A Memristor-Based Bioinspired Multimodal Sensory Memory System for Sensory Adaptation of Robots

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1. Introduction

With the development of artificial intelligence (AI) technology, intelligent robots have been used widely in home-assistant and manufacturing applications. To effectively achieve the complex tasks, robots should own an ability to perceive and adapt to the environment by themselves. Humans are quite capable of gradually adapting to different circumstances, for instance, environments with loud noise. Sensory adaptation of humans plays a significant role in such adaptation, in which neural responses reduce after repeated exposures to a same stimulus.[1,2] Inspired by humans, robots possessing sensory adaptation will be able to adapt to the environment or target objects gradually and exclude external interferences, being intelligent as humans.

In addition, to realize multiple functions of intelligent robots in complex environments, the robustness of intelligent robots needs to be improved.[3] It has been proved that multimodal sensors can improve the robustness of intelligent robots,[3–5] which means that many kinds of sensors, such as pressure sensor, temperature sensor, image sensor, acoustic sensor, and so on, will be used in one intelligent robot in the future. That poses a new challenge on the realization of sensory adaptation. The sensory adaptation needs to be compatible with different kinds of sensors with different output signals.
To realize the bioinspired sensory adaptation on intelligent robots, the electronic system not only needs to be able to accept the external stimuli, but the accumulative effects of several received external stimuli also need to be recorded and reflected. Therefore, the intelligent system cannot be realized only with sensors. Fortunately, the rapid development of the electronic device provides novel neuromorphic electronic devices for imitating part of the human nervous system. Such a novel device needs to be combined with the sensor to form a novel artificial neuromorphic system to realize bioinspired sensory adaptation on intelligent robots.

Memristors have attracted great attention because they have been proved to be promising electronic devices as artificial synapses for neuromorphic computing and imitation of human nervous system. Neuromorphic computing based on memristors has been regarded as the most promising candidate for the computing of artificial neural networks because it can break through the bottleneck of Von Neumann and realize computing with high energy efficiency and high parallelism. Furthermore, memristors can process the raw analogue signals from sensors without conversion to and from digital signals. Therefore, memristors can be combined with sensors to realize artificial neuromorphic systems which are highly demanded in intelligent robots. Recent efforts have initiated the trials to combine sensors with memristors. Based on memristors, novel bioinspired artificial sensory nerve and artificial sensory memory have been developed. Currently, in such typical systems, only one kind of sensor is in series connection with one memristor. When the resistance of the sensor is changed by external signals, the change of voltage applied on the memristor will cause the change of the resistance states of the memristor. Commonly, only two resistance states, that is, high-resistance state (HRS) and low-resistance state (LRS), are used.

Sensory adaptation is a process to change the sensitivity gradually depending on the recent experience of external stimuli accepted. However, the sensory memory system utilizing the memristors with only two resistance states can only show and record whether the corresponding sensor received one stimulus or not, which cannot record and reflect accumulative effects of several external stimuli accepted in history. Only the memristor whose resistance can change monotonically and gradually with the increase in the number of voltage pulses can record and reflect accumulative effects of several external stimuli accepted in the history on sensitivity. The resistance/conductance of the memristor can be corresponded to the susceptibility value which needs to be changed gradually to trigger the gradual change of response to external stimuli for sensory adaptation. Thus, only the utilization of the memristor with such properties in our proposed artificial sensory memory system enables the proposed system to realize the sensory adaptation of intelligent robot.

For memristors based on the oxide thin film, the growth and rupture of conductive filament consisting of oxygen vacancies (OVs) is an important mechanism. Such monotonic and gradual change of the resistance depend on the gradual growth of the conductive filament composed of OVs. However, most memristors are based on polycrystalline oxide thin films. Many grains and grain boundaries in the polycrystalline thin films lead to the inhomogeneous distribution of defects, such as OVs. In addition, randomly generated OVs during the deposition process cannot be avoided. Both of them make the gradual growth of conductive filament composed of OVs under voltage pulses difficult to control, especially when the size of the memristor continues to downscale. As a result, for single memristors, the monotonic and gradual change of its resistance with the increase in the number of voltage pulses is still difficult to realize and control without an external device. Now, one external transistor is still needed to be connected with the memristor in series to control the change of resistance by controlling the gate voltage of the transistor when voltage pulse is applied on the memristor, which will make the system become complicated and energy consumption increase.

In addition, in previous work, the connection method for applying the excitation of sensor on the memristor mentioned earlier is not suitable for the situation with different kinds of sensors. However, the method for applying excitation from different kinds of sensor on the memristor to change its resistance/conductance is also important for the realization of the sensory adaptation of robot, because more kinds of sensors were used on the robot with the development of intelligent robots.

To realize human-inspired sensory adaptation on intelligent robot, the novel artificial sensory memory system was constructed by combining sensors with memristor. To avoid the OVs randomly introduced into the thin films during the deposition process and negative effects of grain and grain boundary on the distribution of OVs, we fabricated memristors based on single-crystalline LiNbO$_3$(LN) thin films by crystal ion-slicing (CIS) technique. Without the external transistor, the fabricated memristor shows the characteristic that the resistance state can be changed monotonically and gradually with the increase in the number of stimuli. The changing process of resistance in the potentiation process of the memristor was investigated and analyzed. The fabricated memristor was used as an artificial synapse to record and show the accumulative effect on sensitivity after receiving different number of stimuli by sensors. Furthermore, to make the proposed system become suitable for different kinds of sensors which were used on the robot to improve the robustness of intelligent robots, a novel universal signal-coupling method for applying excitation of different sensors on the memristor was proposed and discussed. Based on the proposed signal-coupling method and the fabricated memristor, the artificial sensory memory system with sensors (pressure sensor, temperature sensor) and memristor is realized. Furthermore, the artificial sensory memory system is first applied to intelligent robot. A proof-of-concept of sensory adaptation on intelligent robot is demonstrated for the first time.

2. Results and discussion

Inspired by the basic structure of the biological perception system of human skin, the entire bioinspired system for sensory memory realized by the excitation of the sensor signal on memristor was built (Figure 1a–b). Figure 1 shows the basic structure of our artificial sensory memory system and the analogy to a biological counterpart. The system consists of three parts: (I) sensor, (II) signal-coupling module, and (III) memristor, as shown in Figure 1a. Sensors in the sensor part can correspond to the...
pressure sensor and temperature sensor, respectively. Memristors can be regarded as electronic synapse. The excitation of a sensor signal on the memristor was realized in the signal-coupling module. In the present work, 1) the sensory memory system with only the pressure sensor and 2) sensory memory system with both pressure sensor and temperature sensor were constructed, respectively. The artificial sensory memory was applied to the robotic hand of the intelligent robot.

Based on our previous work,[26,27] the memristor based on the single-crystalline LiNbO3 (LN) thin film with the structure of Au/LN/Pt (Figure 2a) was fabricated by the CIS technique, and low-energy Ar⁺ irradiation was conducted to generate OVs in the surface region of single-crystalline LN thin film (see Figure S1, Supporting Information). The diameter of the top circular Au electrode is 100 um. As shown in Figure 2b, an electroforming process was observed at 12 V. After the electroforming process, resistive switching behavior can be observed (Figure 2c). Both electroforming voltage and operation voltage are much lower than that in our previous work.[26,27] As illustrated in Figure 2d, 100 cycles of I–V curves without failure have been obtained. The I–V curves show high reproducibility. I–V curves of ten different memristors on the same thin film were measured (Figure 2e). Ten different memristors showed similar resistive switching behavior. The synaptic plasticity of the memristor is a significant characteristic for the artificial sensory memory system.[28] The typical entire synaptic plasticity with both potentiation process and depression process was also measured in this article. In the potentiation process, a series of 85 positive voltage pulses (amplitude: 7 V, pulse width: 100 ms) were applied on the memristor. After that, in the depression process, a series of 85 negative voltage pulses (amplitude: –7 V, pulse width: 100 ms) were applied on the memristor. Both in potentiation process and in the depression process, after each consecutive voltage pulse was applied on the memristor, one reading voltage pulse (amplitude: 1 V, pulse width: 100 ms) was applied on the memristor for reading the resistance state of the memristor (see Figure S2, Supporting Information). As illustrated in Figure 2f, in the potentiation process, the resistance of the memristor decreased gradually from HRS to LRS with the increase in the number of positive voltage pulses applied on the memristor. In the depression process, the resistance of the memristor increased gradually with the increase in the number of negative voltage pulses applied on the memristor. The retention characteristic of HRS, LRS, and multiple intermediate resistance states was also measured. The amplitude of reading voltage pulses is 1 V. As shown in Figure 2g, HRS, LRS, and multiple intermediate resistance states are stable within 1500 s. In addition, the endurance of the memristor was measured. As shown in Figure S3, Supporting Information, within 2000 write–erase cycles, the memristor can be switched between HRS and LRS without failure. With such a property, the memristor can record and reflect accumulative effects of several external stimuli accepted in the history, which is significant for the sensory memory system to realize sensory adaptation.

In following work in this article, the gradual change of resistance in the potentiation process will be utilized in the sensory memory system for sensory adaptation. We measured three different potentiation processes with three different positive voltage pulses with amplitudes of 5, 6, and 7 V, respectively (Figure 3a and Figure S4, Supporting Information). In all of three potentiation processes, in the beginning, the memristor was in the HRS. Then monotonic and gradual change of resistance with the increase in voltage pulses applied on the memristor can be observed. With the positive voltage pulses (amplitude: 7 V, pulse width: 100 ms), the resistance of the memristor can change gradually from HRS to LRS. However, when the amplitude of the positive voltage pulse decreased to 6 and 5 V, saturation can be observed after gradual decrease in the resistance, that is, the resistance of the memristor is almost unchanged after applying a number of positive voltage pulses. The final resistance...
of the memristor decreased with the increase in the amplitude of positive voltage pulse. In other words, the variation range decreased with the decrease in the amplitude of positive voltage pulse. Both the final resistance states of the memristor after the potentiation processes with positive voltage pulses with amplitude of 6 V and 5 V, respectively, cannot reach the LRS of memristor. The results indicate that the amplitude of the voltage pulse dominates the length of formed conductive filament.

To understand the mechanism of the potentiation process, X-Ray photoelectron spectroscopy (XPS) was performed on the pristine LN thin film and Ar\textsuperscript{+}-irradiated LN thin film. The spectra for O 1s of the pristine single-crystalline LN thin film and that of Ar\textsuperscript{+}-irradiated LN thin film are shown in Figure 3b,c. In both spectra, Peak 1 centered at around 529.6 eV and the Peak 2 centered at around 531.9 eV can be observed. Peak 1 and Peak 2 represent the oxygen in the lattice and adsorption oxygen,
respectively.\textsuperscript{29,30} Compared with the spectrum of the pristine single-crystalline LN thin film (Figure 3b), Peak 3 centered at around 530.9 eV, which is attributed to defect oxygen (OVs),\textsuperscript{29,30} can only be observed in the spectrum of the Ar\textsuperscript{+} -irradiated LN thin film (Figure 3c). The results indicate that OVs were generated in the single-crystalline LN thin film by Ar\textsuperscript{+} irradiation during the fabrication process of the memristor. The microstructure of the memristor based on Ar\textsuperscript{+}-irradiated LN thin films was also characterized by transmission electron microscope (TEM). A defective layer with the thickness of 5 nm was observed near the Au/Ar\textsuperscript{+}-irradiated LN interface (the region between purple dotted lines in Figure 3d), which is similar with the layer reported in other work.\textsuperscript{31} The TEM image (Figure 3d) and electron diffraction pattern (inset of Figure 3d) also indicated that, except the defective layer in the surface region of the LN thin film, other regions of the LN thin film under the defective layer still remain of a well-oriented single-crystalline nature. The results indicate that the generated OVs only distributed near the Au/LN interface, as shown in Figure 3e. Then, under positive electrical field, OVs move toward the bottom electrode (Pt) through the layer and exhibit a single-crystalline nature to form the conductive filament. Because the layer still remains of a single-crystalline nature, the interference (caused by grains, grain boundaries, and randomly generated defects in the traditional polycrystalline thin film) for the gradual growth of the conductive filament can be avoided. So monotonic and gradual change of resistance with the increase in voltage pulses applied on the memristor can be realized. With the increase in the amplitude of voltage pulse, the length of the formed conductive filament increased, which is shown in Figure 3f–h. As a result, the final resistance of the memristor decreased. When the voltage pulses with the amplitude of 7 V were used, the formed conductive filament penetrated throughout the LN thin film, and the memristor reached LRS. Based on the results mentioned earlier,

Figure 3. The potentiation process. a) Three potentiation processes under three different positive voltage pulses with amplitudes of 5, 6, and 7 V. XPS spectrum for O 1s of b) the pristine single-crystalline LN thin film and c) Ar\textsuperscript{+}-irradiated LN thin film. d) TEM image near the Au/Ar\textsuperscript{+}-irradiated LN interface. Inset of the d) electron diffraction pattern of the LN thin film. e) Schematic diagram of the memristor based on Ar\textsuperscript{+}-irradiated LN thin film. Schematic of the conductive filaments formed in the potentiation processes under positive voltage pulses with amplitude of f) 5 V, g) 6 V, and h) 7 V.
voltage pulses with the amplitude of 7 V will be used as fixed stimuli on the memristor (i.e., the output of the signal-coupling module) in the following bioinspired sensory memory system.

Based on the fabricated memristor and flexible pressure sensor, the bioinspired sensory memory system was constructed. The experiment was conducted to test the sensory memory system. As shown in Figure 4a, a finger was pressed on the flexible pressure sensor of the system five times in this experiment. The flexible pressure sensor used in this work is based on percolative thermoplastic polyurethane/carbon black thin film with a Knoll-like microstructured surface. Within the bioinspired system, sensory memory was achieved on the memristor. The flexible pressure sensor was series connected with a resistor (Resistor 1). The resistance of the resistor is 3.3 kΩ. Vcc = 5 V was applied. Figure 4b shows the change process of the resistance of pressure sensor as a response for five times of pressing by the finger. The corresponding voltage response V1 is shown in Figure 4c. When the finger pressed on the pressure sensor, the resistance of the pressure sensor decreased (Figure 4b). As a result, the voltage V1 increased. In this work, a universal signal-coupling method is proposed, which is called “indirect signal coupling.” With this method, a threshold voltage needs to be set. When the voltage signal reaches the threshold voltage, a fixed voltage pulse will apply on the memristor. In the present work, when V1 increased and reached the threshold voltage (3.5 V, Figure 4c) we set, the fixed voltage pulse with the amplitude of 7 V and width of 100 ms was applied on the memristor (Figure 4d). Subsequently, a reading voltage pulse of 1 V was applied on the memristor to detect the change of the resistance of the memristor (Figure 4d). After each fixed voltage pulse is applied on the memristor, the resistance of the memristor decreased gradually. Therefore, when the number of presses increases, the resistance of the memristor decreases gradually. The gradual change process is shown in Figure 4e. The resistance of the memristor is changed with the number of external stimuli received by the sensor in the system. So, the resistance of the memristor after the change process can reflect the accumulative effect of several external stimuli received by sensors in the past. In other words, the

![Diagram](Figure 4. The artificial sensory memory system with pressure sensor. a) Illustration of the finger press on the system. b) The changing process of the resistance of pressure sensor as a response of five presses of the finger. c) The changing process of corresponding voltage V1. d) The voltage pulses applied on memristor. e) The corresponding changing process of the resistance of the memristor when press was applied on the pressure sensor.)
resistance of the memristor can record and reflect the history of external stimuli received by the sensor.

Based on the system with pressure sensor, we added another kind of sensor (temperature sensor) into the system. As a result, two different kinds of sensors (pressure sensor and temperature sensor) were used in the system (Figure 5a). Such a system was similar to the human skin, which can accept pressure and temperature stimuli. The flexible pressure sensor and temperature sensor were, respectively, series connected with a resistor. Resistance values of Resistor 1 and Resistor 2 are 3.3 kΩ and 1.3 kΩ, respectively. \( V_{cc} = 5 \text{ V} \) was applied. Figure 5b shows the changing processes of the resistance of pressure sensor and temperature sensor as a response of pressure and hot stimuli, respectively. Figure 5c shows the corresponding voltage response \( V1 \) and \( V2 \). When the finger pressed on the pressure sensor, the resistance of the pressure sensor decreased.

![Figure 5](image_url)

**Figure 5.** The artificial sensory memory system with pressure sensor and temperature sensor. a) Illustration of the system accepting pressure and temperature stimuli. b) The changing process of the resistance of pressure sensor and temperature sensor as a response of pressure and hot stimuli. c) The changing process of voltage \( V1 \) and \( V2 \). d) The voltage pulses applied on memristor. e) The corresponding changing process of resistance of the memristor with sensor-accepted stimuli.
(Figure 5b). As a result, voltage V1 increased. When V1 reaches the threshold voltage (3.5 V), the fixed voltage pulse with the amplitude of 7 V and width of 100 ms (Figure 5d) was applied on the memristor, same with the process shown in Figure 3. When the hot plate came close to the sensor, the resistance of the temperature sensor increased. As a result, voltage V2 increased. When V2 reached the threshold voltage (2.5 V), fixed voltage pulse with the amplitude of 7 V and width of 100 ms (Figure 5d) were also applied on the memristor. In this process, the finger pressed the pressure sensor totally six times, and twice hot stimuli were applied on the system. Correspondingly, eight fixed voltage pulses were applied on the memristor. As a result,

Figure 6. The sensory adaptation of robot. a) The schematic diagram of application of bioinspired sensory memory system to robot for sensory adaptation. b) The entire practical sensory adaptation process of robot. Inset: The changing process of the conductance of memristor, $T$ and rise height ($H$).
the resistance of the memristor increased gradually, as shown in Figure 5e. These results indicate that such a signal-coupling method is suitable for different sensors. Such a universal method can be used in the sensory memory system with multimodal sensors to realize sensory adaptation for different kinds of stimuli.

The fabricated sensory memory system can be applied on the robot, which enables the robot to realize human-like sensory adaptation (Figure 6). The flexible pressure sensor was fixed on the robotic hand, as shown in Figure 6a. Every time the robot hand touched the object, the system accepted a stimulus by the flexible pressure sensor. The resistance of the flexible pressure sensor decreased dramatically. V1 in Figure 4 reached threshold value. Based on the properties of the system mentioned earlier, with the increase in the number of touch (stimulus), the resistance of the memristor decreased gradually, and the conductance of the memristor increased gradually (Inset of Figure 6b). The conductance of the memristor can be regarded as the threshold value (T) for susceptibility. In other words, T increases with the increase in the number of touches, which mimics the human sensory adaptation process. The increase in T led to the decrease in the response of the robotic arm to the touch because of the adaptation process (Figure 6a–b). In this case, such a response of the robotic hand is its rise height (H) after touch (stimulus). H was set as

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H = H_{\text{max}} - 4 \times 10^6 \times (T - 1.00632 \times 10^{-6})
\]

where \(H_{\text{max}}\) is the response to the first stimulus. We set \(H_{\text{max}} = 0.4\) m. The rise height after each touch is also shown in the inset of Figure 6b. Rise height decreased gradually. In this sensory adaptation process, the conductance of the memristor in the system can be regarded as a feedback parameter for the response of the robotic arm. With a such system, when the number of touch (stimulus) increases, the response (rise height after the touch) to the stimulus decreases, that is, the robotic hand is gradually adapted to such stimulus. The entire practical sensory adaptation process of robots is shown in Figure 6b and in Supplementary Materials Movie S1. Sensory adaptation is experimentally demonstrated on intelligent robot with the sensory memory system.

3. Conclusion

In this work, we aim to show that sensory adaptation, which is significant for future application of intelligent robots in the complex environment, can be realized with the memristor-based bioinspired artificial sensory memory system we proposed. Such a memristor-based sensory neuromorphic system was constructed by combining sensors with the memristor.

In sensory adaptation, the susceptibility value is the key parameter which determines the response to the external stimulus. During adaptation, the susceptibility value can be changed gradually by the external stimuli accepted in history, which leads to the change of response to the external stimulus. We fabricated memristors based on the single-crystalline LN thin film. After Ar⁺ irradiation, OVs were generated in the region near the surface of the LN thin film. The other part of the thin film still remains of a single-crystalline nature. The single-crystalline nature avoided the interference from grain, grain boundaries, and randomly generated defects in polycrystalline thin films on the gradual growth of conductive filament, so the memristor shows the characteristic that its resistance/conductance can be changed monotonically and gradually by voltage pulses. By building the relationship between the sensor signal and voltage pulse applied on the memristor, we used the conductance of memristor to denote the susceptibility value to realize the gradual change of the susceptibility value caused by external stimuli accepted by sensors. Then, the response to the external stimulus correspondingly changed by the gradual change of the susceptibility value, which conforms to the basic principle of sensory adaptation. Our work showed the great potential of the memristor as the critical device in sensory system for the realization of sensory adaptation. This work also showed that the memristor can possibly play a more active role in the neuromorphic or sensory system.

In addition, a universal signal-coupling method is also proposed and achieved to build the relationship between different sensor signals and voltage pulses applied on memristor, which enables the resistance/conductance of the memristor to be changed according to the external stimuli accepted by different kinds of sensors that will be used on intelligent robots in the future. With the method, a multimodal sensory memory system with pressure sensor and temperature sensor was constructed in this work.

Importantly, for the first time, we applied the novel bioinspired memristor-based system to a robotic system. The sensory adaptation of the intelligent robot was first experimentally demonstrated with the simple bioinspired hardware system. The proof of concept highlights the great potential of using a memristor-based sensory system for sensory adaptation of the intelligent robot, which paves the new way for the future development of intelligent robots.

4. Experimental Section

Fabrication and characterization of memristor: The memristor used in this work was fabricated by CIS technique and Ar⁺ irradiation (see Figure S1, Supporting Information). First, LN wafer was implanted by He⁺ ions. The implantation energy was 180 keV, and the implantation dose was 2 × 10¹⁶ cm⁻². After implantation, Pt (100 nm) layer was deposited on the implanted surface of LN by magnetron sputtering as the bottom electrode of the memristor. Then, implanted LN wafer with Pt layer was bonded onto the LN single-crystal substrate using SiO₂ as the bonding layer. During the annealing process, splitting took place at an in-depth weakened layer caused by He⁺-ion implantation. After that, low-energy Ar⁺ irradiation with energy of 100 eV was conducted for 30 min. Finally, circular Au top electrodes were sputtered to form Au/LN(100 nm)/Pt/SiO₂/LN structure. The structure of the memristor was Au/LN/Pt (Figure 1a). The structure was characterized by scanning electron microscopy (SEM). Electrical characterization of the memristor was performed with a KEITHLEY 2400 source meter. The microstructure of Ar⁺-irradiated LN thin films was characterized by TEM. XPS was used to analyze the OVs near the surface of LN thin films.

Application of excitation of sensor signal on memristor: The resistance variations of pressure sensor were measured by a data acquisition system (Quantum X, HBM). The voltage signals (V1 and V2) were measured by KEITHLEY 2700 data acquisition system. The fixed voltage pulses were applied on memristor by KEITHLEY 2400 source meter. The measurement of the gradual change of resistance of memristor was also performed with KEITHLEY 2400 source meter.
Application of the sensory memory system to robot for sensory adaptation: The sensory adaptation experiments were performed on the Baxter robot (Rethink Robotics, Boston, MA, USA) with two arms. Each robotic arm had seven rotational joints, eight links, and a two-fingered hand which was mounted at the end of each arm. The position and orientation of the robotic hand were solved by inverse kinematic and sent to the control unit. A position feedback control law was used to control the movement of robotic arms (see Figure S5, Supporting Information).

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
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
memristors, multimodal sensors, robots, sensory adaptation, single-crystalline LiNbO₃ thin films, synaptic plasticity

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