DOI: **Publication URL:**

FLEXIBLE GRIPPERS WITH PROGRAMMABLE THREE-DIMENSIONAL MAGNETIZATION AND MOTIONS

Huang Lin[a*], Xiang Li[a], Tao Xiao[a], Xi Jinping Wei[a], Hao Yan [a], Lynne Li[b], Bai Tao[a]

[a]Laser Institute, Qilu University of Technology (Shandong Academy of Sciences) Jinan, Shandong, 250104, China
[b]CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei 230027, China

Corresponding Author:

Huang@163.com

Abstract

Programmable magnetic soft grippers are highly desirable for diverse applications in drug delivery, object manipulation and soft robotics. However, current magnetic programming grippers need to be driven by multiple physical fields, which are complicated to operate and single in motion. Here, we report a method for patterning hard magnetic microparticles in an elastomer matrix. Based on vat photopolymerization, this method uses controlled reorientation of magnetic particles and selective exposure to ultraviolet (UV) light to encode magnetic particles in polydimethylsiloxane (PDMS) materials with arbitrary three-dimensional (3D) orientation. The combination of vertical and horizontal magnetic fields can produce different forces, causing different deformation modes of the grippers. Flexible grippers can be fabricated from a single precursor in one process and produce various deformation and motion forms when a single magnetic field is applied. Moreover, the gripper has the advantages of simple manipulation, fast response and flexible movement, which is of great significance in the application of biological devices and soft robots.

Keywords: *flexible grippers, magnetic axis coding, vat photopolymerization, photosensitive polydimethylsiloxane, three-dimensional motion*

INTRODUCTION

Flexible grippers have a growing number of potential applications in healthcare, bioengineering, and microelectromechanical systems (MEMSs) [1-3]. Because programmable grippers are subject to microscale physics and dynamics, the actuation mechanisms commonly used differ from those for traditional large-scale grippers [4, 5]. Common gripper deformation and driving methods include piezoelectricity [6], smart materials [7], chemical fuel [8] and photothermal [9]. However, there are trade-offs among response speed, shape transformation and motion control. Thus, untethered grippers that have instantaneous response, programmable deformation and threedimensional (3D) motion are still not fully achieved. Vat photopolymerization is an image processing technology based on a digital micromirror device (DMD), which digitally processes the light source image signal and then projects it into an image [10]. Because of its high image fidelity, it is widely used in electronic devices such as televisions, projectors and displays [11]. Meanwhile, DMD devices have a large optical modulation range, extremely high response speed and controllability [12], and can realize many applications, such as maskless lithography, 3D printing, spectral detection and machine vision [13, 14]. Based on the high-precision image projection and fast response characteristics of vat photopolymerization technology, plane and 3D structures of different materials can be prepared, and flexible driving of various response modes can be realized.

Magnetic axis coding technology is a kind of machining technology based on the fixed magnetic axis direction of hard magnetic materials [15], which makes the structure realize programmable deformation and sequential driving under the action of an external magnetic field [16]. Flexible grippers based on magnetic axis coding technology have the advantages of noncontact magnetic field manipulation, as well as fast, reversible, and diversified shape memory functions, which have attracted widespread attention from researchers [17]. Sitti et al. mixed unmagnetized NdFeB particles into a silicon elastomer prepolymer. The cured elastomer is fixed on a specific template for unidirectional magnetization, and a flexible gripper with continuous magnetic axis change is obtained [18]. However, this method is limited by the dependence on the template, different templates need to be made separately to process grippers with different deformation functions, and the processing process is complicated. Huang et al. used unmagnetized NdFeB particles and PDMS film to perform multiaxial folding and unidirectional magnetization to obtain a flexible magnetic film [19]. However, the folding-based scheme limits material thickness and coding freedom. Zhao et al. used an inkjet printer to install an electromagnetic coil for aligning magnetic particles in the nozzle part, and realized the printing of a composite ink structure doped with premagnetized NdFeB particles [20]. However, the programmed magnetic axis direction based on the inkjet printing processing principle is limited to the horizontal plane, and the processing equipment is complex. In addition, PDMS is the most commonly used material for flexible structures [21, 22]. However, PDMS prepolymers on the market do not have photoresponse characteristics and cannot be used for rapid vat photopolymerization.

Here, we report a vat photopolymerization method to encode 3D magnetization in planar flexible PDMS composites. First, a photothermal two-stage curable PDMS prepolymer is prepared, which can be converted into a gel state under ultraviolet (UV) polymerization. Then, vat photopolymerization technology based on a DMD is used to project the image signal of the light source after digital processing. To realize the sequential coding of the material by region, the magnetic axis direction of the doped premagnetized NdFeB particles is fixed. Finally, the gel-state PDMS is heated in an oven and solidified into the PDMS elastomer; thus, a flexible gripper with various deformation modes is obtained. Vertical encoding and horizontal encoding produce different forces under the action of external magnetic field, and their combination can make the gripper produce abundant deformation modes. The flexible structure has a simple processing method, adjustable material thickness, high structural fidelity, fast response and strong controllability and has a wide range of applications in the fields of biomedical engineering and MEMSs.

Material and methods

Preparation of materials: The photosensitive PDMS is prepared by mixing the Sylgard-184 precursor (Dow Corning) with a ratio of 10:1 base to curing agent as the main body, adding 20 wt% methacrylic polyester (methacryloxypropyl) methylsiloxane-dimethylsiloxane copolymer (MPDMS) and 0.6 wt% photoinitiator (TPO-L, J&K Scientific). After the mixed solution is stirred evenly, it is vacuumized in a vacuum container. The test results show that the mixed material with a doping concentration of 20 wt% has a viscosity and elastic modulus similar to those of Sylgard184 [23]. TPO-L shows good solubility in PDMS precursors and can be used as a photoinitiator for PDMS photopolymerization [24]. The photosensitive PDMS is mixed with premagnetized NdFeB (MQFP-15-7, Magnequench) particles in a certain mass ratio (30 wt%), and the gel-like PDMS is heated in an oven (120°C, 4 h).

Physical apparatus: Figure 1b shows the physical apparatus for patterning magnetic particles in a UV light source. The apparatus is composed of a permanent magnet, a vat photopolymerization system and a computer control system. The vat photopolymerization system consists of a UV light source, a DMD (pixel 1920×1080) mask and a machining system. The UV light source is a highpressure mercury lamp (Omnicure S1500). The light source can provide ultraviolet and visible light with high irradiance (23 W/cm²), and has a long service life (4000 h). The integrated mercury lamp does not require a complicated collimated light path and can easily adjust the angle of incident light, saving system space. The higher output power of the mercury lamp expands the scope of application of UV-curable materials, which is beneficial to the vat photopolymerization of various materials. The platform of the vat photopolymerization system is a Zaber linear platform (X-LSM100A), which has a stroke of 100 mm, a speed of 104 mm/s and a resolution of 1 μm. A three-axis linkage can be realized by the cross-parallel configuration of three displacement platforms. From the perspective of meeting design requirements and reducing equipment costs, two UV plano-convex lenses made of fused silica are selected as the front group of the optical system. A single focusing objective serves as the rear group. The objective diaphragm, as the aperture diaphragm of the optical system, is located at the back focal plane of the front lens group to construct the object-side telecentric optical path. This design can flexibly replace the rear objective lens with different magnifications and freely adjust the imaging resolution.

Computer control system: The computer system controls the 3D model slicing, the DMD dynamic mask image input and the motion of the electric displacement platform. According to the principle of 3D printing processing, every time the DMD input image information completes a single exposure, the electric displacement platform needs to drive the resin tank to carry out an overall downwards movement, and the cyclic stacking process of 3D printing is completed, which depends on the collaborative work of the DMD panel and the electric displacement platform. In this paper, the processing method of equal layer thickness is adopted. Before processing, parameters such as single layer exposure time, layer thickness and resin filling waiting time should be set in advance. The processing process can be stopped at any time to observe the processing situation in real time.

Fabrication procedure: The 3D device is sliced hierarchically by the vat photopolymerization slice model, and input into the DMD dynamic mask in sequence. First, the 3D model is converted into a point cloud file, and the intervals between points in the x, y, and z directions are set as required.

Since the pixel specification of the DMD chip as a digital mask is fixed, the resolution of the projected image is also corresponding to it. Accordingly, x and y parts corresponding to each z position in the point cloud file are taken to form a two-dimensional lattice. After rendering, it is expanded into a picture with pixels, which is the plane of the z layer. To avoid the problem of missing graphic features due to too low number of points when the lattice is converted into an image, the pixels of each layer of the generated point cloud file are 3840×2160, which is twice the pixels of the rendered graphics (the DMD pixels are 1920× 1080). Then, the machining program is responsible for controlling the collaborative work of the DMD image output and the electric displacement stage, thereby realizing the layer-by-layer 3D printing process.

Motion control: According to the test results of the interaction between the selected permanent magnet and the composite material, the distance between the two is determined. Finally, the DMD image output is controlled by the machining program, the electric displacement table works together, and the 3D printing of layer-by-layer stacking devices is realized. The magnetic actuation of grippers is realized by a permanent magnet (N52 NdFeB: magnetic flux density 0.5 T; diameter 5 mm; height 5 cm).

Results and discussion

Polydimethylsiloxane (PDMS) is a kind of silicone material with high flexibility, high resilience, good biocompatibility and excellent gas permeability, which has a wide range of applications. At present, PDMS has been gradually expanded from the microfluidic control system to a variety of flexible grippers. Therefore, the development of a non-contact PDMS gripper with simple operation and diversified motion forms is of great significance in biomedicine and MEMSs [25]. However, the common PDMS prepolymers do not have photoresponsive properties and cannot be used for rapid prototyping manufacturing using vat photopolymerization technology, and thus do not have the magnetic axis encoding conditions of UV photopolymerization. In order to solve this problem, a PDMS prepolymer with excellent mechanical properties, low raw material cost and photopolymerization is prepared in this paper.

Here, photosensitive PDMS is selected as the material of the flexible gripper. Photosensitive PDMS is prepared by mixing Sylgard-184 precursor, methacrylic polyester (methacryloxypropyl) methylsiloxane-dimethylsiloxane copolymer (M-PDMS) and photoinitiator (TPO-L). Notably, the mass fraction of M-PDMS determines the mechanical properties of the material. Photosensitive PDMS will be transformed into gel-like substances with dense and stable properties under ultraviolet irradiation (**Figure 1a**). The substance has self-supporting ability and plays a fixed role in the solid particles mixed in it. The photosensitive PDMS is mixed with premagnetized NdFeB particles in a certain mass ratio, and the gel-like PDMS is heated in an oven. After secondary curing, a typical crosslinking network is produced, a PDMS elastomer for UV-curing magnetic axis coding is obtained, and its mechanical properties are similar to those of pure Sylgard-184.

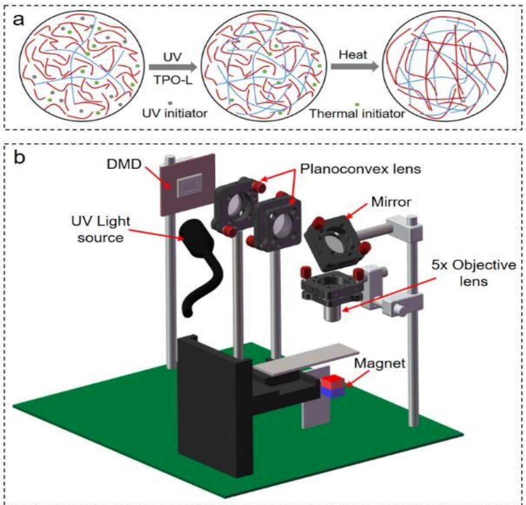

Figure 1. Schematic diagram of the material curing principle and processing device. (a) Network changes of the PDMS macromers following UV and thermal curing. (b) Magnetic coding system based on vat photopolymerization technology.

The processing system for UV lithography magnetic coding of photosensitive PDMS is shown in Figure 1b. The system mainly consists of a permanent magnet and a vat photopolymerization system. The permanent magnet provides a directional magnetic field to align the NdFeB particles in the liquid PDMS prepolymer along a certain orientation. The UV light source emits UV light through a digital mask toward a designated area of a magnetic photosensitive PDMS precursor, and the NdFeB in the area is immobilized. The magnitude, direction and uniformity of the magnetic field generated by the permanent magnet at the exposure position largely determine the quality of the magnetic axis coding. Before curing, it should be ensured that the center of the permanent magnet is facing the exposure area to reduce the orientation error of the magnetic axis caused by the deviation of the magnetic field. In the vat photopolymerization system, the photopolymerization energy requirement of photosensitive PDMS is relatively large. The doped magnetic particles have a UV absorption effect, so photopolymerization requires higher exposure power and longer exposure time. To achieve material polymerization and particle immobilization, for photosensitive PDMS with a thickness of 20 μm, the required exposure power is 2.3 W/cm^2, and the exposure time is 300 ms. In addition, according to the different requirements of the processing size, the objective lens in the projection optical system can be replaced to change the size of the projected light field, or the mobile function of the electric displacement platform can be used to realize splicing processing.

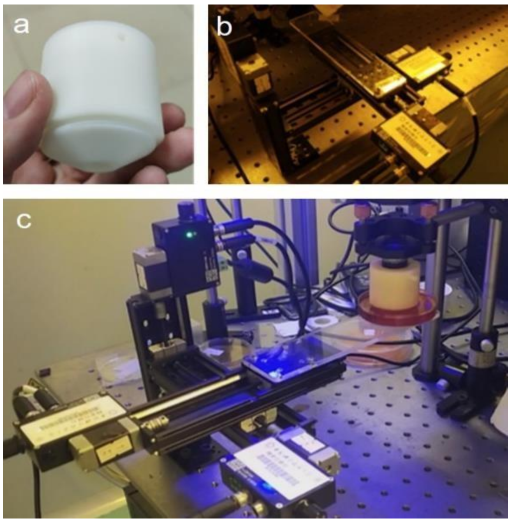

Figure 2. Mechanical processing system installation diagram. (a) Shell of the release film device; (b) Electric displacement platform with three-axis configured in parallel; (c) Mechanical processing system consisting of the release film device, resin tank, and electric displacement platform.

An integrated design scheme of the load stage and resin tank is adopted. The mechanical processing system mainly consists of an electric displacement platform, a resin tank and a release film device. The release film device consists of a shell and a membrane. The shell is used to fix the position of the membrane and drain the liquid in the resin tank. It is designed as a hollow truncated cone structure and can be fixed on the objective lens through mechanical clamping (**Figure 2a**). The film material needs to have extremely high ultraviolet transmittance and low adhesion to the resin material, and different transparent materials need to be selected according to different light-curing precursor solutions. The core of the processing system is the electric displacement platform, which requires extremely high positioning accuracy. The Zaber linear platform is selected to realize the three-axis linkage through the cross parallel configuration of three displacement platforms (Figure 2b). The configuration scheme ensures that the machining system has movement capabilities while reducing the overall height and floor space of the system. The installation method of the release film device, resin tank, and electric translation platform in the actual processing process is shown in Figure 2c.

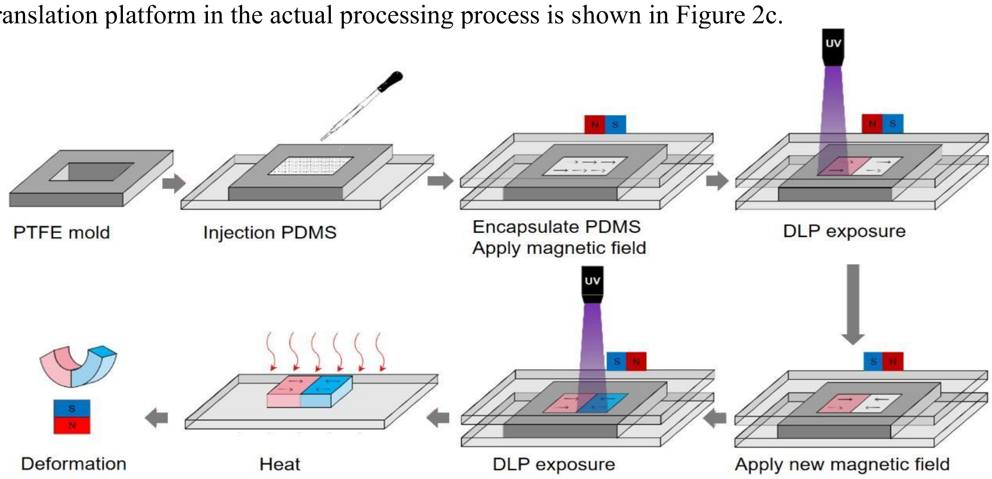

Figure 3. Magnetic response gripper preparation process.

The preparation process of the PDMS magnetic coding gripper is shown in **Figure 3**. A Teflon mold with a predetermined shape is made by laser cutting. The composite material is injected into the mold, and the surface is scraped flat. The mold is fixed and clamped by the upper and lower glass slides and the Teflon film, and the magnetic photosensitive PDMS is sealed in the chamber. A directional magnetic field is applied directly below the area to be exposed to make the magnetic particles uniformly oriented. The patterned light field generated by the DMD projection exposure system solidifies the liquid material into a gel state in the designated area and fixes the orientation of the magnetic particles in the area. Then, the direction and position of the magnetic field are changed, and a new patterned light field is applied to complete the orientation of magnetic particles in the new area. If magnetic coding grippers with different arrangements are prepared, magnetic coding of all areas can be completed only by changing the direction of the magnetic field. Finally, the photopolymerized gel-like PDMS is released from the mold and sent into an oven for heating to complete curing.

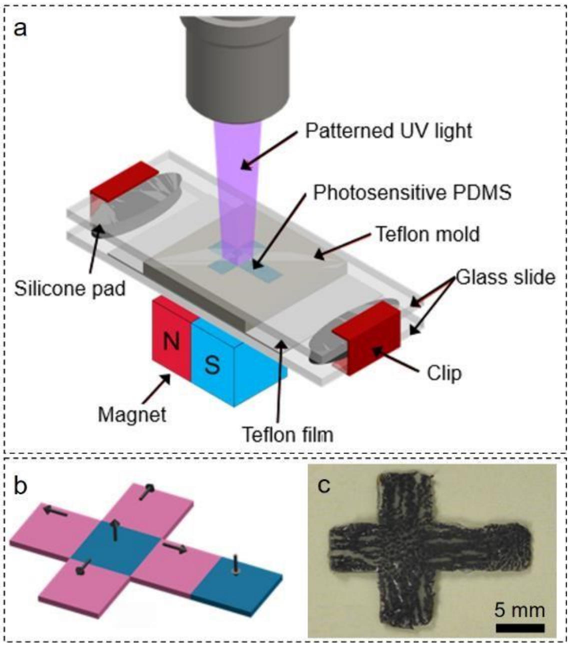

Figure 4. Preparation of magnetic axis coding gripper. (a) Schematic diagram of the magnetic axis coding processing device. (b) Design scheme of magnetic axis coding. (c) A PDMS elastomer with magnetic coding information. Scale bar, 5 mm.

The photosensitive PDMS presents an incompletely cross-linked gel after being irradiated by UV light, and the material is easily deformed under the action of external force. It also cannot be directly immersed in chloroform, toluene and other solvents for cleaning; otherwise, it will affect the subsequent heating and curing process. When the magnetic field applied to the composites is not in the machining plane, NdFeB particles will “stand up” in chains with each other and form multiple ciliated structures [26]. Therefore, to prevent magnetic particles from assembling into chains, composites should be encapsulated in “sandwich” structures with upper and lower rigid constraints. The designed magnetic encoding processing device is shown in **Figure 4a**. To obtain transition-state PDMS gels with precise morphology, a custom mold is needed. Teflon (polytetrafluoroethylene, PTFE) is selected as the mold material, which does not adhere to PDMS. The PDMS precursor is injected into the mold, the upper part of the mold is a glass slide, and the lower part is a PTFE film close to the glass slide. The three parts form a chamber to shape the composite material. The upper and lower glass slides and the middle mold are fixed by nonmagnetic metal clips. A silicone pad is added for cushioning at the clip (the height of the silicone pad is the same as that of the mold), forming a “sandwich” structure. The permanent magnet is placed under the “sandwich” structure.

The photocured gel-like PDMS is attached to the upper glass slide, and after demolding, it is heated in an oven to obtain a PDMS elastomer with magnetically encoded information (Figure 4b, c).

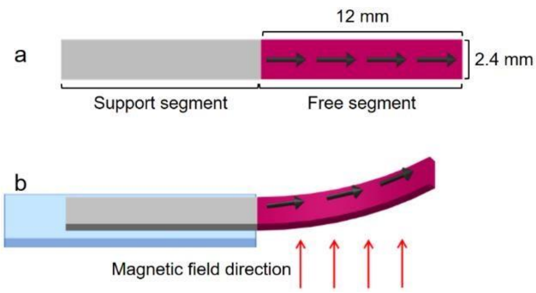

Figure 5. Schematic diagram of the magnetic response deformation of the magnetically coded cantilever structure. (a) The structure consists of a support segment and a free segment. (b) The free segment has a horizontally rightward magnetization direction, when a vertically upwards external magnetic field is applied, the free segment bends and deforms.

To explore the magnetic response characteristics of the PDMS magnetic coding gripper, a long cantilever beam structure (length 24 mm, width 2.4 mm) is prepared. The structure consists of a support segment and a free segment. The support section is fixed on the test platform, does not participate in magnetic response deformation and is not defined by magnetic coding. The free segment has a horizontally rightward magnetization direction, and when a vertically upwards external magnetic field is applied, the free segment bends and deforms (**Figure 5**). The NdFeB concentration affects the free segment bends and deforms of the gripper. When the NdFeB doping concentration is low, increasing the mass fraction of NdFeB particles can effectively improve the magnetic induction intensity of the magnetic coding structure, and obtain stronger bending deformation ability under the same magnetic field. However, when the doping concentration is too high, on the one hand, the mass fraction of PDMS, which is the main deformation body of magnetic axis coding structure, is relatively insufficient, which affects the flexibility and resilience of the structure. On the other hand, the magnetic axis orientation fixation method depends on the coating fixation of NdFeB particles by gel-like PDMS, when the mass fraction of PDMS is insufficient, a large number of NdFeB particles are in free state and cannot be effectively fixed and oriented. The free NdFeB particles show different magnetic field directions from the coded magnetic field under the action of external magnetic field, which interferes with the magnetic response deformation of flexible structures. Therefore, the mass fraction of NdFeB particles in the PDMS prepolymer is 30wt%.

PDMS elastomers embedded with magnetically encoded information are known to deform into specific shapes when an external magnetic field is applied, and quickly return to their original shape after the magnetic field is removed. Here, a variety of patterned structures are designed and fabricated by taking advantage of reversible deformation characteristics of magnetically coded planar materials (**Figure 6**). The structure can be divided into multiple encoding areas. The direction of the magnetic axis in each encoding area is uniform, and the boundary line between encoding areas is the central axis.

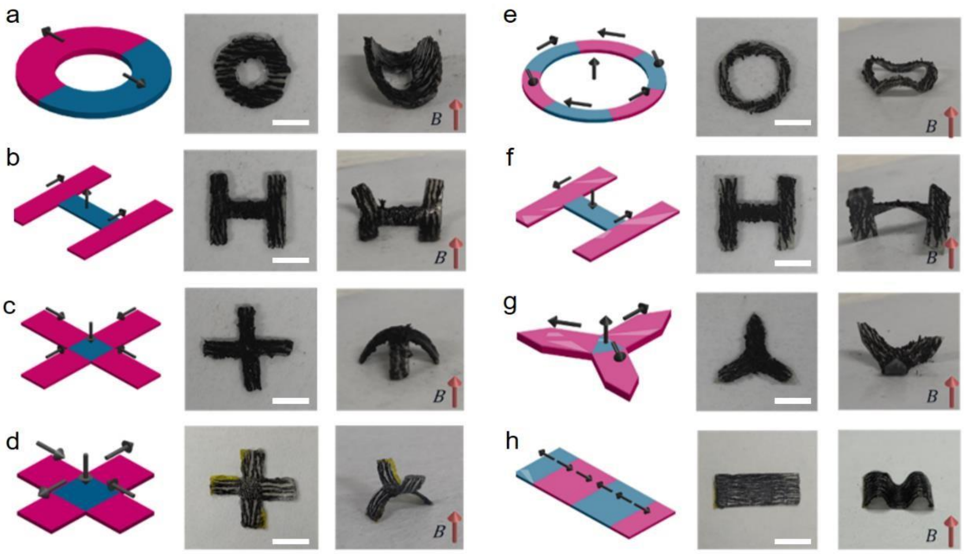

Figure 6. Patterned structures with different magnetic axis coding information. The left side of each image is the magnetic coding design scheme, the black arrow represents the direction of local magnetization, and the right side is the optical image before and after the structure deformation.

Scale bar, 5 mm.

According to whether the direction of the directional magnetic field used in the magnetic coding process is parallel to the machining plane, it can be divided into vertical directional coding and horizontal directional coding. The two coding modes have different forces under the action of external magnetic field, and the combination of them can produce abundant deformation modes. For the structure whose shape and coding information are centrosymmetric, the vertically oriented coding area is the datum plane when the whole structure is deformed. When the horizontally oriented encoding direction is perpendicular to the central axis, this area will bend and deform relative to the datum plane (Figure 6c, d and g). When the horizontally oriented encoding direction is parallel to the central axis, torsional deformation occurs between them (Figure 6f). For structures where the encoded information is not centrosymmetric and there is no vertical orientation coding, there is usually no deformation datum, and the structures alternate with each other to form single-order (Figure 6a) or multi-order (Figure 6e and h) bending structures depending on horizontal orientation coding of different orientations. Besides, there are other types of coding methods, such as the structure shown in Figure 6b, which will undergo unilateral bending deformation under the action of a magnetic field without the overall turnover.

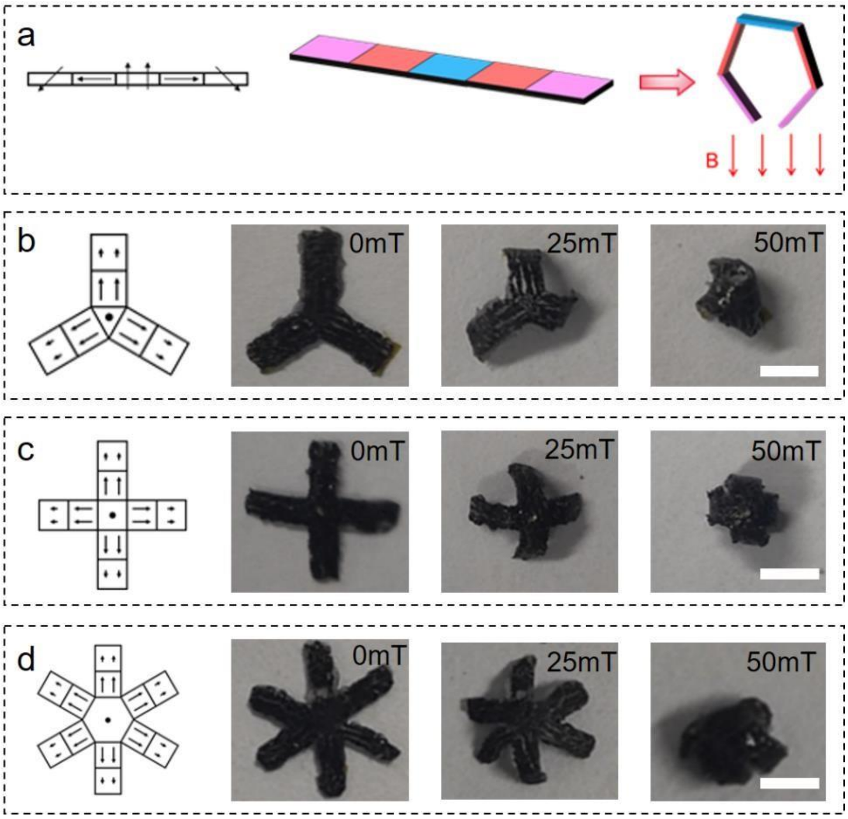

Figure 7. Design scheme and deformation process of the magnetic response gripper. (a) Deformation theory of the magnetic coding gripper, (b) 3-arm magnetic gripper, (c) 4-arm magnetic gripper, and (d) 6-arm magnetic gripper. Scale bar, 5 mm.

To further demonstrate the broad application prospects of flexible grippers in the field of magnetic response drives, a programmable flexible gripper to realize the gripping and handling of cargos is designed and manufactured. The magnetic gripper is a centrosymmetric structure that is composed of the central reference area and the surrounding bending arms. Each arm is defined by two sections of the magnetic axis. Under the action of an external magnetic field, the arm deforms into two sections to realize the clamping and wrapping function of cargos. The magnetic axis coding mode of the gripper is shown in **Figure 7a**. The central region of the structure is vertically oriented encoding, and the two segments of the bending arm are horizontal encoding and oblique encoding. When subjected to an external magnetic field in the vertical direction, the arm bends and deforms in two sections to realize the grasping and wrapping of cargo. Here, three-arm, four-arm and sixarm magnetic grippers are processed, and the magnetic encoding definition scheme of each gripper is shown in Figure 7b-d. The gripper can gradually complete the wrapping of the cargos with increasing external magnetic field intensity and return to the original shape after removing the magnetic field to complete the release of cargos.

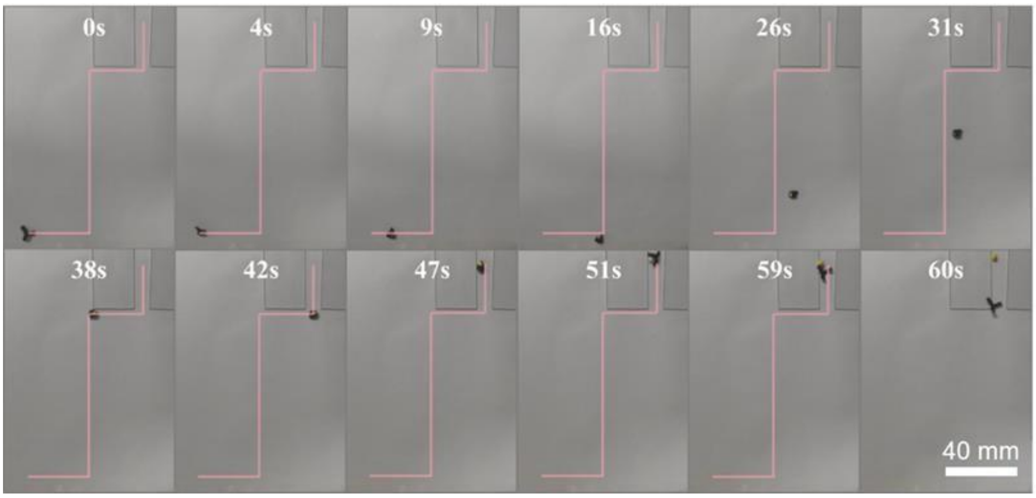

Figure 8. PS ball clamping, transport and release process of the magnetic response gripper. Scale bar, 40 mm.

Here, a three-arm flexible structure is used to demonstrate the cargo transportation process of the magnetic coding gripper. By reducing the distance between the permanent magnet and the gripper to increase the intensity of the external magnetic field, the bending arm of the gripper is folded, and the grasping and wrapping of polystyrene (PS) balls are completed. The wrapped gripper is a magnetic rigid body that slides or rolls along with the horizontal movement of the permanent magnet. When the magnetic rigid body moves to the designated position, the distance between the permanent magnet and the magnetic rigid body is increased. The arm of the gripper is opened, and the gripper is turned over and separated from the PS ball by the rotation of the permanent magnet, thus completing the release of the PS ball. As shown in **Figure 8**, the wrapped PS ball moves linearly on the horizontal plane. The PS ball is sent into the predefined channel to complete the release by changing the direction of motion twice.

Conclusions

We report a simple photothermal two-step curing method for photosensitive PDMS and fabricate a programmable magnetized flexible gripper by magnetic axis coding technology of vat photopolymerization technology. The vertical and horizontal magnetic fields can produce different forces, and the combination of forces can make the gripper produce different deformation modes. Based on the magnetic response characteristics of the PDMS magnetic axis coding structure, the clamping, transporting and releasing functions of the magnetic response gripper for noncontact cargos are studied. The programmable gripper has the advantages of integrated molding and no assembly. The vat photopolymerization technology has the ability of size adjustment and batch preparation. The PDMS material has the characteristics of biocompatibility and gas permeability. Flexible grippers have broad application prospects in the fields of medical care, machine learning and MEMSs.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval

This study does not contain any studies with human or animal subjects performed by any of the authors.

Data or code availability

The data generated in this study are available from the corresponding author upon reasonable request.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Nos. 62305180 and 22104139), the Jinan "20 New Universities" Funding Project (No. 202228019) and the Qilu University of Technology (Shandong Academy of Sciences), Education and Industry Integration Pilot Project (No. 2022PY045).

References

[1]. Roh Y, Kim M, Won S M, et al. Vital signal sensing and manipulation of a microscale organ with a multifunctional soft gripper[J]. Science Robotics, 2021, 6(59): eabi6774.
[2]. Tai K, El-Sayed A R, Shahriari M, et al. State of the art robotic grippers and applications[J]. Robotics, 2016, 5(2): 11.
[3]. Wang B, Kostarelos K, Nelson B J, et al. Trends in micro-/nanorobotics: materials development, actuation, localization, and system integration for biomedical applications[J]. Advanced Materials, 2021, 33(4): 2002047.
[4]. Alapan Y, Karacakol A C, Guzelhan S N, et al. Reprogrammable shape morphing of magnetic soft machines[J]. Science advances, 2020, 6(38): eabc6414.
[5]. Wu S, Hu W, Ze Q, et al. Multifunctional magnetic soft composites: A review[J]. Multifunctional materials, 2020, 3(4): 042003.
[6]. McClintock H, Temel F Z, Doshi N, et al. The milliDelta: A high-bandwidth, high-precision, millimeter-scale Delta robot[J]. Science Robotics, 2018, 3(14): eaar3018.
[7]. Nojoomi A, Arslan H, Lee K, et al. Bioinspired 3D structures with programmable morphologies and motions[J]. Nature communications, 2018, 9(1): 3705.
[8]. Li J, Rozen I, Wang J. Rocket science at the nanoscale[J]. ACS nano, 2016, 10(6): 5619-5634. [9] Villangca M J, Palima D, Banas A R, et al. Light-driven micro-tool equipped with a syringe function[J]. Light: Science & Applications, 2016, 5(9): e16148-e16148.
[9]. Emami M M, Rosen D W. Modeling of light field effect in deep vat polymerization for grayscale lithography application[J]. Additive Manufacturing, 2020, 36: 101595.
[10]. Zhang Y, Surman P, He S. A resolution-enhanced digital micromirror device (DMD) projection system[J]. IEEE Access, 2021, 9: 78153-78164.
[11]. Zhao S, Zhang Z, Gao Y, et al. Generation of structured beams with optional turbulence levels using a digital micromirror device[J]. Optics Communications, 2023, 529: 129084.
[12]. Shaik N E K, Widdicombe B, Sun D, et al. Longwave infrared multispectral image sensor system using aluminum-germanium plasmonic filter arrays[J]. Nano Research, 2023: 1-8.

[13]. John P, Antony I R, Whenish R, et al. A review on fabrication of 3D printed biomaterials using optical methodologies for tissue engineering applications[J]. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 2022, 236(11): 1583-1594.
[14]. Xu T, Zhang J, Salehizadeh M, et al. Millimeter-scale flexible robots with programmable threedimensional magnetization and motions[J]. Science Robotics, 2019, 4(29): eaav4494.
[15]. Deng H, Sattari K, Xie Y, et al. Laser reprogramming magnetic anisotropy in soft composites for reconfigurable 3D shaping[J]. Nature communications, 2020, 11(1): 6325.
[16]. El-Atab N, Mishra R B, Al-Modaf F, et al. Soft actuators for soft robotic applications: a review[J]. Advanced Intelligent Systems, 2020, 2(10): 2000128.
[17]. Hu W, Lum G Z, Mastrangeli M, et al. Small-scale soft-bodied robot with multimodal locomotion[J]. Nature, 2018, 554(7690): 81-85.
[18]. Li Y, Qi Z, Yang J, et al. Origami NdFeB flexible magnetic membranes with enhanced magnetism and programmable sequences of polarities[J]. Advanced Functional Materials, 2019, 29(44): 1904977. [20] Kim Y, Yuk H, Zhao R, et al. Printing ferromagnetic domains for untethered fast-transforming soft materials[J]. Nature, 2018, 558(7709): 274-279.
[19]. Hwang Y, Candler R N. Non-planar PDMS microfluidic channels and actuators: a review[J]. Lab on a Chip, 2017, 17(23): 3948-3959.
[20]. Bucciarelli A, Paolelli X, De Vitis E, et al. VAT photopolymerization 3D printing optimization of high aspect ratio structures for additive manufacturing of chips towards biomedical applications[J]. Additive Manufacturing, 2022, 60: 103200.
[21]. Ji Z, Jiang D, Zhang X, et al. Facile Photo and Thermal Two-Stage Curing for High-Performance 3D Printing of Poly (Dimethylsiloxane)[J]. Macromolecular Rapid Communications, 2020, 41(10): 2000064.
[22]. Wang Y, Xue T, Si Z, et al. Visible-light-induced ultrafast preparation of PDMS membrane for the pervaporative separation of furfural[J]. Journal of Membrane Science, 2022, 653: 120515.
[23]. Eduok U, Faye O, Szpunar J. Recent developments and applications of protective silicone coatings: A review of PDMS functional materials[J]. Progress in Organic Coatings, 2017, 111: 124-163.
[24]. Lu H, Zhang M, Yang Y, et al. A bioinspired multilegged soft millirobot that functions in both dry and wet conditions[J]. Nature communications, 2018, 9(1): 3944.