Dual-Responsive Soft Actuators with Integrated Sensing Function Based on 1T-MoS2 Composite

Qixiao Ji, Zhuang Jing, Jinjie Shen, Ying Hu,* Longfei Chang,* Luhua Lu,* Muye Liu, Jiaqin Liu, and Yucheng Wu

Developing a multiresponsive and multifunctional soft actuator that can output mechanical deformation is crucial to the fields of soft robotics and wearable devices. Herein, a 2D metallic molybdenum disulfide (MoS2)-based soft actuator with dual-response and self-sensing function is designed and fabricated. By using the outstanding photothermal property of 1T phase MoS2, good electrical property and network structure of carbon nanotubes (CNTs), hygroscopic expansion of paper, and thermal expansion of polyimide (PI), the MoS2-based actuator can respond to external voltage and light stimulation and produce rapid and large bending deformation. In addition, the actuator can be used as a flexible strain sensor to realize real-time sensing of bending deformation by using piezoresistive property of the MoS2–CNT composite film. Based on this soft actuator, a flexible mechanical gripper that can manipulate soft objects with irregular shape and intelligent wearable gloves that can automatically close to block the light irradiation are made. Furthermore, combined with the sensing feature of this MoS2-based actuator, the gripper with integrated sensing function is also developed. These results indicate the great prospect of the MoS2-based actuator in intelligent soft mechanical devices, robots, and wearable systems.

1. Introduction

Soft actuators can respond to electricity,[1–4] light,[5–8] heat,[9,10] and humidity[11,12] and produce mechanical deformation output. Owing to a wide range of applications in soft robots,[13] intelligent biomimetic devices,[14,15] biomedical sensing and diagnosis,[16] and wearable devices,[17] they have received more and more research interests recently. According to the external stimuli and actuation mechanism, soft actuators can be divided into many types, such as electrical-induced actuator,[1–4] optical-induced actuator,[5–8] magnetic actuator,[18] and so on. Among them, actuators driven by electrical voltage or light have been widely studied due to their unique characteristics. For the electrical-induced actuator, electrical energy has the advantages of simple operation, easy storage and utilization, and good controllability, whereas the light-induced actuator has unique features, including wireless actuation, remote control, and no contact with the sample.[19–21] Therefore, by combining the advantages of the two types of actuators, the application range and utilization convenience can be largely improved. For example, in microrobot applications, the power system it carries may be restricted due to the limited size of the microrobot. When the electricity is exhausted, the light energy can be supplied to drive the microrobot to continuously work. In space, the sunlight can be used as the driving source of the actuator, and the electric energy is used as the driving source of the actuator once it is in the dark environment, ensuring the normal operation of the actuator and save energy. However, most of the actuators studied only respond to one single stimulus. It is still of great importance to fabricate actuators with high-performance and multistimuli response.

Developing new types of materials with multistimuli responsive property is the key to achieve multistimuli responsive actuators. As a new type of 2D nanomaterials, transition metal dichalcogenide (TMD) nanosheets have attracted enormous attention due to their excellent properties, including tunable bandgap,[22] excellent optical properties, high strength,[23] and so on, which makes them great potential in sensors,[24] batteries,[25] supercapacitors, energy storage and conversion,[26] and actuators. As one of the typical TMDs, molybdenum disulfide (MoS2) has good photothermal conversion characteristics.
It can convert light energy into heat energy, which is considered as one of the promising candidates of photothermal actuators.\textsuperscript{[27]} For example, Lei et al. used chitosan to exfoliate and modify MoS\textsubscript{2} nanofibers simultaneously, and prepared the photothermally responsive anisotropic nanocomposite hydrogels through a facile two-step polymerization. Among them, MoS\textsubscript{2} nanosheets act as photothermal transduction agents and enable remote and precise control of the actuator locomotion. The as-prepared flexible MoS\textsubscript{2}-based hydrogel actuator exhibits remarkable mechanical performance including shape deformation and self-wrapping motion.\textsuperscript{[28]} In addition, MoS\textsubscript{2} also shows outstanding performance in the electroactive actuators. Acerce et al. demonstrated that the dynamic expansion and contraction of electrode films formed by restacking chemically exfoliated nanosheets of 2D metallic MoS\textsubscript{2} on thin plastic substrates can generate substantial mechanical forces. These films were capable of lifting masses that are more than 150 times that of the electrode over several millimeters under low electrical voltage.\textsuperscript{[29]} However, the current MoS\textsubscript{2} actuator can only realize reversible deformation driven by a single stimulus. Thus, the development of high-performance MoS\textsubscript{2} actuator with multistimulus response is highly desirable, for it not only provides the basis for exploring the use of MoS\textsubscript{2} material in novel actuator design, but also enriches the application of 2D materials in actuator field.

In addition to the mechanical deformation output, the realization of real-time sensing of the actuation process is also important for the multifunction design and precise control of the actuators. At present, the sensing of the actuator deformation is mainly realized by simple visual observation. For the tiny deformation that cannot be directly observed, self-sensing function would play a very important role. In addition, similar to the human finger that can sense the grasping action and the targeted object in real time, when the actuator is used to manipulate fragile or soft objects, it is necessary to accurately sense the interaction between the actuator and the objects, which requires the self-sensing function. However, most of the actuators lack the ability to sense their own deformation. To realize the additional sensing function, the conventional way is to integrate the sensor unit onto the actuator. This may increase the complexity of the actuator, and limit the deformation to a certain extent. Therefore, developing actuator materials with both the actuation and mechanical sensing characteristics has become an alternative way. For example, Amjadi et al. designed electrothermal actuators based on graphite and CNT hybrid films capable of simultaneous actuation and sensation.\textsuperscript{[30]} Recently, Chen et al. reported a graphene-based actuator with integrated-sensing function, which realizes real-time measurement of the shape deformation.\textsuperscript{[31]} In the field of mechanical sensing, MoS\textsubscript{2} is also widely used. Because MoS\textsubscript{2} has excellent mechanical properties, high gauge factor (GF), and adjustable bandgap, the MoS\textsubscript{2}-based piezoresistive sensors have high sensitivity and good stability.\textsuperscript{[32,33]} For instance, Chhetry et al. report a highly sensitive and reliable piezoresistive strain sensor fabricated by one-step carbonization of the MoS\textsubscript{2}-coated polyimide (PI) film to obtain MoS\textsubscript{2}-decorated graphene. The sensor provides a high GF of $\approx$1242, low detection limit of 0.025%, wide working range up to 37.5%, and stability over 12,000 cycles with excellent switching response.\textsuperscript{[33]} Therefore, MoS\textsubscript{2} nanomaterials have great potential for the fabrication of soft actuators with multistimuli response and multifunction.

In this work, a dual-responsive soft actuator consisted of paper, MoS\textsubscript{2}–CNT composite structure, and PI is fabricated. This trilayer film actuator can not only produce mechanical bending deformation under external light or electrical voltage stimulation, but also have the self-sensing function. The actuation function in response to light and electrical voltage is mainly attributed to the excellent photothermal properties of MoS\textsubscript{2} nanosheets, the good electrical and thermal conductive network structure formed by CNT, the large thermal expansion of PI, the hygroscopic expansion property of paper, and the designed trilayer actuator structure. And the sensing characteristics are due to the piezo resistance and thermal resistance of MoS\textsubscript{2}–CNT composite structure. The actuator can not only be used to construct a soft mechanical gripper for grasping objects under electrical or light stimulation and smart wearable gloves for automatically blocking the light irradiation, but also be used as strain sensor for detecting the human finger bending and pressing behavior. Moreover, the mechanical gripper also achieves the integrated self-sensing of its light-induced manipulation of the objects. These results reveal the great prospect of this MoS\textsubscript{2} composite-based film actuator in intelligent soft robots, wearable sensing, and human–machine interaction systems.

2. Results and Discussion

The preparation diagram of MoS\textsubscript{2}-based actuator is shown in Figure 1a. The actuator is a sandwich trilayer structure with 1T phase MoS\textsubscript{2} and carboxylic CNT composite film as the intermediate electrothermal conversion layer, and paper and PI films as the actuation active layer. Here, we choose paper and PI as the actuation active unit, mainly because the paper has a low coefficient of thermal expansion (CTE) and a high coefficient of hygroscopic expansion (CHE) of nearly 0.1 C\textsuperscript{-1}, making paper an ideal candidate material for actuator fabrication.\textsuperscript{[34–36]} As we know, for an ideal candidate of the actuator material, it requires to be able to respond to external stimuli and produce reversible mechanical deformation. Paper is probably the most easily accessible example of actuators.\textsuperscript{[37]} It is composed of cellulose fibers network structure and can easily absorb water molecules in the surrounding environment, thus producing reversible volume change under the humidity or temperature change. Once heated, the absorbed water molecules in the paper are desorbed, causing the shrinkage deformation of the paper.\textsuperscript{[13]} On the contrary, PI film has a high CTE and a negligible CHE. The preparation process is as follows: first, the paper is cut into the size of a glass slide, which is closely attached to the slide, and the composite solution consisted of 1T metal phase MoS\textsubscript{2} and CNT is deposited onto the paper. After the composite solution is dried, the PI tape is cut into the desired U shape from the middle part, and the copper wire is connected to the MoS\textsubscript{2}–CNT layer at both ends of the U-shaped film with conductive silver paste, so as to obtain the MoS\textsubscript{2} composite-based actuator.

The surface morphology of paper and MoS\textsubscript{2}–CNT composite structure are characterized by scanning electron microscopy.
As shown in Figure S1, Supporting Information, the paper has a porous cellulose network structure, which is not only helpful for the hygroscopic expansion, but also provides a good structural support for the deposition and penetration of MoS2–CNT composite solution on it. Figure 1b shows the SEM image of the surface of 1T phase MoS2 film. It can be seen that the bonding between pure MoS2 sheets is relatively loose, which leads to the lack of flexibility and fragmentation of MoS2 film. Therefore, pure MoS2 film is not suitable for the construction of soft actuator with large deformation. When dispersing a certain amount of CNT into MoS2 sheets, CNT can form a certain network structure to wrap and connect MoS2 sheets, which makes MoS2–CNT composite film have good mechanical flexibility (Figure 1c,d). This is also advantageous to the better deposition and coverage of MoS2–CNT composites on the paper. The cross-sectional SEM image of paper/MoS2–CNT/PI composite film in Figure S2, Supporting Information, shows that the tight interface structure between MoS2–CNT and polymer is formed. The interface between MoS2–CNT and paper is also in good contact (Figure S3, Supporting Information), and there is no obvious delamination. This facilitates the integrity of the trilayer composite structure during the large deformation. Figure S4, Supporting Information, shows transmission electron microscope (TEM) images of the 1T-MoS2 nanosheets. The high-resolution TEM image in Figure S4b, Supporting Information, provides further evidence for the 1T phase, and the plane distance is measured as about 0.26 nm, which corresponds to the (101) plane. X-ray diffraction (XRD) pattern is also used to further confirm the 1T phase. As shown in Figure S5, Supporting Information, a strong peak located at 14.4° corresponds to the (002) crystal lattice plane of 1T-MoS2, and the other peaks observed at about 22.0° and 29.0° are due to the (011) and (004) planes of 1T-MoS2, respectively, which is consistent with the reported work.[38–40] To further analyze the interaction between CNTs and MoS2, we also measure the X-ray photoelectron spectroscopy (XPS) spectra of the 1T-MoS2 and MoS2–CNT composite. Deconvoluted XPS spectrum of Mo3d and S2p for 1T-MoS2 and 1T-MoS2–CNT are shown in Figure S6, Supporting Information, for comparison. It is found that the band position of both Mo3d and S2p negatively shifts. The Mo3d5/2 of 1T-MoS2 is found to be 228.45 eV (Figure S6a, Supporting Information) and shifts to 228.24 eV of 1T-MoS2–CNT (Figure S6c, Supporting Information), while the Mo3d3/2 of 1T-MoS2 is found to be 231.67 eV and shifts to 231.41 eV of 1T-MoS2–CNT. The S2p of 1T-MoS2 is found to be 161.55 eV (Figure S6b, Supporting Information) and shifts to 161.40 eV of 1T-MoS2–CNT (Figure S6d, Supporting Information), while the S2p3/2 of 1T-MoS2 is found to be 162.88 eV and shifts to 162.67 eV of 1T-MoS2–CNT.[29,41] This peak shift indicates that electron penetration from carbon nanotube to 1T-MoS2 in the hybrid of 1T-MoS2–CNT is due to the fact that carbon nanotube is an electron-rich material. Moreover, light shocking is verified to be a simple and effective way to controllably tune the interlayer coupling of the 2D material heterostructure and modify the optical and electronic properties.[42] Therefore, during the light-induced actuation, irrigated by light may be helpful for further modulating the electronic and optical property of MoS2–CNT composite structure. This is worthy of further exploration in future work.

The electrical-induced actuation performance of the MoS2 composite film-based actuator under the external electrical voltage stimulation is investigated, as shown in Figure 2. To better measure the detailed deformation, the composite film is cut into the U shape, with the open end fixed and connected to the electrodes so that the other end can deform freely. This actuator can generate bending deformation under the applied low electrical voltage, with the bending direction toward the paper side (Figure 2a). The mechanism of this electrical-induced actuation is attributed to the electrothermal effect of MoS2–CNT composite interlayer, the contraction of paper on one side under thermal stimulation, and the thermal expansion effect of PI layer on the other side. As we all know, paper is a porous network structure composed of cellulose fibers, which has excellent hydrophilicity. The CHE of paper is particularly high (0.1 C−1).
compared with that of the PI polymer (almost negligible), but its CTE is low (about 4 ppm °C⁻¹) which is only one-tenth of the CTE of PI polymer. In high humidity environment, paper can absorb water and produce expansion deformation. When heated, it can lose water molecules and produce shrinkage deformation. On the contrary, the PI has high CTE (55.6 ppm °C⁻¹) and negligible CHE accompanied with other advantages including remarkable mechanical property and high-temperature resistance, which is suitable and widely used for the preparation of thermal responsive actuators. When 15 V voltage is applied to the U-shaped actuator, a current of about 40 mA is generated in the MoS₂–CNT middle layer. Through the Joule heat effect, electric energy is converted into heat energy. This causes shrinkage of the paper layer and thermal expansion of the PI layer, making the actuator to bend to the paper layer side. The actuator can generate a bending deformation with an angle of about 80° in 10 s under the electrical stimulation, as shown in Figure 2b. When the electrical power is turned off, the actuator returns to its original shape, showing that the electrical-induced actuation is completely reversible (Movie S1, Supporting Information).

Moreover, the deformation can be controlled by changing the applied electrical voltage. As shown in Figure 2c, when the voltage decreases, the bending angle also decreases. The temperature change in the actuator under different voltage stimulation is also studied (Figure 2d). The change trend of the temperature is almost the same as that of the bending angle, indicating the electrothermal mechanism of this actuation. Figure 2e shows the maximum bending angle variation of the actuator under different electrical voltage stimulation. The results show that
the maximum bending angle increases with the increase in voltage, which reveals the good controllability of this electrothermal actuator. Because the bend deformation is resulted from the thermal mismatch in the different layers of the actuator, we also studied the mismatch of the thermal and elastic behavior of the different layers. Figure S7, Supporting Information, shows the curve of thermal deformation of the paper/MoS$_2$–CNT composite film as a function of the temperature. With the temperature increasing, this composite film produces shrinkage deformation mainly due to the water loss in the paper. The stress–strain property of this composite film is also measured (Figure S8, Supporting Information), and its Young’s modulus is calculated to be about 500 MPa. Combined with the thermal expansion deformation feature of PI film and its large mechanical elasticity (2500 MPa), a large bending deformation can be generated in this paper/MoS$_2$–CNT/PI composite actuator. According to these parameters, finite element method (FEM) is used to simulate the bending deformation of the actuator (Figure S9, Supporting Information), which is almost in consistence with that of the experimental results. The actuation stability under electrical voltage stimulation is also tested, as shown in Figure 2f. During three cycles of electrical-induced actuation, the deformation angle has good repeatability. Long time stability of the MoS$_2$-based actuator is also examined (Figure S10, Supporting Information). During about 100 cycles, the bending angle change keeps stable without any obvious change. As we know, the paper and PI film have good thermal and mechanical stability. The MoS$_2$–CNT composite layer as the electrothermal conversion unit is sandwiched between the paper and PI layer, as it can be well protected. Therefore, the actuator has good operation stability.

In addition to the external electrical stimulation, the actuator also generates reversible bending deformation when the light irradiation is applied to the actuator. As shown in Figure 3a, under the simulated sunlight irradiation (249 mW cm$^{-2}$), the actuator bends to the paper side with the deformation angle of about 94° in 15 s. After turning off the light source, it returns to its original shape (Movie S2, Supporting Information). Once the intensity of the incident light is changed, the bending angle of the actuator is also changed. Figure 3b shows the detailed deformation angle change in actuator with different light intensity during the light-induced actuation. With the increase in light intensity from 148 to 249 mW cm$^{-2}$, the maximal deformation angle simultaneously increases. In the process of light-induced actuation, the measured temperature of the actuator increases with the increase in light intensity (Figure 3c). And the trend of temperature variation is nearly consistent with that of deformation angle shown in Figure 3b. This reveals the light-induced actuation is related to the photothermal effect. When the light is irradiated on the actuator, MoS$_2$–CNT composite layer with good photothermal conversion property can absorb light energy and convert it into heat energy. Through the good contact with paper and PI layers, the paper and PI layers are heated to generate shrinkage and expansion, respectively. The combination of these two layers leads to bending deformation of the whole actuator. Under the cyclic illumination of external light

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Light-induced actuation of the MoS$_2$-based actuator. a) Optical images of the actuator under the light irradiation. b) Bending angle change in the actuator under the applied light irradiation with different incident intensity (148, 194, and 249 mW cm$^{-2}$). c) Temperature variation of the actuator under different incident light irradiation. d) Angle change in the actuator under cyclic light irradiation.
with the intensity of 196 mW cm$^{-2}$, the deformation angle of the actuator has almost kept the same (Figure 3d), further confirming the stability of the actuator in the light-induced actuation. The mechanical output of the actuator is also tested. As shown in Figure S11 and Movie S3, Supporting Information, under light irradiation, the actuator can lift a metal clamp with a weight (1.2 g) of about 30 times its own weight to a height of 4 mm, revealing the potential in soft robotic devices. Moreover, to investigate the influence of the CNT on the photothermal effect of MoS$_2$-based actuator, we have prepared a pure MoS$_2$-based film and measured its temperature change under light irradiation (Figure S12, Supporting Information). Compared with the MoS$_2$-CNT composite film, the pure MoS$_2$ film shows a slight decrease in temperature increasing speed. But their maximal temperature keeps almost consistent, indicating the photothermal effect of the actuator is mainly resulted from the MoS$_2$ component. We also compare the comprehensive performance of our actuator with the same type of actuators reported in the literature. In terms of stimulus, deformation amplitude, response time, load of picking, and self-sensing function, our fabricated actuator performs well.

We further study the applications of this MoS$_2$-based actuator in the fields of soft robots and intelligent wearable devices. First, a biomimetic mechanical gripper is constructed, with the upper end connected with the external circuit through the conductive electrodes and the MoS$_2$-based actuators adhered to the lower ends as the fingers. The mechanical gripper can grasp objects with different shapes under the external stimulation of light and electrical voltage. As shown in Figure 4a and Movie S4, Supporting Information, the intelligent mechanical gripper can realize the manipulation function of dry rose (weight of 0.5 g) under electrical voltage stimulation. When the external electrical voltage of 13 V is applied, this mechanical gripper can grasp the rose, and it is moved from position A to position B through moving the mechanical gripper. When the electrical voltage is turned off, the mechanical gripper opens to put down the rose, thus realizing the mechanical manipulation of the object with a distance of about 60 mm. In addition, the gripper can also be used to grasp the objects with irregular shape, including a twig (Figure 4b) and a leaf (Figure 4c). In addition to the electric-induced actuation, when the light irradiation is used as the stimulus source, the mechanical gripper can be driven to grasp and lift the object (Figure 4d). The MoS$_2$-based actuator can be also used to prepare wearable devices to prevent human body from being irradiated by the strong sunlight. To realize this function, we prepared an intelligent rubber glove with the top part hollowed out and covered by a rectangular MoS$_2$-based actuator (Figure 4e). Small strip arrays are partially cut out from the actuator to form the movable “window” parts. Before light illumination, these strips are pre-bent upward to make them open and the hand skin exposed outside. After exposed to the light irradiation, these movable parts on the glove start to bend down and close, preventing the human skin from being irradiated by strong sunlight.

The strain sensing performance of the MoS$_2$-based actuator is also studied, as shown in Figure 5. The actuator is cut into rectangle with the dimension of 18 $\times$ 5 mm$^2$, and the copper foil electrode is connected to its two ends with the conductive silver paste. Electrochemical workstation is used to record the resistance change during the bending deformation. The sensing principle is mainly due to the compression of the MoS$_2$-CNT composite film in the bending deformation process, resulting in the closer contact between the CNTs and the reduction of the resistance $t$ (Figure 5a). The 2D MoS$_2$ nanosheet has relatively poor electrical conductivity, while 1D CNT is highly conductive. In the MoS$_2$-CNT composite film, the MoS$_2$ nanosheets are

![Figure 4](https://example.com/figure4.png)

**Figure 4.** a–c) Manipulation of objects (including a dried rose, a twig, and a leaf) by the mechanical gripper under the applied electrical voltage. d) Grasping of a plastic ball by the mechanical gripper under light irradiation. e) Reversible deformation of the intelligent wearable glove with the light irradiation on and off. The insets are the side optical images of the deformation of the movable parts.
wrapped and connected by the CNT to form flexible layered network structure. When the bending deformation is applied to the actuator film, the conductive path network formed mainly by the CNT becomes tighter due to the compression of the MoS$_2$–CNT composite interlayer, resulting in an increase in the contact area among CNTs. Thereby, the resistance of the composite film is reduced. When the applied deformation is removed, the MoS$_2$–CNT layered network becomes loose, and the contact area of the conductive CNT gradually decreases, leading to the increase in the contact resistance. The sensing performance of the actuator under different bending strains is shown in Figure 5b. To better evaluate the sensing performance, the normalized resistance change $\Delta R/R_0 = (R-R_0)/R_0$ is adopted, where $R$ is the resistance in the deformation process, and $R_0$ is the initial resistance when the actuator is not deformed. The larger the bending deformation, the larger the resistance change. When the strain increases from 0.25% to 0.5%, the resistance change improves from 4.3% to 10.68%. The relationship between chord length $C$ and radius of curvature $R$ is: $C = 2R \sin(L/2R)$, where $L$ is the arc length of the sample in bending state.$^{[44,45]}$ The strain $\epsilon$ of the actuator can be expressed as: $\epsilon = \pm H/(2R)$, where $H$ is the thickness of the actuator (160 $\mu$m). The relationship between the resistance change $\Delta R/R_0$ and strain $\epsilon$ is shown in Figure 5c. For calculation, the GF (defined as $GF = (\Delta R/R_0)/\Delta \epsilon$) is about 24.75. Although this value is smaller than some reported flexible strain sensors, it is comparable with that of the similar resistive-type sensors.

Due to the sensing performance, this actuator can be utilized in wearable devices to detect the human motion. As shown in Figure 5d, the sensor is adhered to the finger joint of a rubber glove which is put on the person’s hand, and the electrodes are connected to the electrochemical workstation to record the change in resistance. The cyclic finger joint bending motion from the flat state (marked as “1”) to the bending state (marked as “2”) can be detected by the recorded resistance changes, which reveals that the actuator has good sensing performance for human motion monitoring. Furthermore, the response time of the actuator in mechanical sensing is also tested, which is realized by rapidly applying pressure to the surface of the actuator. When the surface of the actuator is rapidly pressed by a finger, its resistance decreases rapidly (Figure S13a, Supporting Information). This is mainly due to the increase in the contact area between CNTs in the pressed area. The sensing response time of the actuator is estimated to be about 200 ms (Figure S13b, Supporting Information). In addition, the long-term stability is an important factor for the sensing performance of the sensor. Therefore, the resistance change in the actuator during multiple cycle bending is also measured, as shown in Figure S14, Supporting Information. During 200 cycles of bending deformation, the resistance change in the sensor keeps basically stable, with only a slight degradation of about 2%, which confirms the repeatability and stability of this actuator in sensing performance. Apart from the simple mechanical sensing, we further study the resistance change in the actuator during the actuation
process. When the actuator deforms under the external stimulation, its resistance change is mainly affected by two factors: one is the piezoresistive effect caused by the change in the contact area of the CNT during the bending deformation process; the other is the thermal resistance effect of the material (the temperature dependence of the resistance). Therefore, the resistance change in the actuator under different temperatures is measured (Figure S15, Supporting Information). It shows that the resistance decreases as the temperature increases, indicating that the actuator has a negative temperature coefficient of resistance (TCR) similar to that of CNT. Therefore, the resistance change in the sensor is determined by the strain and temperature changes. When the temperature of the actuator increases, the resistance of the actuator decreases. At the same time, the temperature rise leads to the bending of the actuator, which causes the reduction of resistance. Because the piezoresistance and thermo-resistance have the same change trend, the piezoresistive signal can be amplified by the temperature change during the thermal actuation process, which is beneficial to the integration of the self-sensing function of the actuator.

Based on the actuation and sensing performance of the actuator, we further study the integrated sensing function of the mechanical gripper in the process of light-induced actuation. Figure 6 shows the output resistance signal of the mechanical gripper at different stages of manipulating the plastic ball under light irradiation. In the initial stage, the gripper is open in the absence of light, and the resistance hardly changes (black line). When the light source is turned on, the actuators bend to gradually approach the ball until the gripper completely grasps the ball. In the meanwhile, due to the influence of temperature and strain, the resistance decreases rapidly (blue line). After that, the gripper grasps the ball, picks up, and moves it from position “A” to position “B.” During this process, the resistance continues to decrease (red line). Finally, after the light source is turned off, the mechanical gripper releases the ball, and the resistance gradually increases and returns to the initial value (green line). The results show that the mechanical gripper can sense the different actions in the process of grasping, picking up, and releasing objects. In addition, the tiny deformation of the actuator that is not observed by eyes (Figure S16a, Supporting Information) can be detected through the self-sensing function of the actuator by the resistance change (Figure S16b, Supporting Information).

3. Conclusion

A dual-responsive soft actuator based on paper, MoS2–CNT composite film, and PI film is fabricated. The actuator not only shows good electrical/optical-actuated actuation with large deformation, but also realizes the sensing function of bending deformation. Based on the actuator, we not only construct a flexible mechanical gripper for manipulation of the objects driven by light/electricity, but also develop mechanical sensors for detecting finger bending and pressing behavior. Moreover, the mechanical gripper based on the soft actuator can realize the integrated sensing of its own light-induced grasping process. Those works reveal the importance of the MoS2-based materials in the next generation of intelligent soft actuators and related multifunctional devices and robots.

4. Experimental Section

Materials: Carboxylate CNT was purchased from Nanjing XFNANO Materials Tech Co., Ltd. Paper was normal A4 printing paper with a thickness of about 90 μm and density of 70 g m^{-2}. PI self-adhesive with the thickness of 50 μm film tape was purchased from commercial products.

Synthesis of 1T-MoS2: Butyllithium (16 mL) was dissolved in 100 mL hexane and then 2 g MoS2 was immersed in above solution in a Flask saturated with argon for 3 days, filtered to obtain the Li2MoS2, and washed with hexane (300 mL) for several times to remove excess lithium. Then, the ultrasonicating treatment (Fisher Model 505 horn ultrasonicator) was conducted immediately for 1 h at 150 W in the deionized water to exfoliate the MoS2. The mixture was centrifuged several times to remove the unexfoliated precipitate. The obtained uniform dispersion was the 1T-MoS2.[28]

Fabrication of the MoS2-Based Actuator: The CNT powder (10 mg) and 3 1T-MoS2 powder (30 mg) were, respectively, dispersed into 10 mL N,N-dimethylacetamide (DMF) solution under 200 W, 20 kHz horn sonication treatment (2 s on and 5 s off) in ice water bath for 30 min. Then, the mixed MoS2–CNT composite solution was dropped onto the surface of paper and heated at 45 °C for 6 h to completely evaporate the organic solvent, obtaining the paper/MoS2–CNT composite film. Afterward, the PI film tape was pasted on the MoS2–CNT side of the composite film, and the position for connecting external wires was reserved. Then, the tri-layer film was cut into the required U shape from the middle part. After that, the copper foil electrode was connected to the MoS2–CNT composite surface of the U-shaped tri-layer film with conductive silver paste, and heated at 60 °C for 2 h to make the conductive silver paste fully solidified. Thus, the MoS2-based actuator was obtained.

Actuation Characterization: Electrical voltage stimulation was supplied by ITECH IT6834 DC power supply, and light stimulation was supplied by Xe lamp (AULIGHT) equipped with simulated sunlight filter. A digital camera was used to record the electrical/light-induced actuation process. The temperature change in electrical voltage/light-induced actuation was measured by using the thermal infrared imager (Fotric 225-1).

Sensing Characterization: The rectangular MoS2-based actuator was placed between the motorized translation stages (Beijing Optical Century Instrument Co., Ltd., MTS121) with the two ends fixed for the mechanical sensing test. Computer-controlled step motor was used to control the strain and the deformation times of the actuator.
was connected to an electrochemical workstation (CHI 660E) through the
two sides by the copper foils. A 0.1 V voltage was applied on the actuator
and the resistance change was collected by the electrochemical
workstation.

Characterization: The SEM images were obtained by a Zeiss Gemini 300
field-emission scanning electron microscope. The TEM images were
obtained by a field-emission transmission electron microscope (Tecnai
G2 F20 S-TWIN). The XRD patterns were obtained on X’Pert-Pro MPD
(Cu Kα). The thermal deformation was conducted by a thermomechanical
analysis (TMA 402 F1 Hyperion) with a heating rate of 10 K min⁻¹. The
stress–strain property was measured by a universal material testing
machine (Instron 3365).

The experiments involving human subjects have been performed with
their full, informed consent.

Supporting Information
Supporting Information is available from the Wiley Online Library or from
the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
Research data are not shared.

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