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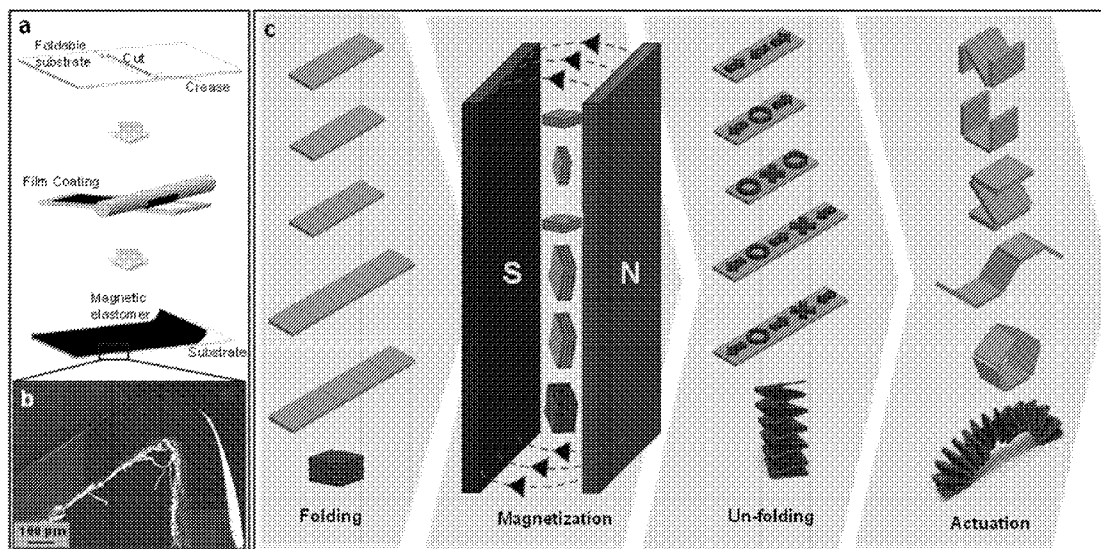


Figure 14

(57) Abstract: An actuator for a robotic system, a robotic system incorporating the actuator, a method of fabricating an actuator for a robotic system, and the use of the actuator in a robotic system. The actuator comprises a substrate layer, and an elastic layer on the substrate layer, the elastic layer comprising a first material with non-zero coercivity embedded in a second material; wherein the substrate layer exhibits anisotropic mechanical properties to promote preferential mechanical deformation of the substrate layer and the elastic layer during actuation of the actuator under an actuation electromagnetic field based on the interaction of the actuation electromagnetic field and the first material.



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AN ACTUATOR FOR A ROBOTIC SYSTEM AND A METHOD OF FABRICATING THE SAME

FIELD OF INVENTION

- 5 The present invention relates broadly to actuators for robotic systems, which incorporate the actuators, methods of fabricating actuators, and the use of the actuators in robotic systems, in particular to origami-inspired soft robots with magnetic domain programming.

BACKGROUND

- 10 Any mention and/or discussion of the prior art throughout the specification should not be considered, in any way, as an admission that this prior art is well known or forms part of common general knowledge in the field.

- “Soft robots” are made from soft, elastic materials and offer unique opportunities in areas in which conventional rigid robots are not viable; for example, for drug delivery, non-invasive
15 surgical procedures, as assistive devices, prostheses, or artificial organs [1] [2]. Magnetic actuation has advantages of no contact and precise control [3]-[10], which is especially suitable for the biomedical field.

- The conventional mold approach for the fabrication of soft robots will be described in more detail. The general production process of molds is shown in Figure 1. Figure 1(a) shows a
20 photograph of an example 3D printer for use in manufacturing molds. Mold fabrication is an essential step in the conventional mold approach for soft robots. On the one hand, by using 3D printing technology, the molds can be manufactured based on the designed size and structure of the robot, with 3D printing being capable of creating complex structures. However, the accuracy of a 3D printer is limited, and issues with an overhang can complicate the mold
25 production. When designing molds, one must ensure that the liquid material, prepared with magnetic particles suspended therein as illustrated in Figure 1(b), can be easily poured into the mold and retain the required shape. Notably, referring to Figure 1(c), (i) typically a first mold is used to cast a film of a hexapede as an example of a soft robot actuator. During magnetization, a second mold (ii) is used to rotate the legs of the hexapede into the correct
30 position, as illustrated in Figure 1(c). The inventors have recognized that the requirement of designing multiple molds the manufacture of soft robots more complex, and any changes to the design require customizations to the molds rendering the molding approach to the fabrication of soft robots time and cost-intensive.

Embodiments of the present invention seek to address at least one of the above problems.

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SUMMARY

In accordance with a first aspect of the present invention, there is provided an actuator for a robotic system, the actuator comprising:

a substrate layer; and

- 5 an elastic layer on the substrate layer, the elastic layer comprising a first material with non-zero coercivity embedded in a second material;

wherein the substrate layer exhibits anisotropic mechanical properties to promote preferential mechanical deformation of the substrate layer and the elastic layer during actuation of the actuator under an actuation electromagnetic field based on the interaction of the actuation

- 10 In accordance with a second aspect of the present invention, there is provided a robotic system comprising the actuator of the first aspect.

In accordance with a third aspect of the present invention, there is provided a method of fabricating an actuator for a robotic system, the method comprising the steps of:

providing a substrate layer;

- 15 providing an elastic layer on the substrate layer, the elastic layer comprising a first material with non-zero coercivity embedded in a second material; and

imparting anisotropic mechanical properties to the substrate layer to promote preferential mechanical deformation of the substrate layer and the elastic layer during actuation of the actuator under an actuation electromagnetic field based on the interaction of the actuation
20 electromagnetic field and the first material.

In accordance with a fourth aspect, there is provided an actuator fabricated by the method of the third aspect.

In accordance with a fifth aspect of the present invention, there is provided use of the actuator of the first aspect in robotic activation.

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BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

- 30 Figures 1(a) to (e) schematically illustrate a conventional production process for mold cast silicone magnetic robot.

Figures 2(a) to (f) show schematic drawings illustrating a fabrication process of an actuator for a robotic system, according to an example embodiment.

Figures 3(a) and (b) show schematic drawings illustrating development of a flat film actuator into a letter N shape, according to an example embodiment.

Figures 4(a) to (c) show schematic drawings illustrating configuration of an actuator for magnetization in a reduced volume configuration, according to an example embodiment.

- 5 Figures 5(a) to (c) show schematic drawings illustrating configuration of an actuator for magnetization in a reduced volume configuration, according to an example embodiment.

Figures 6(a) to (f) show photographs illustrating a fabrication process of an actuator for a robotic system, according to an example embodiment.

- 10 Figures 7(a) and (b) show schematic drawings illustrating mapping a complex pattern for an actuator for a robotic system into a unit cube for magnetization, according to an example embodiment.

Figures 7(c) to (f) show photographs illustrating an origami-inspired parallel manipulator which can have multiple stable states due to the folding interactions of vertexes, according to an example embodiment.

- 15 Figure 8 shows a graph showing the magnetization curves of three sample materials for use in an actuator according to an example embodiment.

Figure 9 shows a flow diagram illustrating a control mechanism for use with an actuator according to an example embodiment. The inset shows a photograph of electromagnetic workspace for use with an actuator according to an example embodiment.

- 20 Figures 10(a) to (c) show schematic drawings illustrating self-folding of differently programmed actuators according to example embodiments.

Figures 11(a) to (e) show schematic drawings illustrating locomotion activation of a programmed actuator according to an example embodiment.

- 25 Figures 12(a) to (c) show schematic drawings illustrating grasping and locomotion of a programmed actuator according to an example embodiment.

Figures 13(a) to (d) show photographs illustrating grab action of a programmed prototype actuator according to an example embodiment.

Figures 14(a) to (c) illustrate the approach to programming magnetic origami-inspired actuators according to example embodiments.

- 30 Figures 15 (a) to (h) illustrate the permutations of origami-inspired design according to various embodiments.

Figures 16(a) to (g) illustrate magnetic origami-inspired actuators structures moving with a wave motion according to various example embodiments.

Figures 17(a) to (g) illustrate four limb magnetic origami-inspired actuator structures according to example embodiments.

Figures 18(a) to (c) illustrate parallel magnetic origami-inspired actuators (bi-stable Sarrus linkages, twisted tower) according to example embodiments.

- 5 Figures 19 (a) to (f) illustrate a foldable graphene oxide templated platinum-based actuator according to an example embodiment.

Figures 20(a) to (i) illustrate the mass fabrication of versatile actuators or robots according to example embodiments.

- 10 Figures 21(a) to (f) illustrate a magnetic origami-inspired slinky according to an example embodiment.

Figures 22(a) to (d) show a magnetic remote-center-of-motion actuator according to an example embodiment.

Figures 23(a) to (f) illustrate paper backbone (or substrate) and force transmission.

- 15 Figures 24(a) to (f) illustrate re-programmable magnetic domain folding according to an example embodiment.

Figure 25 shows a schematic diagram illustrating an actuator for a robotic system according to an example embodiment.

Figure 26 shows a schematic diagram illustrating a robotic system comprising the actuator of Figure 25 and the use of the actuator in robotic activation, according to example embodiments.

- 20 Figure 27 shows the flow chart illustrating the method of fabricating an actuator for a robotic system, according to an example embodiment.

DETAILED DESCRIPTION

- 25 Fabrication of Magnetic origami-inspired actuators (MOR), according to example embodiments, involves a predetermined arrangement of submillimeter magnets in a curable soft elastomer. An origami approach is proposed to make the fabrication process easier without imposing constraints on complexity. The magnetic domains are arranged in a 2D plane and folded into a 3D conformation for magnetization or actuation. The development into a 3D form is determined by the crease pattern and its interplay with the magnetic domains and the applied
- 30 external field. Complex forms may require multiple crease patterns for actuation or magnetization.

Magnetic Origami-inspired actuators (MOR) can be provided according to example embodiments, which can move/actuate under an applied magnetic field. The MOR, according to example embodiments, is a composite of magnetic particles suspended in an elastomer

mounted on a substrate (such as paper). It is noted that the terms “substrate” and “scaffold” are used interchangeably herein. The substrate utilizes various principles from origami to synergize with the actuation of magnetic particles and the elastic properties of the elastomer. The origami substrate is also beneficial/useful in simplifying fabrication.

- 5 Generally, a method of fabrication, according to an example embodiment, has multiple steps.
a) Assembly of parts; b) magnetization; c) postprocessing,

Specifically, according to an example embodiment, step a) comprises suspending magnetic particles in the elastomer, curing/casting elastomer, mounting, and folding of substrate/origami. Step b) comprises the magnetization of the magnetic particles. It is noted
10 that magnetization imposes a limitation on the work area (as work area increases magnetic flux density falls, a minimum density is required for magnetization using readily available magnetization equipment. An alternative is to use expensive equipment for designs with increased work area). Advantageously, the Origami approach helps to minimize the volume while preserving the required magnetic orientations. Step c) comprises post-processing to
15 reorganize the structure as the magnetization confirmation is usually not the final confirmation.

Embodiments of the present invention can provide one or more, preferably all, of:

- a) deformation/actuation of the magnetic domain along origami-inspired boundaries, e.g., crease lines. These magnetic domains can generate soft robotic motions remotely through magnetic interactions.
- 20 b) Breaking of symmetric motion in magnetic field inversion allowing multiple states using strain stiffening/ snap-through/ bi-stabilities to modify the motions
- c) a simple method of integration of rigid and soft component in a system blending benefits of both
- d) origami-inspired boundaries couple/link the individual magnetic dipole domains such that
25 they respond in a pre-programmed motion under an input magnetic field

Embodiments of the present invention can be used with an external magnetic field generator, which could be as simple as a permanent magnet. Actuation of the robotic domains is coupled by Lorentz force, which for example, can be done by tetherless permanent magnet perturbations or by current-carrying coils. The application of MORs, according to example embodiments,
30 can include actions such as grasping, locomotion, form transformation, self-assembly. Such actions benefit applications requiring tetherless control, a lightweight end effector, transformable miniaturization, and soft contacts. As mentioned above, embodiments of the present invention advantageously leverage from the benefits of both soft and hard components as well as a simple fabrication approach for programmable structures.

Methodology according to an example embodiment

Figure 2 is a schematic drawing illustrating the approach to fabricate soft robots with origami-inspired substrates, e.g., 200 according to example embodiments, which does not need a mold and instead uses folding of the substrate, e.g., 200 to arrange the magnetic domains. Advantageously, the substrate, e.g., 200, can be folded, see Figures 2(c),(d), and unfolded, see Figure 2(f). The regions of programmable folds in this embodiment are defined by a crease pattern 202 in the substrate, e.g., 200, see Figure 2(a).

Specifically, Figure 2(a) illustrates the crease pattern 202 transferred to the substrate 200 for the robot template. Figure 2(b) illustrates material preparation for the soft component of the MOR, e.g., silicone with dispersed NdFeB particles. Figure 2(c) illustrates the casting and curing of the soft component onto the substrate 200. Figure 2(d) illustrates folding into configuration 206 for magnetization. Configuration 206 illustrated in Figure 2(d) is inserted into a magnetizer 208 to set the magnetic directions in the respective magnetic domains, as illustrated in Figure 2(e). After magnetization, the configuration can be unfolded, and optionally additional folding steps can be performed, achieve the actuator quiescent configuration 210, illustrated in Figure 2(f), to provide a robotic actuator now magnetized to be magnetically actuated according to an example embodiment.

It is noted for completeness that while an origami-inspired approach has previously been applied in microfluidic diagnostics field [12][13], embodiments of the present invention apply an origami-inspired approach to the unrelated field of magnetic domain programming from simple folding for the fabrication of soft robots according to example embodiments, also referred to herein as MORs according to example embodiments. The competitive advantage of the MORs according to example embodiments stems predominantly from removing the need for mold to orientate domains during magnetization. This approach, according to example embodiments, should also be simpler/cheaper than multi-stage magnetization assemblies or dynamic/multi-axis magnetization (e.g. printed magnetization).

Figures 3(a) and (b) are schematic drawings illustrating developing a flat (2-D) origami-inspired actuator film 300 into an example 3-D letter N: As illustrated in Figure 3(a), when a magnetic field is applied in the appropriate direction (compare Figure 3(b)), the various magnetic domains, e.g., 301-303 in the actuator film 300 orientate to fold the creases, e.g., 304-306 to form the 3-D letter N structure or shape 308. As illustrated in Figure 3(b) and indicated at i), the top segment is repelled while indicated at iii), the bottom region is attracted and, indicated at ii), the middle section experiences a torque to orientate the domain to the applied field 310. The magnetic domains, e.g., 301-303 which are programmed are shown in Figure 3(a) and they are coupled to each other by the creases, e.g., 304-306. In Figure 3(a), the drawing on the right shows the structure transformation from the flat state to the folded state. The medial view of the folded structure 308 takes on the shape of a small letter “n” where the certain domains, e.g., 302, 309 are parallel to the ground while other domains, e.g., 301, 303 are perpendicular to the ground. If one views the folded structure 308 from the front as illustrated in the drawings on the right of Figure 3(b), the folded structure 308 shows a large figure “N”.

The arrows in the domains, e.g., 301, 303, circles, e.g., 309 (pointing inside the paper) and crosses, e.g., 302 (pointing outside the plane) are indicating the magnetization directions of magnetic domains.

Another benefit of using origami-inspired folding according to example embodiments can be to reduce the volume of the structure during magnetization, which allows for a stronger magnetic field. A magnetizer typically involves a magnetic circuit which has an air gap for magnetization, the object to be magnetized has to fit into the air gap. However, if the air gap is too large, the magnetic field strength decreases to the square of the distance. As such, a particularly powerful magnetizer would be needed for a substantial volume. Using origami-inspired folding according to example embodiments would, advantageously, allow the object to fold and compress the volume such that a simpler magnetizer can be used, as will be described in more detail with reference to Figure 4 below.

Figures 4(a)-(c) are drawings illustrating folding and compressing the robot template with the cast and cured magnetic material using origami-inspired creases, according to an example embodiment. Specifically, Figure 4(a)(i) shows the robot template configured as an N shape object 400 and Figure 4(b)(ii) shows a unit cube 401 on the right. The N shape 400 is three times higher and wider than the unit cube 401, thus requiring a large magnetization volume if used in this configuration during magnetization of the robot template. On the other hand, Figure 4(b) illustrates folding of a portion 403 of the robot template in which the crease lines, e.g., 404 run parallel to the magnetization direction, e.g., 405, which allows for the folding to align all domains of the portion 403 defined by the crease lines, e.g., 404 in the same magnetization direction and for reducing the width, see Figure 4(b)(iii). Figure 4(c) illustrates the folding of a portion 406 of the robot template in which the crease lines, e.g., 407 are perpendicular to the magnetization direction, e.g., 408, which allows for folding to reduce the length of the portion 406. However, when flat folded, the magnetic domains defined by the crease lines, e.g., 407 do not align with their magnetization in the same direction, see Figure 4(c)(iii) and (iv).

To resolve the misalignment issue, one or more null regions, each with two additional creases, can be introduced between the magnetic domains, according to example embodiments. The null region(s) does not require magnetization but can be folded for magnetization and subsequently tucks away after magnetization for reconfiguration into the robotic actuator. This is illustrated in Figure 5.

Specifically, Figure 5 illustrates magnetization volume reduction and resolving the domain misalignment with null spaces 500, 502 added according to an example embodiment. In Figure 5(a), the null spaces 500, 502 can be tucked away to form a portion 503 of a robot template using two additional crease lines, e.g., 504, 506 for each of the null spaces 500, 502. As illustrated in Figure 5(b) the null spaces 500, 502 can also be reconfigured to pleats 505, 507 such that the flat-folding allows for the magnetic domains, e.g., 508 defined by the crease lines, e.g., 510 to be aligned with the magnetization directions, e.g., 512 in the same direction, see Figure 5(b)(iii) and (iv), and reducing the length of the portion 503 of the robot template during

magnetization. This is in contrast with Figure 4(c)(iii) and (iv), where the alignment is not achieved.

In example embodiments of the present invention, the origami-inspired approach finds a folding pattern to map the desired magnetization orientation of the robot template into a smaller space based on the general principles described above with reference to Figures 4 and 5, including the introduction of null region(s) which helps to map parallel regions on top of other parallel regions with their magnetization direction aligned and such that the volume required for magnetization can be reduced. The null region(s) can be tucked away post magnetization to form the robotic actuator. This entire process is tested on an actual prototype for the soft robotic actuator to be magnetically actuated into a letter N shape according to an example embodiment, as will be described below with reference to Figure 6.

Specifically, Figure 6(a) illustrates a crease pattern (darker lines) transferred to a substrate 600 for the robot template. Figure 6(b) illustrates the unrequired holes of the letter N shape (when actuated) cut away from the substrate 600. Figure 6(c) illustrates pre-folding the null regions, e.g., 601 along the null region creases to tuck away the null regions, e.g., 601. Figure 6(d) illustrates the application and curing of silicone 603 with dispersed NdFeB particles onto the pre-folded substrate 600. As illustrated in Figure 6(e), the null regions, e.g., 601 are then unfolded to allow subsequent folding into the configuration for magnetization, illustrated in Figure 6(f). The configuration illustrated in Figure 6(f) is inserted into the magnetizer to set the magnetic directions in the respective magnetic domains. After magnetization, the configuration can be unfolded to return to the configuration illustrated in Figure 6(e), and then the null regions are tucked away again to achieve the configuration illustrated in Figure 6(d), to provide the robotic actuator now magnetized to be magnetically actuated into the letter N shape according to an example embodiment,

The concept of domain mapping resulting in the configuration, as illustrated in Figure 6(f) can be applied to extremely complicated domains into a simple miniaturized magnetization unit, as exemplified and described above with reference to Figures 4 and 5. For example, Figures 7(a) and (b) show a complex domain pattern 700 mapped into a unit cube 702 for magnetization, which would have been difficult to make by pure casting according to existing techniques.

Also, embodiments of the present invention can have additional actuation modes compared to conventional magnetic actuators, in which the magnetic motion is typically stable in only two states and the transition between the two states would define the motion. For example, depending on the crease patterns (compare Figure 6(a)) the deformations of the actuator, according to an example embodiment, can have stiffness changes and snap through stabilities for creating more than two stable states. In one example embodiment illustrated in Figures 7(c) to (f), the origami-inspired robot template 710 for a parallel manipulator 712 allows three stable states for respective stable magnetic inputs, due to the folding interactions of vertexes. In comparison, a similar 6 bar linkage would only have two stable states under an applied passive field.

Sample Material Selections according to an example embodiment

The soft base material, according to an example embodiment, is selected to be Silicon, which is as soft as human skin and commonly used for soft robots. The magnetic material is selected to be NdFeB powder, which has strong remanence and high coercivity and makes the magnetic property better and more reliable for the robots. In an example fabrication process, first, mix Silicon Part A and Part B with NdFeB powder in a certain ratio. Here, the Silicon is Smooth-on Dragon skin 10, the NdFeB powder is MQFP-B 5 μ m size (Br=863 mT, Hci=732 kA/m, ρ =7.61 g/cm³), and the weight ratio is selected as 1:1:1. Of course, the Silicon and NdFeB can also be mixed in other ratios. Three samples with different ratios were fabricated, i.e., the ratios of Silicon Part A, Part B, and NdFeB were 2:2:1, 2:2:2, and 2:2:3 respectively, and the magnetization curves of these three samples were measured and are shown as curved 801-802, respectively, in Figure 8. As can be seen from Figure 8, as the proportion of NdFeB powder increases, the saturated magnetization and residual magnetization of the mixture are stronger, which means the magnetic force on the robot would be greater under the same external magnetic field, or, to complete the same action, the applied magnetic field can be relatively small for the robot. Meanwhile, the material will become harder due to the increase of the metallic powder ingredient. Therefore, the ratio of Silicon and NdFeB should be reasonably selected to balance the magnetic characteristic and mechanical characteristic of the designed robot according to example embodiments.

Control of the actuator according to an example embodiment

The actuation of the magnetic robots can be predicted by the analytical method [8] [9] or finite element method [10]. The magnetic force F_m and magnetic torque T_m exerted on a magnet by an external magnetic field B can be expressed as follows:

$$F_m = V(\mathbf{M} \cdot \nabla) \mathbf{B}$$

$$T_m = V \mathbf{M} \times \mathbf{B}$$

where $\mathbf{M}$ is the magnetization intensity of the magnet and V is the volume of the magnet. Specifically, a magnetic moment will be subjected to torque in a uniform magnetic field and a force in a gradient magnetic field. In practice, permanent magnets or coil systems can be used to generate the external magnetic field to control the MORs according to example embodiments. Permanent magnets can provide a strong magnetic field freely, but it is a non-uniform field, i.e., the direction and magnitude of the magnetic field change significantly in space. In order to control the MOR according to an example embodiment precisely, the permanent magnet can be assembled on a controllable platform, or a robot arm or a magnetic field can be generated by a coil system, which is more flexible and easier to control, but the strength is usually weak. In coils systems, the Helmholtz coils can produce a uniform magnetic field for the rotational movement of the magnetic moment, and the Maxwell coils can produce a gradient magnetic field for the translational movement of the magnetic moment. By using three pairs of Helmholtz coils and three pairs of Maxwell coils in X, Y, and Z directions, the required magnetic field can be synthesized in the workspace (see inset photo in Figure 9), and

the magnetic field can be adjusted by controlling the magnitude and direction of the coil currents. Consequently, the precise motions of the MOR according to an example embodiment can be implemented in this magnetic field.

Figure 9 illustrates a control mechanism 900 according to an example embodiment for the magnetic actuator where the inputs can come from permanent magnets or electromagnetic coils. The magnetic field control (mechanical/current) indicated at numeral 902 provides for a magnetic field source indicated at numeral 903 to provide the Lorentz interactions with the magnetic domains for the actuator, indicated at numeral 904, for control of the robotic motion as indicated at numeral 906, and the resulting mechanical output, indicated at numeral 908 facilitated by the origami creases patterns according to an example embodiment. It is noted that the robotic motion can impose stiffening mechanisms due to the origami-inspired crease patterns, as described above, with reference to Figures 7(c) - (f), which can constrain deformation as indicated at numeral 910, adding to the robotic motion control. The entire system can be subsequently closed with a feedback controller, as indicated at numeral 912, for example, using optical tracking.

Variations according to other example embodiments

Variations to material, structure, and magnetization determine the action and function of a MOR according to various example embodiments. In general, by making the substrate material non-uniform or anisotropic [5] [6], the magnetic forces act on the partial area or direction of the robot to implement a specific action. Origami-inspired example embodiments can achieve this through the introduction of creases. Alternatively or additionally, the substrate material can also be varied in concentration to make certain region actuation dominate over other regions. The spatial arrangement and coupling of the magnetization direction can be permuted to fit the user needs according to various example embodiments, i.e., origami is not the only way for fabrication. The conventional deployable mechanisms, including linkage, bar-joints would function similarly to introduce non-uniform or anisotropic characteristics.

The actuation and motion of the actuators for robots, according to example embodiments, are shown in Figures 10-13, show that the magnetized robots tend to actuate and return to the state of magnetization when an external magnetic field is applied. The external magnetic field can be a single-pole source with non-uniform magnetic field gradients, such as from permanent magnets, or can be a complex multi-pole field and/or uniform fields such as from a magnetic resonance imaging (MRI) machine or equivalent electromagnetic field generators.

Results and analysis of example embodiments

In the following, the actuation and application of MORs according to example embodiments to self-folding, locomotion, and grasping will be described.

Self-folding according to an example embodiment

When an external magnetic field is applied on the programmed MOR according to an example embodiment in the magnetization direction, the samples will be deformed by the magnetic force to return into the state of magnetization, for example, to form different letters.

- 5 As shown in Figure 10, the same MOR sample 1001-1003 can be programmed through the initial magnetization configuration to be actuated to form different letters under a magnetic force (a) N, (b) U, (c) S. In other words, the configurations 1011 to 1013 in which the MOR samples 1001-1003 were magnetized/programmed determines the configuration upon activation under an external field in the magnetization direction, indicated at numeral 1014.

10 Locomotion according to an example embodiment

In an example embodiment, a rotational field can be used, which would allow for a traveling sin wave that is able to reduce friction. The field should also have a gradient that promotes continuous motion **[Please clarify.]**. The shape formed under different field directions is shown in figure 11.

- 15 Specifically, Figure 11 illustrates the shape of a MOR 1100 formed under different field directions of a traveling sin wave: In Figure 11(a) with no applied field, the MOR 1100 is flat, indicated at numeral 1102. In Figure 11(b) with an upward field applied, the MOR 1100 forms a sine wave indicated at numeral 1104, which lifts regions of the MOR 1100 off the ground. In Figure 11(c), the field points to the left and the MOR 1100 deform as if the wave propagates towards the left, indicated at numeral 1106. The change in the field from Figure 11(b) to (c) can be continuous. The configurations shown in Figures 11(d) and (e) are an inversion of Figures 11(b) and (c), and the cycle repeats.

Grasping and locomotion according to an example embodiment

- 25 For a grabbing MOR 1200 according to an example embodiment, when there is no external magnetic field, the claw-shaped MOR 1200 is opened as a result of the inherent elasticity of the material of the MOR 1200, as shown in Figure 12(a). When an external magnetic field is applied along the magnetization direction, the claw-shaped MOR 1200 will be closed, as shown in Figure 12(b). When an external magnetic field is applied opposite the magnetization direction, the center portion of the claw-shaped MOR 1200 will be lifted, as shown in Figure 12(c).

The actions of the claw-shaped MOR 1200 are controlled by the magnetic field of a permanent magnet according to an example embodiment. A demonstration of the grasping is shown in Figure 13.

Fabrication and magnetization of magnetic origami structures by folding according to various example embodiments

The approach to programming magnetic origami-inspired actuators, according to example embodiments, is further illustrated in Figures 14(a) to (c). Specifically, as illustrated in Figure 14(a), a crease pattern introduces the intended anisotropy into the plane of the substrate such that the individual flap structure can deform in a precise manner under external magnetic fields. Existing origami design resources can help to design the required crease patterns [14, 15]. In this embodiment, a cut further facilitates the anisotropy imparted. The magnetic particles are dispersed in a curable elastomer and film-coated onto the template, forming the magnetic elastomers. Given the porous nature of the paper used as the substrate in this example embodiment, the magnetic elastomer bonds adequately with the template, as seen in the secondary electron microscopy (SEM) image shown in Figure 14(b). The magnetic origami structure is folded to encode/program the magnetic orientations into the respective origami domains. For instance, magnetic domains sharing the same crease are only allowed to rotate due to the hinge-like constraint of the crease. The origami-inspired crease pattern defines the boundary and the relative motions allowed for adjacent domains. Each domain can have its own magnetization direction and hence experience different forces and torques when a magnetic field is applied. The aggregate of magnetic domain interactions and mechanical fold constraints defines the possible shape morphing motions for the magnetic origami-inspired actuator. The magnetization process is an insertion and removal from the magnetic field, as illustrated in Figure 14(c). The magnetizer used according to example embodiments has a magnetization volume of 5 mm thickness, 15 mm by 15 mm in the area, and a flux density with at least 1 Tesla. Post magnetization, the structure is unfolded/refolded, and the magnetic origami-inspired robot can be remotely controlled with an external magnetic source. Different magnetization patterns can result in different actuated shapes, although the origami pattern is the same, highlighting the benefits of diversified programmability, as illustrated in Figure 14(c). Also, for example, the sine wave structure described above can express different locomotion modes based on the magnetic input. Changing the origami structure can generate vastly different motions according to various example embodiments. This fabrication process, according to an example embodiment, allows for the magnetization of multiple structures in a single process that facilitates large-scale customizable batch manufacturing and bypasses the investment for molds. This easy to implement folding approach according to example embodiments offers diversified programmability and re-programmability of robotic motions compared with the magnetic elastomer printing or mold casting approaches.

There is an additional option to remove the backbone template after magnetization to achieve a soft, pure magnetized elastomer according to example embodiments. Pure magnetic elastomers advantageously produce continuous deformations and are more compliant when compared to the discrete actuation from the relatively rigid origami-inspired backbone structures (Young's modulus is usually below 10 MPa for magnetic elastomer while Young's modulus of paper is generally above 100 MPa). The backbone template has an effect on the force transmission, which could be a consideration during structural design. An intermediate

choice without changing the template material is to induce structural cuts to enhance joint flexibility (compare Figure 14(a)). The magnetic domains can be reprogrammed, for example, after demagnetization using heating, to generate different actuated structures, as will be described in more detail below with reference to Figure 24. The combination of these fabrication techniques can be applied to build magnetic origami-inspired structures such as slinky robots, which can express diverse locomotions. By changing the magnetization pattern, the geometry of the structure and/or the magnetic field input, motions such as omega inching, peristaltic crawling, and flipping motions were observed according to example embodiments. In addition to open chain structures, closed chain linkage structures such as remote-center-of-motion structures and parallel mechanism structures were built utilizing this fabrication approach according to various example embodiments.

Further magnetic origami-inspired structures according to various example embodiments

Variations in magnetization state can influence the actuation of the eventual structure according to example embodiments. Similarly, the origami-inspired geometries can be designed to change the actuation characteristics of the magnetic origami structure. In Figures 15 (a) to (h), permutations of origami-inspired design according to various embodiments are shown, where on the left, serial linked kinematic chains with no cyclic linkages are shown (Figures 15(a) to (d)). Specifically, the design in Figure 15(a) generates a wave-like motion as described above, the design in Figure 15(b) can grasp and crawl as described above, the design in Figure 15(c) can rectify a large frame as described above, and the design in Figure 15(d) is a magnetic elastomer analog of the design in Figure 15(a), i.e., with the backbone substrate removed. On the right, the origami-inspired structures mimic closed linked kinematic chains that are parallel structures and are anchored to the ground at the base (Figure 15(e) to (h)). Specifically, the design in Figure 15(e) generates a vertical motion with a snap-through transition, the design in Figure 15(f) has vertical motion, bending and twisting continuously, the design in Figure 15(g) transforms between a parallelogram and its flat folded state, the design in Figure 15(h) is the pure magnetic elastomer analog of the design in Figure 15(g), i.e., with the backbone substrate removed. The design in the last row (Figures 15 (d) and (h)) have structures with pure magnetic elastomer. The energy transfer from one segment to another and the coupling of motion due to vertex constraints decrease as the planes are deformable. The difference in the material deformation during tensile testing showcased the effect of the template on the compliance (stiffness modulus) of magnetic elastomers. For example, a pure paper was measured to have a Young's Modulus of 190 MPa, while magnetic elastomers have a Young's Modulus of 0.03 MPa, and their composites ranged between 90 MPa to 205 MPa.

Magnetic origami-inspired actuators moving with a wave motion according to various example embodiments

Motion generation mechanism with five domains was demonstrated according to example embodiments, where the magnetization directions are oscillating with subsequent domains resulting in an oscillating pattern. Rotating a magnetic field under the magnetic origami-

inspired actuator at an oscillation frequency of about 0.4 Hz will induce a wave-like crawling motion, as shown in Figures 16(a) and (b). The actuator oscillates with the field and is capable of crawling forward with a speed of 0.076 mm/sec, as illustrated in the graphs shown in Figures 16(f) and (g). Under the wave-like crawling motion, a segment is raised, which contracts the projected length of the unit, but the reduction does not retard the forward position of the unit. Like an inchworm, the raised segment subsequently lowers, which translates into an increase in overall horizontal length and advances the forward position of the unit. This method of rectilinear locomotion is slower due to the entire unit only advancing by small increments each cycle, but the motion is very stable due to the segments having constant ground contact. When the magnetization field gradient increases (the magnet source is closer for actuation reducing the air gap to less than 5 mm), the structure can curl up and tracks the magnet by rolling, as illustrated in Figures 16(c) and (e) instead of crawling, which increases the locomotion speed as illustrated in the graphs in Figures 16 (f) and (g). It was observed that the rolling motion could achieve a velocity of 9.9 mm/sec. This locomotion modulation, according to example embodiments, showcases the importance of customizable actuation of magnetic origami structures where the magnetization, origami-inspired design, and the actuation field can be tuned to generate the desired motions.

Four limb magnetic origami-inspired actuators according to example embodiments

Crawling motion was induced in a four-legged (tetrapod) origami-inspired actuator according to an example embodiment by magnetic domain folding, as shown in Figures 17(a) to (g). The individual legs and the core body of the actuator were designed to perform grasping tasks as illustrated in Figures 17(a) and (c) or to move as illustrated in Figures 17(b) and (d). The design allows the core of the actuator to be repelled while the legs are attracted with respect to an external field, causing the actuator to stand up, as illustrated in Figure 17(d). When this magnetic field is inverted, the actuator core is attracted while the legs are repelled, which causes the structure to invert and close with a grasping motion, as illustrated in Figure 17(a). This invertible motion generation mechanism is comparable to the sine wave structure (compare Figures 16(c) and 17(b)) curling up into a cylinder, converting into a rollable ring. The grasping motion can hold on to an example package (4 mm paper cube weighing 10 mg) for later release, as illustrated in Figure 17(a). If the field intensity is maintained and rotated, the grasped structure can rotate with the external field, as illustrated in Figure 17(b), transporting the grasped package. The actuator, upon reaching the target location, can release the package, as illustrated in Figure 17(c). The actuator is tilted (by rotating the external field by 45 degrees), and decreasing the magnetic field gradient reduces the forces closing the arms to release the object. The actuator can be flipped over by inverting the field and can subsequently crawl away, as illustrated in Figure 17(d). While the external magnet field bobs up and down (air gap varies from 5mm to 10 mm in an example embodiment), the actuator follows in sync. As the actuator bobs up and down in the direction of gradient source, the advancement of the actuator can be controlled by biasing the external field source towards the intended direction (e.g., approximately half a body length). For each actuation cycle, the actuator extends towards the magnetic gradient source when the field intensity is decreased (causing leg adduction) or

increased (causing leg abduction). The combination of these crawling, grasping, and rolling motion with tether-less magnetic actuation potentially benefit drug delivery applications, as simulated in the colon model. **Parallel magnetic origami-inspired actuators (bi-stable Sarrus linkages, twisted tower) according to example embodiments**

5 To demonstrate unique properties such as flat-foldability and multi-stability of deployable parallel mechanisms by origami-inspired domain programming according to example embodiments, two parallel mechanisms were folded, as shown in Figure 18(a): a six-bar Sarrus linkage on the left and a twisted tower of ten-bar linkage on the right. Both structures can be folded from a flat template with specific magnetization domains, as indicated by the arrows, circles and crosses. This folding separates the structure into segments which are magnetically responsive (those with arrows, circles or crosses), and segments that are passive origami-inspired structures (those without arrows, circles or crosses). The passive origami-inspired structures serve different mechanical purposes in imparting snap-through stability such that there is an energy barrier between the maximally compressed state and the maximally extended state, as illustrated in Figure 18(b). The structure on the left can have two distinct ranges of motion (e.g., 15-20 mm and 0-10 mm vertically) under the same magnetic field input (the air gap varies between 5 mm to 25 mm), due to the origami-inspired structures as illustrated in Figure 18(c). The transition between the actuation states requires the forces exerted to overcome the snap-through stability barrier, and this force can be externally applied, or the magnetic field gradient can be increased to generate the snap-through force required. This six-bar parallel mechanism shows a case of two motion states in a single structure due to the origami design (Movie. S10).

A parallel actuator, according to an example embodiment that has continuous twist deformation between its maximally compressed state and maximally extended state, is illustrated on the right in Figures 18(a) to (c). It can rotate in the three principal axes by changing the field direction and gradient. The magnetization direction is normal to the domain plane, which can be attracted or repelled for vertical motion. If the applied field is normal to the domain plane, half of the plane is attracted while the other half is repelled, which causes the structure to bend. For the twisting motion, the external magnet is kept parallel to the magnetization plane, and rotations of the external magnetic field (180 degrees) are coupled to the magnetic domain. The twisted-tower origami-inspired structure, unlike the bi-stable design, utilizes specific cuts/holes to increase the degrees of freedom while preserving the necessary constraints, which allows the motions observed. In addition to these two parallel structures, alternative closed linkage structures, such as a remote-center-of-motion structure, can be built according to example embodiments. Remote-center-of-motion structures are adept at tool insertion and manipulation about a virtual static point, which is helpful in minimally invasive surgeries to constrain unwanted motion in a particular plane.

Foldable graphene oxide templated platinum-based actuator according to an example embodiment

The customizability of embodiments of the present invention was demonstrated with an origami-inspired template made with Graphene Oxide templated platinum, as shown in Figures 19, (a) to (f), which functionalized the actuator with catalytic capabilities. This platinum material is unique in contrast to a standard film of metal as this material is flexible and fibrous similar to paper. A 4 mm by 10 mm porous film of platinum is prepared from the decomposition and oxidation of intercalated platinum ions in Graphene Oxide multilayers similar to [16]. This sheet is implemented as the foldable substrate, as described in Figure 14(a) and with a similar design to that shown in Figure 16(a). It is capable of the same sine wave crawling motion, as illustrated in Figure 19(a), curling up as illustrated in Figure 19(b) and moving towards the magnetic gradient source, as illustrated in Figure 19(c). The translation motion is used to move the actuator on the low-friction petri-dish into a drop of hydrogen peroxide, where the platinum material acts as a catalyst to accelerate the decomposition of hydrogen peroxide to effervesce oxygen reaction products as illustrated in Figures 19(d) to (f). This magnetic origami-inspired actuator fabrication, according to an example embodiment, merged tetherless magnetic actuation with catalytic activity, which demonstrates that the fabrication-by-domain-folding technique is extendable to the different foldable substrate according to various example embodiments. For example, targeted drug therapies can involve such catalytic activities inside the folding structure, which, upon an external field, would change its conformation to reveal the catalytic/therapeutic core.

As described above, a magnetic domain programming methodology with a fabrication-by-folding approach according to example embodiments is provided, which imparts actuation patterns (such as shape-morphing, locomotion, deployment, object manipulation) to developable surfaces/actuators. The tetherless magnetic interaction, allows the proposed actuators or robots to work in isolated environments such as inside the human body. Manipulations requiring joint positioning can utilize the proposed parallel mechanisms for position management. These robots can make use of folding states from origami to minimize its volume or to couple motion for minimally invasive procedures in the human body. Other advantages of the fabrication approach, according to example embodiments include the ease of translating and upscale production in addition to the customizability (magnetization direction, crease-pattern, template material) in design. The fabrication is able to magnetize multiple distinct segments in a single magnetization step, which could translate to time and equipment savings. The structures built from this approach can be refolded to meet different requirements.

The folding templating approach, according to example embodiments, can have some limitations in the template material and foldable size. For example, stiff metal sheets can be challenging to fold as high stress is required to form the required creases. The porous nature of the template is preferred to allow the magnetic elastomer to strongly bond with the foldable template. Smooth surfaces can be provided with some form of chemical and/or mechanical modifications to prevent delamination. The size of the actuator structure is preferably in the mesoscale (millimeters to centimeters) as it can be challenging to fold smaller submillimeter

sizes for magnetization without specialized equipment and the upper limit may be restricted by the magnetic field generated by the magnetic field sources.

In the origami-inspired approach according to example embodiments, the mechanical constraints of the creases and domains advantageously aid the control of proximal magnetic domains. The origami-inspired crease pattern can couple multiple flap domains and apply restrictions to the direction and range of motion for each flap domain. This kinematic constraint can be observed from the parallel mechanisms according to example embodiments described above, which restricted the motions of the domain with the crease patterns from origami. Without origami-inspired kinematic coupling, according to example embodiments, independent magnetic domains are prone to rotate and orientate to the external field direction. Additionally, without kinematic coupling, the independent domains are free to interact with neighbors and nucleate together.

Material composition according to example embodiments

The components of the fabrication according to example embodiments described herein by way of example, not limitation, comprise NdFeB 5 um particles (Magnequench International, MQFP-B(D50= 5 microns) 20076-089) dispersed in platinum-cured elastomer (Smooth-On, Dragon Skin™ 10 MEDIUM). The composition of the mass ratio is 1:1:4 (Silicone part A: Silicone part B: magnetic powder). Varying the mass ratio composition will affect the material response to the external magnetic source. The magnetic particle properties and the magnetization field affect the magnetic moment during the selection for the magnetic coercivity, remanence, and the magnetic field strength required for magnetization. The elastomer can have a different material stiffness, but this should be distinguishable from the material properties of the template. An 80 Gsm A4 paper (Double-A) was used where the crease lines can be defined by scoring or embossing (silhouette, curio™) or complete excision for a predefined length segment of the crease. To increase material flexibility and enhance crease anisotropy, a parallel section of the crease can be cut, which reduces the plasticity while retaining the flexibility and constraints of the crease to act as a joint. The film coating method is a variant of screen printing, where the magnetic elastomer mixture spreads across the template surface (for example, a spin coater could be an alternative for coating). The material is cured at room temperature (298 Kelvins) for an hour. Excess material is trimmed, and the structure is folded for magnetization.

Magnetization method according to an example embodiment

The magnetization can be done with an electromagnet at 1.2 T (Lake Shore Cryotronics, EM4-HVA-S) with field uniformity, by way of example, not limitation. The sample is mounted, and the field is applied in three ramped pulses, where the sample is rotated 180 degrees after each pulse about the magnetization direction. A robotic permanent magnet set-up with NdFeB cube magnets (Titan Magnetics Inc.) functions similarly to the magnetic field generator. The magnetometer used is TD8620 from Tunkia Co., Ltd.

Fabrication of flexible platinum backbone according to an example embodiment

The cut, folded papers were soaked into diluted graphene oxide (GO) dispersion (5 mg mL⁻¹) for 12 hours and air-dried to achieve the GO-cellulose composite templates. The GO-cellulose templates were then soaked into various platinum chloride (PtCl₄) solution (0.1 M) for another 12 hours and air-dried to obtain the Pt-GO-cellulose as the template. The Pt-GO-cellulose template was put into a tube furnace (Thermal Craft, Polaris Science Pte., Ltd.) and annealed under argon with a specific heating program shown in the following: set temperature: 800 °C, ramp time: 1 hour, hold time: 2 hours. After the furnace was cooled down, the origami replica was calcined under air for another 1 hour at 500 °C. After the furnace was cooled down naturally, the as-synthesized platinum replicas were taken out carefully. The dilute PDMS solution was then prepared by mixing PDMS curing agent and base in a 1-to-10 weight ratio and diluting with dichloromethane (300 mg mL⁻¹). The PDMS solution was slowly dripped onto the surface of platinum replicas followed by the curing process in an oven at 70 °C for 3 hours, and then the flexible platinum films were obtained. This backbone material is utilized as the paper template outlined in (Fig. 1) where the flexibility of the material is beneficial for deflections and the porosity if useful for the magnetic elastomer bonding and as a surface area for catalysis.

Figures 20(a) to (i) illustrate the mass fabrication of versatile actuators or robots according to example embodiments. Specifically, from a single 80 mm by 80 mm sheet, one can quickly amass a pile of customized magnetic origami-inspired robots. Most steps can be efficiently automated, although the folding stage may require different processes for the different crease folding. A curio cutting and embossing machine were used by way of example, not limitation, which can be further optimized with a laser cutting CNC. Figure 20(e) shows the back of the paper with the printed design, which is mounted to the plastic sheet with PVA adhesive. Figure 20(f) shows the front of the paper, which is film-coated with magnetic elastomer shown in Figure 20(g). As shown in Figure 20(i) from this process, multiple structures can be made from the same sheet.

Figures 21(a) to (f) illustrate a magnetic origami-inspired slinky according to an example embodiment. As illustrated in Figure 21(a), omega motion allows the spring-like actuator or robot to move from point to point. The two ends of the robot have magnetic directions which can be manipulated by changing the input magnetic fields. As illustrated in Figure 21(b), the peristaltic motion of the robot is achieved by changing the input magnetic field and could be used for locomotion in a constrained environment. As illustrated in Figure 21(c), flipping motion is achieved by changing the magnetization pattern and the length of the robot. As illustrated in Figure 21(d), the combination of these motions can be applied to navigate through a silicone phantom of a colon. In Figure 21(e), the displacement profiles for the different locomotion modes are compared, lateral displacement (top) and vertical displacement (bottom). In Figure 21(f), the associated velocity profiles, as derived from Figure 21(e), are shown.

Figures 22(a) to (d) show a magnetic remote-center-of-motion actuator according to an example embodiment. Figure 22(a) shows a computer-aided design representation of the remote-center-of-motion (RCM) parallel structure. Figure 22(b) shows the range of motion for the RCM structure, where the actuation is driven by changes in the applied magnetic field. Figure 22(c) shows representative frames from the actuation where the dot indicates the RCM point. Figure 22(d) shows an optic flow field for the RCM motion.

Figures 23(a) to (f) illustrate paper backbone (or substrate) and force transmission. Specifically, Figure 23(a) contrasts a magnetic origami-inspired actuator according to an example embodiment with a paper substrate (left column) against a pure magnetic elastomer no paper substrate actuator according to another example embodiment (right column). The paper actuator is more discrete, creating an N shape with a smaller radius of curvature and more confined regions with curvature. The paper actuator is flexible at the creases and rigid at the domains with remarkable plasticity of the hinges. The pure elastomer structure is entirely compliant with no plasticity. Figure 23(b) shows a paper substrate magnetic origami-inspired grasper according to an example embodiment which grasps onto a ring suspended by a tension member. It can be observed that the deformation of the grasper is discrete, and the structure is well preserved. Figure 23(c) shows a pure silicone magnetic grasper according to another example embodiment that perform the same task of gripping on to a suspended ring. Figure 23(d) shows that the pure silicone actuator is less defined and can collapse unpredictably under its own stresses. Figure 23(e) shows the maximum force recorded in the tension member indicates that the paper substrate-based actuator can generate higher transmission forces. Figure 23(f) shows that the average force supports the observations in the maximum force.

Figures 24(a) to 9(f) illustrate re-programmable magnetic domain folding according to an example embodiment. Specifically, Figure 24(a) shows a common precursor can be folded in different shapes for magnetization – the shape of a U as shown in Figure 24(b), or the shape of an N as shown in Figure 24(c). Figure 24(d) illustrates that the magnetized structure, for example, the one that was programmed to actuate into the N shape shown in Figure 24(c), can be heated at 180 °C for an hour to demagnetize a predominant portion of the domains. Some remnant is still observed. As illustrated in Figure 24(e), the structure after heating can be reprogrammed by folding into a different shape to change the dipole directions. This structure is magnetized into a U shape where it previously had the programming of an N shape. As shown in Figure 24(f), when the magnetic field turned off, the structure reverts to the flat precursor shape. This re-programming capability similarly applies to the structure initially programmed to actuate into the U shape shown in Figure 24(b). In Figure 24, grids in the background correspond to 4 mm squares.

A device, according to an example embodiment, comprises a magnetic material, curable polymer, and a scaffold/substrate are provided according to example embodiments. The magnetic material can, e.g., be microparticle NdFeB suspended in a curable polymer of silicone on top of a scaffold/substrate, which can be cellulose-based. The scaffold/substrate can be modified to be non-uniform or anisotropic to have preferential flexibility such as through folding creases like in origami to define a predetermined arrangement of magnetic domains

that can have independent magnetization directions. Devices, according to example embodiments, can be used to make soft magnetic robots that leverage the benefits from both origami-inspired design and magnetic control to achieve actuation. Devices according to example embodiments can be realized by a simpler fabrication method for complex designs compared to the conventional mold-based approach, and the use of the origami-inspired configuration can impart additional actuation dimensions (such as through snap-through instabilities).

Figure 25 shows a schematic diagram illustrating an actuator 1400 for a robotic system according to an example embodiment. The actuator 1400 comprises a substrate layer 1402; and an elastic layer 1404 on the substrate layer 1400, the elastic layer 1404 comprising a first material with non-zero coercivity embedded in a second material; wherein the substrate layer 1404 exhibits anisotropic mechanical properties indicated at, e.g., numeral 1406 to promote preferential mechanical deformation of the substrate layer and the elastic layer during actuation of the actuator under an actuation electromagnetic field based on the interaction of the actuation electromagnetic field and the first material.

The anisotropic mechanical properties of the substrate layer may be the result of creases formed in the substrate layer for origami-type folding of the substrate layer and the elastic layer thereon.

The anisotropic mechanical properties of the substrate layer may be the result of cuts formed in the substrate layer for kirigami-type manipulation of the substrate layer and the elastic layer thereon.

The anisotropic mechanical properties of the substrate layer may be the result of the substrate layer exhibiting different material compositions in different regions thereof. The different material composition is the result of additive manufacturing, such as doping.

The anisotropic mechanical properties may further promote preferential mechanical deformation of the substrate layer and the elastic layer before and after magnetization. The preferential mechanical deformation of the substrate layer and the elastic layer before magnetization may be into a magnetization configuration having a reduced volume compared to an actuation configuration.

An elastomeric property of the second material may define a quiescent configuration of the actuator when no actuation electromagnetic field is applied.

The preferential mechanical deformation may occur along fold lines defining a plurality of domains of the actuator, wherein a magnetization direction of each domain can be programmed. A combination of the fold lines and the magnetization direction of the domains may determine the deformation of the substrate layer and the elastic layer under the actuation electromagnetic field. The fold lines may determine the magnetization direction under a magnetization electromagnetic field.

The substrate layer may contribute to one or more additional properties of the actuator, such as conductivity.

The second material may have a predetermined young's modulus and shear modulus.

The first material may comprise NdFeB microparticles.

- 5 The second material may comprise a curable elastomer, such as silicone rubber.

The substrate layer may comprise one or more of a group consisting of a carbohydrate polymer, such as cellulose, a metal, a metal oxide, and a silicate mineral.

- 10 Figure 26 shows a schematic diagram illustrating a robotic system 1500 comprising the actuator 1400 and the use of the actuator 1400 in robotic activation, here to grab an object 1502, according to example embodiments.

- 15 Figure 27 shows flow chart 1600 illustrating the method of fabricating an actuator for a robotic system, according to an example embodiment. At step 1602, a substrate layer is provided. At step 1604, an elastic layer is provided on the substrate layer, the elastic layer comprising a first material with non-zero coercivity embedded in a second material. At step 1606, anisotropic mechanical properties are imparted on the substrate layer to promote preferential mechanical deformation of the substrate layer and the elastic layer during the actuation of the actuator under an actuation electromagnetic field based on the interaction of the actuation electromagnetic field and the first material.

- 20 The anisotropic mechanical properties of the substrate layer may be the result of creases formed in the substrate layer for origami-type folding of the substrate layer and the elastic layer thereon.

The anisotropic mechanical properties of the substrate layer may be the result of cuts formed in the substrate layer for kirigami-type manipulation of the substrate layer and the elastic layer thereon.

- 25 The anisotropic mechanical properties of the substrate layer may be the result of the substrate layer exhibiting different material compositions in different regions thereof. The different material composition is the result of additive manufacturing, such as doping.

- 30 The anisotropic mechanical properties may further promote preferential mechanical deformation of the substrate layer and the elastic layer before and after magnetization. The preferential mechanical deformation of the substrate layer and the elastic layer before magnetization may be into a magnetization configuration having a reduced volume compared to an actuation configuration.

An elastomeric property of the second material may define a quiescent configuration of the actuator when no actuation electromagnetic field is applied.

The preferential mechanical deformation may occur along fold lines defining a plurality of domains of the actuator, wherein a magnetization direction of each domain can be programmed. A combination of the fold lines and the magnetization direction of the domains may determine the deformation of the substrate layer and the elastic layer under the actuation electromagnetic field. The fold lines may determine the magnetization direction under a magnetization electromagnetic field.

The selection of the substrate layer may contribute to one or more additional properties of the actuator, such as conductivity.

The second material may have a predetermined young's modulus and shear modulus.

10 The first material may comprise NdFeB microparticles.

The second material may comprise a curable elastomer, such as silicone rubber.

The substrate layer may comprise one or more of a group consisting of a carbohydrate polymer, such as cellulose, a metal, a metal oxide, and a silicate mineral.

The method may further comprise removing the substrate layer to form a soft actuator.

15 In one embodiment, an actuator fabricated by the method described above with reference to Figure 25 is provided.

Embodiments of the present invention can have one or more of the following features and associated benefits/advantages.

Feature	Benefit/Advantage
- Magnetic actuation of programmed domains, a method to determine domain and method of magnetization profile	- Customizable fabrication due to origami - Tether-less actuation from magnets
- Origami techniques to simplify fabrication during magnetization	- Improving ease in fabrication, reducing the requirements on magnetization size
- Exploiting origami crease for additional degrees of freedom or additional stability states.	- Increasing modes of actuation beyond pure magnetic actuation - Leverage of both soft and hard components - Leverage origami backbone for programmable motion generation and structural strength
- Complex and programmed motion with a single input or multiple inputs	- Under-actuation simplification where multiple domains are predictably

controlled simultaneously with a single magnetic source.

Commercial applications, of example embodiments:

Biomedical devices are requiring in-vivo tetherless actuation or deployment of in-vivo structures.

- 5 Cell level mechanical interactions.

Artificial muscular motion.

Aspects of the systems and methods described herein, including, but not limited to, the domain mapping into the desired actuator configuration and/or into the reduced volume magnetization configuration, and the control of the applied magnetic field, may be implemented as
10 functionality programmed into any of a variety of circuitry, including programmable logic devices (PLDs), such as field-programmable gate arrays (FPGAs), programmable array logic (PAL) devices, electrically programmable logic and memory devices and standard cell-based devices, as well as application-specific integrated circuits (ASICs). Some other possibilities for implementing aspects of the system include microcontrollers with memory (such as
15 electronically erasable programmable read-only memory (EEPROM)), embedded microprocessors, firmware, software, etc. Furthermore, aspects of the system may be embodied in microprocessors having software-based circuit emulation, discrete logic (sequential and combinatorial), custom devices, fuzzy (neural) logic, quantum devices, and hybrids of any of the above device types. Of course, the underlying device technologies may be provided in a
20 variety of component types, e.g., metal-oxide-semiconductor field-effect transistor (MOSFET) technologies like complementary metal-oxide-semiconductor (CMOS), bipolar technologies like emitter-coupled logic (ECL), polymer technologies (e.g., silicon-conjugated polymer and metal-conjugated polymer-metal structures), mixed analog and digital, etc.

The above description of illustrated embodiments of the systems and methods is not intended
25 to be exhaustive or to limit the systems and methods to the precise forms disclosed. While specific embodiments of, and examples for, the components and methods of the system are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the systems, components, and methods, as those skilled in the relevant art will recognize. The teachings of the systems and methods provided herein can be applied to other
30 processing systems and methods, not only for the systems and methods described above.

The elements and acts of the various embodiments described above can be combined to provide further embodiments. These and other changes can be made to the systems and methods in light of the above-detailed description.

In general, in the following claims, the terms used should not be construed to limit the systems
35 and methods to the specific embodiments disclosed in the specification and the claims but should be construed to include all processing systems that operate under the claims.

Accordingly, the systems and methods are not limited by the disclosure, but instead, the scope of the systems and methods is to be determined entirely by the claims.

Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," and the like are to be construed in an inclusive sense as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to." Words using the singular or plural number also include the plural or singular number, respectively. Additionally, the words "herein," "hereunder," "above," "below," and words of similar import refer to this application as a whole and not to any particular portions of this application. When the word "or" is used in reference to a list of two or more items, that word covers all of the following interpretations of the word: any of the items in the list, all of the items in the list and any combination of the items in the list.

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CLAIMS

1. An actuator for a robotic system, the actuator comprising:

a substrate layer; and

an elastic layer on the substrate layer, the elastic layer comprising a first material with
5 non-zero coercivity embedded in a second material;

wherein the substrate layer exhibits anisotropic mechanical properties to promote preferential mechanical deformation of the substrate layer and the elastic layer during actuation of the actuator under an actuation electromagnetic field based on the interaction of the actuation electromagnetic field and the first material.

10 2. The actuator of claim 1, wherein the anisotropic mechanical properties of the substrate layer are the result of creases formed in the substrate layer for origami-type folding of the substrate layer and the elastic layer thereon.

3. The actuator of claims 1 or 2, wherein the anisotropic mechanical properties of the substrate layer are the result of cuts formed in the substrate layer for kirigami-type
15 manipulation of the substrate layer and the elastic layer thereon.

4. The actuator of any one of claims 1 to 3, wherein the anisotropic mechanical properties of the substrate layer are the result of the substrate layer exhibiting different material compositions in different regions thereof.

5. The actuator of claim 4, wherein the different material compositions are the result of
20 additive manufacturing, such as doping.

6. The actuator of any one of claims 1 to 5, wherein the anisotropic mechanical properties further promote preferential mechanical deformation of the substrate layer and the elastic layer before and after magnetization.

7. The actuator of claim 6, wherein the preferential mechanical deformation of the
25 substrate layer and the elastic layer before magnetization, is into a magnetization configuration having a reduced volume compared to an actuation configuration.

8. The actuator of any one of claims 1 to 7, wherein an elastomeric property of the second material defines a quiescent configuration of the actuator when no actuation electromagnetic field is applied.

30 9. The actuator of any one of claims 1 to 8, wherein the preferential mechanical deformation occurs along fold lines defining a plurality of domains of the actuator, wherein a magnetization direction of each domain can be programmed.

10. The actuator of claim 9, wherein a combination of the fold lines and the magnetization direction of the domains determines the deformation of the substrate layer and the elastic layer
35 under the actuation electromagnetic field.

11. The actuator of claims 9 or 10, wherein the fold lines determine the magnetization direction under a magnetization electromagnetic field.
12. The actuator of any one of claims 1 to 11, wherein the substrate layer contributes to one or more additional properties of the actuator, such as conductivity.
- 5 13. The actuator of any one of claims 1 to 12, wherein the second material has a predetermined young's modulus and shear modulus.
14. The actuator of any one of claims 1 to 13, wherein the first material comprises NdFeB microparticles.
15. The actuator of any one of claims 1 to 14, wherein the second material comprises a
10 curable elastomer, such as silicone rubber.
16. The actuator of any one of claims 1 to 15, wherein the substrate layer comprises one or more of a group consisting of a carbohydrate polymer, such as cellulose, a metal, a metal oxide, and a silicate mineral.
17. A robotic system comprising the actuator of any one of the preceding claims.
- 15 18. A method of fabricating an actuator for a robotic system, the method comprising the steps of:
 - providing a substrate layer;
 - providing an elastic layer on the substrate layer, the elastic layer comprising a first material with non-zero coercivity embedded in a second material; and
 - 20 imparting anisotropic mechanical properties to the substrate layer to promote preferential mechanical deformation of the substrate layer and the elastic layer during actuation of the actuator under an actuation electromagnetic field based on the interaction of the actuation electromagnetic field and the first material.
- 25 19. The method of claim 18, wherein the anisotropic mechanical properties of the substrate layer are the result of creases formed in the substrate layer for origami-type folding of the substrate layer and the elastic layer thereon.
20. The method of claims 18 or 19, wherein the anisotropic mechanical properties of the substrate layer are the result of cuts formed in the substrate layer for kirigami-type manipulation of the substrate layer and the elastic layer thereon.
- 30 21. The method of any one of claims 18 to 20, wherein the anisotropic mechanical properties of the substrate layer are the result of the substrate layer exhibiting different material compositions in different regions thereof.
22. The method of claim 21, wherein the different material compositions are the result of additive manufacturing, such as doping.

23. The method of any one of claims 18 to 22, wherein the anisotropic mechanical properties further promote preferential mechanical deformation of the substrate layer and the elastic layer before and after magnetization.
- 5 24. The method of claim 23, wherein the preferential mechanical deformation of the substrate layer and the elastic layer before magnetization, is into a magnetization configuration having a reduced volume compared to an actuation configuration.
25. The method of any one of claims 18 to 24, wherein an elastomeric property of the second material defines a quiescent configuration of the actuator when no actuation electromagnetic field is applied.
- 10 26. The method of any one of claims 18 to 25, wherein the preferential mechanical deformation occurs along fold lines defining a plurality of domains of the actuator, and the method further comprises programming a magnetization direction of each domain.
- 15 27. The method of claim 26, wherein a combination of the fold lines and the magnetization direction of the domains determines the deformation of the substrate layer and the elastic layer under the actuation electromagnetic field.
28. The method of claims 26 or 27, wherein the fold lines determine the magnetization direction under a magnetization electromagnetic field.
29. The method of any one of claims 18 to 28, wherein the selection of the substrate layer contributes to one or more additional properties of the actuator, such as conductivity.
- 20 30. The method of any one of claims 18 to 29, wherein the second material has a predetermined young's modulus and shear modulus.
31. The method of any one of claims 18 to 30, wherein the first material comprises NdFeB microparticles.
- 25 32. The method of any one of claims 18 to 31, wherein the second material comprises a curable elastomer, such as silicone rubber.
33. The method of any one of claims 18 to 32, wherein the substrate layer comprises one or more of a group consisting of a carbohydrate polymer, such as cellulose, a metal, a metal oxide, and a silicate mineral.
- 30 34. The method of any one of claims 18 to 33, further comprising removing the substrate layer to form a soft actuator.
35. The use of the actuator of any one of claims 1 to 16 in robotic activation.
36. An actuator fabricated by the method of any one of claims 18 to 34.

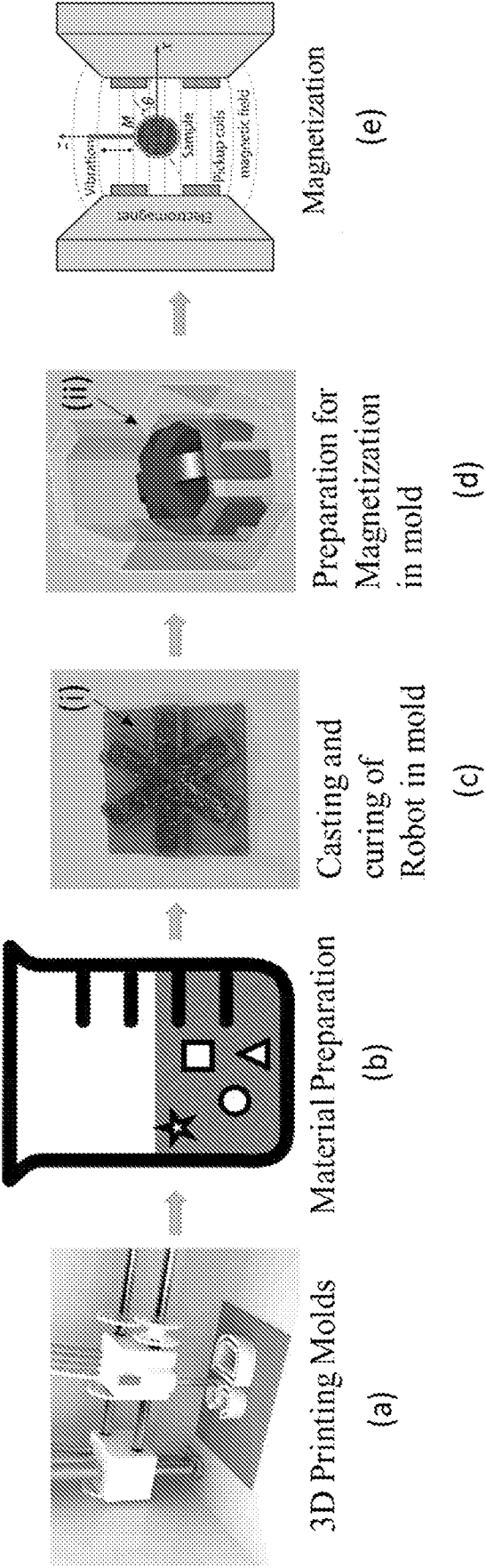


Figure 1
(Prior Art)

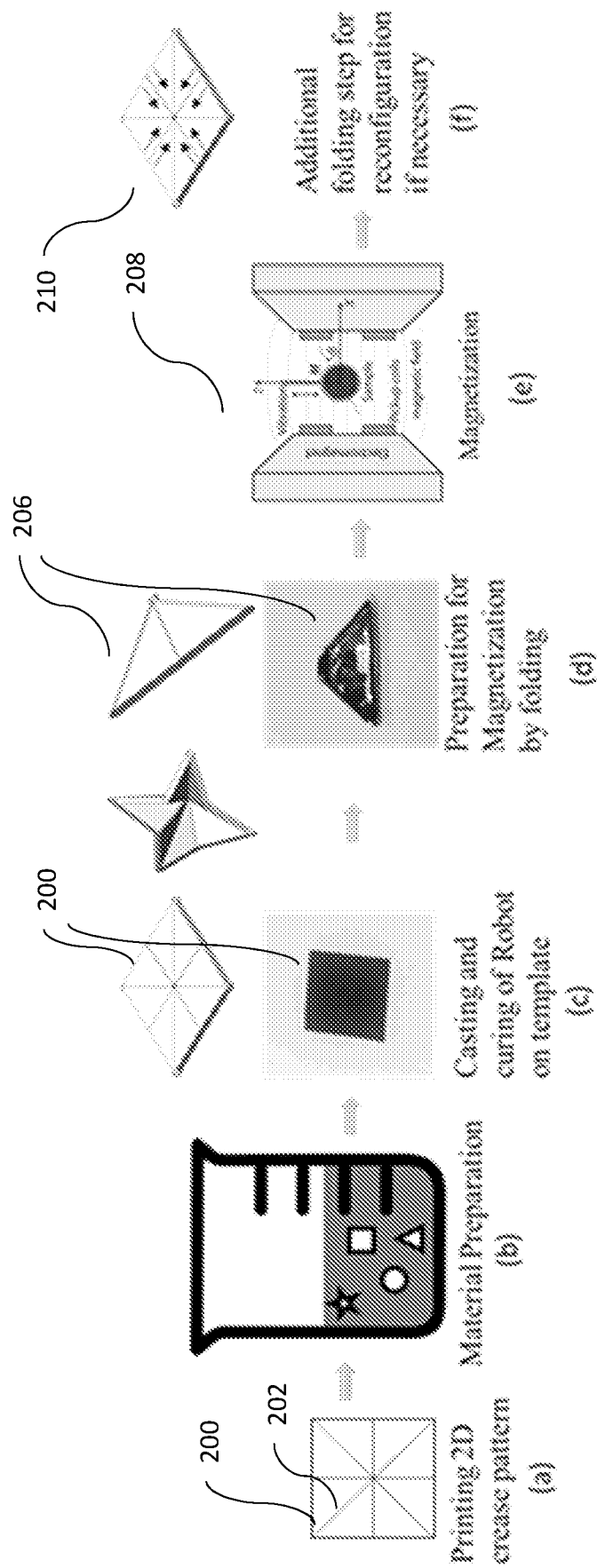


Figure 2

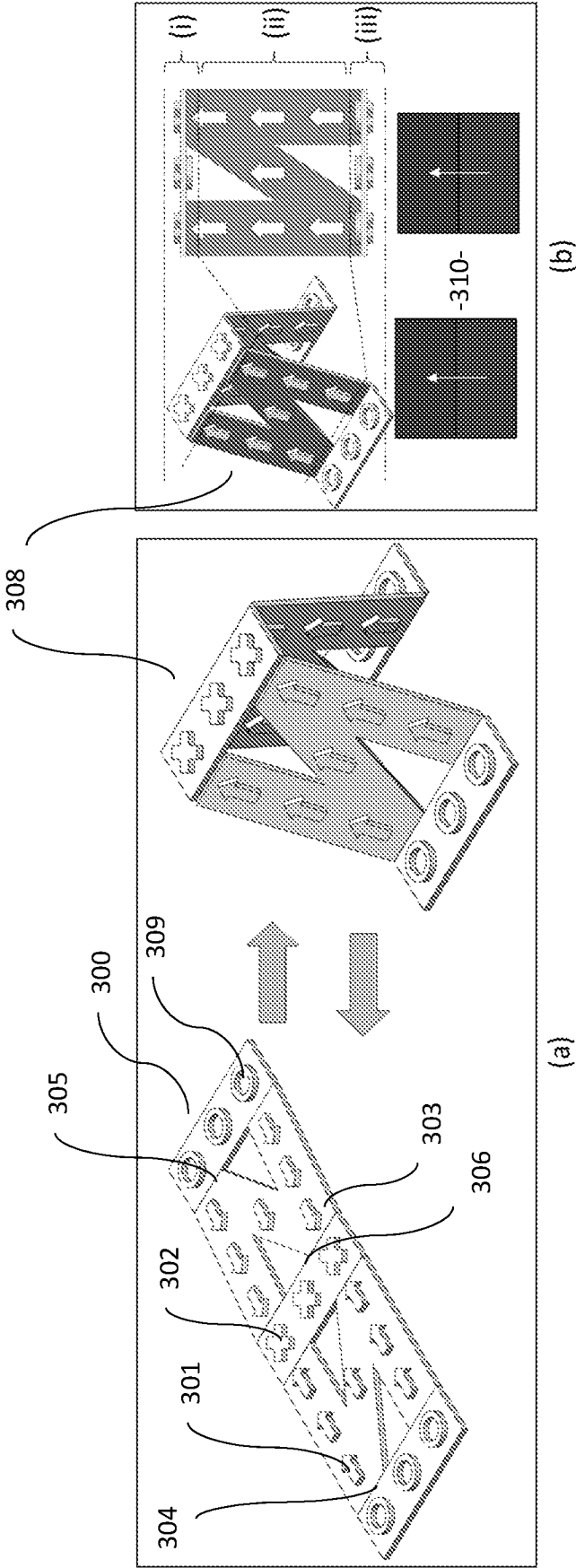


Figure 3

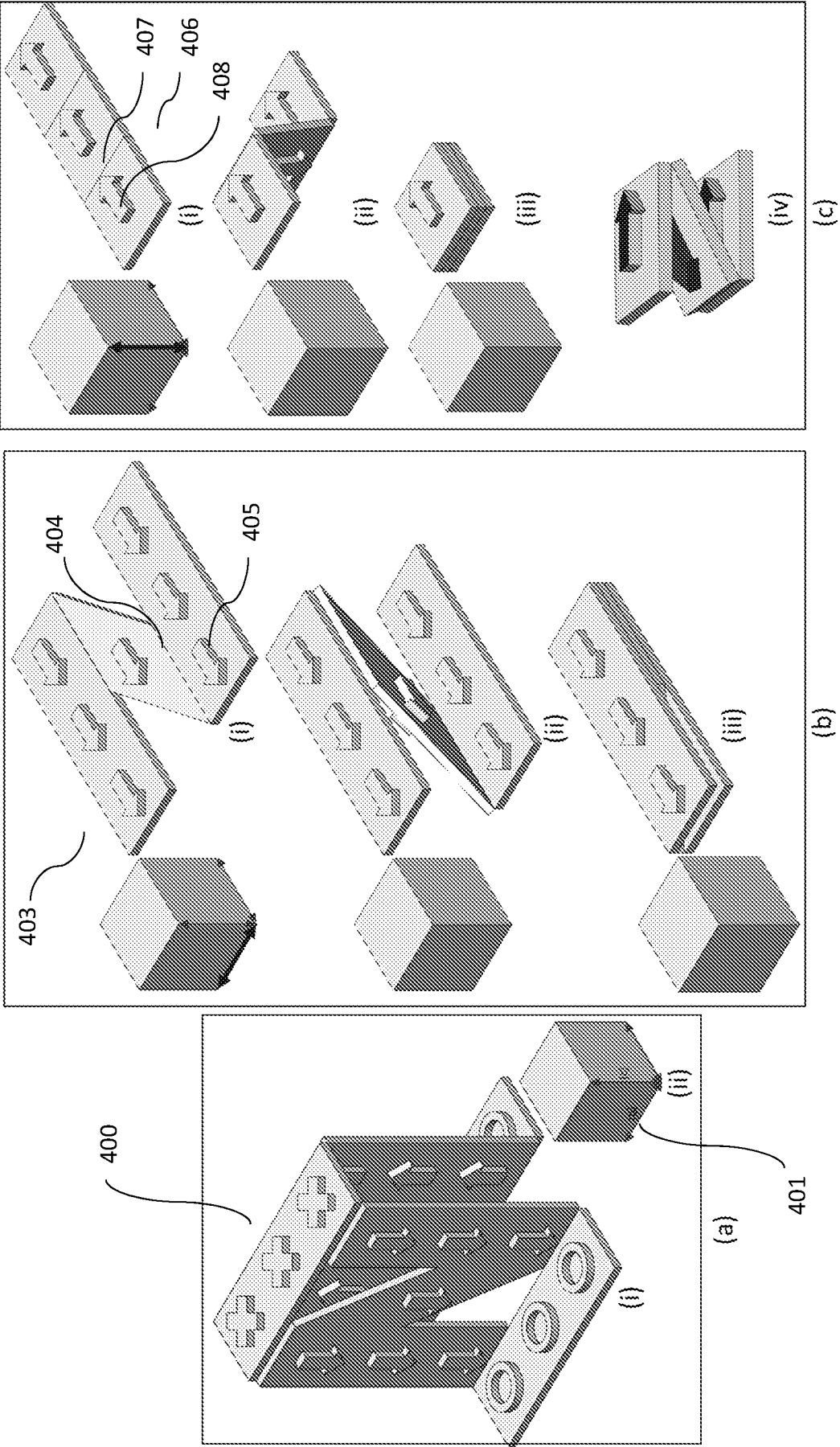


Figure 4

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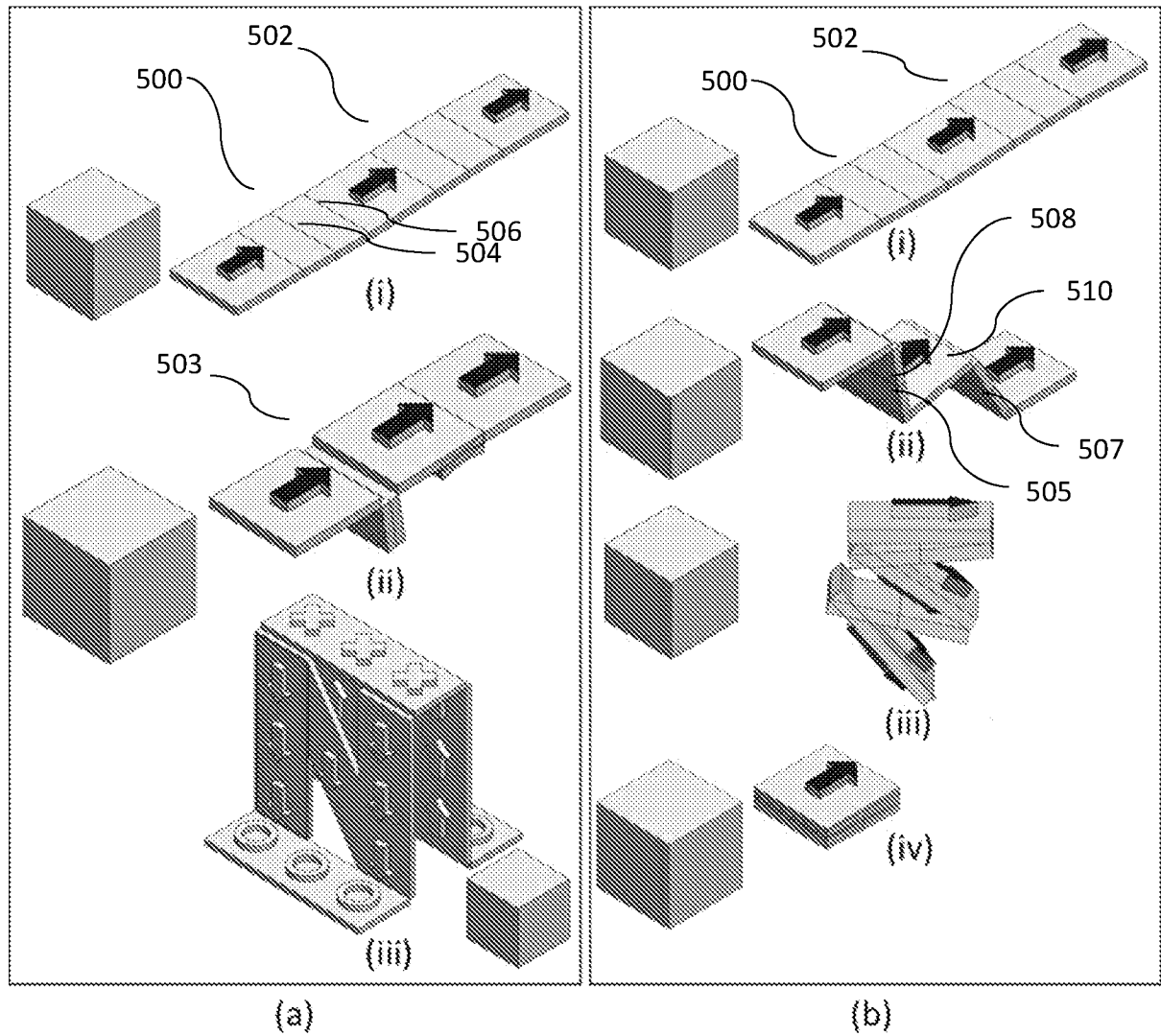


Figure 5

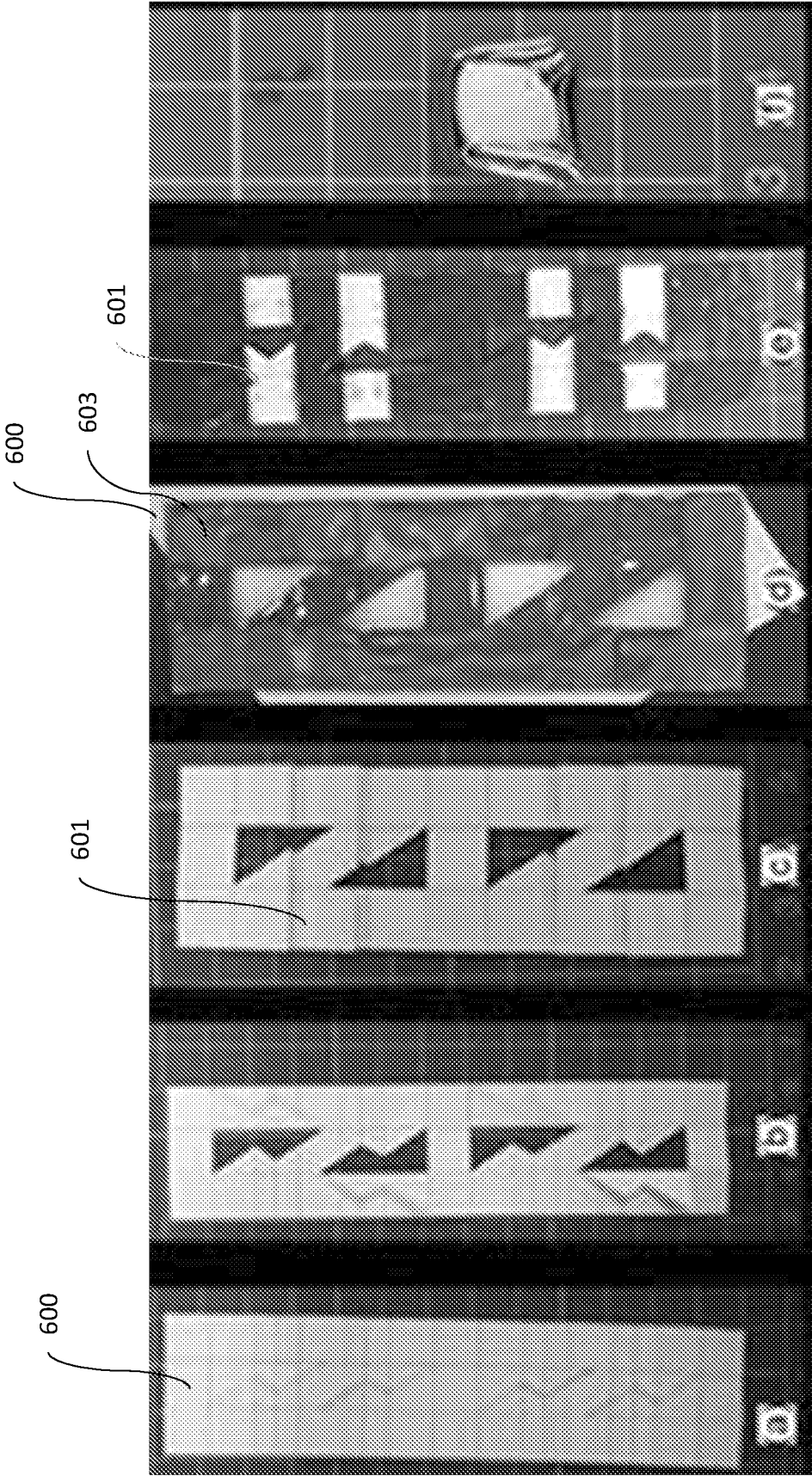


Figure 6

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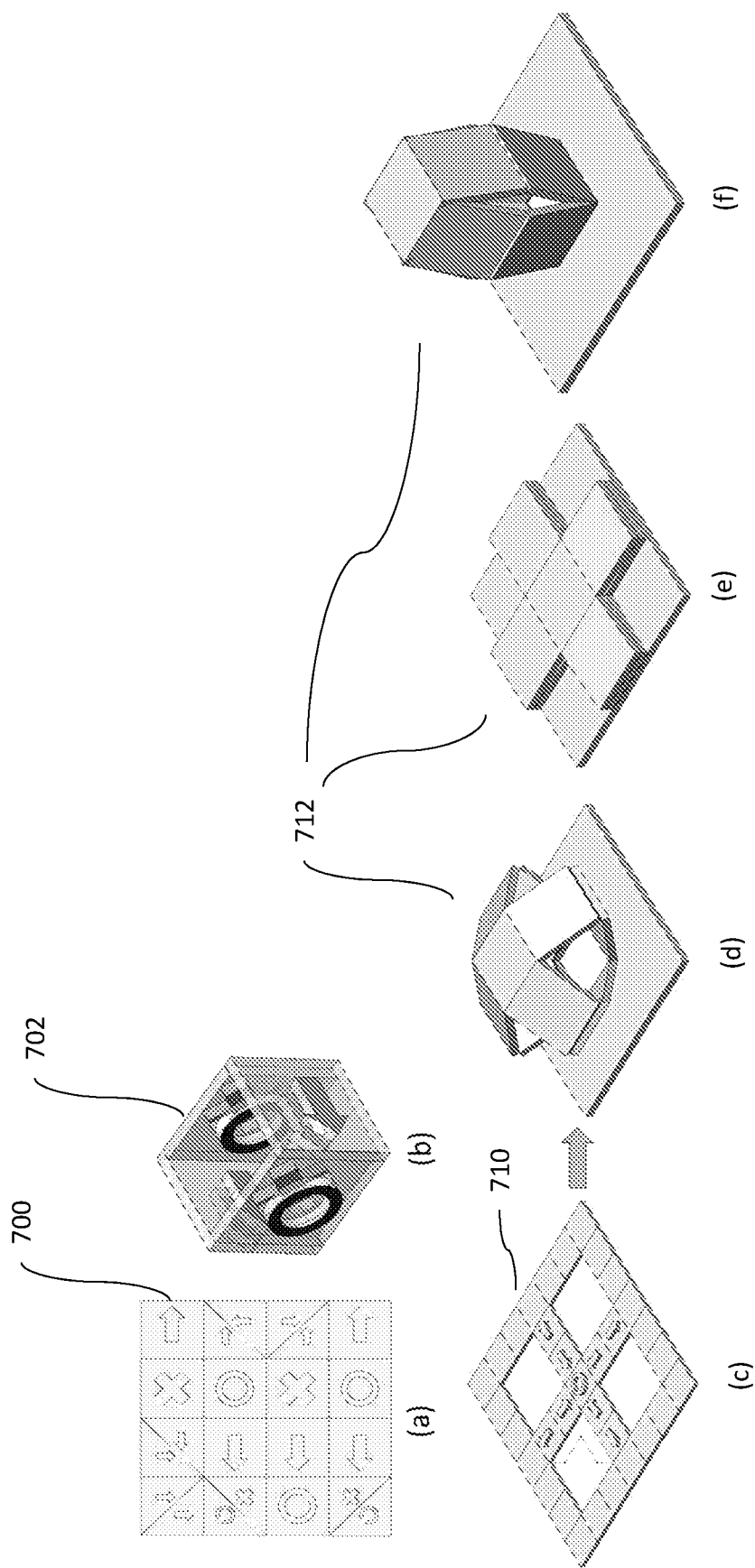


Figure 7

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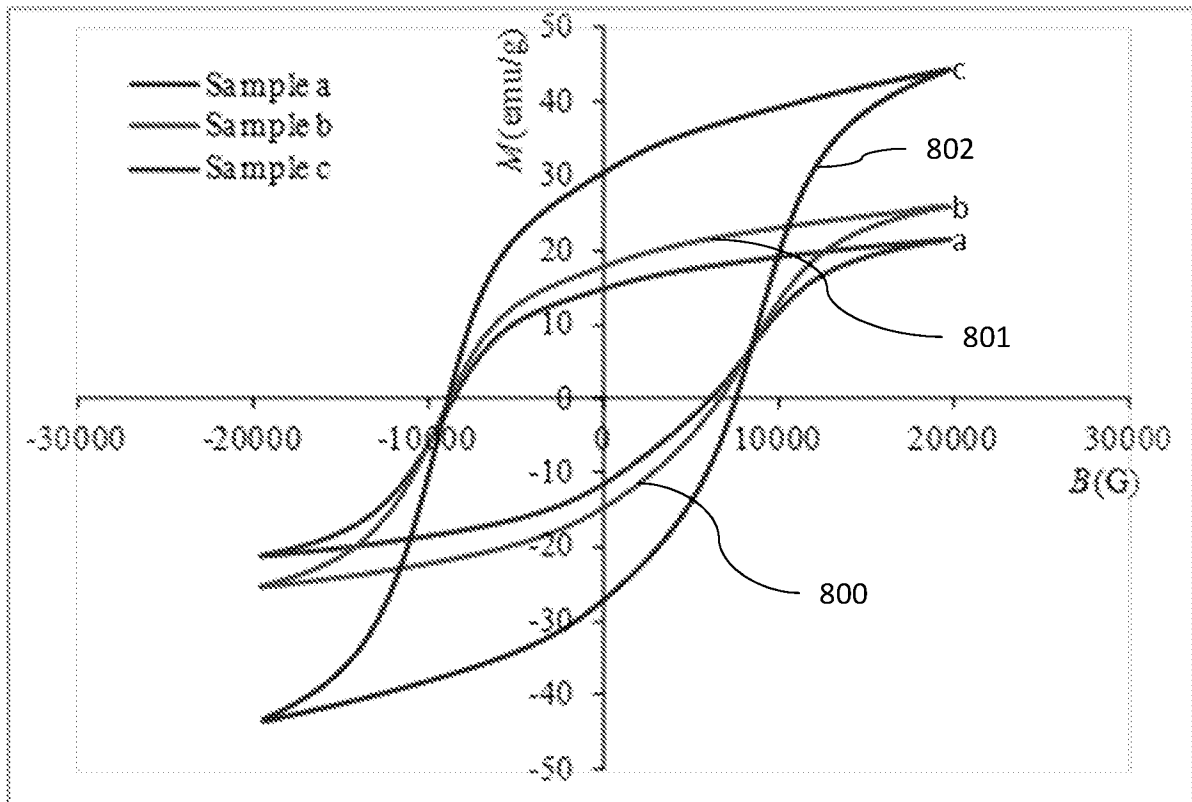


Figure 8

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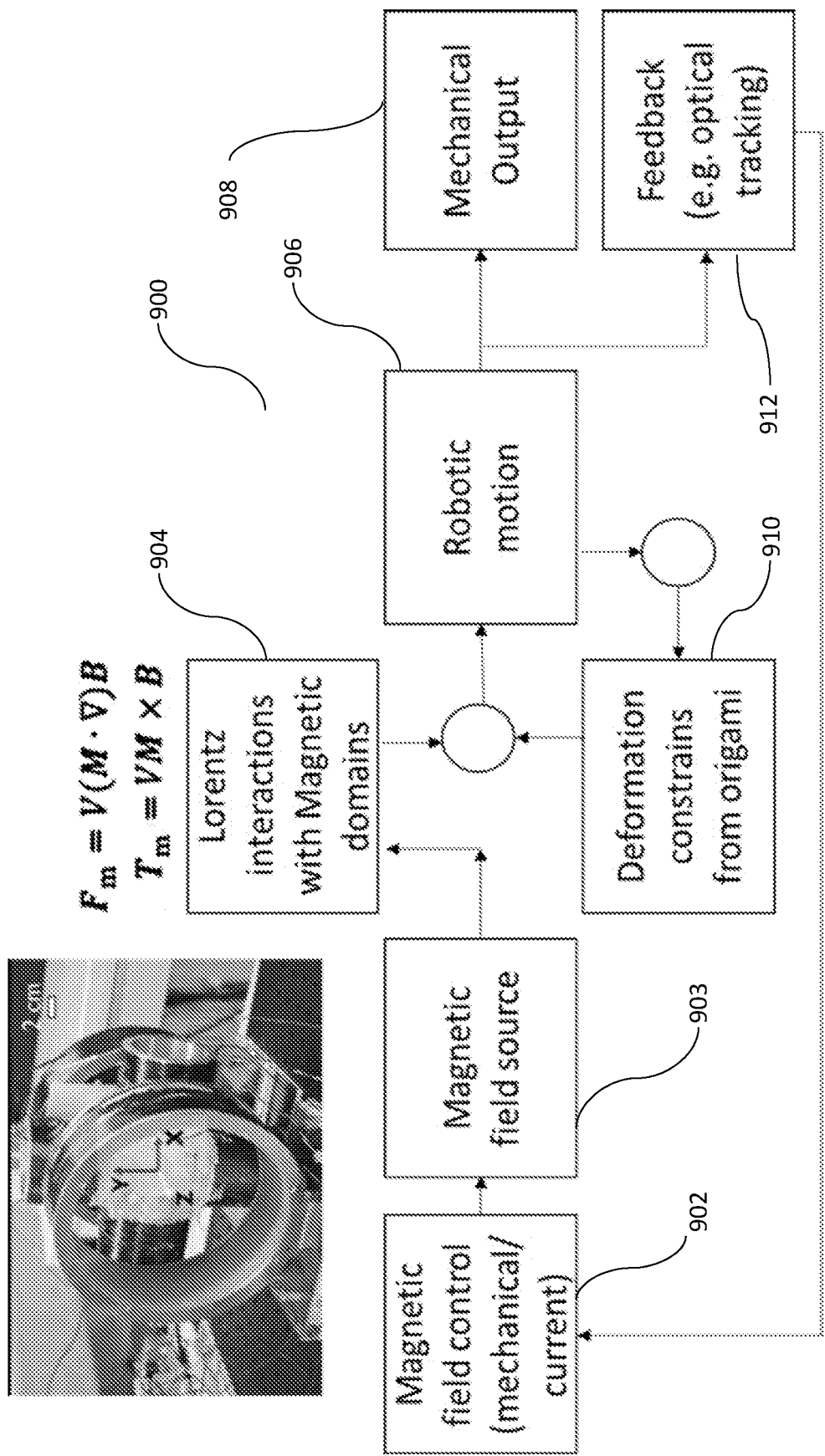


Figure 9

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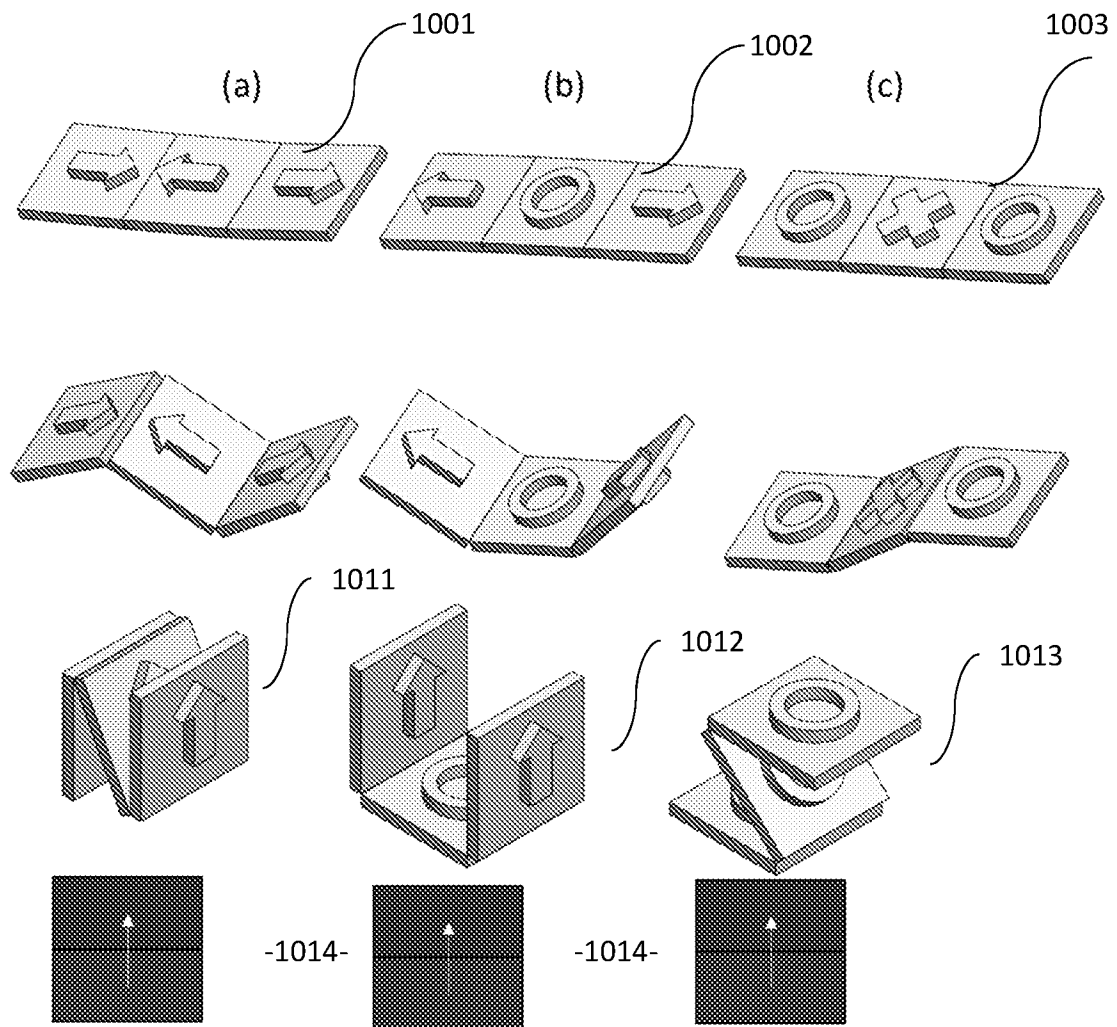


Figure 10

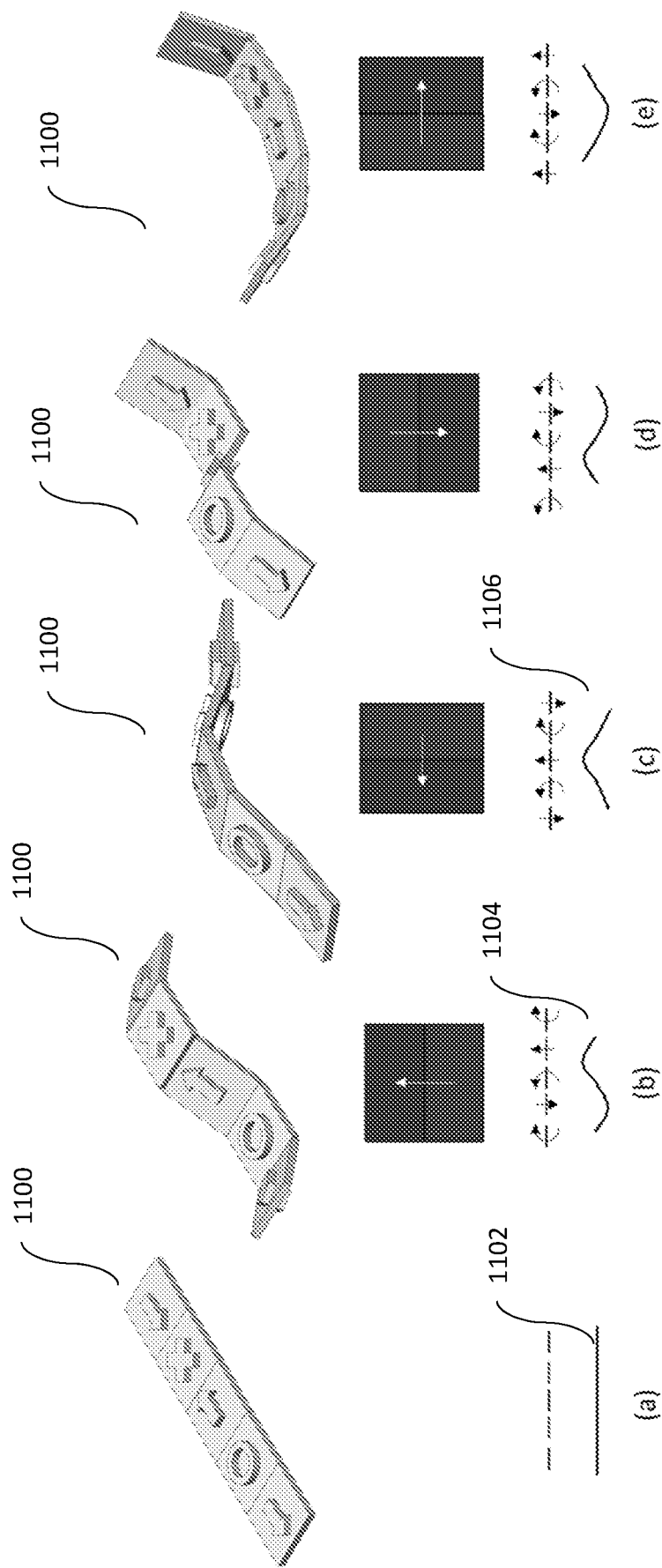


Figure 11

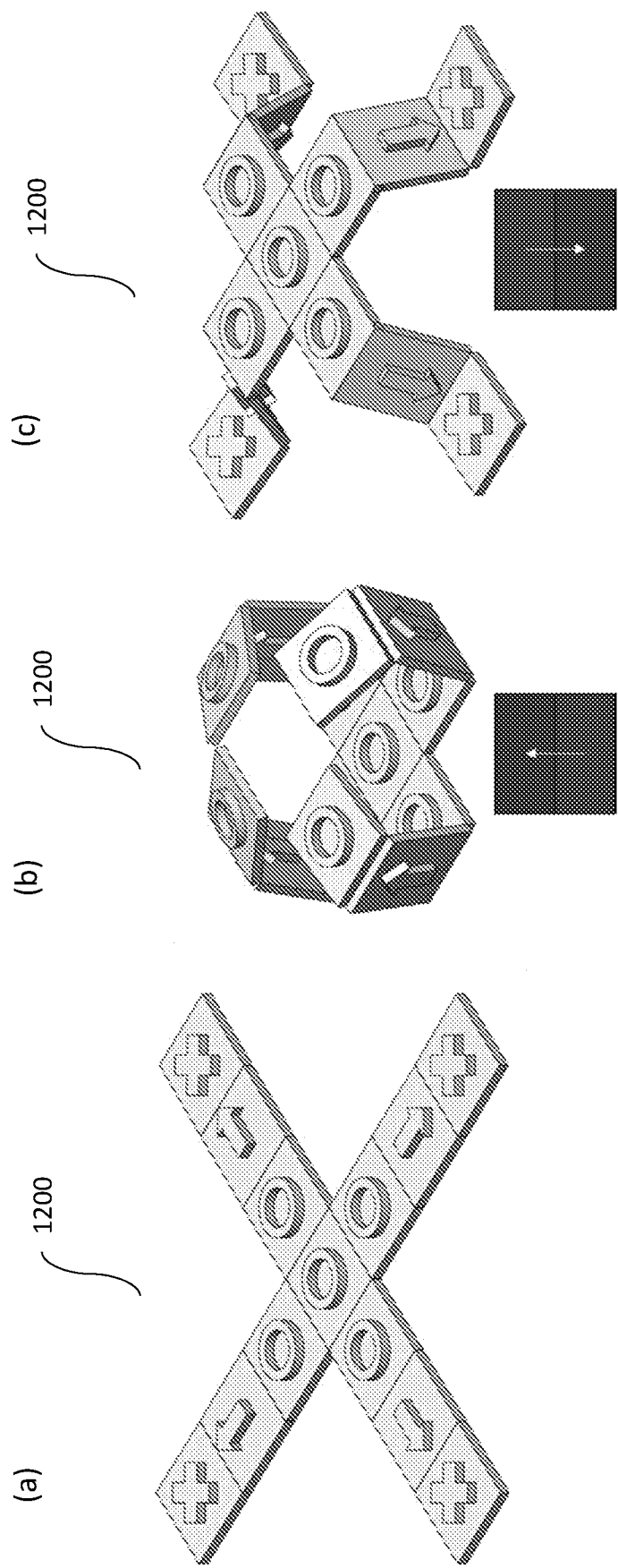


Figure 12

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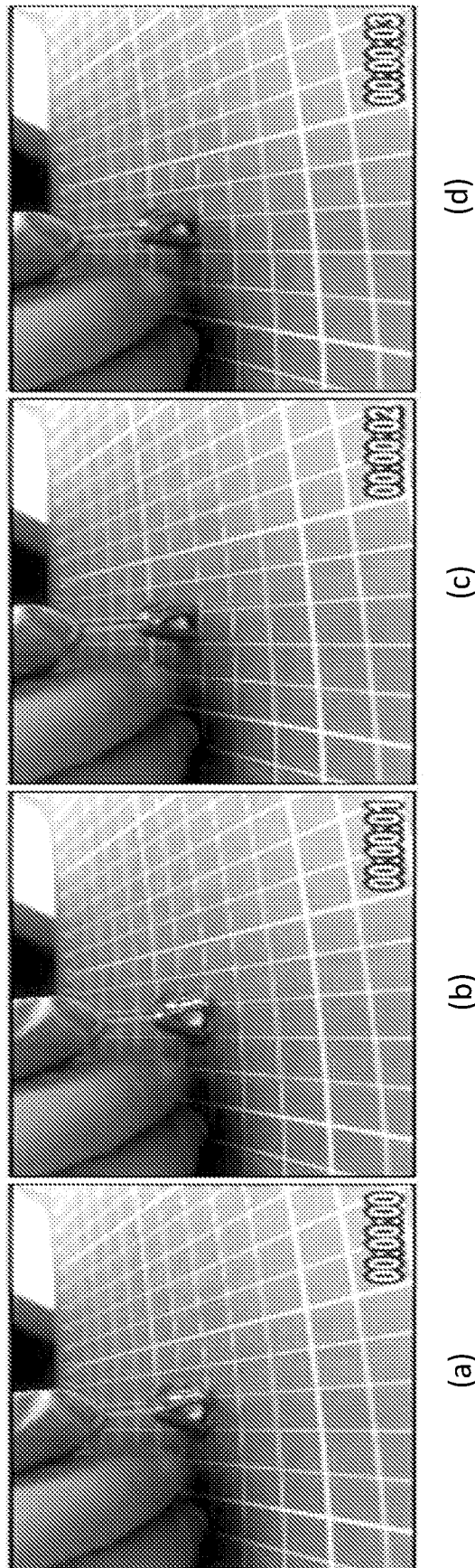


Figure 13

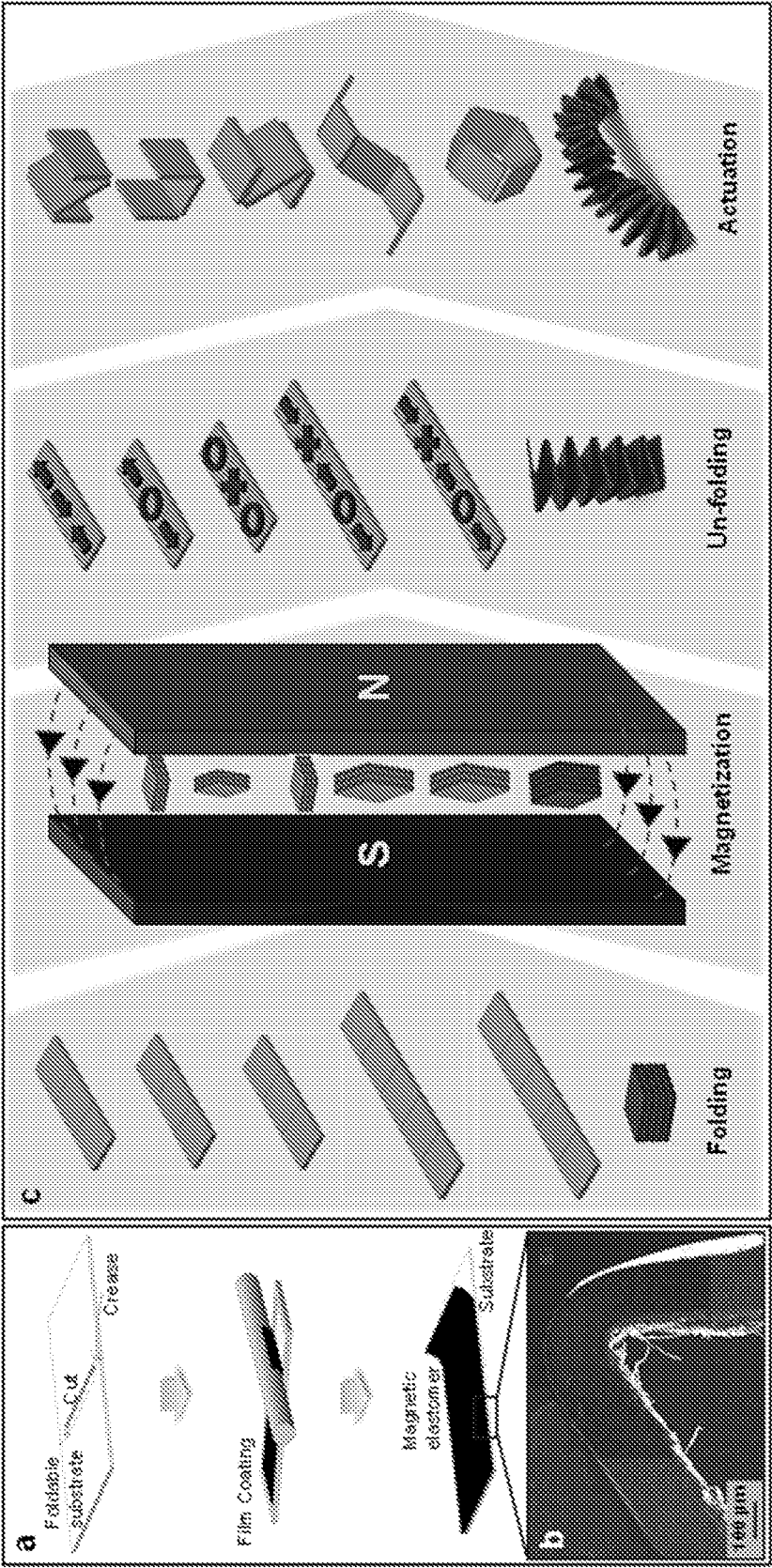


Figure 14

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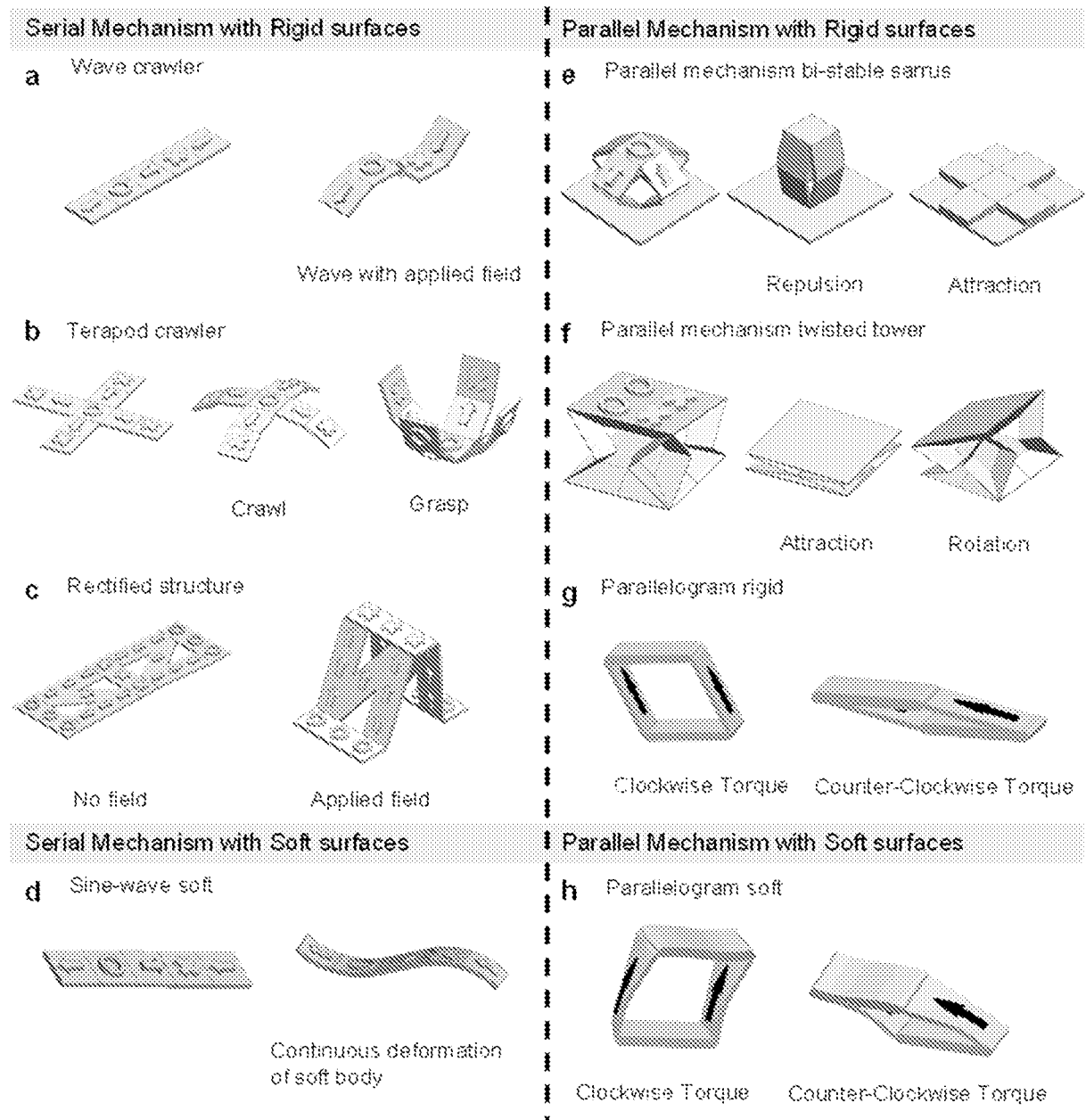


Figure 15

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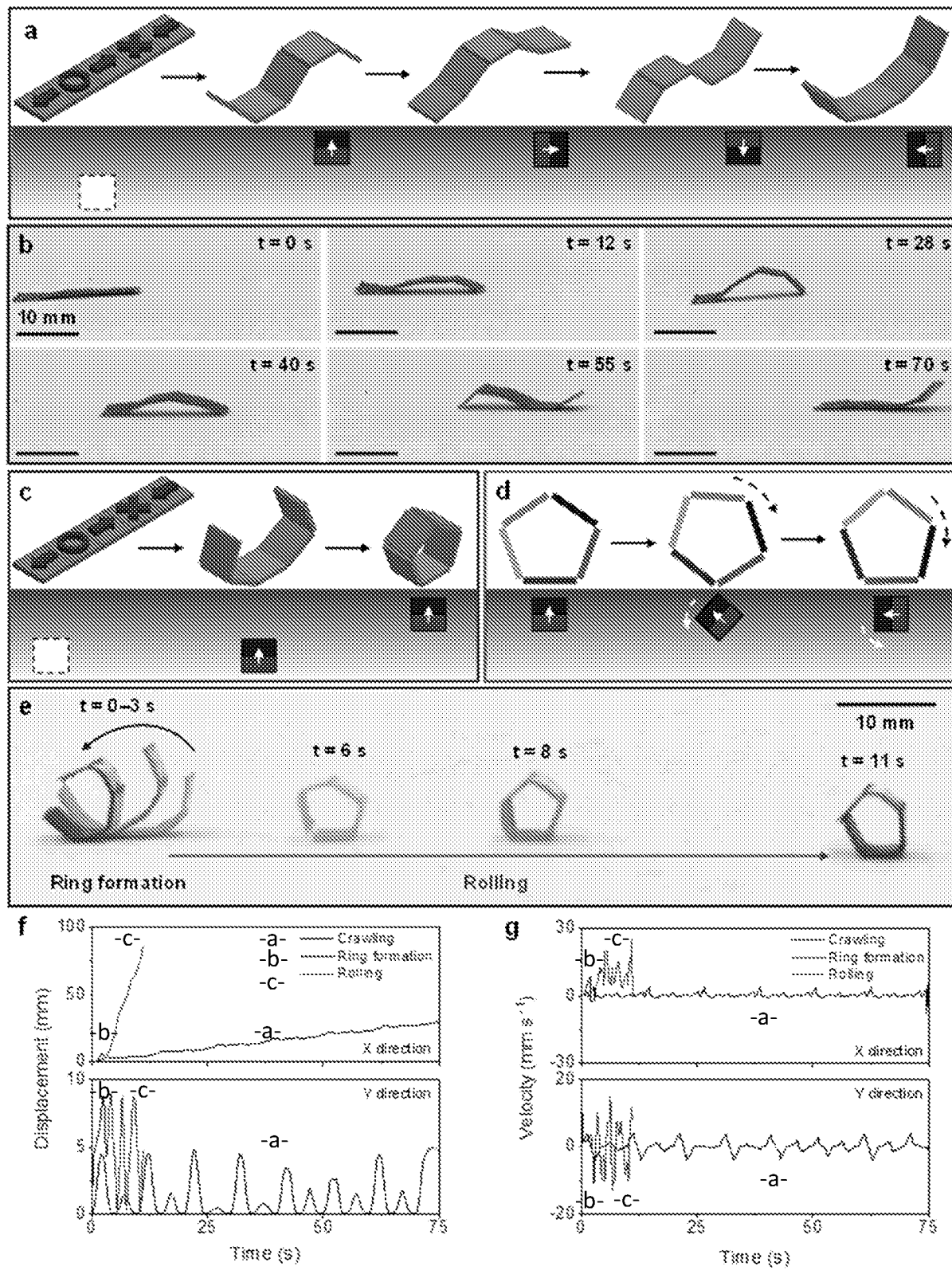


Figure 16

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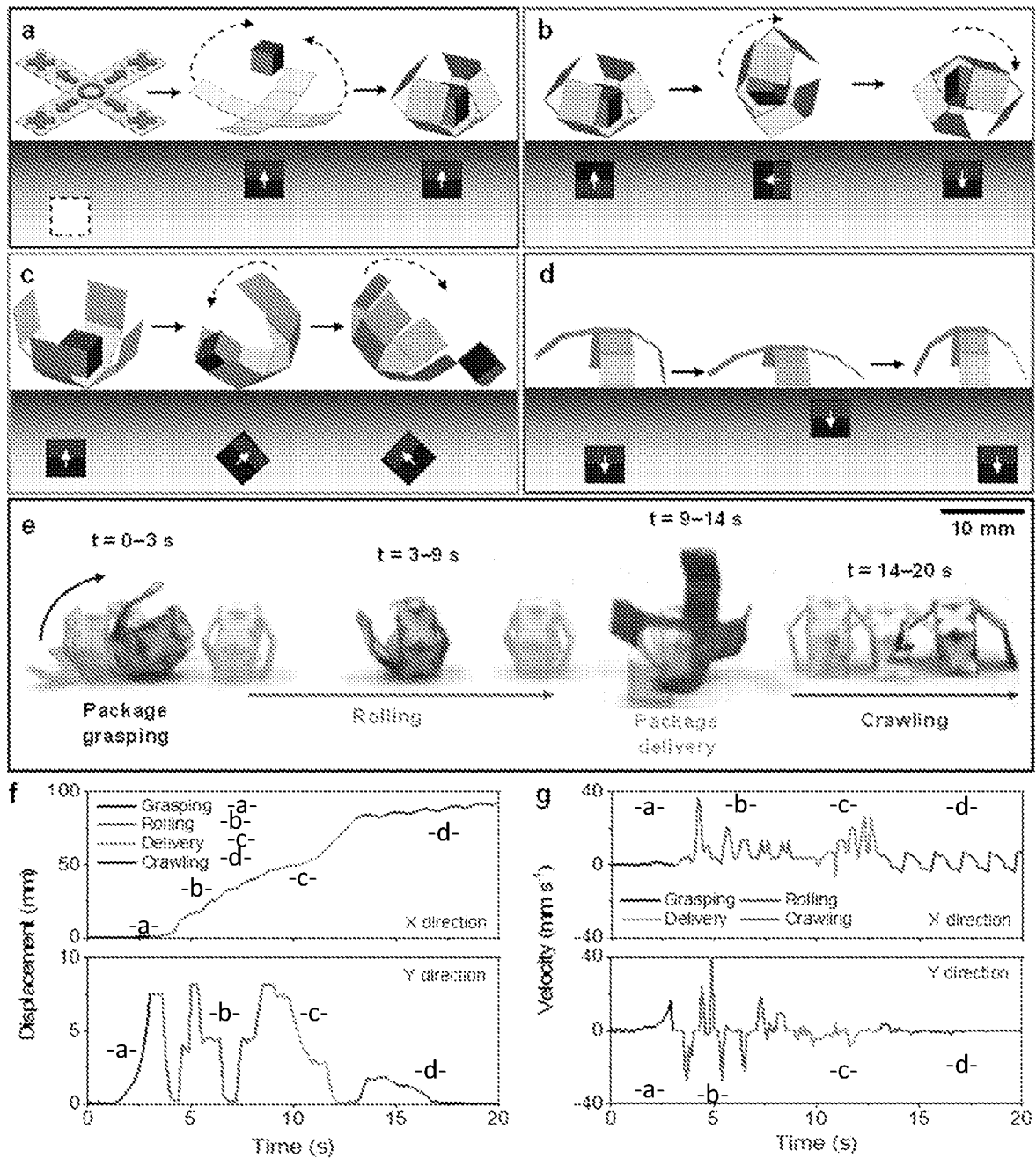
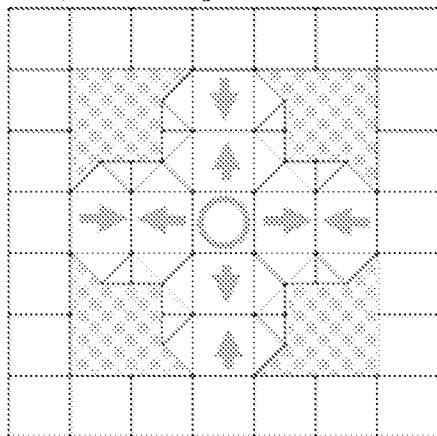
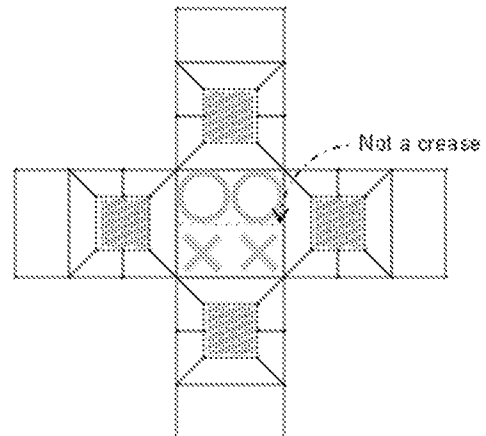


Figure 17

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a Crease pattern Design

Bi-stable sarrus



Twisted tower

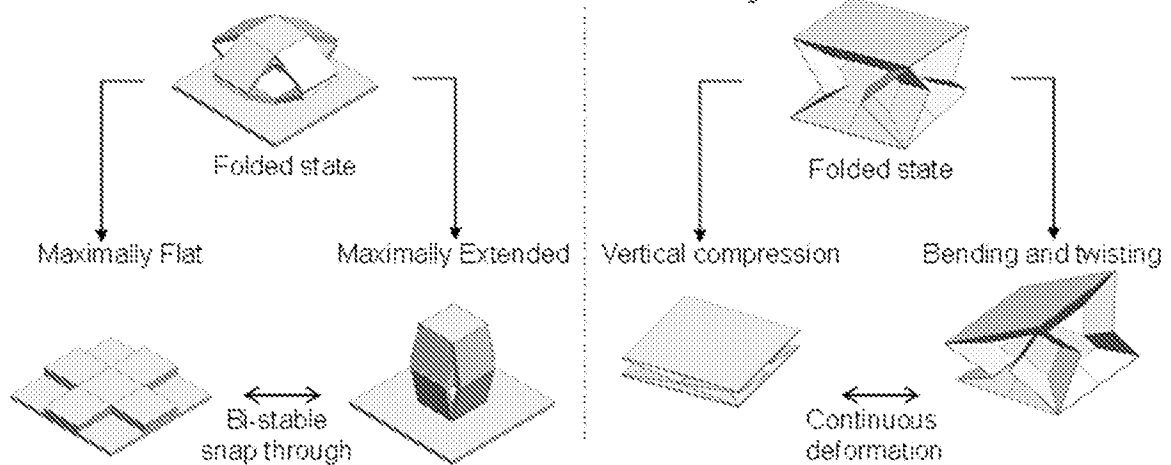
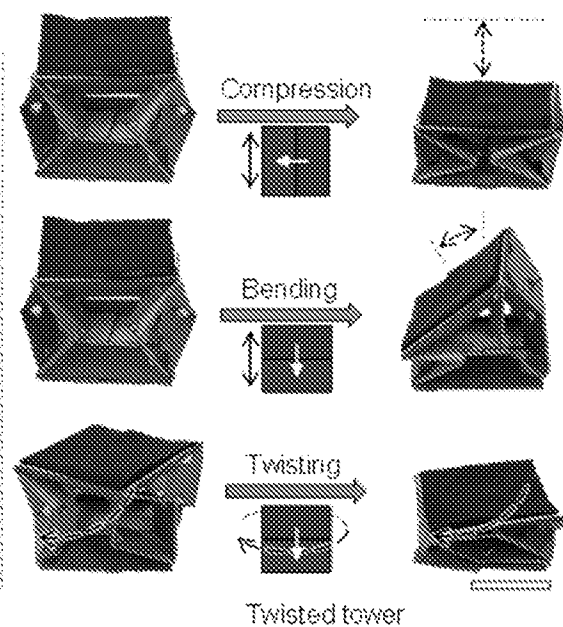
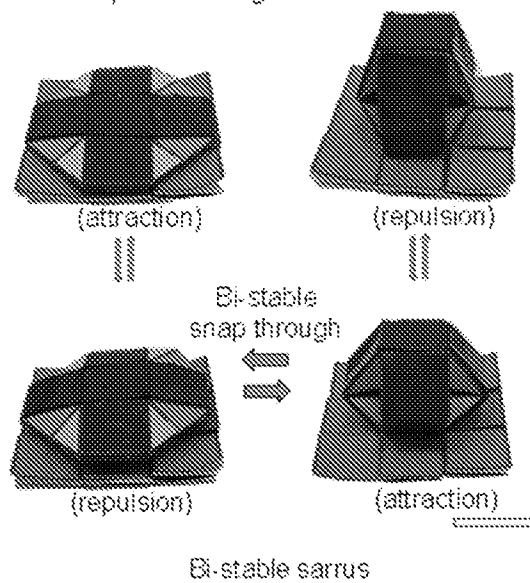
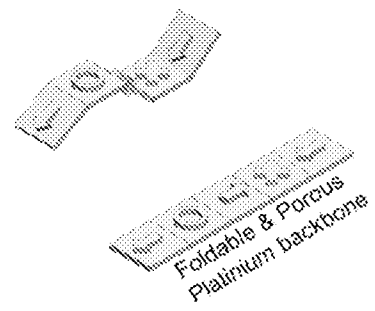
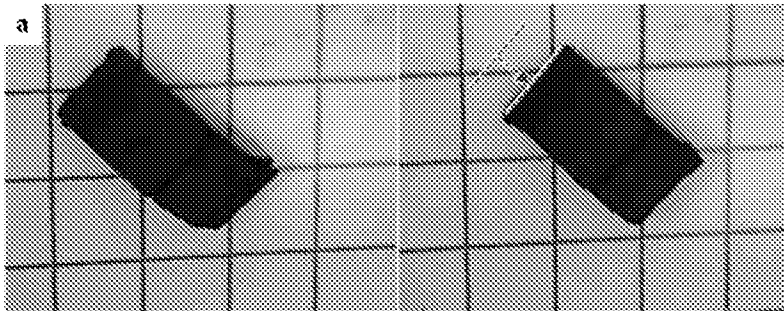
b Different structural deformations derived from variations in origami constraints**c** Crease pattern Design

Figure 18

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Pt robot wave crawling motion



Pt robot rolling up

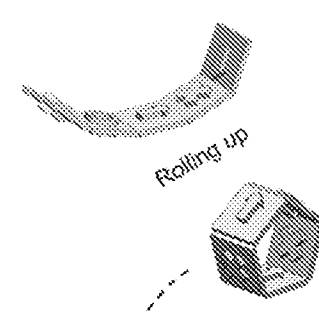
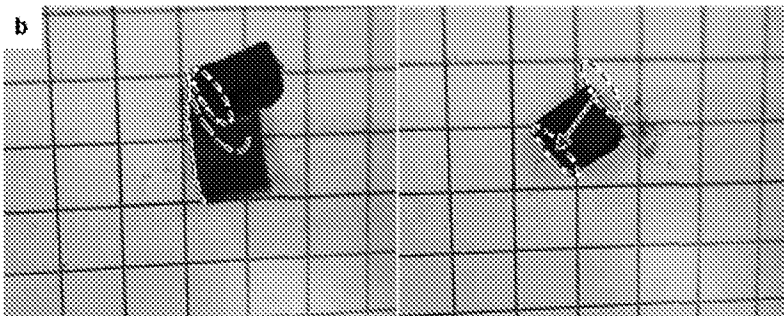
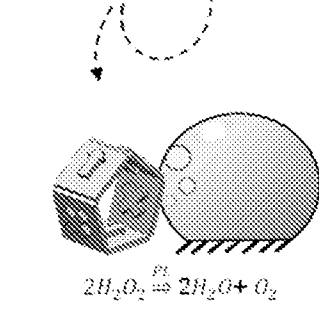
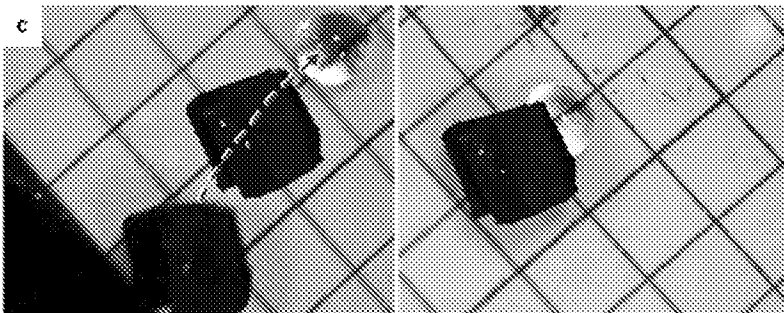
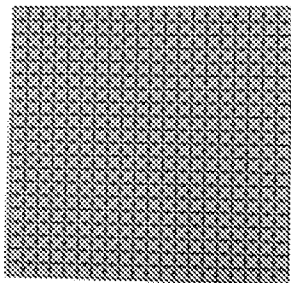
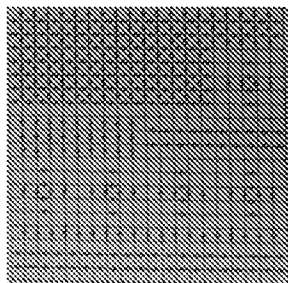
Pt robot moving to a H₂O₂ droplet

Figure 19

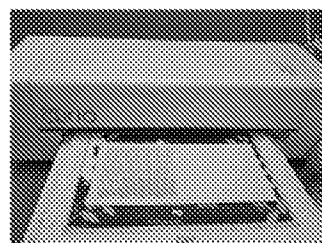
a 4mm template



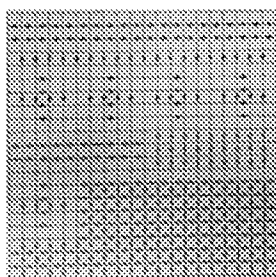
b Design Robots



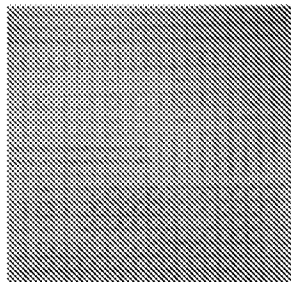
c Curio scores and cut



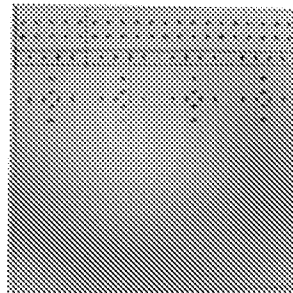
d After scoring and cutting



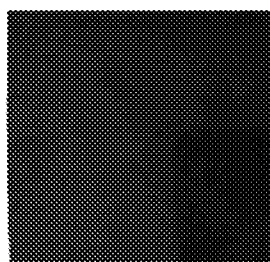
e Mounting to Plastic sheet



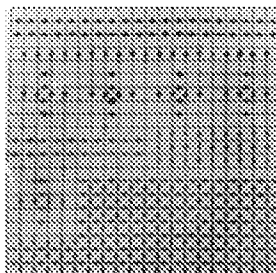
f Mounting paper frame



g Film coating Magnetoelastomer



h Removing plastic sheet



i Removing & magnetization

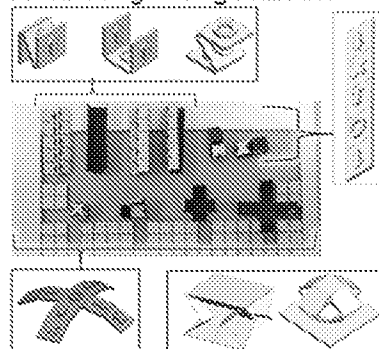


Figure 20

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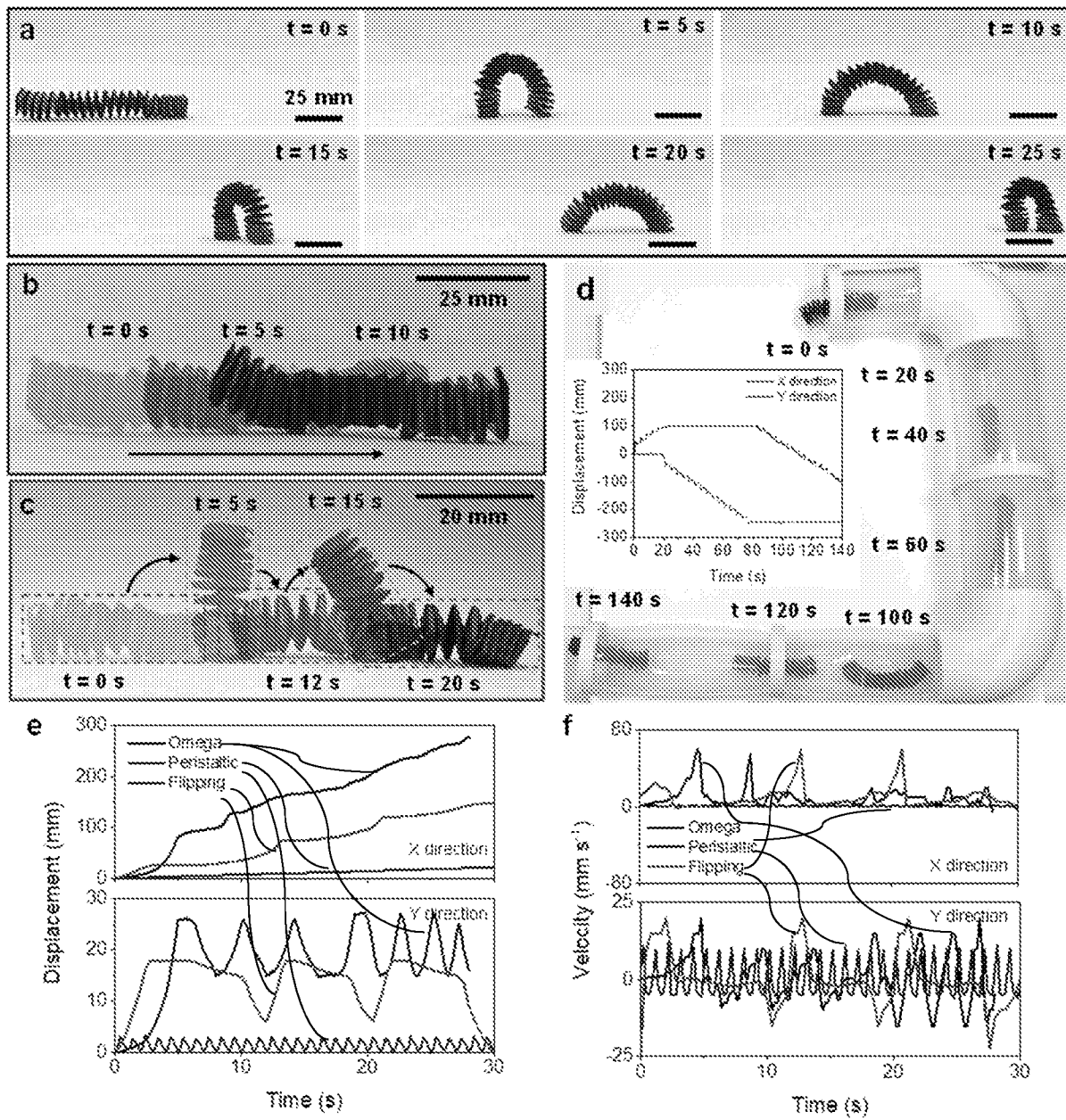


Figure 21

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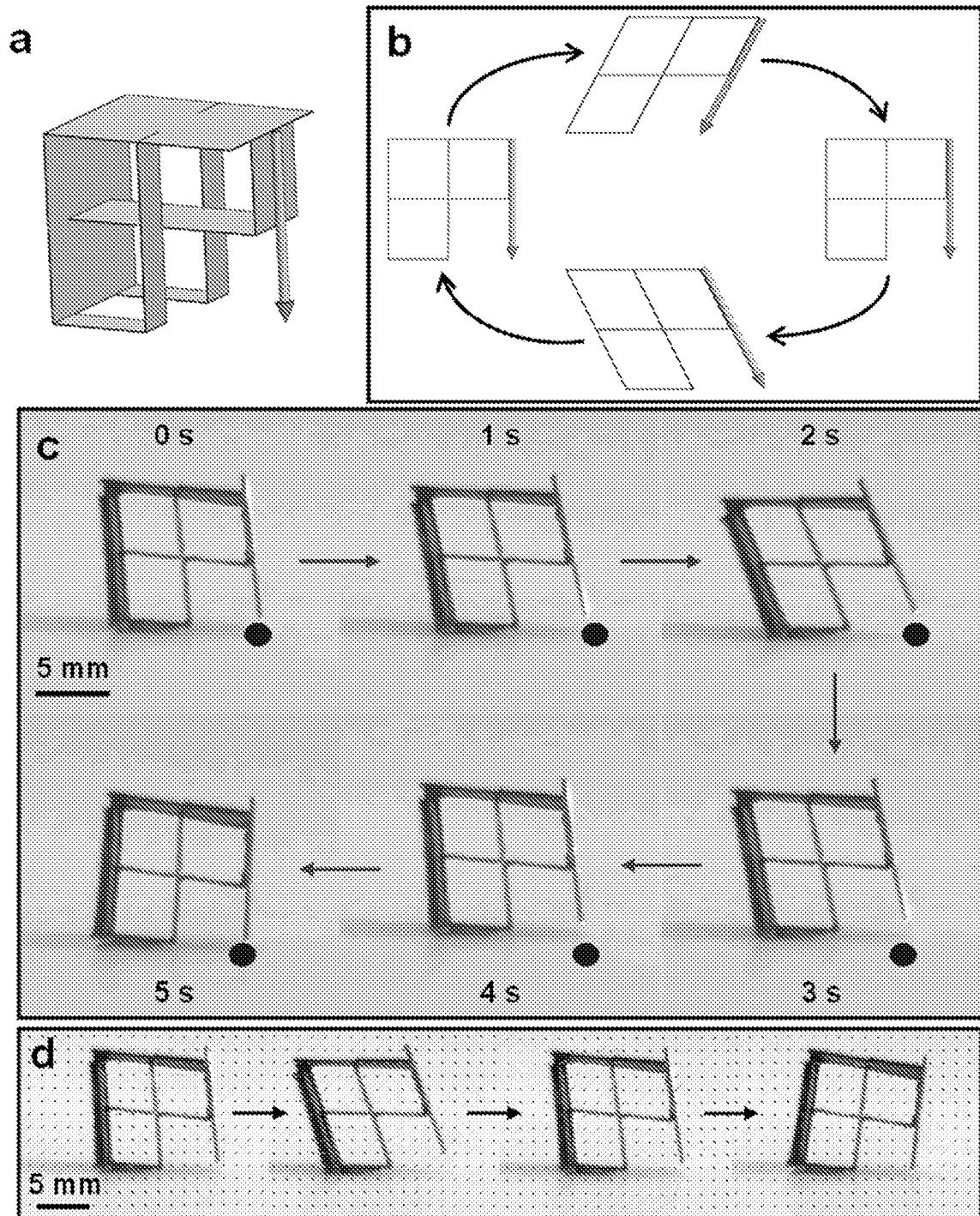


Figure 22

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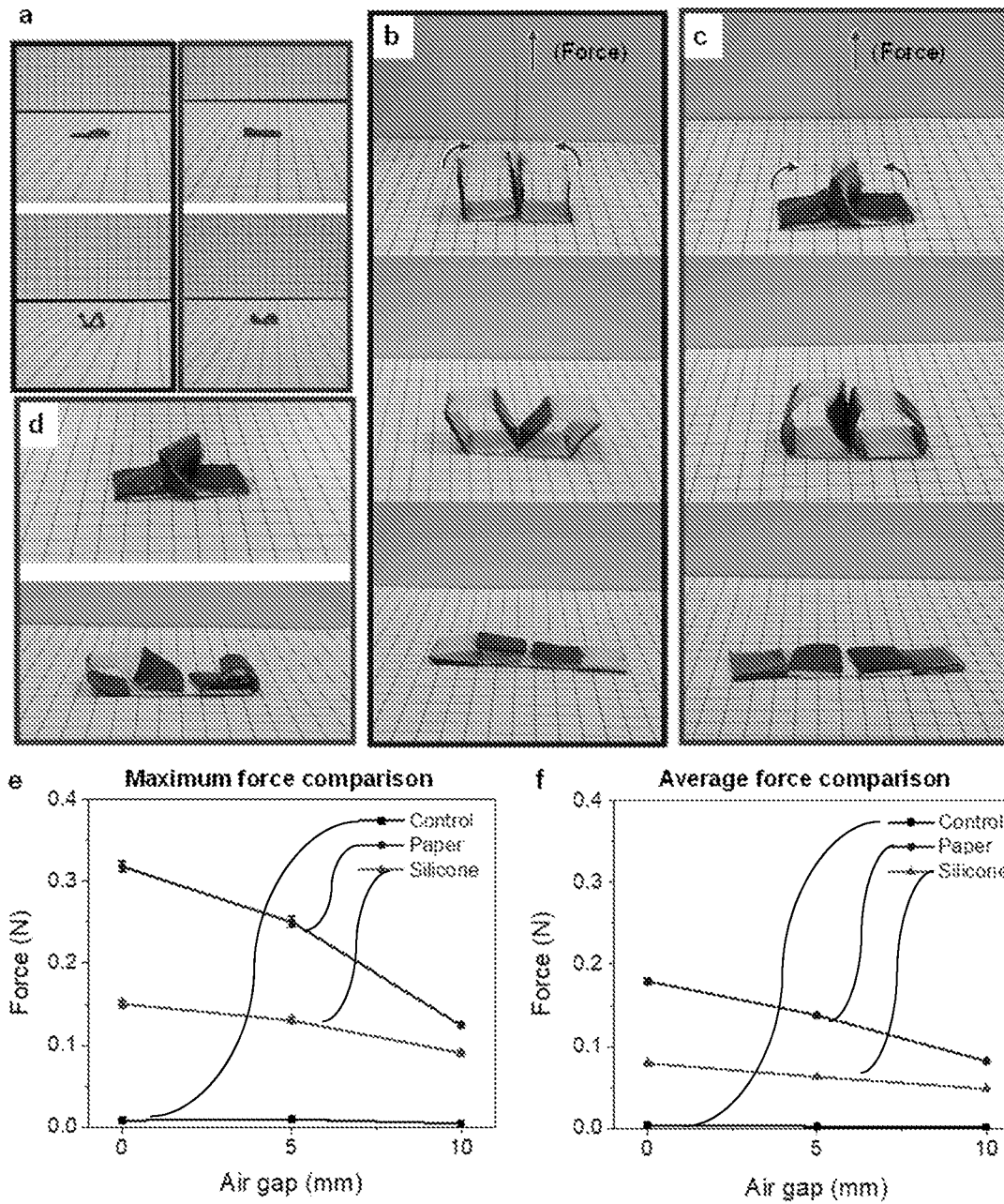


Figure 23

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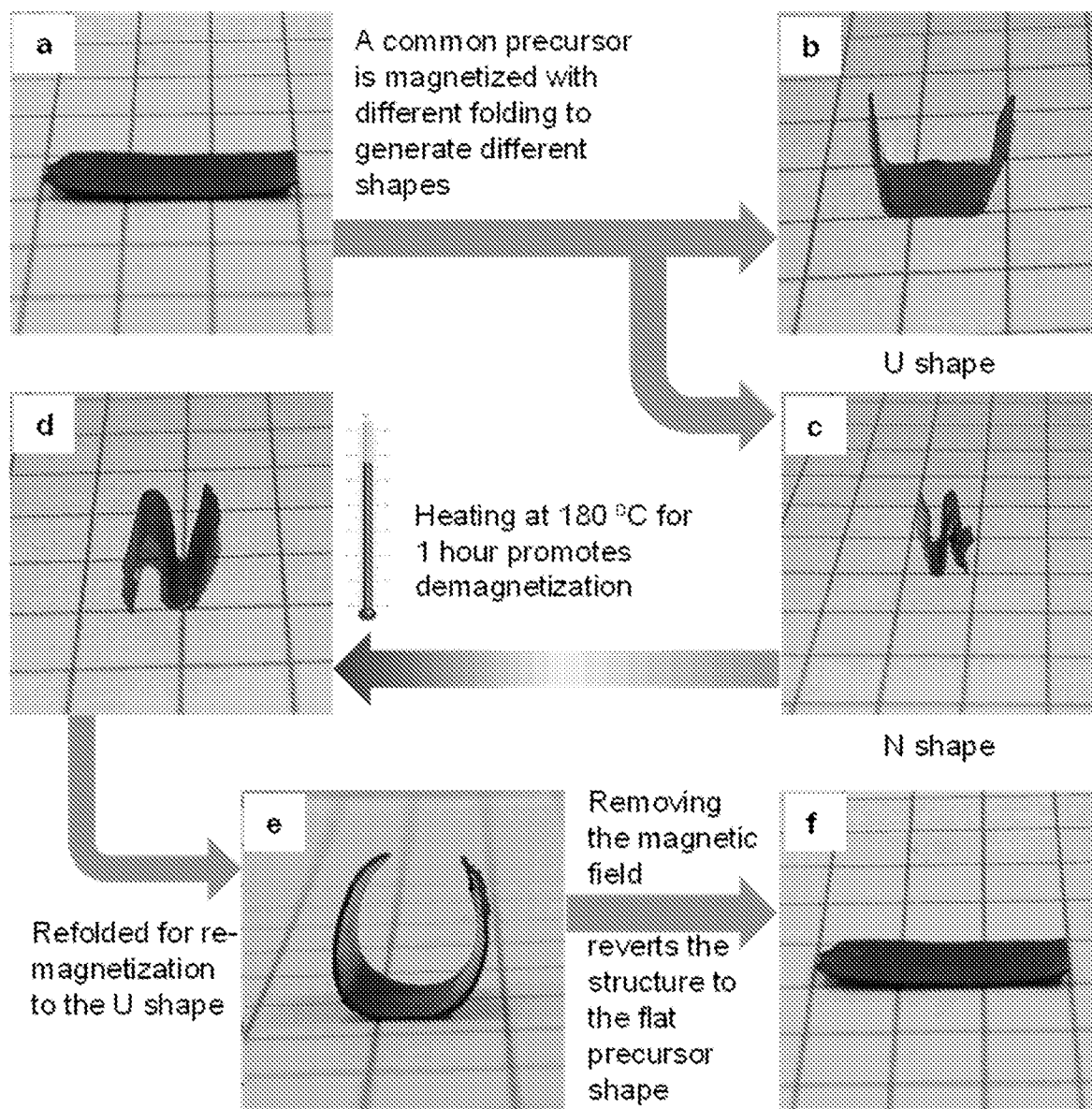


Figure 24

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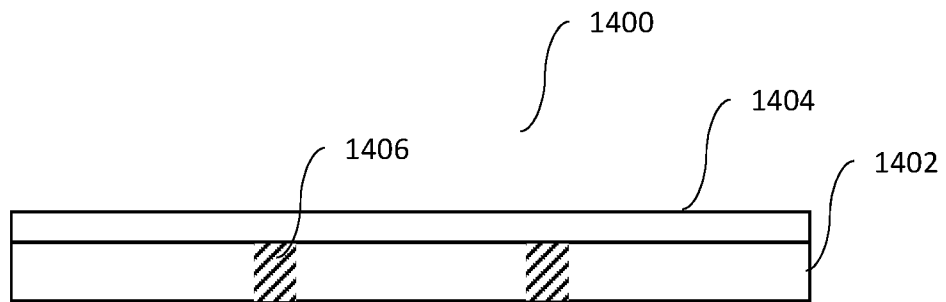


Figure 25

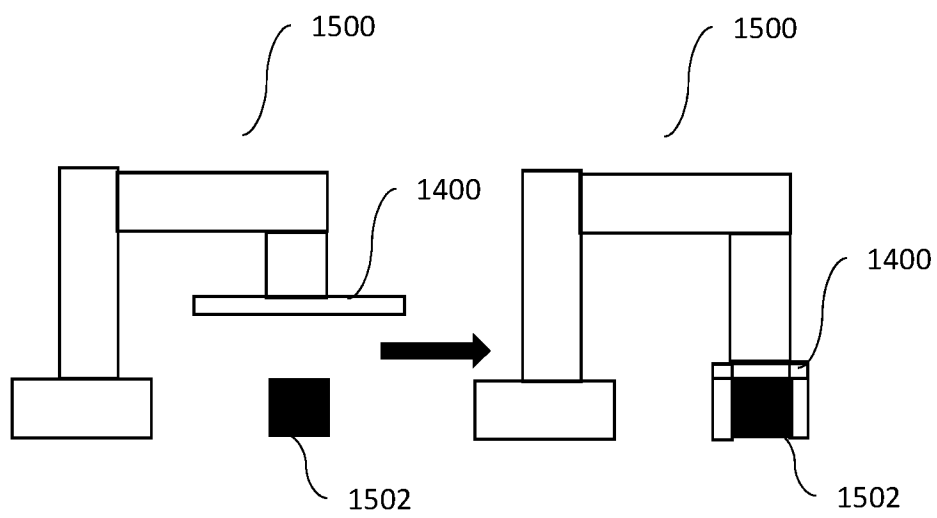


Figure 26

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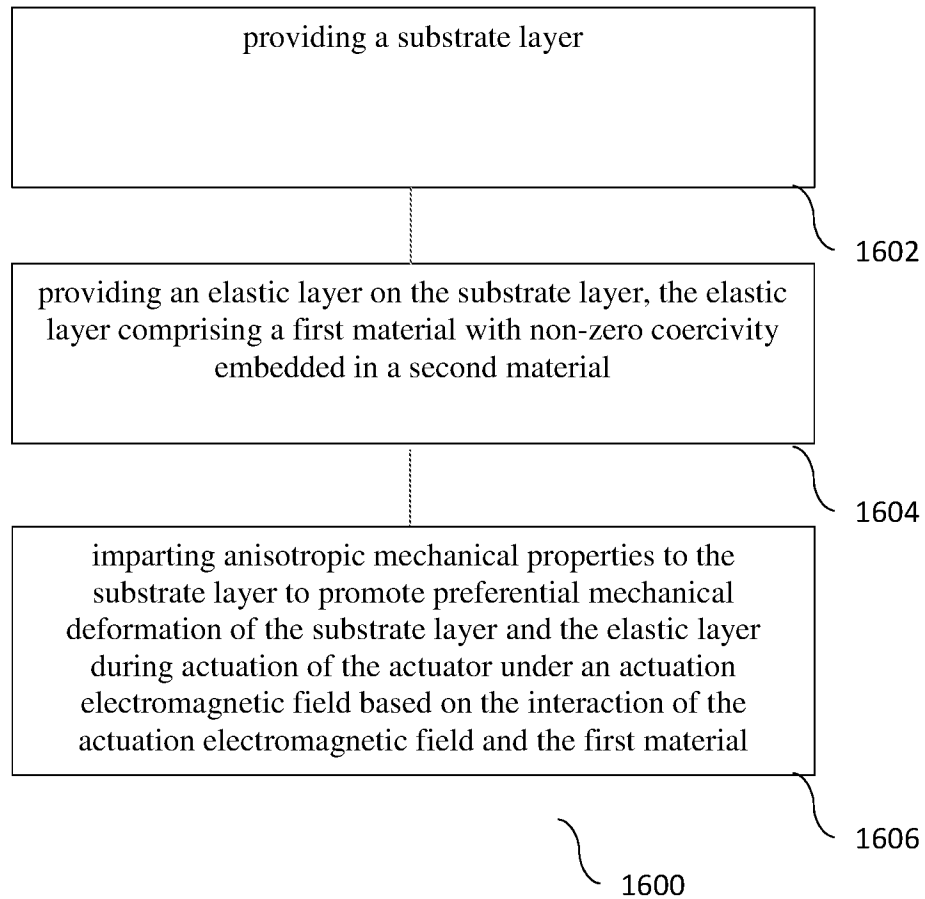


Figure 27

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2020/050097

A. CLASSIFICATION OF SUBJECT MATTER**B29C 61/06 (2006.01) B32B 3/00 (2006.01) B25J 9/00 (2006.01)**

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B29C, B32B, B25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Fampat, Caplus, Compendex, Inspec: actuator, robot, origami, kirigami, self-folding, elastomer, magnet and related terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BOWEN, L. ET AL., Design, Fabrication, and Modeling of an Electric-Magnetic Self-Folding Sheet. <i>Journal of Mechanisms and Robotics</i> , 9 March 2017, Vol. 9, No. 2, pages 021012-1 – 021012-13 [Retrieved on 2020-03-20] <DOI: HTTPS://DOI.ORG/10.1115/1.4035966> Page 021012-5 right column paragraph 3, page 021012-9 left column paragraph 5, figures 19, 21, 24	1-36
X	US 2017/0303965 A1 (RUS, D. ET AL.) 26 October 2017 Paragraphs [0031], [0033], [0037], [0069], [0084], figures 1, 2, 5, 7	1-36
A	US 2016/0136877 A1 (ROGERS, J. A. ET AL.) 19 May 2016 Whole document.	-
P,X	YANG, H ET AL., Graphene Oxide-Enabled Synthesis of Metal Oxide Origamis for Soft Robotics. <i>ACS Nano</i> , 21 March 2019, Vol. 13, No. 5, pages 5410-5420 [Retrieved on 2020-03-30] <DOI: HTTPS://DOI.ORG/10.1021/ACSNANO.9B00144> Whole document.	1-36

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

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"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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30/03/2020

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2020/050097

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2017/0303965 A1	26/10/2017	US 2020/0038061 A1 WO 2017/185003 A1	06/02/2020 26/10/2017
US 2016/0136877 A1	19/05/2016	NONE	