by remaining 93% of its original length after 1000 cycles of actuation (Fig. 4c). Second, rotating the magnet around the spring actuator changes the magnetic field direction, yielding the bending configuration of the spring actuator as shown in Fig. 4d. The bending angle can be precisely controlled up to 180° by manipulating the magnet orientation. Third, the bent spring actuator can further realize 360° rotation around its fixed end when rotating the magnet surrounding the actuator, as shown in Fig. 4e.

Last but not the least, the spring actuator can achieve rolling locomotion actuated by a rolling magnet. We demonstrate such rolling locomotion by navigating the spring actuator through several obstructions including stairs, obstacle, narrow path, and groove in Fig. 4f (Movie S5). By rotating the magnet, the spring actuator can climb stairs and step over a 10-mm height obstacle easily. Next, by moving the magnet closer, the spring actuator is contracted from 18 mm to 11 mm, followed by a quick transit through a narrow path with a height of 12 mm. Thereafter, it recovers to its normal length and successfully crosses a groove with a width of 10 mm. Due to the excellent ability of shape-morphing and rolling locomotion, the spring actuator accomplished those complex tasks under untethered magnetic actuation in an enclosed environment around 30 s. Above all, the diverse transformation and locomotion behaviors of the magneto-origami spring actuator can be precisely regulated through the control of the external magnetic field \(B\), showing promising applications in adaptive soft robots and multivariant actuators.

Magneto-origami electronic robot (ME-robot). Towards potential medical applications, we develop a deployable magneto-origami electronic robot (ME-robot) with remotely controlled locomotion and wireless charging capability (Fig. 5a-c and Movie S6). On the paper side of the 2D sheet, the ME-robot consists of an electronic circuit that can be wirelessly charged by the alternating magnetic field (Fig. S9). The ME-robot can be folded into a cuboid-like structure with dimensions of 16 mm×16 mm×10 mm (Fig. 5a). We demonstrate the potential application of the ME-robot in performing electrical stimulation therapy in a pig stomach phantom. By vibrating the magnet at a frequency of 40 Hz, the ME-robot can navigate
across the uneven surfaces of the stomach phantom at a speed of ~1 mm/s. When it reaches the target area, on-demand unfolding is performed by moving the magnet closer to the ME-robot. Thereafter, an alternative magnetic field is applied to generate an electric current, producing a stable voltage of 3.3 V that lights two LEDs (Fig. 5c).

**Magneto-origami 8-3 encoder.** Analogous to digital devices, magnetic soft robots can also be programmed as mechanical encoders. Utilizing the bending and rotation configurations of the spring actuator in Fig. 4, we present a magneto-origami 8-3 mechanical encoder in Fig. 5d-f. The logical circuit design of 8-3 encoder is illustrated in Fig. 5d where Y0-Y7 represents 8 input channels and the on/off state of 3 LED indicates the output A0-A2 of the encoder. The electronic circuit design of the 8-3 encoder is shown in Fig. S10 and the truth table of the encoder is given in Fig. 5e. To endow the conductivity of the encoder, the spring actuator is coated with a thin layer of gold. Initially, one end of the magneto-origami spring actuator is fixed at the center and connected with the positive pole of the power supply. Upon application of the magnetic field, the spring actuator bends and touches one input of Y0~Y7, turning on/off the corresponding LEDs. Four representative modes are shown in shown Fig. 5f and Movie S7. For example, when the spring actuator contacts with Y0, all LEDs are turned off (i.e., A0=A1=A2=0); when the spring actuator contacts with Y3, LED0, and LED1 are turned on while LED2 is off (i.e., A0=A1=1, A2=0).

**Magneto-origami quadruped robot.** Combining the deployable flower gripper and the spring actuator (Fig. 4), we develop a magneto-origami quadruped robot that can execute cargo-release tasks (Fig. 5g and Movie S8). Four spring actuators are equipped as the legs of the robot for transportation during which the gripper can firmly grasp the cargo. The transportation of the cargo is enabled by actuating the two legs in the front. First, the frontal legs bend forward by moving the magnet forward. Then, manipulating the magnet a little bit away will cause the bent frontal legs to drag the robot forward. In a gait circle, the robot can stride with a displacement of 2 mm in less than 2 s (Fig. 5h). By repeating such a gait circle, the quadruped robot can walk forward step by step rapidly. When it reaches the destination, the magnet is moved closer to the flower gripper to open the petal such that the cargo is released on time. The demonstration of the quadruped robot manifests that by combining different magneto-origami, we can construct magnet soft robots with advanced functionalities for complex tasks.

**Discussion**

Directly folding a magnetic sheet into an origami structure is a simple fabrication method for magneto-active soft machines with customizable geometry and functionality. Upon magnetic actuation, the magneto-origami machines can rapidly change their morphologies and execute locomotion tasks on demand, e.g., large deploying, self-locked folding, and sequential folding into predesigned shapes. Since the transformation relies on the origami technique that has been widely explored in history, magneto-origami machines can achieve high structural complexity either by directly folding or assembling origami unit cells. In addition, the large degree of freedom in controlling the magnetic field allows for various actuation modes of the magneto-origami machines to accomplish different tasks. The deployable
magneto-oragami electronic robot can unfurl by 12 times of its folded area and translate alternating magnetic field into direct current at the target destination, which can be used for electrical stimulation therapy in minimally invasive surgery. Owing to the multivariant motions of magneto-oragami spring, the magneto-oragami encoder can translate eight inputs into three binary outputs. Last but not the least, the quadruped robot can carry the cargo steadily and perform on-demand release rapidly. The direct 2D-to-4D origami-enabled strategy allows fabrication of magneto-active soft machines in a simple, fast, and high-throughput manner, showing potential applications in sensors, actuators, soft robotic, active metamaterials, and collapsible spacecraft modules.

**Materials And Methods**

**Preparation of magnetic sheet.** An ink was firstly prepared by mixing Ecoflex 00–10 with NdFeB microparticles (average diameter: 30 µm) at a mass ratio of 1:2. Subsequently, the magnetic composite ink was uniformly coated on a commercial A4 paper (thickness: 90 µm). The prepared samples were cured in an oven at 80°C for 60 min. Finally, a bilayer magnetic paper was fabricated.

**Magnetor-origami machines.** The patterns were designed using SolidWorks (Version 2016, Dassault Systems, France) and engraved via a laser cutter. The pattern was manually folded into the predesigned shape and subsequently magnetized by an impulse magnetic field (3T) using a magnetizer (MA-2030, Shenzhen JiuJu Company, China). The magnetic paper for origami spring was coated with conductive Au film by radiofrequency magnetron sputtering deposition (VTC300, Shenyang Micro Technology Co., Ltd, China). The ME-robot was fabricated by transferring a layer of copper wire on the magnetic sheet. The copper wire was obtained by laser cutting a copper layer (thickness ~ 50 µm) and removing the needless part. The electronic components (rectifier, capacitance, voltage stabilizer) and the copper wire were joined by soldering.

**Characterization.** The surface topography of dual-layer magnetic paper was observed using an industrial digital camera (CM2000, KUY NICE, China). The magnetic flux density of magneto-origami was measured by a gauss meter (Shanghai Daxue Electromagnetic Equipment Co., Ltd., China). The contractions strain and folding angle of magneto-origami actuators was characterized by analyzing the Movies recorded by a digital camera (EOS 5D, Canon, Japan) using Image J. The magnetic hysteresis loop of bilayer matter was obtained using a vibrating sample magnetometer (VSM, Lake Shore 7410, USA).

**Manipulation.** The spatially varying magnetic actuating field was generated by a NdFeB permanent magnet (N42, 50mm×25mm×25 mm, Beijing Zhongke Sanhuan High Technology Co., Ltd., China) for manipulation of magneto-origami machines. Dynamical transformations of magneto-origami machines were realized by the combination of vertical, horizontal, and rotational movements of the magnet. The magnetic field can be tuned via the distance between magneto-origami machines and the magnets.

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Declarations

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Figures
Figure 1

Direct 2D-to-4D programming of magneto-origami machines. (a) Preparation of 2D magnetic sheet by depositing and curing magnetic composite (thickness ~100 μm) on the raw paper (thickness ~90 μm). The designed pattern was cut by a laser machine and torn off from the sheet. (b) Schematic illustration of folding the 2D magnetic sheet, imparting magnetization by applying a strong impulse magnetic field, partial recovery to the rest state, and actuating by applied magnetic fields. (c) Experimental pictures of a roll of the magnetic sheet that allows for the mass fabrication of 2D patterns by a roll-to-roll process. (d) Example of folding Miura origami structure from the 2D magnetic sheet in which red solid lines represent the mountain folds while black dashed lines denote valley folds. The insert shows the finalized Miura origami structure. (e) Demonstrations of shape morphing of the Miura magneto-origami by tuning the magnetic field. Left panel: schematic of the magnetic polarity pattern (i.e., magnetization direction) and origami folds. Right panel: corresponding experimental pictures.
Figure 2

Self-folding/unfolding of deployable magneto-origami machines. (a) The origami pattern and the unfolding process of magneto-origami flower under a magnetic field $B \sim 200$ mT. The blue sign indicates the magnetization of the machine is pointing outward. (b) The origami pattern and the deploying process of the starshade machine under magnetic actuation. The red marker indicates the movement of a marginal point during the deployment process. (c) The diagonal length $d$ of the magneto-origami starshade during the deployment process. (d) Twisting and folding process of the square-twist origami machine under magnetic actuation. (e) Diagonal length $\delta$ of the square-twist machine during the folding process. Magneto-origami machines in both (b) and (d) show a snap transition after being actuated for 7.5 s.
Figure 3

Sequential folding and unfolding of the magneto-strips. (a-c) The schematic illustrations and experimental demonstrations of magneto-origami strips programmed with alternating magnetic polarity patterns. The magneto-origami strips can be sequentially folded into predesigned 3D shapes: (a) lamellar, (b) triangular, and (c) square, by moving and rotating the permanent magnet. (d) Experimental demonstrations of sequential folding of magneto-origami strips into letters “b”, “m”, and “e”. Corresponding origami and magnetic polarity pattern are shown on the right panel.
Figure 4

Different actuation modes of a magneto-origami spring actuator. (a) The spring actuator can contract when the magnet is placed in its axial direction. (b) The contraction ratio \( \frac{L_0 - L}{L_0} \) of the spring actuator plotted as a function of magnetic field strength up to 220 mT. (c) The spring actuator remains 93\% of the original length \( L_0 \) after a 1000-cycle actuation (B \( \sim \) 220 mT). (d) Bending behaviors of the spring actuator. Panels show bending angles are 0°, 45°, 90°, 180°, respectively. (e) The 360° rotation behavior of a bent spring actuator by rotating the magnet surrounding the actuator. The yellow arrow represents the rotation direction of the rotating magnet. (f) Experimental demonstration of the rolling locomotion of the spring actuator by passing through several obstructions including stairs, obstacle, narrow path, and groove. The height of the stair, obstacle, and narrow path is 10 mm, 10 mm, and 12 mm, respectively. The width of the groove is 10 mm.
Figure 5

Demonstrations of applications of magneto-origami machines. (a) The optical image of the folded magneto-origami electronic robot (ME-robot). Insert: the origami pattern of the ME-robot. (b) The locomotion and on-demand deployment of the E-robot in a pig stomach phantom by vibrating the magnet at the frequency of 40 Hz. (c) The deployed ME-robot can be remotely charged by the alternating magnetic field. (d) The logical circuit design of mechanical 8-3 encoder where Y0~Y7 represent the input channel and A0~A2 denote the output. (e) The truth table for the magneto-origami mechanical encoder. (f) Representative examples of the 8-3 mechanical encoder under different inputs. The red square in the circular inset represents the position of the magnet. (g) Dynamic locomotion and on-demand cargo release of the magneto-origami quadruped robot. (h) The bending angle (black line) and transportation displacement of the frontal legs (red line) in two gaits.

Supplementary Files
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- MovieS3.mp4
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