Unterthered microbot powered by giant magnetoelastic strain

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Abstract

Magnetic elastomers deform under a magnetic field, working as a soft actuator. Untethered microbot made of magnetic elastomers have great potentials in performing medical tasks inside human body as mini doctors. However, the lack of a highly deformable and efficient actuator strongly limits the development of magnetic microbots. In this paper, we developed an actuator of magnetic elastomer capable of large deformation strain by harnessing magnetic pull-in instability. We design three prototypes of untethered microbots by using this actuator: a robot grips objects with a large rotating angle, a robot navigates in a fluid channel and delivers drug, and a robot self-accelerates and quickly jumps up. The pull-in mechanism enables a new type of soft robot with fast response, remote wireless control and extremely high power density.

Introduction

Subject to an external magnetic field, magnetic particles embedded in a soft matrix tend to rotate along the field direction and meanwhile interact with one another. This mechanism has been used as soft magnetic actuators for about two decades. Magnetic elastomers can be actuated either by a permanent magnet [1-4] or a controllable gradient magnetic field from an electromagnet [5-7]. Driven by a gradient magnetic field, the magnetic elastomer tends to move towards the magnetic field source. Driven by a uniform magnetic field, lined-up magnetic particles can bend locally, leading to various deformation modes. For example, Kim et al. patterned the magnetic particle chain in a photocurable resin and achieved snake-like movement under a uniform magnetic field [8]. Huang et al. fabricated self-assembly membranes, which could reconfigure its shape in a magnetic field as a microbe-like swimmer [9]. Schmauch et al. also designed the magnetic membranes to function as a lifter, valve and accordion [10]. Another recent [11] printed magnetic ink into heterogeneous membrane, which could transform under magnetic field into complicated 3D structures through exquisite design and control. However, the actuation strain in all the above actuators is very small. No soft actuators capable of large magnetic actuation strain under a uniform magnetic field have been demonstrated so far.

The high magnetic field is harmless to human body, leading to the great development of the technique of nuclear magnetic resonance in the field of medical diagnosis. In recent years, it becomes a hotspot topic to carry out precise surgical tasks inside human body with a magnetic microbot [12-15]. Magnetic microbots can be injected into human body and move by an external magnetic field to the target area to perform tasks, such as navigating in blood vessels to deliver drug [16-18], cleaning out block [19], executing local hyperthermia [20] and marking pathologies [21]. For example, Jeong et al. and Ullrich et al. respectively conducted vivo experiments to manipulate a magnetic unit moving in the blood vessel of a pig and the eye of a rabbit [22, 23]. Felfoul et al. used the magnetic bacteria as the substrate of the hybrid microbot, and controlled the movement of these bacteria with magnetic field [24]. However, these microbots are still far from being an effective medical tool, due to the lack of a deformable and efficient magnetic actuator.

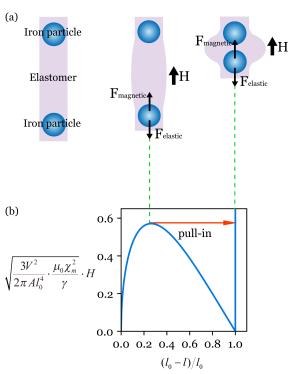
In this work, we revealed the mechanism of magnetic pull-in instability of magnetic elastomers. We fabricated a soft magnetic actuator capable of reversible 60% actuation strain in a uniform magnetic field by harnessing the localized pull-in instability. As demonstrations, we designed three robots with simple geometries to show the powerful functions of soft magnetic actuators. The first robot can grip object with a large rotating angle, the second robot can navigate in a fluid environment and deliver drug at the designated location, and the third robot can quickly jump up under a magnetic field, raising its gravity center several times higher.

Large magnetoelastic strain

Pull-in instability of two magnetic particles

Consider two spherical iron particles embedded in an elastomeric matrix. The two particles are placed along the vertical direction. A uniform magnetic field H is applied in the same direction (Fig. 1a). The two particles are magnetized and the distance

Figure 1. Magnetic pull-in instability in a uniform magnetic field. (a) Two iron particles are embedded in a bulk of elastomer. When the applied magnetic field is small, the magnetic force $(F_{magnetic})$ is balanced with the elastic force $(F_{elastic})$. When the magnetic field reaches a critical value, the two particles pull in together, squeezing the elastomer in between dramatically. (b) The normalized magnetic field as a function of the distance change of the two particles.



between them change from l_0 in the absence of magnetic field to l. The equilibrium is reached by balancing the elastic force F_e and the magnetic force F_m . Gravity is neglected. We assume the distance between the two particles l is large compared to the radius of particle R and take the two particles as two dipoles. To a first approximation, the magnetic force is roughly $F_m \approx 3\mu_0 m^2/(2\pi l^4)$, where μ_0 is the permeability of vacuum, and m is the magnetic dipole moment of each particle. We further simplify that the relation between the dipole moment and the applied field is linear $m = V \chi_m H$, where V is the volume of particle and χ_m is the effective magnetic susceptibility. The elastomeric matrix is taken to be a neo-Hookean material so that the elastic force is estimated as $F_e = A\gamma [l/l_0 - (l/l_0)^{-2}], \text{ where } A \text{ is}$

the area of section in the undeformed state and γ is the shear modulus of the matrix. Force balance gives that

$$\sqrt{\frac{3V^2}{2\pi A l_0^4} \cdot \frac{\mu_0 \chi_m^2}{\gamma^2}} \cdot H = \sqrt{(l/l_0)^5 - (l/l_0)^3}$$
 (1)

The normalized applied magnetic field as a function of compressive strain $(l_0-l)/l_0$ is plotted in Fig. 1b. When the magnetic field is small, the matrix is stiff enough to resist the magnetic force and the elastic deformation is small. As the magnetic field increases, the distance between the two particles decreases and the magnetic force increases much more rapidly than the elastic force. Once the distance reaches a critical value, the two particles suddenly pull-in and squeeze the matrix in between significantly. The critical condition corresponds to the peak point in Fig. 1b. Once the geometric parameters A, l_0 , V are given, the critical condition to trigger the pull-in instability is determined by the competition between elastic modulus γ and the magnetic Maxwell stress $\frac{1}{2}\mu_0\chi_m^2H^2$. When the matrix is soft and the magnetic susceptibility of particles is high, the magnetic pull-in instability is prone to happen. The maximum compressive displacement is roughly the initial distance between the two particles, as indicated by the vertical line in Fig. 1b.

Experimental demonstration of magnetic pull-in

We synthesized a transparent polyacrylamide hydrogel as the soft matrix. Five cylindrical particles made of pure iron were embedded in the matrix (Fig.2a). The

Figure 2. A linear magnetoelastic actuator. (a) Five aligned iron particles embedded are embedded in a soft hydrogel matrix in the absence of magnetic field; (b) Subject to a uniform vertical magnetic field the particles pull in together, generating a linear actuation strain about 60%.





(a) Reference state

(b) Current state

particles were painted in white color. The size of hydrogel was $12mm \times 9mm \times 55mm$, and the size of each particle was $3mm \times 3mm \times 4mm$. When a small uniform magnetic field was applied, the relative displacement between particles was unapparent. When the magnetic field was increased to about 0.4T, the particles suddenly pulled in, producing a large deformation (Fig.2b). The length between the top and the bottom particle changed to roughly 40% of its initial value. When the magnetic field was

removed, the actuator returned to the initial state. The shear modulus of the hydrogel matrix is about 2kPa. The magnetic susceptibility of particles χ_m is roughly 3, accounting for the demagnetization effect [25]. The critical magnetic field for pull-in is estimated to be 0.3T, according to Eq.1. The comparison between the theoretical prediction and the experiments is reasonable. The discrepancy is possibly due to the simplification of geometry and the linear magnetization relation.

Placement of magnetic particles

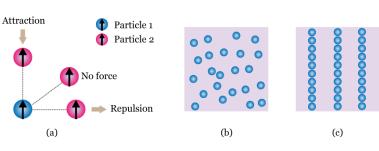
Consider two magnetic particles placed in a soft matrix along a direction which is not parallel with the external magnetic field. Set the origin of the coordinate on one particle, and the other particle has the relative coordinate (x,y). When the distance between the particles is large compared to the particle size, the potential energy of the two particles can be estimated as $-\frac{\mu_0 m^2}{4\pi} \frac{2y^2 - x^2}{(x^2 + y^2)^{\frac{5}{2}}}$ [26, 27]. When the external

magnetic field is along the vertical direction, the two particles are subject to attractive force if they are placed vertically, are subject to repulsive force if placed horizontally, and are subject to zero force if they are placed with an inclined angle (Fig. 3a).

Figure 3. Placement of magnetic particles greatly affects the overall response. (a) Under a uniform vertical magnetic field, particle 1 and particle 2 are subject to attractive force if they are placed vertically, subject to repulsive force if they are placed horizontally. (b) and (c) two commonly used magnetic elastomers: random distribution and chain-like distribution.

Figure 4. Spatially equidistant distribution. (a) In reference state, 27 Iron particles were uniformly placed in a soft matrix to form a cubic lattice. (b) In current state, under a vertical magnetic field, the particles pull in

together.



Consequently, if magnetic particles are randomly placed in the soft matrix (Fig. 3b), the attractive force and repulsive force offset each other and the achievable actuation strain is

very small [28]. Magnetorheological elastomer, cured in a magnetic field to form the chain-like particle distribution (Fig. 3c), can change stiffness under a magnetic field [29, 30]. The structure avoids the force offset but is not suitable for strain actuation, because the distance between adjacent particles is too small and no space is left for generating compressive strain.

We design a cubic lattice distribution of magnetic particles in a soft matrix which can avoid the force offset and undergo large deformation. We assembled 27 iron particles into a silicone matrix (ecoflex-0030) (Fig.4a). The particles were placed as

.4a). The particles were placed as uniform as possible,

Iron particle
Soft matrix

(a) Reference State (b) Current state

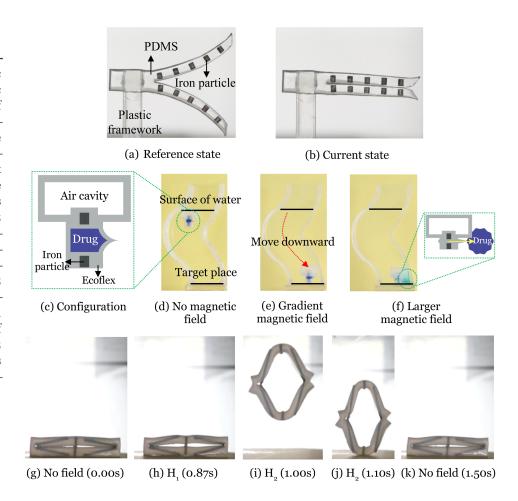
but imperfections are inevitable. When we increased the magnetic field, the two particles with the shortest distance pulled in first. This localized pull-in distorted the whole structure. When we increased the magnetic field a little further, other pairs of particles pulled in subsequently. In the end, all particles pulled in along the vertical direction. The distance between the top particle and the bottom particle changed by about 50% and the

overall strain of the structure is about 16%.

Magnetoelastic microbot

Giant magnetoelastic strain by magnetic pull-in enables to design useful magnetic microbots. With the designed arrangement of magnetic particles in soft matrix, the microbots are capable of different functions. In this section, we show three prototypes of untethered microbots: a robot for gripping, a robot for drug delivery and a robot for jumping.

Figure 5. Magnetoelastic actuator. (a)-(b) The magnetic gripper, (c)-(f) The magnetic drug-deliverer: (c) the sketch of the microbot; (d) the robot initially floats at the surface of the water tank; (e) a gradient magnetic field drags the robot to sink down to the target place; (f) the magnetic field further increases and the iron particles in the robot pulled in to release drug. (k) The magnetic jumper (g) reference state; (h) when a small magnetic field H_1 is applied, the robot deforms slightly; (i) when the magnetic field reaches a critical level H_2 , the robot suddenly jumps off the ground; (j) the jumping robot falls down; (k) the robot returns to its initial state when the magnetic field is removed.



Grip

We poured uncured PDMS and curing agent (weight ratio=10:1) into a gripper-like mold, and placed ten iron particles inside. The PDMS matrix was cured in 60 °C for 4h and then fixed to a plastic framework with super glue (Fig.5a). When a sufficiently large vertical uniform magnetic field was applied, the distance between the particles decreased and the magnetic force increased dramatically. The leftmost pair of particles with the smallest distance and the largest force pulled in first, acting like the leading wire of firecrackers (Fig.5a). It induced the other pairs to get closer in distance and pull in one by one. The pull-in of each pair of particles finally lead to a complete closure of the gripper (Fig. 5b). This design can be further programmed to adapt to the arbitrary target shape with a large gripping angle.

Deliver drug

Fig.5c shows a microbot consisting of an elastic framework made of Ecoflex 00-30, an air cavity, a liquid chamber, and two iron particles. Iron particles were placed in the robot before the framework was cured. Blue water was injected into the liquid chamber to represent drug. The microbot floated on the surface of a water tank in the absence of magnetic field due to the buoyant force provided by the air cavity (Fig.5d). We applied a vertical uniform magnetic field superposed with a very weak magnetic field gradient.

The weak field gradient overcome the buoyant force and dragged the microbot from water surface to the bottom, mimicking the guided movement in animal blood vessels (Fig.5e). When the microbot moved to the designated location, we further increased the magnitude of the uniform magnetic field so that the iron particles inside the robot pulled in and the drug was squeezed out (Fig.5f). The untethered microbot was able to perform two tasks by controlling the applied magnetic field: move along the channel and deliver drug.

Jump

Fig.5 (g-k) shows a jumping robot driven by a uniform magnetic field. Six iron rods were placed in a soft matrix made of Ecoflex 00-30. Four long iron rods were placed diagonally and two short iron rods were placed vertically in the center. The two short rods were separated by a narrow horizontal chink (Fig.5g). When the robot was subject to a vertical magnetic field, the long rods tended to rotate to the direction towards to the external field, while the short rods tended to attract each other by pull-in effect. When the magnetic field was small, the pull-in effect of the short rods dominated compared the rotation effect of the long rods. Consequently, the robot deformed and the chink slightly opened (Fig.5h) compared to the undeformed state (Fig.5g). The short rods restrained the movement of the robot and stored the magnetic energy. When the applied magnetic field exceeded a critical value, the rotation effect of the long rods dominated, and thus the robot suddenly jumped up (Fig.5i). The energy stored in two short rods were suddenly released to accelerate the robot. The response time was roughly 0.1s. The gravity center of the robot was raised to about 8 times higher than its initial state, demonstrating a large momentum powered by magnetic pull-in.

Conclusion

We report a new mechanism of magnetic pull-in instability for soft magnetic actuators. The critical condition to trigger the magnetic pull-in instability depends on the competition between the shear modulus of the matrix and the magnetic Maxwell stress. The placement of magnetic particles in the matrix greatly affects the magnetoelastic strain. We demonstrate the magnetic pull-in instability in a transparent hydrogel matrix with iron particles embedded. We further harness the magnetic pull-in to design three prototypes of untethered microbots. The first robot can grip objects with a large rotating angle. The second robot can flow in a fluid channel by magnetic navigation and perform the task of drug delivery. The third robot can self-accelerate and jump to the height 8 times of its initial height. These demonstrations show the advantages of the design soft magnetic actuators in large deformation, fast response, high power density, untetherness and robustness by the principle of magnetic pull-in instability. This mechanism may help to design versatile soft robotics towards to the applications of biomimetics and medical microbots.

Acknowledgments

The work was supported by NSFC (No. 11772249).

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