Triple-responsive Soft Actuator with Plastically Retentive Deformation and Magnetically Programmable Recovery

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Abstract. Multi-stimuli responsiveness and programmable shape recovery are crucial for soft actuators in soft robotics, electronics, and wearables. However, existing strategies for actuation cannot attain power-free shape retention after removing external energy supply. Here, a self-assembled density deposition method was developed to fabricate electrothermal-NIR-magnetic triple-response actuator which was composed of cellulose nanofiber/polyvinyl alcohol/liquid metal (CNF/PVA/LM) and magnetic polydimethylsiloxane (MPDMS) layer. Interestingly, the large deformation can be controllably fixed and the temporary configuration will be programmable recovered under magnetic field due to the thermal-plastic transferring behavior of the CNF/PVA/LM. Prepared rolling robot based on soft actuators exhibits fantastic ability to avoid obstacles. In addition, the handling and programmable release capabilities of the carrier robots demonstrate that the new actuation approach will contribute to realize more application environments with various stimuli.

Possible Sessions

21. Soft matter, 24. Testing of composite materials

Introduction

Soft actuators have attracted much attention due to their effective applications in biomedicine, long-distance transportation, camouflage, and perception technology.[1-2] Different from traditional rigid actuators, the softness and high deformability of soft actuators enable them to morph the body, easily reconfiguring and deforming around object contours.[3] Thus far, substantial efforts have been devoted to developing the driving methods of actuators, including temperature, light, pH, humidity, and electric and magnetic fields.[4-6] Although various response mechanisms of actuators have gained considerable development, it remains as a crucial issue to implement multiple responses at the same time, which has limited their wider applications. Besides, enabling the actuator to maintain any intermediate state configuration without continuous stimulation is a key strategy for expanding the application of the actuator.

In this work, we report a triple-stimulus-responsive soft actuator with a new actuation regime. The coupling synergistic effect of thermal shrinkage of CNF/PVA/LM and thermal expansion of MPDMS enables the actuator bends and undergoes plastic deformation under electrothermal and photothermal stimuli, and exhibits programmable shape recovery in response to a magnetic field in a thermal environment. With the good multi-field coupling energy conversion ability of soft actuators, the successful application of rolling robots and carrier robots demonstrates the great potential of actuators in soft robots and smart devices.

Results and Discussion

The preparation of CNF/PVA/LM/MPDMS(CPLMMP) film as shown in Fig. 1a. In brief, the CNF/PVA/LM film is obtained by static sedimentation and evaporation. Then, the plasma treatment and mechanical pressure are applied to form strong bonding between the MPDMS film and the CNF/PVA/LM film. Finally, the triple-responsive soft CPLMMP film is obtained. Under the stimulation of electrothermal and photothermal, the CNF/PVA/LM layer of the actuator shrinks, while the MPDMS layer expands, resulting in bending deformation of the CPLMMP actuator, which enables programmable shape recovery of the actuator by applying a magnetic field in a thermal environment (Fig.1b).

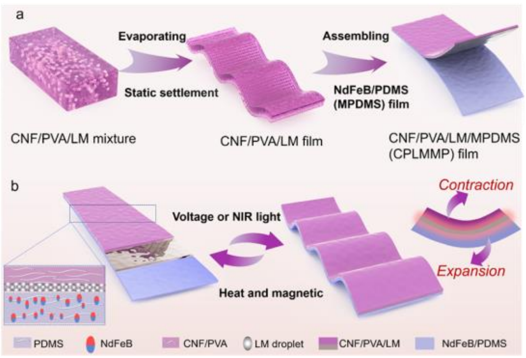

Fig. 1. (a) Schematic diagram for preparation of CPLMMP film. (b) Schematic diagram of CPLMMP actuator deformation under external electro-activated or light stimulation and shape recovery under magnetic stimulation in thermal environment.

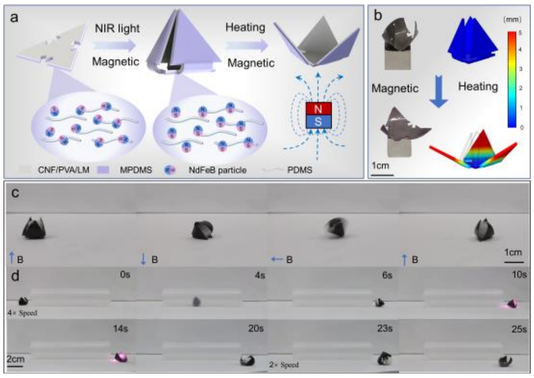

Fig. 2. (a) Schematic diagram of photothermal deformation and thermal/magnetic recovery of a carrier robot. (b) Three limbs of carrier robot released under magnetic attraction in a thermal environment. The illustration is the result of finite element simulation of magnetic release process (c) The carrier robot is wrapped in an optical picture of an object moving in a magnetic field for one cycle. (d) Process optical image of a carrier robot wrapping an object through a frosted pipe and releasing the object at a fixed point.

Based on the origami magnetization strategy, the CPLMMP film was fabricated into a regular triangle carrier robot by cutting method. Fig. 2a displays the process of retracting and releasing the three limbs of the carrier robot. After being heated, the modulus of the three limbs of the carrier robot decreases. Under the attraction of the edge magnetic field of a 1×1×1 cm^3 magnet, the three limbs bend outward, thereby the object was released (Fig. 2b). Driven by magnetic force, the carrier robot wrapped around the goods achieved a rotational motion within 3 seconds, demonstrating excellent transport speed (Fig.2c). Fig. 2d illustrates the carrier robot carrying goods, smoothly passing through a frosted pipeline under a rotating magnetic field, and achieving the release of goods under the control of NIR and magnetic field at the edge of the magnet. This simple and excellent photothermal plastic thermal magnetic recovery feature greatly expands the application field of soft actuators.

Conclusion

In summary, a soft actuator composed of a combination of CNF/PVA/LM films with excellent electrical conductivity and magnetic PDMS was designed and fabricated. The soft actuators possess electric-NIR-magnetic triple-response performance, exhibiting a new driving method. The CNF/PVA/LM layer of the actuator contracts under electrothermal or NIR light stimulation while the MPDMS layer expands, resulting in bending deformation of the CPLMMP actuator. After the stimulus being removed, the shape of the actuator is fixed. Finally, programmable shape recovery of the actuator is achieved by applying a magnetic field in a thermal environment. This study develops a new actuation strategy integrated with multi-stimuli response, remote control, ultra-low driving voltage, and programmable complex deformation, which will provide high potential in exploring smart materials for complex biomimetic systems.

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