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AI-enhanced Multifunctional Haptic Rings for Cross-space Perception and Sensation in Metaverse

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Advancements of virtual reality technology pave the way for developing wearable devices to enable somatosensory sensation, which can bring more comprehensive perception and feedback in metaverse-based virtual society. Here, we propose augmented tactile-perception and haptic-feedback rings with multimodal sensing and feedback capabilities. This highly integrated ring consists of the triboelectric and pyroelectric sensor for tactile and temperature perception, and the vibrator and nichrome heater for vibro- and thermo-haptic feedback. All these components integrated on the ring can be directly driven by a custom wireless platform of low power consumption for wearable/portable scenarios. By fusing the multimodal sensing and feedback functions, an interactive metaverse platform with cross-space perception capability is successfully achieved, giving people a face-to-face like immersive virtual social experience.

NOMENCLATURE

VR = virtual reality
AI = artificial intelligence
IoT = Internet of things
ERM = eccentric rotating mass
TENG = triboelectric nanogenerator
PVDF = Polyvinylidene Fluoride

1. Introduction

The newly proposed concept "Metaverse" refers to a network of 3D virtual worlds that utilize VR technology to enhance the connections between the real and cyber spaces. To establish an immersive VR system, besides visual stimulus enabled by head-mounted displays, other wearable devices, i.e., data gloves, etc., that can simultaneously sense human motion and simulate human sensation, are experiencing significant attention recently towards full-body perception to further bridge the physical and cyber world.

Due to the merits of diversified material choices, simple fabrication process, low cost and self-generated signals, sensing technology based on triboelectricity provides a new possibility to develop the highly flexible tactile perception system with extremely low power consumption [1]. Additionally, pyroelectric materials are known to self-generate electrical signals with varying temperatures [2], which have been frequently investigated as self-powered temperature sensors and show the great potential to be integrated into the sensing system to provide additional sensory information for multimodal sensing purposes. Meanwhile, the emerging AI-based data analytics reveal the possibility of enriching the sensor functionalities to realize intelligent sensing. With machine learning's strong feature extraction capability, subtle valuable features hidden in the complex signal outputs could be perceptible, and utilized to achieve advanced perceptions, e.g., gesture recognition, object identification, etc. [3].

Wearable actuation systems are also indispensable parts to enhance the interactive experience in metaverse. To enable a more immersive VR experience, a highly integrated wearable system with multimodal sensing and feedback functions that can provide diversified somatosensory perception and feedback simultaneously is needed [4]. However, nearly all the current wearable solutions for VR sensing/feedback devices are glove-based with complicated structures and require large external driven power. A highly integrated minimalistic ring with multimodal sensing and feedback functions that are fully compatible with IoT platforms for portable/mobile

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application scenarios has not been achieved.

Herein, we propose multifunctional haptic rings for VR applications, which consist of TENG tactile sensors for continuous bending sensing, flexible pyroelectric sensors for temperature detecting, ERM vibrators for vibro-haptic feedback and nichrome metal wires for thermo-haptic feedback. All the sensors and stimulators are integrated into rings with wires connected to an IoT module as illustrated in Fig. 1. This minimalistic designed ring uses self-powered sensing units and low driven-power feedback elements to achieve low power consumption, and show great potential to provide cross-space perception and sensation in metaverse.

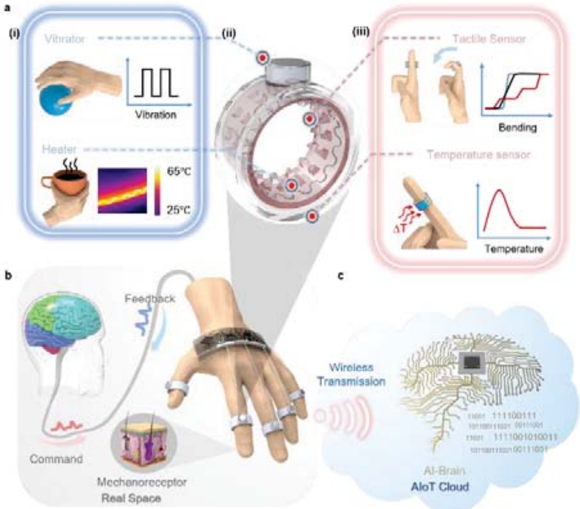


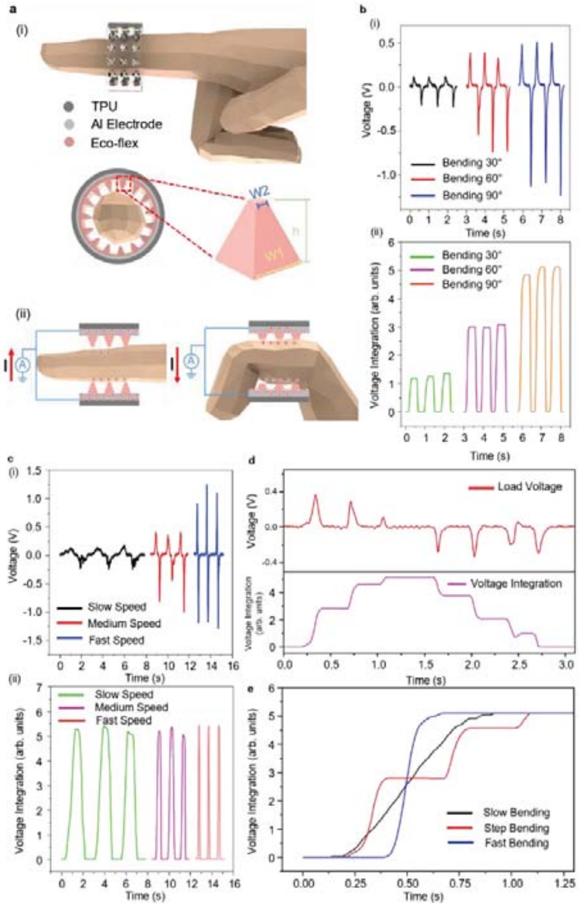
Fig. 1 (a) Illustration of the multifunctional haptic ring. (b) The biolog ical neural network corresponding to the human finger sensation. (c) The cloud server for wireless data transmission and processing.

2. Results

2.1 Characterization of the ring for bending sensing

The structure of the TENG tactile sensor is shown in Fig. 2a(i). A layer of silicone rubber film with pyramid structures on one side is attached to the inner surface of a ring serving as the negative triboelectric material. The aluminum film attached between the silicone rubber and the ring acts as the output electrode of the sensor. As shown in Fig. 2a(ii), when the finger bends, the contact area between the finger skin and the silicone rubber pyramid structure will increase due to the muscle swelling, resulting in the electrical potential change in the output electrodes based on the triboelectrification on the contact surface. This potential variation can further drive the electron flow and generate the outputs due to electrostatic induction.

The outputs of the TENG tactile sensor for measuring different bending degrees are shown in Fig. 2b. When the bending speed is the same, the greater the bending angle of the finger, the larger the output voltage and voltage integration value. However, as shown in Fig. 2c(i), the speed of the finger bending also affects the amplitude of the output voltage, resulting in the inability to accurately identify the bending angle. While in Fig. 2c(ii), the voltage integration value is virtually unaffected by the bending speed, which can be used as a reliable reference to measure the bending angle of the finger. Fig. 2d and 2e show the capability of the voltage integration method for continuous detection. In Fig. 2d, the load voltage can only reflect the angle of each step bending, while the voltage integration value curve can record the continuous angle change during the whole bending process. By comparing the plots in Fig. 2e, bending speed information could also be extracted from the slope of the voltage



integration curves, to enable more comprehensive tactile sensing.

Fig. 2 (a) The structure and working mechanism of the TENG sensor. Load voltage and the corresponding integration value for bending with different (b) angles and (c) speed, and (d) step bending. (e) Continuous bending verification.

2.2 AI-enabled gesture/sign language recognition system

The emerging AI-based data analytics reveal the possibility of enriching the sensor functionalities to realize intelligent sensing. Here we select 14 American sign language gestures as illustrated in Fig. 3a to test the recognition performance based on the pulse-like signals (Fig. 3b(i)) and voltage integration signals (Fig. 3c(i)), respectively. The bending angle of fingers for each gesture can be reflected both by the peak values in the pulse-like spectrum or the stable values in the voltage integration spectrum. Each gesture category contains 120 samples, where 80 samples were used for training and 40 samples were used for testing. By using the principal component analysis (PCA) for feature reduction, the preliminary classification results were visualized in Fig. 3b(ii) and Fig. 3c(ii). It is clear that the

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aggregation effect based on the voltage integration is better. While for the pulse-like signals, many categories are mixed, indicating that the 3 features extracted from the pulse-like output spectrum used to distinguish different categories are not so effective. A similar result could be achieved when adding a supporting vector machine classifier for further identification. The highest accuracy for the voltage integration based dataset could reach 99.821%, while the highest accuracy for the pulse-like signal based dataset could only reach 97.143%. This phenomenon shows that the voltage integration-based approach can use fewer computing resources to achieve better performance when compared with the conventional pulse-like signal based solution. Though the voltage integration method appears to be just a further data processing of the load voltage, the feature differences between different gestures are more obvious after such processing, which can help the machine learning model to better extract and interpret.

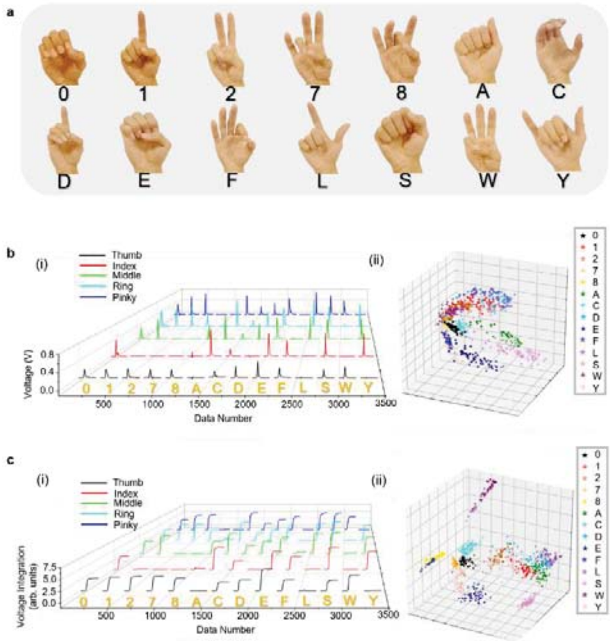

Fig. 3 (a) Illustration of the 14 American sign language gestures for recognition. The (b) pulse-like and (c) voltage integration signals with corresponding PCA clustered results for 14 gestures.

2.3 Haptic feedback system compatible with IoT platform

Besides the advanced sensing capability, the feedback functionality of the VR wearable device is also indispensable to give users a simulated sensation to enhance the interactive experience in the virtual environment. A tactile feedback system with extremely low driven power can be implemented by integrating the ERM vibrators onto the ring as illustrated in Fig. 4a. In Fig. 4b, a virtual hand is controlled to touch a soft ball in the virtual world. The feedback intensity during this process has three stages. The first stage is that when the finger just touches the soft ball without applying an external force, the amplitude of the vibrator is very small due to the small applied voltage. In the second and third stages, the soft ball is gradually deformed by the human virtual finger. The driven voltage will increase accordingly, so the intensity of the vibration will increase to provide stronger vibro-haptic feedback to simulate the actual feeling of squeezing. Additionally, the simultaneous multi-finger control and haptic feedback can also be achieved via a VR piano training demonstration in Fig. 4c, showing the potential for future virtual educational training applications. Besides vibro-related feedback, thermo-haptic feedback is also an important function to provide users with a more comprehensive perception of the object. Here, we embed the nichrome metal wire based heater into the TENG tactile sensor as a thermal feedback unit as illustrated in Fig. 4d(i), whose temperature could be easily heated up to a high temperature with an extremely low power supply. The relationship between the driven power and the final maintained temperature is also plotted. As illustrated in Fig. 4d(ii), a virtual space with coffee cups of different temperatures is established. A virtual hand can be real-time controlled by the TENG sensor to grasp the coffee cup first. Then the embedded heater will be heated up to a specific temperature according to the predefined temperature value of the selected coffee cup. The final stable temperature captured by the infrared camera is almost equal to the preset temperature of the corresponding coffee cup in the virtual space, verifying the temperature feedback capability of the system.

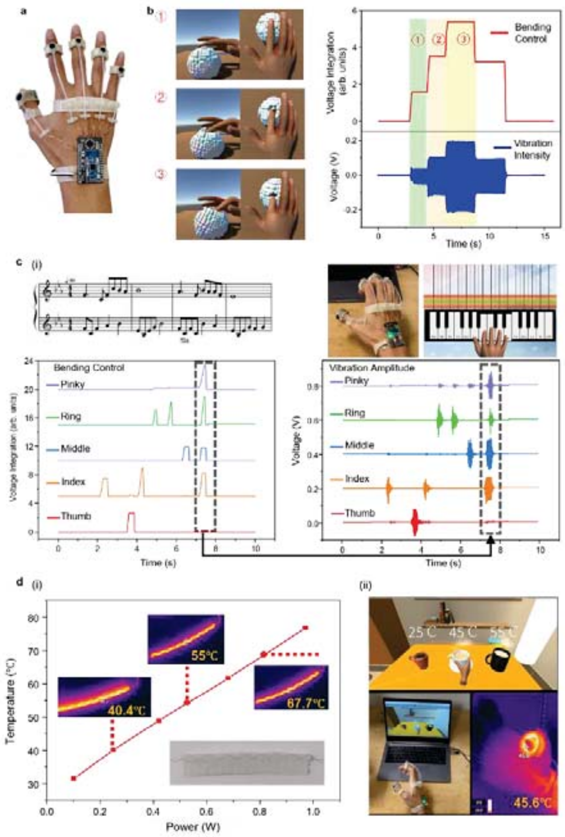

Fig. 4 (a) Illustration of the haptic ring with ERM vibrators. Control and vibro-feedback signals of (b) squeezing a soft ball with one finger and (c) playing a virtual piano with multiple fingers. (d) Thermo-haptic feedback enabled by the nichrome metal wire heater.

2.4 Multimodal sensing and feedback platform for metaverse

The current metaverse-based virtual social platform is still limited by conventional interactive media, i.e., visual or voice. To further

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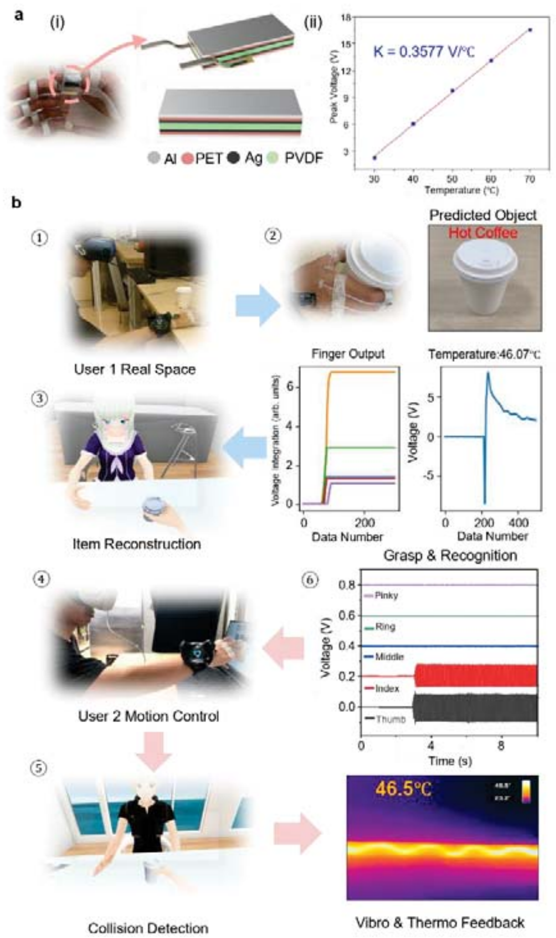
enhance the interactive experience, we proposed an augmented VR chat platform enabled by the augmented haptic rings, where the two users can achieve cross-space perception and sensation thanks to the multimodal sensing and feedback capabilities brought by the highly integrated system. To realize such a system, the grasped object recognition function is needed. The gesture recognition ability of the haptic rings has been demonstrated in the above section on machine learning, and object recognition could also be realized based on the variation in finger motions when grasping objects of different objects. Besides the shape-related information from the TENG sensors, the temperature sensing function is also important to bring in more comprehensive information to enhance the recognition capability. Here, a PVDF temperature sensor with the same advantage of self-generated output and high flexibility is utilized to be integrated with the TENG tactile sensor to form a fully self-powered sensing system. The detailed structure and characterization results are illustrated in Fig. 5a. Fig. 5a(ii) depicts that the pyroelectric peak



value is approximately linear in the temperature range of 30 °C to 70 °C and increases with the raised temperature. Hence, it can serve as a reliable reference for object temperature perception.

Fig. 5 (a) The structure and calibration result of the PVDF temperature sensor. (b) The real-time system operation process of the metaverse platform with the testing object of a cup of hot coffee.

The operation details of the established system are shown in Fig. 5b. a cup of hot coffee is first grasped by user 1 in the actual space. Then based on the collected 5-channel TENG sensor output and PVDF sensor output, the shape information of the grasped object could be extracted by the AI analytic and fused with the temperature information to reconstruct the corresponding object in the virtual space in the cloud, which is also visible to user 2 in a remote real space. After user 1 puts the hot coffee in both the actual and virtual space, user 2 can control the virtual hand in real-time to grasp the reconstructed virtual object. Here, user 2 uses the thumb and index finger to grasp the hot coffee. Upon detecting the collision signal in the virtual space, the vibrators and heater will start to operate to provide vibro- and thermo-haptic feedback in real-time. The vibration intensity and the feedback temperature could also be monitored and is visualized in Fig. 5b, which corresponds to the contact finger channel (thumb and index) and shows high similarity to the temperature value obtained by the infrared sensor from user 1 side, verifying the multimodal sensing and feedback proposed system. As a result, the cross-space perception and sensation function could be achieved to help the user to feel the actual space of others.

3. Conclusions

In summary, we develop an AI-enhanced haptic ring with multimodal sensing and feedback capabilities. This highly integrated ring consists of the triboelectric and pyroelectric sensor for tactile and temperature perception, and the vibrator and nichrome heater for vibro- and thermo-haptic feedback. By leveraging AI analytics, high-accuracy gesture and object recognition can be realized. Besides, an interactive metaverse platform with cross-space perception capability is also successfully achieved, giving people a face-to-face like immersive virtual social experience.

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