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Multi-functional stretchable and flexible sensor array to determine the location, shape, and pressure: Application in a smart robot

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The rapid increase in the aging population prompts the development of wearable devices and sophisticated robots. With their ability to collect complex information about their surroundings via e-skins, robots could perform more dynamic and variable tasks such as rescue missions or caring for the elderly. In this paper, we present a new concept of utilizing a very simple, highly flexible and stretchable capacitor sensor array, that can be attached on the surface of a retractable robot hand to realize three functions: determining the location, shape, and pressure of an object. This adaptive sensing system is accomplished using capacitors connected by aligned carbon nanotube (CNT) films constructed on an elastomer dielectric material, which can reduce the requirement on the accuracy of the machine vision system. This study has a very broad application in the manufacture of intelligent software robots.

sensor array, stretchable, location, shape, pressure

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1 Introduction

With the rapid increase in aging population, there is a driving factor for the development of sophisticated robots, prosthetics, and wearable devices. Electronic skin (e-skin) tactile sensor promise important advancements in the fields of robotics and medical devices [1–5]. With their ability to collect complex information about their surroundings via e-skins, robots could perform more dynamic and variable tasks such as rescue missions or caring for the elderly [6,7]. A remarkable property of the sensor skins is its ability to accommodate body movements while maintaining its sensing property, which requires exceptional flexibility as well as stretchability [6–10]. In general, the tactile sensing capabilities of an e-skin include measurements of the pressure, strain, shear forces, and vibrations [7,11–18]. These tactile stimuli are usually converted into electrical signals, including changes in the resistance or capacitance and the production of a voltage using piezoelectric components. Until now, research studies were mainly focused on improving the sensitivity, spatial resolution and stretchability of tactile sensors [19–21], and very recently, the focus is on sensing multiple stimuli using e-skin systems [22–25].

Here, we fabricated a very simple, highly stretchable sensor array composed of capacitors connected with aligned carbon nanotube (CNT) strips constructed on elastomer dielectric materials. Further, we presented a new concept of utilizing this highly stretchable capacitor sensor array to realize three functions: determining the location, complex shape, and pressure. We design an application in care robot

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using attaching the stretchable capacitor array on the surface of a retractable robot hand. Usually the care robot system is very complicated. For example, when a robot wants to support the elderly, a high-precision robot vision system is required for the robot to place his hand on the elderly's body, and then control the robot's movement and strength. This design will reduce the requirement on the accuracy of the machine vision system. Just having a rough outline of the human, using proximity sensing property of the stretchable capacitor array, the robot with a very small hand can firstly detect the location to touch at one point, then spread around the elderly's arm to determine the shape of the arm, and finally hold it suitably by pressure sensing property of capacitors. Because of proximity sensing, flexibility and stretchability of this sensor system, the robot hand will be safer and more comfortable.

2 Experimental section

Materials. Commercial products styrene-(ethylene-butylene)-styrene (SEBS) copolymer was first washed with dishwashing liquid and clean water, and then washed with ethanol and distilled water in a ultrasonic cleaning equipment for 30 min, then dried in an air drying oven. The cleaned SEBS was cut into a square of 50 mm×50 mm and used as the elastic substrate. 2.18 g of washed SEBS was added into 50 mL of cyclohexane (99%), and the mixture was sonicated for 60 min to accelerate its dissolution. The aligned CNT strips were directly drawn from spinnable, multiwalled carbon nanotube forests grown by chemical vapor deposition.

Fabrication of the sensor. The substrate was stretched biaxially by fixing its four edges with fixture. The specimens were pre-strained at 0, 50%, 100%, 200%, and 300% strains. First, a single layer of the aligned CNT strip was paved on the pre-strained substrate. Then, 600 μL of the mixed SEBS solution was poured into a spray gun with a pipette, and the mixed solution was sprayed on the CNT strip surface. After drying in an air oven, another CNT strip layer was paved on the substrate, in a direction perpendicular to the previous CNT strip, and the spray process was performed as in the previous step, and the specimen was dried in the air oven. The sensor array was fabricated in a process similar to that of the single capacitor, but several parallel CNT strips were paved on the substrate. Then, an epoxy-resin adhesive was cured on the surface of each individual capacitor, with the aim of preventing the single capacitor from deforming when the sensor array system is stretched. Finally, a silver paste was coated on the tail end of each CNT strip on one side to attach the copper wires.

Characterization. The pressure test of the sensor was carried out between 100 kHz–1.0 MHz and the sensor system was positioned on electronic scales. A Digital camera was used to monitor the change in the reading of the capacitance. The capacitance was measured by a precision LCR Meter (TH2829, 20–1 MHz, Tonghui, China). SEM images were obtained from a scanning electron microscope (Smart SEM, Supra55VP, ZEISS, Germany).

3 Results and discussion

Three-dimensional (non-coplanar) patterning involves buckling of aligned CNT strips by depositing aligned CNT strips on a pre-stretched elastomer, and then releasing the applied strain. Aligned CNT strips were obtained from drawable CNT forests (denoted as CNT strips). The CNT forests (with ~6 walls; ~350 μm in height and ~9 nm in outer diameter) were synthesized by chemical vapor deposition [26–28]. The strip resistance of a single CNT layer was measured to be ~700–1000 Ω cm^{-1}, depending on the areal density of the CNT strip (which is a function of the forest height) [29]. The elastic substrate and dielectric material are composed of styrene-(ethylene-butylene)-styrene (SEBS) copolymer. To fabricate the sensor, a layer of aligned CNT strip was paved on the biaxially pre-stretched SEBS substrate (biaxial tensile ratio: 0–300%), followed by spraying a SEBS/cyclohexane solution as the dielectric layer. Then, another CNT strip layer was paved perpendicular to the previous CNT strip and the SEBS solution was sprayed again as a covering layer. Subsequently, the strain applied on the stretched rubber was slowly released to obtain the unstretched (relaxed) sample. The capacitor cell is formed at the intersection of the perpendicular carbon strips. The carbon strip not only serves as the electrode of the capacitor cell but also as the conductor connecting the capacitors. Finally, an epoxy-resin adhesive was covered on the surface of the capacitor cell to avoid capacitance change during stretching and bending. To fabricate the stretchable sensor array, several parallel strips were paved instead of one CNT strip, as shown in Figure 1.

Figure 1 shows the pre-strained planar structure of the sensor array and the released three-dimensional structure. The inset in Figure 1 shows the surface scanning electron microscopy (SEM) image of a 200% pre-strained specimen in the relaxed state. The formation of a buckled structure can be observed in the SEM images of the capacitor cell and CNT strip, respectively. The mismatch between the equilibrium strains of the aligned CNT strip and soft substrate results in the bending-dominated deformations of CNT strip and the stretching/shearing-dominated deformations of the substrate, causing the CNT strip to wrinkle in response to the relaxation of the applied strain [30]. CNT is highly oriented in the CNT strip drawing direction, and shows much higher Young's modulus in this direction than in the transverse di-

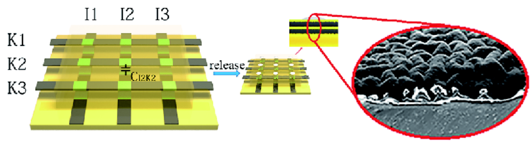

Figure 1 (Color online) Fabrication of stretchable array composed of invariable capacitors and stretchable connecting conductors.

rection. Figure 2 shows the SEM images of the released bulk structures of the capacitor cells that were bi-axially pre-stretched at 50%, 100%, 200%, and 300% strain. The higher the degree of pre-strain of the substrate is, the higher the extent of deformation is and denser the wrinkles are. In addition, with respect to the 200%–300% bi-axially pre-stretched specimens, the location of the capacitor cell on the SEBS substrate was slightly raised. This phenomenon can be rationalized by the fact that the dielectric layer and covering layers that are un-strained in the pre-stretched state are forced to shrink upon the release of strain. Table 1 lists length change ($\Delta L_e/L_{e0}$) and area change ($\Delta S_e/S_{e0}$) of biaxial stretched elastomer substrate and area change ($\Delta S_c/S_{c0}$) of the capacitor.

3.1 Dependence of the capacitance on the test frequency

Figure 3(a) illustrates the typical dependence of the capacitance (C) on test frequency for the capacitor with planar (fully stretched) and buckled structures (the capacitor bi-axially pre-stretched at 200% and then released). We observed that in the frequency range of 100 kHz to 1 MHz, the capacitance of the capacitor with the planar structure decreased with an increase in the frequency; instead, the ca-

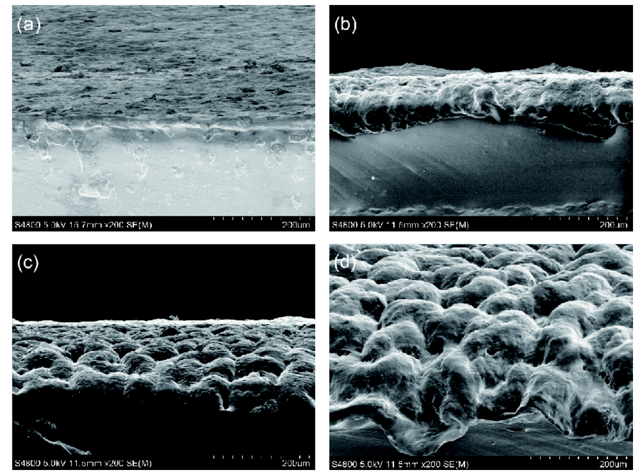

Figure 2 SEM images of the released bulk structures of the capacitor cells that were bi-axially pre-stretched at (a) 0, (b) 100%, (c) 200%, and (d) 300% strain.

Table 1 Length change ($\Delta L_e/L_{e0}$) and area change ($\Delta S_e/S_{e0}$) of biaxial stretched elastomer substrate and area change ($\Delta S_c/S_{c0}$) of the capacitor

Sample	$\Delta L_e/L_{e0}$ (%)	$\Delta S_e/S_{e0}$ (%)	$\Delta S_c/S_{c0}$ (%)
*C*50	50	125	78
*C*100	100	300	156
*C*200	200	800	216
*C*300	300	1500	611

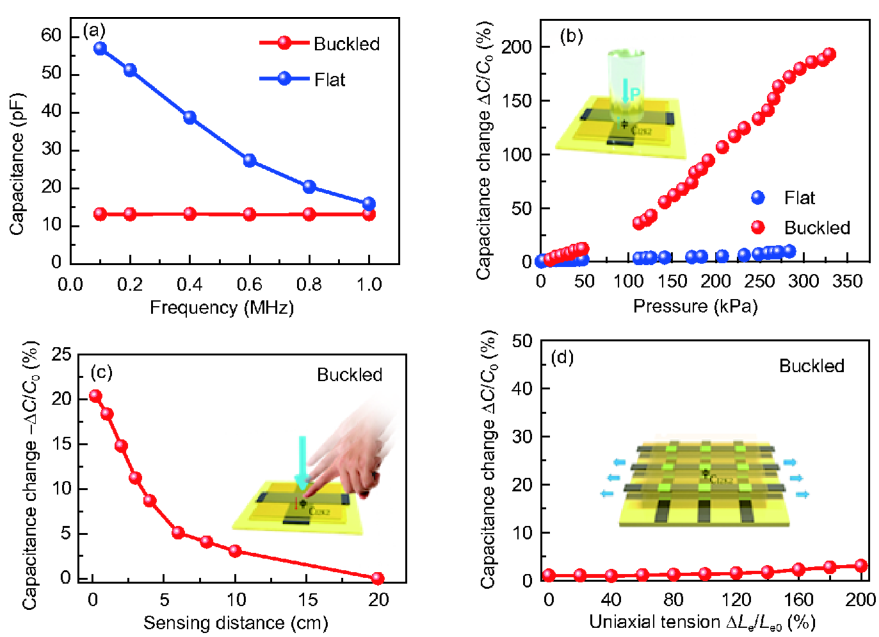

Figure 3 (Color online) (a) The typical dependence of the capacitance on frequency for the capacitor with a planar structure (fully stretched) and a buckled structure (200% bi-axially pre-stretched capacitor at released state). (b) The change of capacitance along with pressure for the capacitor with a planar structure (fully stretched) and a buckled structure (200% bi-axially pre-stretched capacitor at released state) measured at 200 kHz, respectively. (c) The dependence of capacitance on distance (D) from interface of the sensor for the buckled capacitor with 200% pre-strain measured at 200 kHz. (d) The dependence of capacitance of buckled capacitor (200% pre-strained) on stretching degree measured at 200 kHz.

pacitor with the buckled structure presents a stable capacitance, and its loss D is small. The change in the capacitance $((C_{max}-C_{min})/C_{max})$ with respect to the frequency between 100 kHz to 1 MHz for the buckled capacitor is 1.59%, whereas it is larger than 250% for the planar capacitor. This implies that the buckled structure is favorable to render the capacitor operational over a wide frequency range.

3.2 Pressure sensing

The change in the capacitance along with pressure for the capacitors with planar and buckled structures was measured at 200 kHz as shown in Figure 3(b). The capacitance increased with an increase in the pressure, and the pressure sensitivity of the capacitor with the buckled structure (0–284 kPa) is superior to that of the planar capacitor (0–329 kPa). A comparison of the capacitance change ($\Delta C/C_0$) for specimens bi-axially pre-stretched at 50%, 100%, 200%, and 300% strain under the released state as a function of the change in the pressure is shown in Figure S1 (Supporting Information). The pressure sensitivity (S), defined as the slope of the traces, is commonly used to evaluate the performance of a pressure sensor. The sensitivities are 0.443, 0.501, 0.630 and 0.299 kPa^{-1}, respectively. Compared with previously reported capacitive pressure sensors, the sensitivity of our sensors is higher than those with carbon nanotube electrodes (0.23 MPa^{-1} over the pressure range up to ~1 MPa) [11], those with serpentine gold electrodes (0.48 MPa^{-1} over the pressure range up to 0.25 MPa) [16], and those based on gold thin films embedded in silicone rubber (0.4 MPa^{-1} for pressure up to 160 kPa) [31]. Our sensor showed a similar bilinear response to the highly sensitive pressure sensors (0.55 kPa^{-1} for less than 2 kPa and 0.15 kPa^{-1} for 2–7 kPa) using a microstructured PDMS dielectric layer and a PET substrate [12]. In general, the capacitance increases considerably with the variation in the distance between the electrodes induced by pressure, which can be used to detect the pressure. A capacitive pressure sensor requires an air-embedded microstructured dielectric layer such as a pyramidal elastomer or foamed elastomer to improve the sensitivity. In this work, when the bulked structure of the capacitor was formed, air gaps were also formed in the structure. Under applied pressure, the air gaps get closer and the dielectric layer is squeezed so that the area of the electrodes increases and the inter-electrode distance decreases, resulting in an increase in the capacitance. When the pre-straining of the SEBS substrate is larger, the more dense the folds are formed after release and the height of the folds is higher, which promises a larger distance change between the two capacitor plates. So, the value S gets larger with the degree of pre-straining of the substrate from 0 to 200%. However, S300% is less than S200%, which can be rationalized by the wrinkles of the former capacitor being too dense and squeezed together.

3.3 Touch sensing

Our capacitive sensors can also be used to detect finger or body touch, more broadly, the touch of a grounded conducting medium [32]. The approach of a finger leads to a drop in the capacitance between the electrodes as shown in Figure 3(c). When a finger touches a capacitor, the fringing electric field (through the medium directly above the sensor) is partially intercepted and shunted to ground by the finger, resulting in decreased capacitance. Figure 3(c) illustrates the dependence of the capacitance change (ΔC) on the distance (D) from the interface of the sensor for the buckled capacitor that was 200% pre-strained. The capacitive sensor shows a bilinear response to the proximity of the finger in the range of 0 to 20 cm, demonstrating its high sensitivity to a finger in very close proximity. The relative capacitance change of our touch sensor is comparable to that of capacitive touch sensors reported in the literature [33]. The lateral position of the finger can be detected on the basis of the observed capacitance changes, and the capacitances of different positions are determined as shown in Figure 4(c). A similar mechanism is widely used in capacitive touch screens.

In some touch sensing applications, forces from finger touch are inevitable. Figure S2 and Movie 1 (Supporting Information), illustrate the working process of two different modes, where the capacitance changes resulting from gentle finger touch (no force applied) and strong finger press (large force applied) were shown for investigation. In the pressing mode, the finger pressing has two opposing effects on the capacitance: finger as a grounded conductor leads to a decrease in the capacitance while physical pressing causes an increase in the capacitance as the pressure sensor does. The capacitance increased because the influence of physical pressing was much larger than that of electric field. Due to high pressure sensitivity of the capacitor, it was found that even with very little force, the capacitance would increase. Consequently, we can easily differentiate the two sensing in proximity mode (no force applied) and pressing mode (force is applied). This characteristic could be very useful in applications of nursing robots.

The capacitances of stretchable capacitors usually change under stretching and bending. Here, we designed a facile method to maintain the capacitance constant on the sensor array by covering an epoxy-resin adhesive on the surface of each individual capacitor, with the aim of preventing the capacitor from deformation when the sensor array system is stretched. In our previous work, we have demonstrated that the resistance of a CNT strip with a buckled structure on elastic substrate is nearly invariant even under 1400% strain [30]. Now, the capacitance in the stretching process remains the same as shown in Figure 3(d) and Movie 2 in Supporting

InformationThis can guarantee that during the stretching or bending the elastic substrate, the decrease in the capacitance is caused by the closing to the human body, or the increase in the capacitance is caused by the pressure, as shown in Figure 3(b) and (c).

3.4 Application of the stretchable sensor array

We have demonstrated the pressure and touching sensing modalities using our capacitive sensors. Based on the above analysis, we fabricated a 2×4 sensor array (the unit size of sensor array is 6 mm×6 mm, the units are spaced 4 mm apart from each other, the whole size of the 2×4 sensor array is 24 mm×44 mm) composed of 8 capacitors connected to buckled CNT strips operating as stretchable conductors to identify the shapes and edges of objects, which can be used in nurse robots. As shown in Figure 4, the 2×4 sensor array was designed to be attached on the surface of the retractable palm of nurse robots that can take care of an elderly or patient. Using a low precision imaging system, the outline of an object can be estimated. In the first step as shown in Figure 4(a), the robot can confirm whether the contacted object is the human leg using differentiate ability on the two sensing in proximity mode (no force applied) and pressing mode (force is applied). As shown in Figure 3(c), the distance between the human body and the surface of the sensor of the sensor array can be detected according to the capacitance change. The capacitance showed a similar linear response to pressure (the sloped curve as shown in Figure 3(b)), which can determine the force applied on the sensor array. This can be used to assist robots to navigate and avoid injuring humans. To grope the human leg, the robot can spread out its palm as shown in Figure 4(b), meaning stretching the sensor array, to recognize the edge of the human leg by detecting the capacitance change in each capacitor, according the lateral position detecting, as shown in Figure 4(c). The movement of the robot hand can be controlled through capacitive changes, as the controlling of LED switches shown in Movie 3 (Supporting Information). The work mechanism of the sensing array is discussed in detail in the Figure S3 (Supporting Information). Subsequently, the robot hand can hold the human leg with an appropriate force using pressure sensing of the capacitors. If the robot wants to push the wheelchair and take the elderly man out as shown in Figure 4(d). The perception mechanism for the robot hand to seize the metal handle is different than that used for gripping a human leg. As shown in Figure 4(f), a metal was placed on the sensor array above the two buckled CNT strips connecting the capacitor to result in two additional capacitors, because the CNT strips are covered by a thin elastic membrane. The two additional capacitors are in series with each other and are connected in parallel with the previous capacitor. As the capacitor enters or leaves the edge of the object, the additional capacitors will emerge or disappear suddenly,

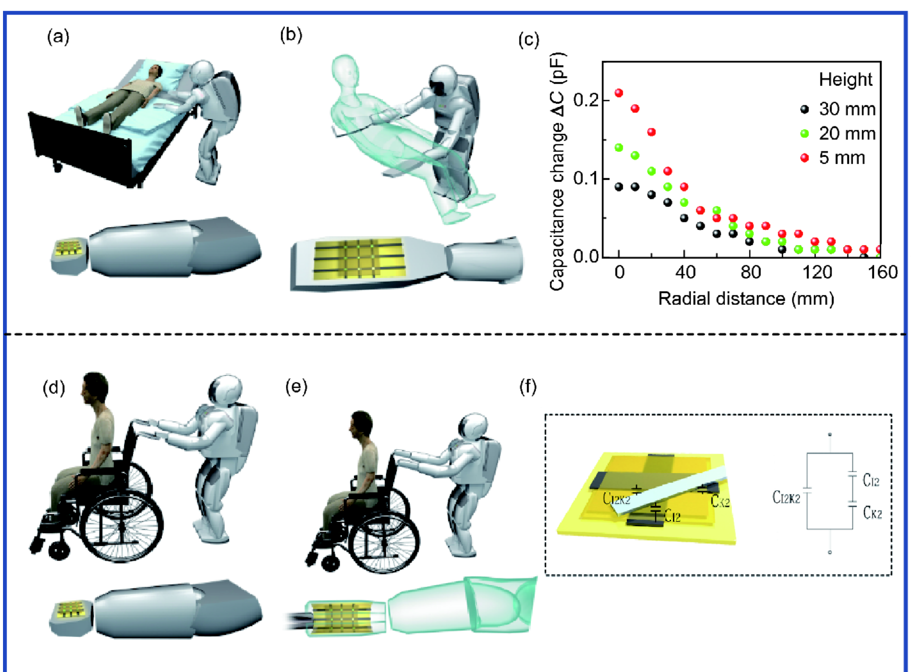

Figure 4 (Color online) (a) The robot can confirm whether the contacted object is the human leg using the touch sense of the capacitors attached on the robot's palm. (b) The robot spread out its palm, meaning stretching the sensor array, to recognize the edge of the human leg. (c) Capacitance change along the lateral position. (d) The robot places its contracted hand with the released sensor array on the surface of the metal handle. (e) The sensor array is stretched to reach an edge of the metal handle and to hold the leg, controlling the applied force by the pressure sensor. (f) The measured capacitance between CNT strip I_n and CNT strip K_m.

which means the obtained capacitance will change suddenly. The additional capacitor with the CNT strip and metal electrodes separated by the elastic membrane is determined by the length of the CNT strip covered by the metal, which can be expressed as

$$C'_{I_nK_m} = C_{I_nK_m} + (C_{I_n} \times C_{K_m}) / \left(C_{I_m} + C_{K_m}\right), \tag{1}$$

where n=1, 2, 3, 4, m=1, 2, $C_{I_nK_m}$ is the capacitance of the capacitor consist of CNT strip I_n and CNT strip K_m, C_{I_n} is of the capacitor between CNT strip In and metal, and C_{K_m} is of the capacitor between CNT strip K_m and metal. When the sensor array is stretched, the area of metal right over the CNT strip gets larger, thereby contributing to an increase in the measured capacitance. With the stretching of the sensor array, the measured capacitance $C'_{I_nK_m}$ would first increase continuously, the subsequent sharp decrease in the capacitance $C'_{I_nK_m}$ would indicate that the capacitor has moved to the metal handle border. Based on this principle (discussed in detail in Figure S4, Supporting Information), the 2×4 sensor array can be used to detect the metal handle border. Figure 4 (d) illustrates that the robot places its contracted hand with the released sensor array on the surface of the metal handle. Figure 4(e) shows as the sensor array is stretched uniaxially in one direction, the measured capacitance begins to increase continuously, as shown in Movie 4 (Supporting Information); then, the capacitance decreases sharply implying that one CNT strip on the sensor array has reached an edge of the metal handle as shown in Movie 5 (Supporting Information). The other vertical directions and so on. Similar to holding the leg, the force applied can be controlled by the pressure sensor to perform the following action.

4 Conclusion

In summary, we fabricated a stretchable sensor array via a simple process by paving CNT strips on a pre-stretched highly elastic substrate. After the strain was released, buckled structures were formed on the CNT strips, imparting crucial sensing characteristics to the sensor array. The capacitor with the buckled structure could detect the change in pressure (with an increase in capacitance with an increase in pressure) and induction (with a decrease in the capacitance upon the approach of an object to its surface). Furthermore, we used a facile method to maintain the capacitance of the capacitors connected to the stretchable buckled CNT strips constant, by covering them with a thin elastic membrane. The stretchable sensor array installed on the robotic retractable palm could be used to determine the location, shape, and pressure of an object and to control the robotic grab movement, which has a very broad application prospect in flexible device and robotic systems. The concept presented here provides a novel route for the manufacture of intelligent software robots.

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Supporting Information

The supporting information is available online at tech.scichina.com and www.springerlink.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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