

Programmable multi-responsive MXene actuator based on micro-ridge structures

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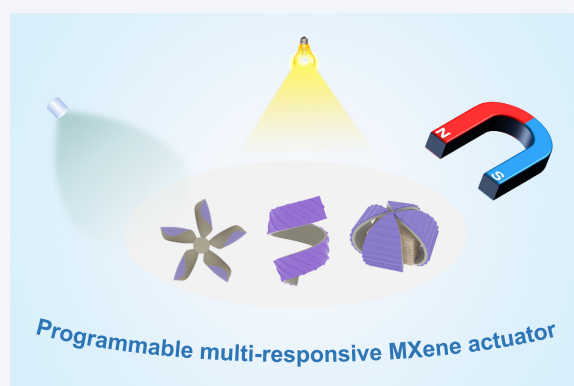
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ABSTRACT: MXene ($\text{Ti}_3\text{C}_2\text{T}_x$), which is known for its exceptional hydrophilicity, remarkable electrical/thermal conductivity, and superior mechanical strength, has emerged as an ideal candidate for developing stimuli-responsive actuators. However, current MXene-based actuators are unable to simultaneously achieve both multiple stimuli responses and programmable deformation, which restricts their practical applications in real-world scenarios. Here, we have developed a multi-responsive MXene/paraffin wax (PW)& Fe_3O_4 actuator with shape programmability by introducing micro-ridge structures. Since the different hydrophilicity and thermal expansion characteristics between the two layers, the actuator exhibits stimuli-responsive deformations under humidity, light, and magnetic field. Additionally, by controlling the orientation of the micro-ridge structures, combined with heat-welding methods, various complex three-dimensional configurations of actuators can be programmed. As proof of concept, several smart devices, such as a biomimetic *Trachelospermum jasminoides*, a spiral gripper, and a maze robot, are demonstrated, offering new insights for the development of future flexible smart devices.



KEYWORDS: actuators, multi-responsive, MXene, programmable deformation, soft robots

1 Introduction

In recent years, soft actuators have attracted significant attention owing to their capacity to convert environmental energy into mechanical energy by responding to external stimuli, including light [1–3], humidity [4–6], heat [7], pH [8], solvents [9], magnetic fields [10, 11], and electric fields [12, 13]. These actuators are capable of achieving continuous deformation and complex movements similar to biological muscles, which shows great potential in the applications of microelectromechanical systems (MEMS) [14], biomedical devices [15–17], and intelligent robots [18–23]. With advancements in materials science, various stimulus-responsive materials have been successfully developed and applied in actuators, such as hydrogels [19, 24], shape-memory polymers

[25, 26], electroactive polymers [20, 27], and carbon-based materials [28–32]. Currently, emerging $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (two-dimension transition metal carbides) has become an ideal candidate for developing actuators, especially in multi-responsive actuators, due to its high electrical/thermal conductivities, hydrophilicity, photothermal conversion capability, and excellent mechanical properties [33–35]. For example, Hao et al. [36] developed a multi-stimulus responsive actuator based on MXene-carbon nanotubes hybrid film, which exhibits desirable mechanical robustness with a tensile strength of 153.8 MPa and a fracture strain of 4.65%. Zhai et al. [37] fabricated a multi-stimuli-responsive actuator that can respond to humidity, light, or heat based on $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-cellulose nanowhiskers (CNWs)-polyvinyl alcohol (PVA)/polydimethylsiloxane (PDMS) multilayer membranes, which can achieve bidirectional deformation. Zhang et al. [38] prepared a multi-responsive actuator integrated with self-sensing capability using a MXene/cellulose nanofiber (CNF) Janus film, which can not only produce actuation but also self-monitor its bending deformation. To date, MXene-based multi-response actuators have achieved substantial progress in terms of mechanical strength, response diversity, functional integration, and so on.

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Nevertheless, current MXene-based multi-responsive actuators tend to exhibit relatively simple deformation modes, such as fundamental bending, expansion, or contraction. Moreover, their initial configurations and deformation pathways are predetermined during the fabrication process. This predefined deformation mechanism, in turn, restricts their ability to adapt to complex real-world environments and diverse task requirements. To solve these problems, some researchers have attempted to develop new types of actuators that can achieve programmable and complex deformation through material composites and structural innovation. Zhang et al. [39] prepared a flexible torsion photoactuator based on MXene, carbon nanotube (CNT), and paraffin wax (PW) using a layer-by-layer method. This actuator can achieve chiral and helical bending by adjusting the orientation of the CNT layer. Wang et al. [40] fabricated a shape-programmable near-infrared (NIR) light-driven MXene-containing anisotropic hydrogel actuator, in which a low electric field was applied to enable a spatial distribution of MXene nanosheets, thereby imparting anisotropy into the hydrogel network. This actuator is capable of undergoing shape transformation into various geometries by regulating indium tin oxide (ITO) electrode pattern, direct-current electric field direction and mask-assisted photopolymerization. Despite the fact that rapid progress has been made in this dynamic field, most existing MXene-based actuators with shape programmability can only respond to a single stimulus. Less attention has been devoted to simultaneously achieving multiple responses and shape programming, which are crucial for their practical application. Thus, the development of MXene-based actuators that enable multiple responses and programmable deformation remains challenging.

In this work, we report a multi-responsive MXene-based actuator with programmable deformation capabilities, which is composed of a MXene film patterned with micro-ridge structures and a PW/Fe₃O₄ composite film. Given the differing hydrophilicity in MXene and PW&Fe₃O₄ films, the bilayer actuator exhibits distinct swelling/shrinking behaviors in response to humidity and light. In this way, the strain mismatch at the bilayer interface results in the deformation of MXene/PW&Fe₃O₄ actuator. The incorporation of Fe₃O₄ nanoparticles also endows the actuator with magnetic actuation capability. Interestingly, the deformation of the actuator such as chirality and helical structure could be programmed by the orientation of the micro-ridge structures. Furthermore, these basic actuators can be welded together using heat-welding methods, which facilitates the construction of various complex three-dimensional (3D) configurations. Leveraging its advantages of multi-responsive capabilities and programmable deformation, this MXene/PW&Fe₃O₄ actuator can be applied to soft robots, such as biomimetic *Trachelospermum jasminoides*, smart spiral grippers, and maze robots. This work may open new avenues for the development of MXene actuators.

2 Experimental

2.1 Preparation of MXene dispersion

Commercial Ti₃AlC₂ powder (Jilin 11 Technology Co., Ltd.) was etched using a modified LiF/HCl method. Specifically, 2 g of LiF was slowly dissolved in 25 mL of HCl under stirring, followed by the gradual addition of 2 g Ti₃AlC₂ powder. This mixture was stirred at 35 °C for 48 h to selectively etch Al atoms using HF, yielding Ti₃C₂T_x. The product was then repeatedly

washed via ultrasonication and centrifugation in deionized water (12,000 r/min, 15 min) until the supernatant reached pH 5–6. Ethanol was then added, followed by ultrasonication and centrifugation to achieve intercalation and exfoliation of Ti₃C₂T_x nanosheets. Finally, the sedimented aqueous solution was ultrasonicated and centrifuged at low speed (3500 r/min, 3 min); the upper dark brown supernatant was collected as the MXene dispersion (8 mg/mL).

2.2 Preparation of MXene/PW&Fe₃O₄ bilayer film with micro-ridge structures

First, 5 mL of MXene solution was drop-cast onto a pre-cut and hydrophobically treated record. After drying under ambient conditions, the MXene film with micro-ridge structures was obtained by peeling it off from the record. Then, 5 g of PW and 1 g of Fe₃O₄ nanoparticles were mixed on a hot plate at 80 °C, followed by stirring thoroughly for 30 min to obtain a uniform PW&Fe₃O₄ mixture. Subsequently, the molten PW&Fe₃O₄ mixture was drop-cast onto the MXene film at 80 °C. After cooling, the MXene/PW&Fe₃O₄ bilayer film with micro-ridge structures was obtained for further usage.

2.3 Characterizations

Scanning electron microscopy (SEM) characterization and elemental analysis were conducted with a Nihon Electronics JSM-7900F system equipped with energy dispersive spectrometry. Transmission electron microscopy (TEM) imaging was performed using a JEOL F200 high-resolution TEM. Atomic force microscopy (AFM) was performed using a Bruker Dimension ICON instrument. X-ray photoelectron spectroscopy (XPS) analysis was conducted on a Thermo Scientific ESCALAB Xi+ spectrometer. X-ray diffraction (XRD) measurements were obtained with a Rigaku Smartlab 9KW diffractometer employing Cu K α radiation (λ = 0.15418 nm). Fourier transform infrared (FTIR) spectrum was obtained using a Bruker INVENIO S instrument from Germany. The bilayer film and its application were photographed using an Olympus TG-7 digital camera. Controlled humidity environments (~ 33%, 44%, 57%, 75%, 86%, and 100% relative humidity (RH)) were generated using saturated solutions of MgCl₂, K₂CO₃, NaBr, NaCl, KCl, and H₂O, respectively. During applications, a humidifier maintained 100% RH conditions, whereas 44% RH was achieved by placing samples in the ultra-clean laboratory atmosphere. Surface wettability was characterized by measuring static water contact angles with a KRÜSS DSA100S system.

3 Results and discussion

3.1 Design and fabrication of multi-responsive MXene/PW&Fe₃O₄ bilayer film

Figure 1(a) demonstrates the fabrication of the MXene/PW&Fe₃O₄ bilayer actuator with micro-ridge structures utilizing a record as a template. First, MXene aqueous solution was drop-cast onto a pre-cut record template and dried in ambient air, thereby forming a freestanding MXene film with micro-ridge structures. Then, the molten PW&Fe₃O₄ mixture was cast on the structured MXene film at 80 °C. After cooling at room temperature, the MXene/PW&Fe₃O₄ bilayer film with micro-ridge structures was obtained, which exhibits good flexibility (Fig. 1(b)). The entire fabrication process is straightforward and free of additional harmful

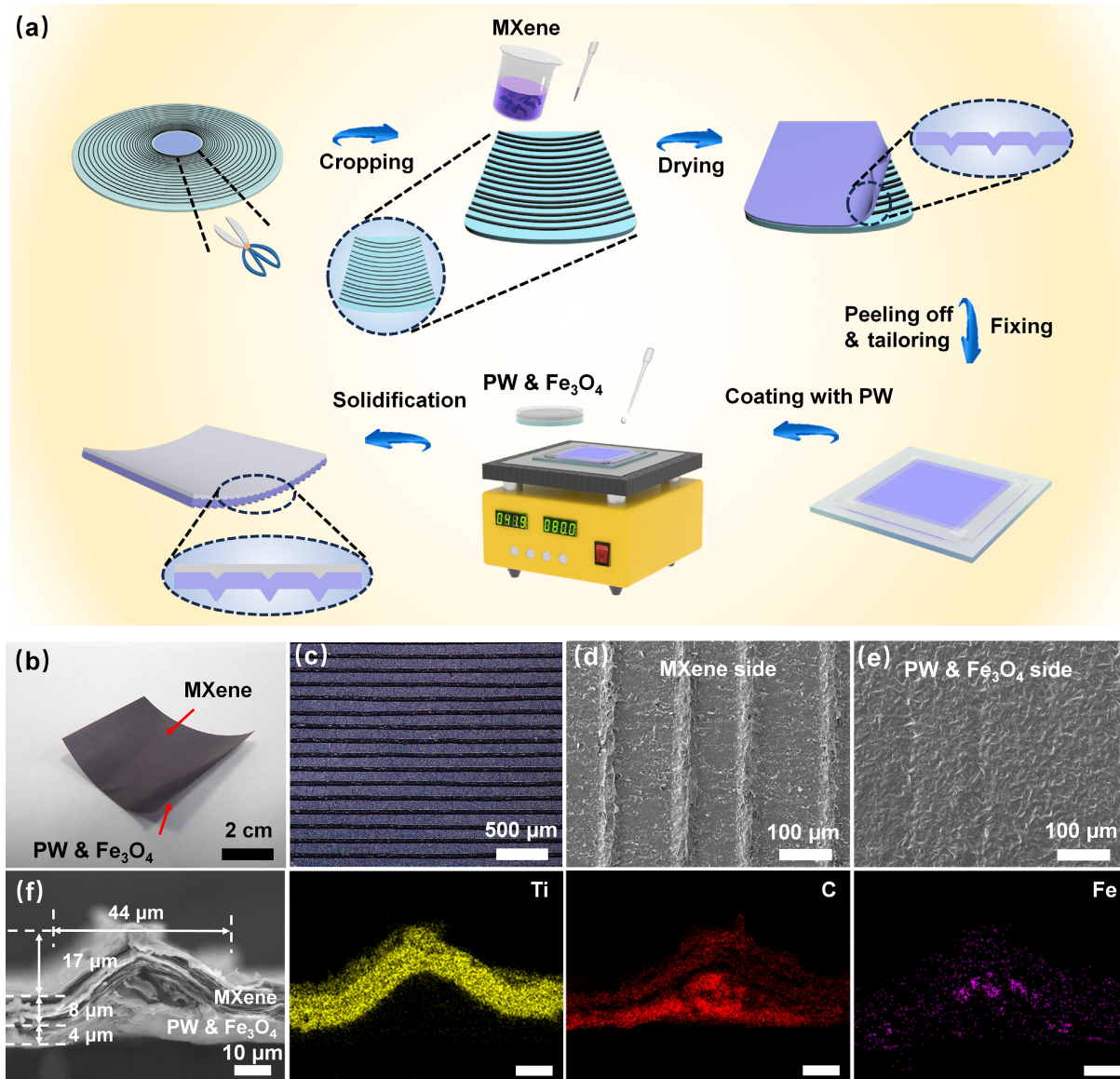


Figure 1 Fabrication and characterization of multi-responsive MXene/PW&Fe₃O₄ bilayer film. (a) Schematic illustration of the fabrication process for the MXene/PW&Fe₃O₄ bilayer film. (b) Optical photograph of the MXene/PW&Fe₃O₄ actuator. (c) High-resolution microscopy image of the MXene side of the bilayer film. (d) and (e) Surface SEM images of the MXene side and the PW&Fe₃O₄ side of the bilayer film, respectively. (f) Cross-section SEM image of the MXene/PW&Fe₃O₄ bilayer film and corresponding elemental mapping images of Ti, C, and Fe.

chemicals. Figure 1(c) shows the high-resolution microscope image of the MXene side of the bilayer film, demonstrating periodic micro-ridge structures. Furthermore, surface SEM images (Figs. 1(d) and 1(e)) illustrate the morphologies of the MXene side and the PW&Fe₃O₄ side, clearly revealing the micro-ridge structures on the MXene surface (with a spacing of approximately 100 μm) and a relatively smooth texture on the PW surface. Additionally, to characterize the interlayer structure of the bilayer film, cross-sectional SEM characterizations were performed. As shown in Fig. 1(f), the PW&Fe₃O₄ layer has a thickness of $\sim 4 \mu\text{m}$, while the MXene layer has a thickness of $\sim 8 \mu\text{m}$. The MXene layer presents a layered structure composed of stacked MXene nanosheets, and the two layers maintain the good interfacial contact. Additionally, the micro-ridge structures on the MXene layer have a width of $\sim 44 \mu\text{m}$ and a height of $\sim 17 \mu\text{m}$, which endow the actuator with the potential for complex deformation. Moreover, elemental mapping

analysis confirmed a uniform carbon distribution throughout the bilayer, with Ti and Fe elements exclusively distributed on the MXene and PW&Fe₃O₄ sides, respectively. This result verifies the successful fabrication of the bilayer structure.

To elucidate the multi-responsive mechanism of the MXene/PW&Fe₃O₄ actuator, we utilized a series of characterization techniques such as TEM, AFM, XRD, and XPS to analyze the intrinsic structure and chemical composition of each component layer. First, the TEM image (Fig. 2(a)) demonstrates the intact morphology of large-area MXene nanosheets, confirming the successful synthesis of MXene via the modified LiF/HCl etching method applied to the MAX (M is an early transition metal, A is an element from III or IV main groups, and X is carbon or/and nitrogen) precursor. AFM characterization (Fig. 2(b)) indicates that the MXene nanosheets possess a thickness of approximately 1.7 nm. Subsequently, Fig. 2(c) presents the comparative XRD

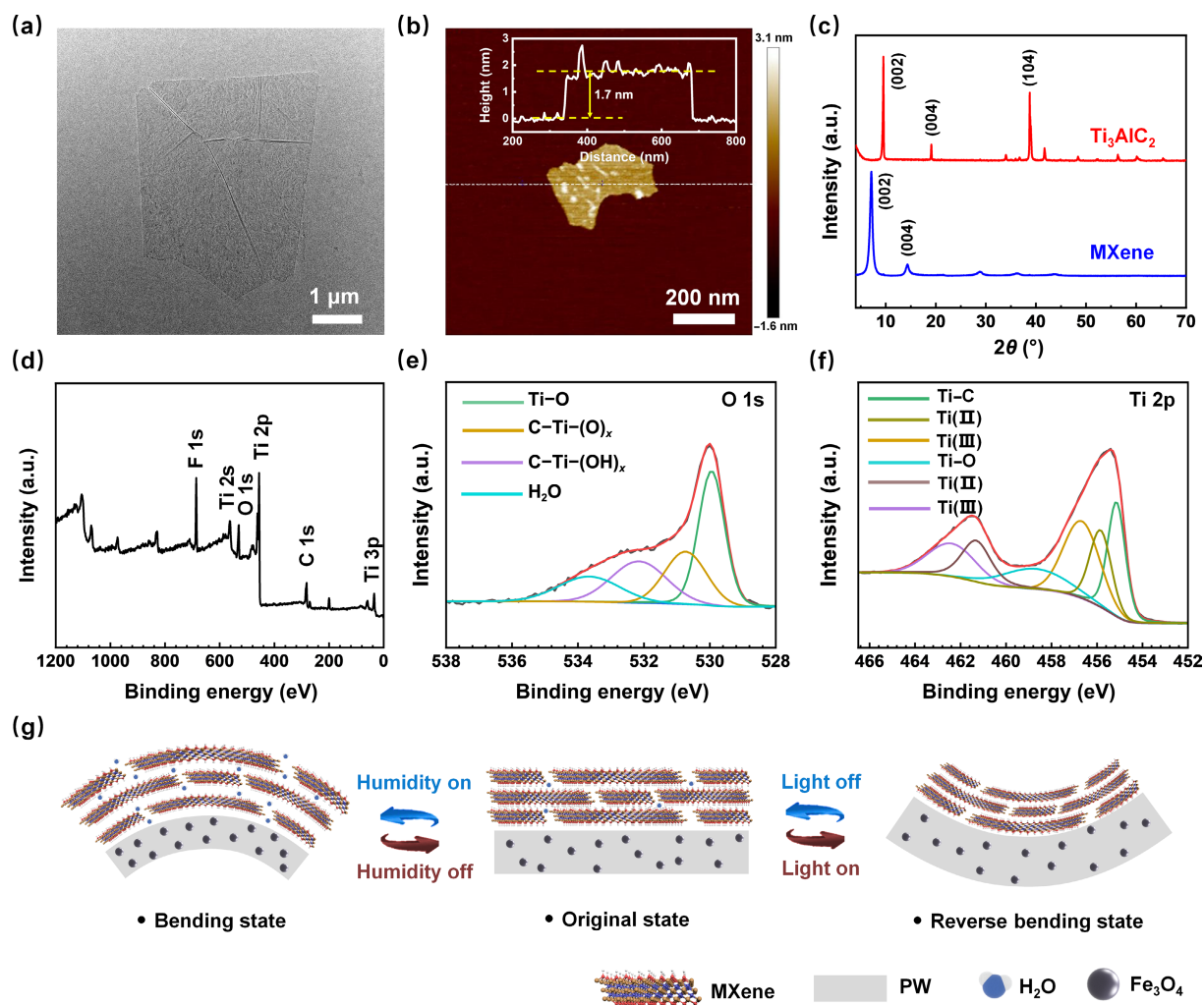


Figure 2 Multi-responsive mechanism of the MXene/PW&Fe₃O₄ film. (a) TEM image of the MXene nanosheets. (b) AFM image of the MXene nanosheets. (c) XRD patterns of Ti₃AlC₂ and the MXene film. (d) Survey XPS spectrum of MXene. (e) O 1s spectra of MXene. (f) Ti 2p spectra of MXene. (g) Schematic of the multi-responsive actuation mechanism of the MXene/PW&Fe₃O₄ bilayer film.

patterns of the pristine Ti₃AlC₂ MAX phase powder and the as-prepared MXene film. The disappearance of the characteristic (104) peak ($2\theta \approx 38.8^\circ$) of the MAX powder indicates complete etching of the aluminum layers [41] and the shift of the (002) peak from 9.5° to 7.2° collectively confirm the successful synthesis of the MXene film. The diffraction peak at 7.2° further corresponds to an interlayer spacing of approximately 1.2 nm between MXene nanosheets, suggesting a naturally layered stacking structure of the MXene film. Furthermore, the XPS survey spectrum (Fig. 2(d)) confirms the presence of C, Ti, O, and F elements in the MXene nanosheets. Meanwhile, analysis of the O 1s spectrum (Fig. 2(e)) identifies a peak at 531.2 eV corresponding to C-Ti-(OH)_x bonds, which suggests MXene contains hydroxyl groups (-OH) [42]. The strong absorption peak at approximately 3400 cm⁻¹ in the FTIR spectrum (Fig. S1 in the Electronic Supplementary Material (ESM)) is characteristic of O-H bond stretching vibrations, further substantiating the presence of hydroxyl groups [43]. These oxygen-containing groups (OCGs) endow MXene with hydrophilicity through the formation of hydrogen bonds with water molecules. Additionally, the Ti 2p XPS spectrum (Fig. 2(f)) confirms the presence of typical Ti-C bonds in MXene, whereas the peak intensity corresponding to Ti-O bonds is weak. This observation

suggests that MXene nanosheets undergo minimal oxidation during the template transfer process for preparing the MXene film with micro-ridge structures [44].

Based on the aforementioned results, the multi-responsive mechanism for the MXene/PW&Fe₃O₄ actuator is schematically illustrated in Fig. 2(g). Consistent with previous findings, MXene demonstrates excellent hydrophilicity due to its rich OCGs, and it thereby acts as the active layer in the bilayer actuator structure. Conversely, the PW&Fe₃O₄ layer is hydrophobic and humidity-insensitive, serving as the passive layer, which is confirmed by the water contact angles shown in Fig. S3 in the ESM. When exposed to high humidity, the hydrophilic MXene layer absorbs water molecules through hydrogen bonding and swells, whereas the passive PW&Fe₃O₄ layer is inert in moisture. This asymmetric expansion induces a strain mismatch at the bilayer interface, resulting in bending deformation towards the PW&Fe₃O₄ side and thus converting humidity into mechanical energy. Reversibly, as humidity decreases, the MXene/PW&Fe₃O₄ film returns to its initial state because of water desorption. Besides humidity actuation, the bilayer film is also light-responsive due to the efficient photothermal conversion capability of MXene and the significant difference in the thermal expansion coefficients (CTEs) between the

MXene layer ($1 \times 10^{-6} \text{ K}^{-1}$) and the PW layer ($1.24 \times 10^{-2} \text{ K}^{-1}$) [45]. Under light irradiation, the temperature of the bilayer film would increase due to light-to-heat conversion, which results in the contraction of MXene layer owing to the desorption of water molecules and the thermal expansion of PW&Fe₃O₄ layer. This asymmetric volume change consequently generates strain mismatch at the interface, causing the bilayer to bend towards the MXene side. The light actuation is also reversible. Additionally, the incorporation of Fe₃O₄ nanoparticles within the PW matrix endows the actuator with magnetic actuation.

3.2 Multi-responsive properties of the MXene/PW&Fe₃O₄ bilayer film

To quantitatively assess the actuation performance in response to multiple stimuli, we examined the bending behavior of the actuators under humidity, light, and magnetic field conditions (Fig. 3). Strips (~ 20 mm in length and ~ 1.5 mm in width) were cut from the as-prepared MXene/PW&Fe₃O₄ bilayer film to evaluate their actuation characteristics. Generally, MXene exhibits hygroexpansion effects upon moisture conditions due to the formation of hydrogen bonding between OCGs and water molecules. In contrast, the PW&Fe₃O₄ layer remains insensitive to

moisture. The resulting differential volumetric expansion between MXene and PW&Fe₃O₄ creates interfacial strain mismatch, causing the bilayer film to bend towards the PW&Fe₃O₄ side. As shown in Fig. 3(a), the actuator bends significantly from 10° to 269° as the relative humidity increases from 33% to 100%, demonstrating considerable shape deformation. Furthermore, the humidity actuation is reversible, with response and recovery time of ~ 97 and ~ 48 s, respectively (Fig. 3(b)). The slower response speed may be attributed to the introduction of micro-ridge structures, which slightly reduced the MXene's lateral hydrophilicity (Fig. S2 in the ESM). Notably, the actuator maintains consistent performance over 100 actuation cycles (Fig. 3(c)) and exhibits high stability (Fig. S4 in the ESM).

Taking advantages of the photothermal effect of MXene, the bilayer actuator is light-responsive. Under light irradiation, the MXene layer can realize light-to-heat conversion, which promotes the contraction of the MXene layer due to the desorption of water molecules. Meanwhile, the PW&Fe₃O₄ layer expands due to thermal expansion. In this way, the MXene/PW&Fe₃O₄ actuator bends to the opposite side under light stimulus. As shown in Fig. 3(d), with the light power density rising from 0 to 65 mW/cm² (RH = 44%), the bending angle of the actuator changes from 45° to

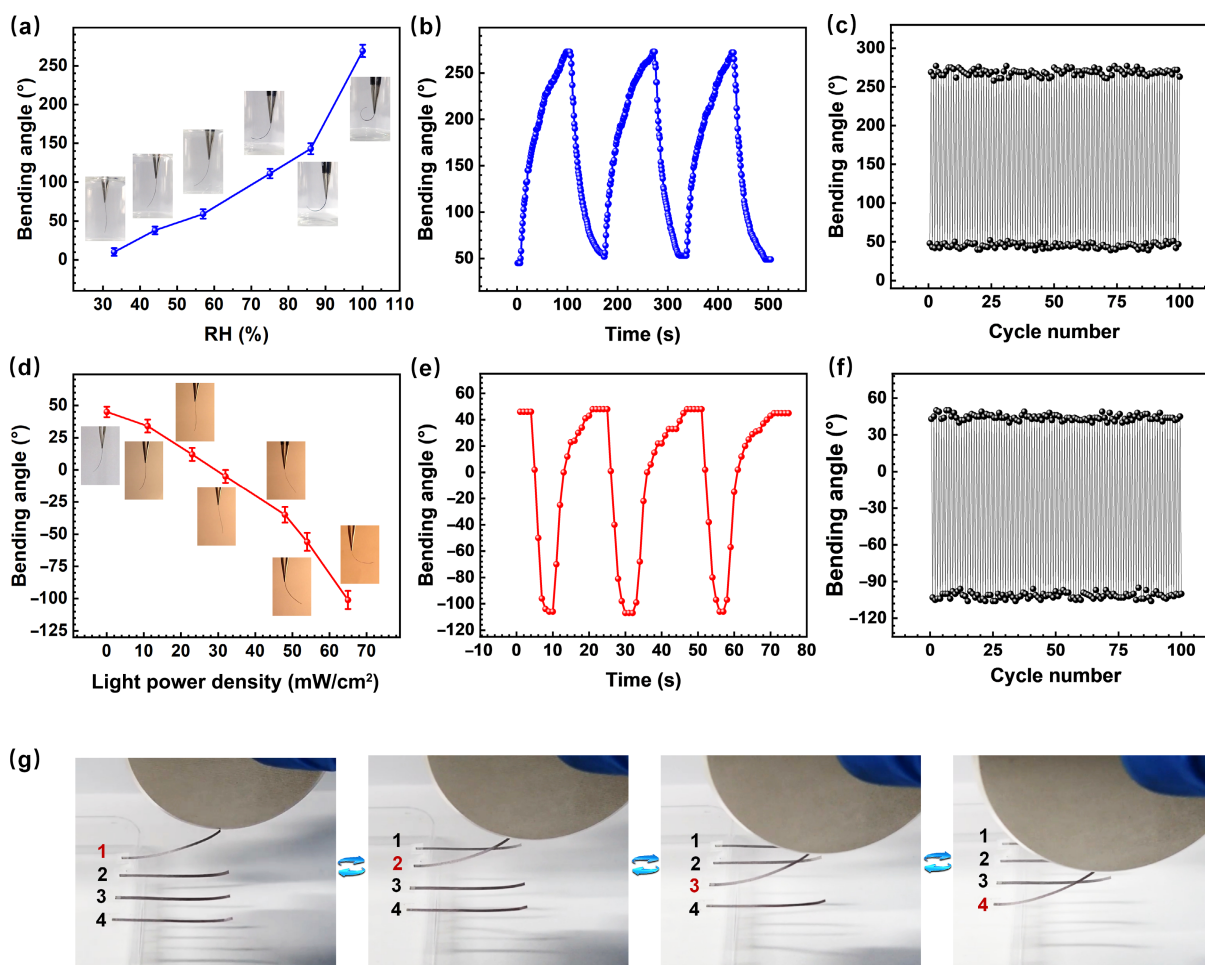


Figure 3 Multi-responsive actuation performance of the MXene/PW&Fe₃O₄ bilayer film. (a) Correlation between the bending angle of the bilayer film and RH under humidity stimuli. (b) Response and recovery curves of the bilayer film between RH = 44% and RH = 100%. (c) Durability test of the bilayer film for 100 deformation cycles, the humidity was switched between RH = 44% and RH = 100%. (d) Correlation between the bending angle of the bilayer film and light power density. (e) Response and recovery curves of the bilayer film between 0 and 65 mW/cm². (f) Durability test of the bilayer film for 100 deformation cycles, the light power density was switched between 0 and 65 mW/cm². (g) Optical images of the bilayer films under a magnetic field.

-101° . In addition, the light-driven bending-straightening deformation is also reversible (Fig. 3(e)), in which the response and recovery time is of ~ 6 and ~ 15 s, respectively. Moreover, the response time is remarkably fast, which is attributed to the synergistic effect of the contraction of MXene layer and the expansion of PW&Fe₃O₄ layer. The actuator also endured 100 continuous light-actuation cycles with no notable loss in performance (Fig. 3(f)). After 30 d, its actuation performance under light irradiation remained largely unchanged, further evidencing its robust stability (Fig. S5 in the ESM). Importantly, owing to the incorporation of Fe₃O₄ nanoparticles, the MXene/PW&Fe₃O₄ bilayer actuator is also responsive to magnetic fields. As depicted in Fig. 3(g), the actuator precisely moves toward and attaches to the strip actuator upon gradual approach of a magnet, confirming its high magnetic sensitivity. The actuation capability remains functional even after 30 d (Fig. S6 in the ESM). Furthermore, after 100 bending cycles under multi-stimuli actuation, the PW/Fe₃O₄

and MXene layers exhibit stable bonding without delamination, demonstrating their robust interlayer adhesion (Fig. S7 in the ESM).

3.3 Programmable complex deformation behaviour of MXene/PW&Fe₃O₄ actuators

The oriented arrangement of cellulose microfibrils in plant cell walls is the core mechanism underlying the curling deformation phenomenon [46]. This natural structural strategy provides important insights for developing biomimetic flexible actuators with programmable deformation capabilities. Since MXene/PW&Fe₃O₄ films feature micro-ridge structures, the stimuli-responsive deformation of the MXene/PW&Fe₃O₄ actuators can be controlled by the orientation of the micro-ridge structures (Fig. 4(a)). We prepared rectangular MXene/PW&Fe₃O₄ films with different orientations, in which the angle of the micro-ridge structures orientation varies from 0° to 90° . Under humidity

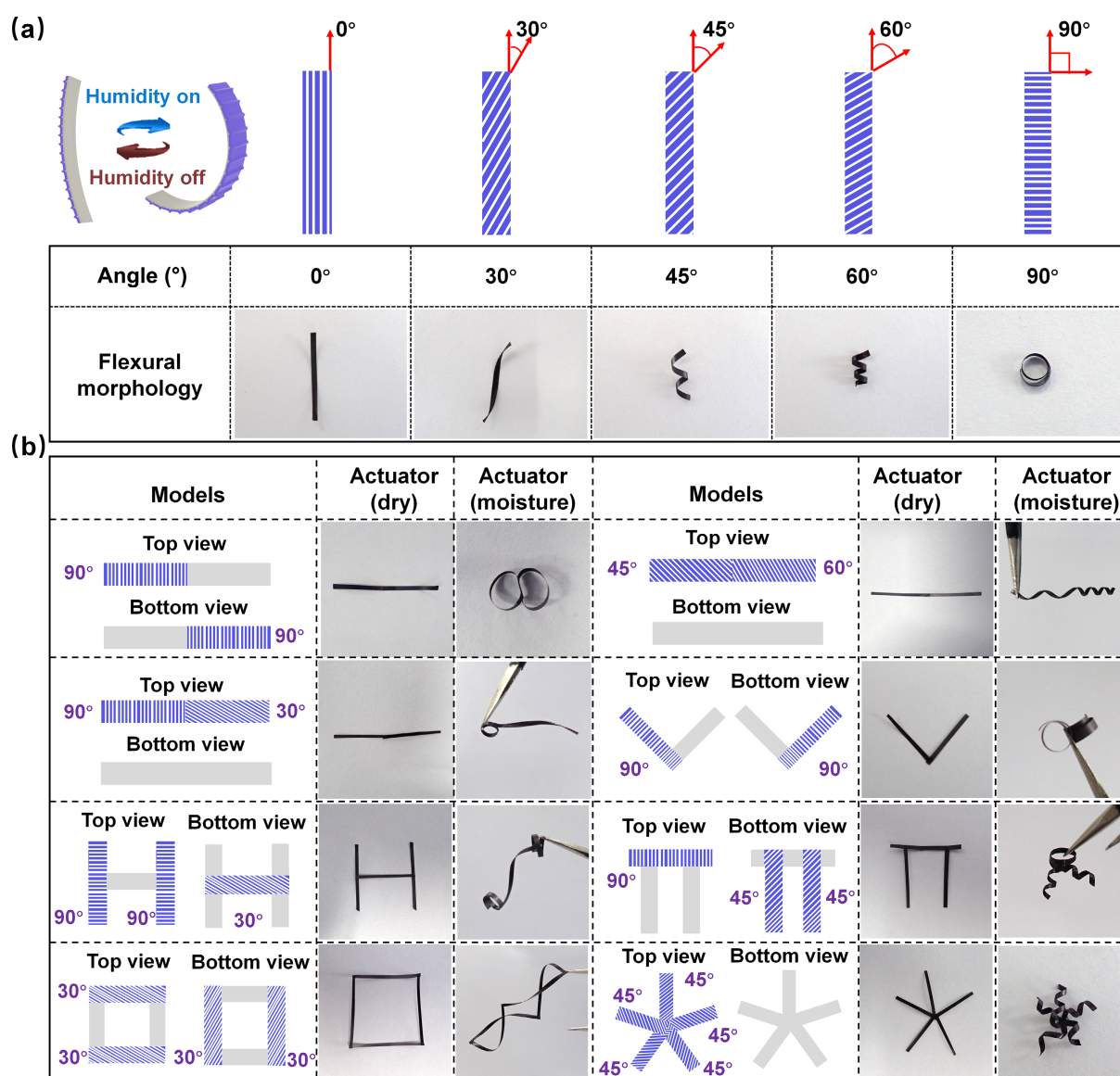


Figure 4 Programmable complex deformation behaviour of MXene/PW&Fe₃O₄ actuators. (a) The deformation of rectangular MXene/PW&Fe₃O₄ actuators with different orientation of the micro-ridge structures under humidity actuation. (b) A series of complex 3D configurations assembled by different MXene/PW&Fe₃O₄ strips through heat-welding methods; from left to right are models, photographs of the real actuators under dry conditions and their deformation under moisture actuation. The dimensions of each MXene/PW&Fe₃O₄ strips are 20 mm $\times$ 1.5 mm in size (length $\times$ width) and the RH is 100%.

actuation, these actuators display different twisted configurations, as illustrated in Fig. 4(a) (bottom). With an increase in the angle, the spiral count increases incrementally, accompanied by a corresponding reduction in spiral length. Therefore, the programmable deformation of the actuator can be achieved by adjusting the orientation of the micro-ridge structures.

More interestingly, leveraging the thermal phase change properties of PW, multiple actuators can be assembled together via heat-welding methods (Fig. S8 in the ESM), which enables the construction of actuators capable of various complex deformations. As shown in Fig. 4(b), eight types of 3D configurations assembled by rectangular MXene/PW&Fe₃O₄ strips with different micro-ridge structure orientations were designed. Under humidity stimuli, these actuators absorb a large amount of water molecules and bend towards the PW&Fe₃O₄ side, which achieves a controllable transformation from a 2D planar structure to the pre-designed 3D

configurations. Reversibly, when the humidity is removed, these actuators recover to their original initial state. Compared to previously reported soft actuators (Table S1 in the ESM), this MXene/PW&Fe₃O₄ actuator not only exhibits remarkable multi-response capabilities but also demonstrates greater shape programmability, revealing broader application potential in multi-field coupled manipulation.

3.4 Biomimetic *T. jasminoides*

Utilizing the above-mentioned multi-responsive properties and complex deformation capabilities of MXene/PW&Fe₃O₄ actuators, several soft robots have been successfully prepared. Inspired by the natural *T. jasminoides* (Fig. 5(a)), we first fabricated a biomimetic *T. jasminoides* that can bloom in response to humidity and light. Figure 5(b) shows the structure and working principle of the biomimetic *T. jasminoides*. Briefly, this biomimetic *T. jasminoides*

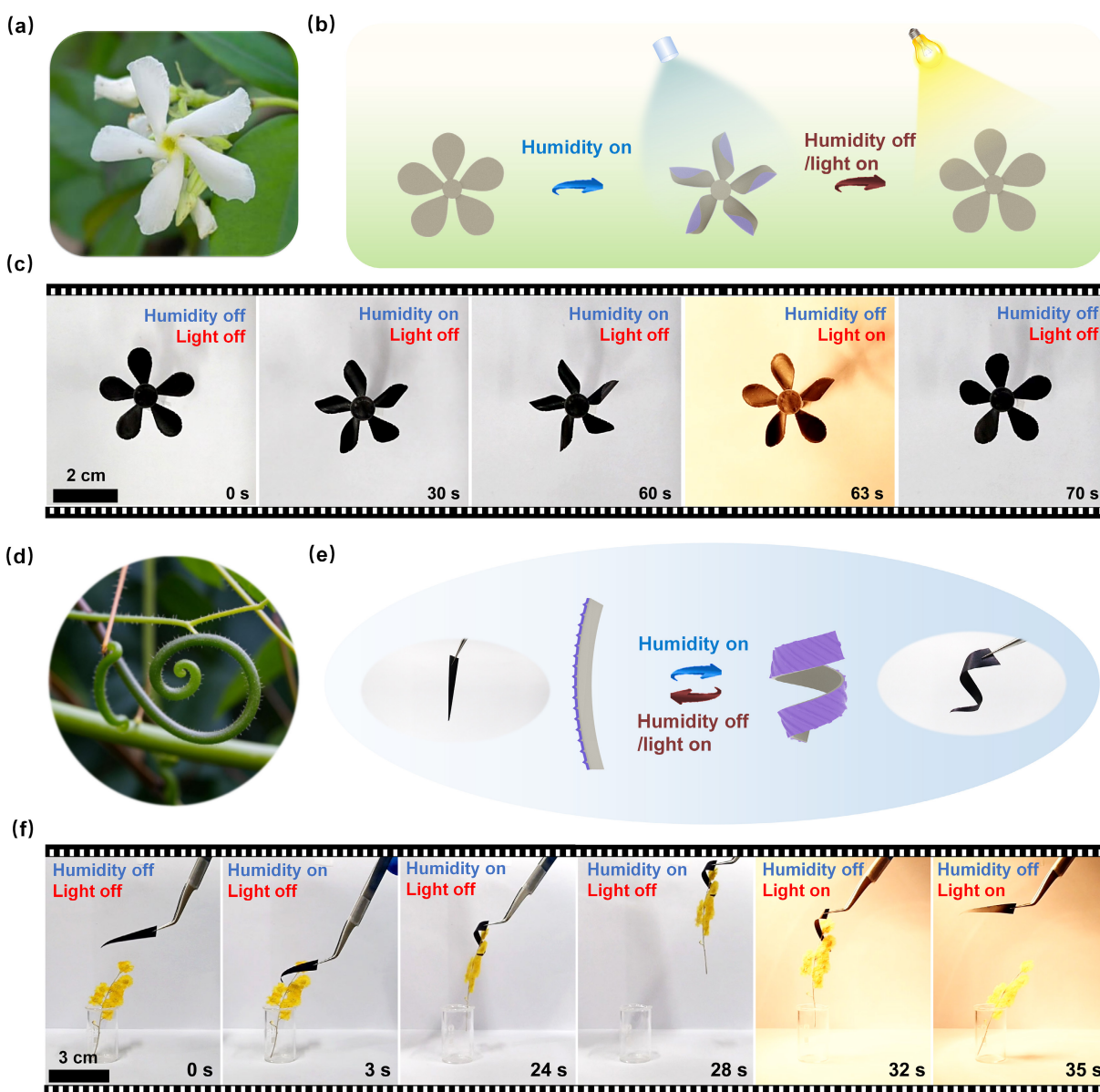


Figure 5 (a) Physical picture of *T. jasminoides*. (b) Schematic diagram of biomimetic *T. jasminoides* blooming. (c) Sequential snapshots of the blooming process of the biomimetic *T. jasminoides*, where the values of RH and light power density are 100% and 65 mW/cm², respectively. (d) Physical picture of loofah tendrils. (e) Schematic representation of the smart spiral gripper. (f) Manipulation of the smart spiral gripper using humidity and light, where the values of RH and light power density are 100% and 65 mW/cm², respectively.

consists of five teardrop-shaped petals (length: 12 mm, width: 5 mm) and a round stamen (5 mm in diameter), all of which were welded together by heat-welding methods. To mimic the distinctive morphological features of the *T. jasminoides* petals as closely as possible, the orientation of the micro-ridge structures of petal-like actuator needs to be 30°. Under ambient humidity, the petals appeared flat and straight. When humidity is applied using a humidifier, the biomimetic *T. jasminoides* petals would absorb water and produce a spiral bending towards the PW&Fe₃O₄ side, mimicking the morphology of the blooming *T. jasminoides*. Reversibly, when the humidity was withdrawn and the light (65 mW/cm²) was turned on, the petals quickly returned to the initial flat state. Figure 5(c) vividly demonstrates the dynamic blooming process of the biomimetic *T. jasminoides* under humidity and light stimulation (Video S1 in the ESM).

3.5 Smart spiral gripper

Tendrils-climbing plants, e.g., loofahs, can climb upward via a specialized climbing organ known as tendrils, which wrap around external supports such as tree branches and cling firmly to them to achieve a secure grip (Fig. 5(d)). Inspired by this morphological feature of the loofah tendril, we have also designed a simple smart spiral gripper that can be manipulated by humidity and light fields. Figure 5(e) shows the structure and driving mechanism of the smart spiral gripper. Briefly, an elongated triangular actuator (30 mm in height) was cut from the bilayer membrane to function as the smart spiral gripper, where the orientation of the micro-ridge structures is at 45°. Figure 5(f) shows the entire process of the smart spiral gripper grasping a yellow flower under the synergistic stimulation of humidity and light field (Video S2 in the ESM). Initially, the smart spiral gripper was kept flat when there was no humidity stimulus. When the humidity was switched on (RH = 100%), the gripper produced a spiral bending due to asymmetric water absorption, which can tightly wrap around the yellow flower and lift it up easily. Reversibly, after removing the humidity and switching on the light (65 mW/cm²), the gripper returned to its initial state and unloads the yellow flower. Notably, the 8 mg smart spiral gripper can easily lift a 100 mg yellow flower (12 times its own weight), and it outperforms previous smart grippers in terms of simpler structure, higher payload, and stronger competitiveness [41, 47, 48].

3.6 Multifield-coupling manipulation of maze robot

Considering the multi-responsive properties of the MXene/PW&Fe₃O₄ film, we also designed a maze robot, which can grasp and carry objects through the maze path by collaborative multi-field manipulation. Figure 6(a) illustrates the structure and operational principles of this maze robot. Each of its four petals (13 mm in length) consists of a MXene/PW&Fe₃O₄ bilayer film. Here, the micro-ridge structures orientation of the petal actuator is taken at an angle of 90° to the micro-ridge structures. Initially, under humidity actuation, the maze robot grasps a 6 mg foam block. Under the synergistic stimulation of humidity and magnetic fields, the maze robot can then successfully grasp and transport the foam block along a predetermined maze path. Eventually, the foam block is released when the humidity and magnetic field are removed, with the light field applied simultaneously. This multifield-coupling manipulation strategy (humidity, light, magnetic) allows the robot to grasp, retain, move, and place the object efficiently (Fig. 6(b), Video S3 in the ESM). Additionally, we recorded the full

trajectory of the maze robot. Figures 6(c)–6(e) illustrate that under multi-field synergistic control, the maze robot transported the target object 120 mm along the X-axis while maintaining a consistent path along the Y-axis, and its actual trajectory was further validated by the coordinate displacement plot in Fig. 6(e). These results confirm that the robot can achieve flexible, non-contact manipulation via coupled physical fields, underscoring its promising potential as a versatile soft robotic solution.

4 Conclusions

In conclusion, we fabricated a multi-responsive MXene/PW&Fe₃O₄ actuator with programmable-shaping capacity by introducing micro-ridge structures. Owing to the asymmetric water adsorption/desorption and different CTEs between the MXene layer and the PW&Fe₃O₄ layer, the actuator exhibits excellent responsive deformations under humidity, light and magnetic field stimuli. Benefiting from micro-ridge structures on the MXene surface, the actuator enables programmable deformation by adjusting the orientation of the micro-ridge structures. Interestingly, assembling these basic actuators together via heat-welding methods enables the achievement of various complex configurations, thereby further boosting their programmability under external stimuli. Taking advantages of the multi-responsive capabilities and programmability of the MXene/PW&Fe₃O₄ actuator, several soft robots including a biomimetic *T. jasminoides*, smart spiral grippers, and maze robots have been demonstrated. This work provides a straightforward and effective strategy to develop soft actuators that can simultaneously exhibit multiple responses and realize shape programming. And this strategy holds promise for advancing next-generation robotics, particularly in domains requiring intelligent environmental interaction, such as autonomous micro-robot swarms for complex tasks (search, rescue, exploration) or micro/nanorobots for targeted drug delivery within the human body.

Electronic Supplementary Material: Supplementary material (FTIR spectrum, water contact angles, the multi-responsive performance of the actuator after 30 d, SEM images, heat-welding methods, comparison table, etc.) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908345>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

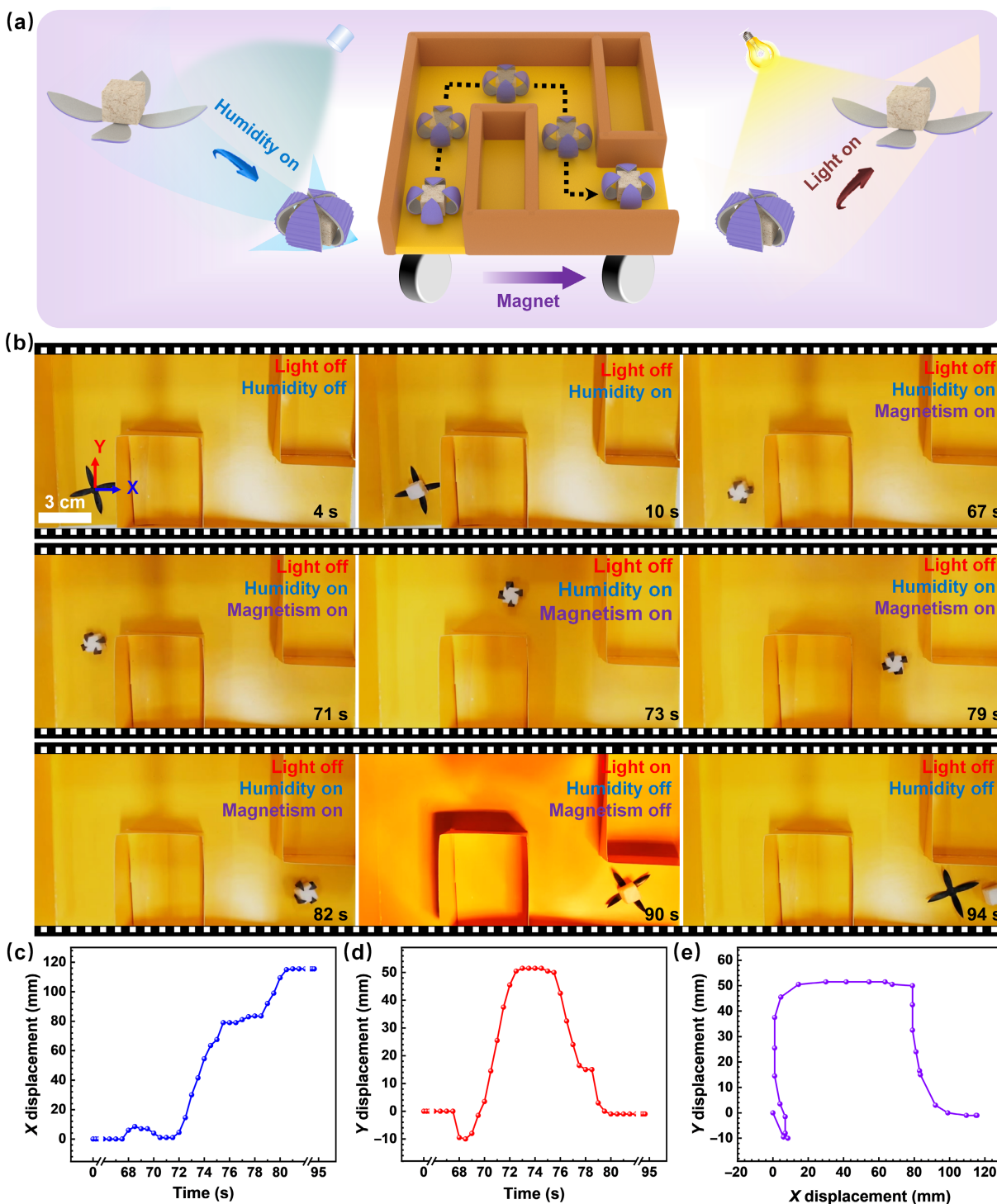


Figure 6 Multifield-coupling manipulation of the maze robot. (a) Schematic representation of the maze robot manipulated by humidity/light/magnetism. (b) Sequential snapshots of the maze robot in action, where the values of RH and light power density are 100% and 65 mW/cm², respectively. (c) and (d) Temporal evolution of X, and Y displacements of the maze robot, respectively. (e) The coordinate displacement trajectory map of the maze robot.

Author contribution statement

B. M.: methodology, validation, data curation, writing-original draft, and visualization. J. N. M.: conceptualization, methodology, formal analysis, investigation, and writing-review & editing. K. W.: investigation. D. M. Z.: investigation. K. D. Z.: validation. Y. Z.: formal analysis. S. B. S.: writing-review & editing, and project administration.

Use of AI statement

None.

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