Smart Glove Human-Machine Interface Based on Strain Sensors Array for Control UAV

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***Abstract*—Smart gloves have attracted much attention as a typical representative of wearable Human-Machine Interface (HMI). Traditional sensors on smart gloves are limited due to high cost, complex manufacture, which can't meet the requirements of bio-friendliness and sustainability. This paper presents a smart glove human-machine interface based on strain sensor array of conductive hydrogels. A flexible, transparent, stretchable and sensitive hydrogel strain sensor is prepared based on a "one-pot" preparation method. The smart glove was constructed using 3D structural design combined with the sensor array. Combing with the signal processing system, the smart glove can realize the spatial motion control of the Unmanned Aerial Vehicle (UAV). The smart glove based on the hydrogel flexible sensor array showed great application prospects in the field of human-machine interaction of robot and Virtual Reality (VR).**

***Index Terms*—Human-machine interface, hydrogel, strain sensor, smart glove**

I. Introduction

In recent years, with the development of flexible electronics, a variety of flexible wearable devices have been widely used in the field of human-machine interaction [1–7] As these flexible wearable devices can be worn directly on the body, they can collect various sensory/motor information from the body, differentiate between different motor behaviors and ultimately achieve a number of functions such as disease diagnosis [8] and motion detection [9]. Therefore, using of flexible wearable devices as human-machine interfaces is an important direction in the development of human-machine interaction.

Smart gloves are of great interest as a typical representative of (Human-Machine Interfaces) HMIs in life and scientific experiments. The current smart gloves for HMI fall into two main categories: 1) gesture-based smart gloves [10–12] and 2) touch-based smart gloves [13]. Gesture-based gloves mainly use inertial measurement units (IMUs) of different fingers to detect finger movements [14], while touch-based gloves mostly use existing commercially available sensors and rigid brakes to acquire touch characteristics. However, the high cost of preparation, complex structure and high price of sensing units in these gloves, which do not meet the requirements of bio-friendliness and sustainability, have limited the development of smart gloves to some extent.

Hydrogels is widely used in the field of wearable sensing and HMI because of their remarkable biocompatibility, inherent electrical conductivity and unique mechanical properties [15–19]. Wearable human-machine interfaces made of hydrogels are also being reported. Kim's team designed a polyacrylamide hydrogel human-machine interface containing lithium chloride salts [20]. Chen *et al*. designed a 3D smart human-computer interface based on corn starch hydrogel (SFT) [21]. Zhang *et al*. designed a cross-control interface based on hydrogel sensors for the control of electric servo motion [22]. The design and application of these hydrogel HMIs further demonstrate the feasibility of hydrogel sensors in the field of smart gloves.

Herein, we present a smart glove human-machine interface to control the UAV motions. The conductive hydrogels-based sensors showed biodegradable, self-healing, transparent, highly stretchable (100%), low hysteresis (110ms) and highly sensitive (Gauge $Factor_{max}$=3.6) properties, where the conductive hydrogels with adhesion properties were prepared by a simple one-pot preparation process. 3D gloves were designed by studying the finger structure to complete the smart glove assembly by combining the hydrogel array with 3D gloves. Combing with the signal processing system, the smart glove captures the motion signals of the four fingers. Importantly, the smart gloves system can complete the spatial motion control for the (Unmanned Aerial Vehicle) UAV based on the coupling effect of different sensors, and the signal acquisition and processing. The smart glove based on a hydrogel flexible sensor array has crucial potential for more in-depth human-machine interface research.

II. Experimental Section

A. Fabrication Process of Strain Sensor

The process of manufacturing corn starch hydrogels can be divided into five main steps: Preparing a flexible

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substrate by placing Ecoflex 00-30, Part A and Part B (volume ratio 1A:1B), into a machined aluminum mold. The 6 wt % Polyvinyl alcohol (PVA) powder was placed into deionized water bath and stir at 1000rpm/min for 2h to produce PVA solution. The hydrogel solution was the mixture of deionized water, calcium chloride, PVA solution, and corn starch (mass of the ratio is 12:1:2:2). The mixture was stirred at 600 rpm/min at 60 °C for 30 minutes and finally placed on an Ecoflex 00-30 flexible substrate at 70 °C for 20 min. The electrodes were led from both ends of the prepared hydrogel and encapsulated with a layer of Ecoflex 00-30 to produce a strain sensor.

B. Measurements of Strain Sensor

The electrical characteristics of the strain sensor under different conditions are recorded directly through LCR-TH 2838 laboratory smart data acquisition system and PWS-Motor-1SV-0.1R-250 single-axis translation table at room temperature. The hand motion signals are sensed by the smart gloves.

C. Fabrication Process and Measurements of Smart Gloves

The smart glove shell part is fabricated by 3D printing and consists of the finger part and the palm part. There are flexible strain sensors on the back of the fingers, which are attached by tape so that a total of four strain sensors for two fingers constitute the strain sensor array of the smart glove. The smart gloves sense the hand motion. The sensing process was measured by home-made instrument.

III. Results and Discussion

The concept of an HMI based on a hydrogel strain sensor array to control an unmanned aircraft is shown in Fig. 1. The HMI proposed in this paper consists of 4 parts, a smart glove unit with four strain sensor arrays, a signal acquisition unit, a signal processing unit and an unmanned control unit. The design of the flexible sensors is mainly based on the use of corn starch hydrogel as an intermediate sensitive layer, by depositing silver wires as electrodes and fully encapsulated by Ecoflex 00-30, and can avoid some interference caused by unnecessary contact.

A. Characterization of Strain Sensors

To further demonstrate potential application in human-machine control of UAVs, a series of tensile performance tests were conducted on our strain sensors and the results were shown in Fig. 2.

In order to fully characterize the basic performance of this hydrogel sensor, a series of performance indicators are introduced and characterized in this paper, including sensitivity, hysteresis, repeatability, stability, and detection range. The gauge factor (GF) is used to define the sensitivity.

$$GF = \frac{\Delta R / R_0}{\varepsilon} \tag{1}$$

where ΔR is the change in resistance relative to the nominal resistance R_0 at initial strain, and ε is the strain of the sensor.

The variation of the resistance ratio $\Delta R/R_0$ of the hydrogel sensor at low strain (0.1%, 1%, 10% and 50%) and high strain (100%) of the stretch-release cycle is shown in Fig. 2 (a). A small strain of 0.1% changes in $\Delta R/R_0$ are detected, and the $\Delta R/R_0$ of the sensor increases gradually with increasing deformation. These results prove that the sensors have good tensile response characteristics. As shown in Fig. 2 (b), the variation of $\Delta R/R_0$ at different frequencies is basically the same, indicating that the sensor can be applied to different motion scenarios.

Stability is an essential performance for strain sensors to be investigated, which is crucial for adaptation to various environmental applications. The strain sensors in this paper have been subjected to ~3000 cycles at 50% deformation, which still maintain a rate of change in resistance comparable to the initial time. This indicates that the obtained sensor has a strong tensile stability (Fig. 2 (d)).

It is well known that the voltage-current curve for different deformations is an important indicator of strain sensors. We have used the Keithley 4200A-SCS parameter analyzer to characterize the voltage-current characteristics of the sensor over a wide range of deformations from 0% to 500% (Fig. 2 (c)). It can be seen that the voltage and current differentiation of the sensor under different deformations is high, proving that the sensor has the ability to operate in the 0% to 500% deformation range.

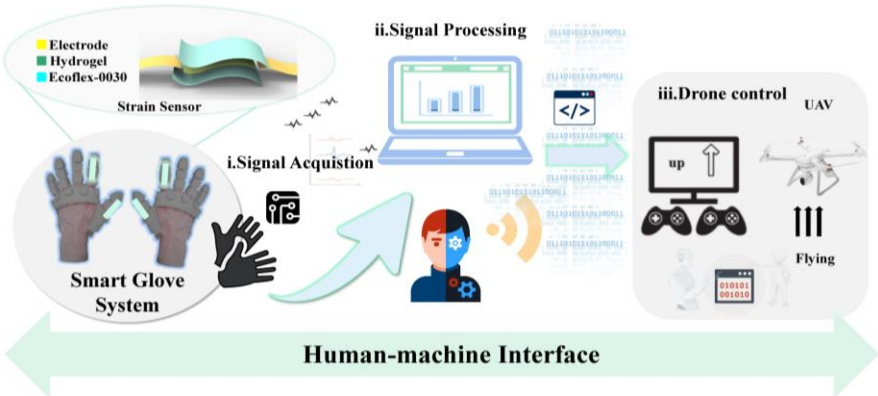

Fig. 1. Human-machine interface based on smart gloves.

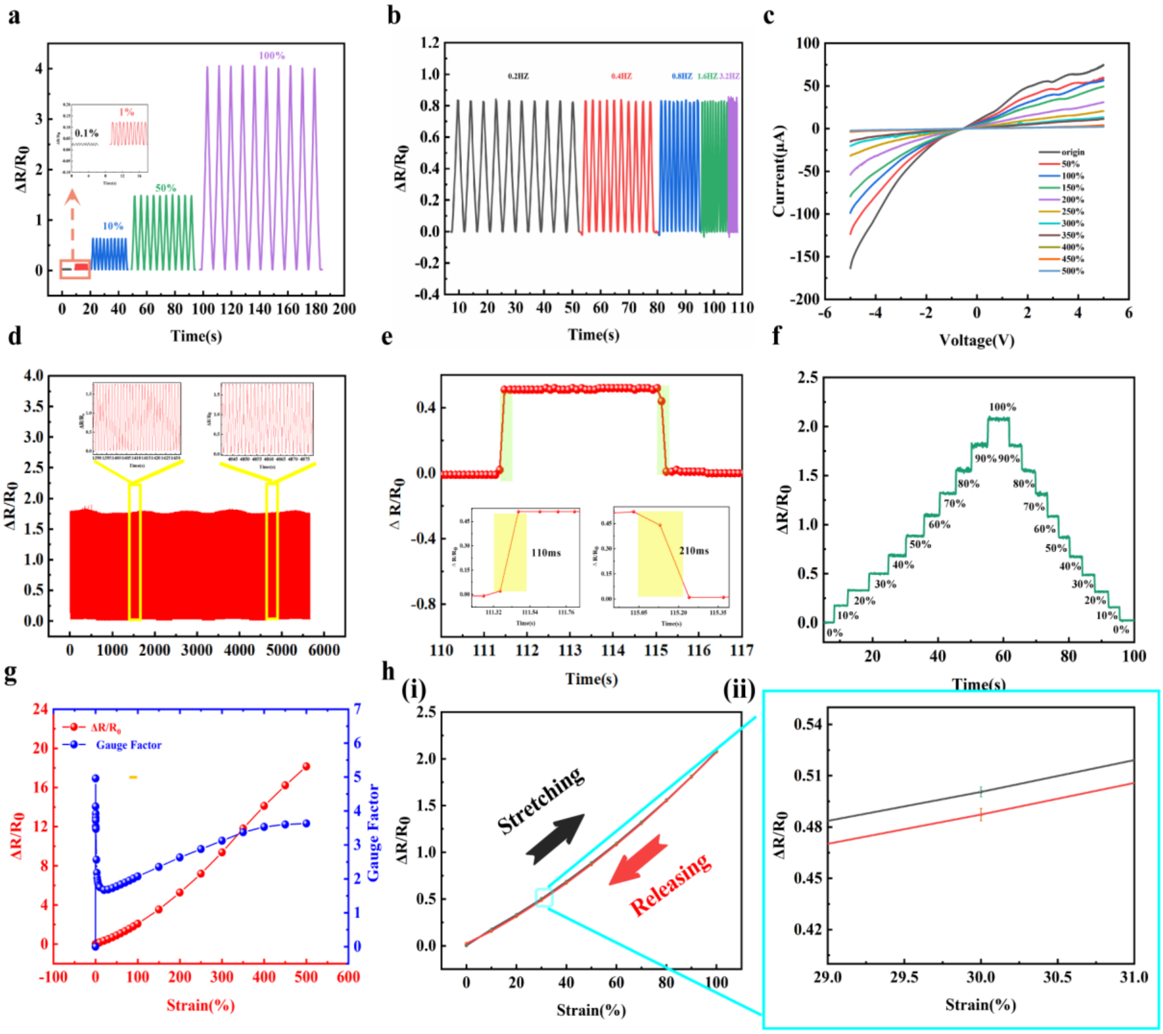

Fig. 2. Tensile properties characterization of strain sensors: (a) Stretch response at different lengths; (b) Tensile response at different frequencies; (c) The current-voltage characteristic curves at different strains; (d) ~3000 cycles of stability testing; (e) Tensile response and unloading response times for 10% deformation; (f) Step characteristics of the 100% deformation of the sensor from stretch to unload; (g) Comparison of sensor sensitivity and rate of change of resistance at 0-500 deformation; and (h) Hysteresis curve at 0-100% stretch.

As a sensing unit for deformation subjected to stress, the response time for tension and the response time for unloading are another important indicator of its basic characteristics. Fig. 2 (e) shows that the sensor has a fast response time of 110ms at 10% deflection and can recover to its original shape in a shorter interval of 210ms after unloading, demonstrating the fast response time and quick recovery time of our strain sensors.

Fig. 2 (g) shows the gradual increase in the rate of change of the sensor's resistance with increasing strain for deformations of 0% to 500%. As can be seen from the blue sensitivity data, the sensor has a high sensitivity at the initial deformation, which decreases as the deformation increases and finally stabilizes at 3.6. This indicates that our sensor has a high sensitivity. Table I shows the comparison between the sensitivity of our strain sensor and the recently published strain sensor. The maximum sensitivity of our hydrogel strain sensor can reach 3.6. Compared with many recently reported hydrogels, the average value of the maximum sensitivity of the gel sensor in the six references is 3.13, the maximum is 4.9, and the minimum is 1.3. Our maximum sensitivity is somewhere in this range and above the mean, proving that this result is quite excellent [23]-[28].

TABLE I: GF_{MAX} COMPARISON OF THE REPORTED CONDUCTIVE ORGANOHYDROGELS AND THE ORGANOHYDROGEL FABRICATED IN THIS WORK

Samples	GF_{max}	Refs
PG/Borate/AM/PPy/Bis·H_2O/Glycerol	4.9	[23]
AA/CS	2.57	[24]
Eg/Gl/AM/KCl/Carrageenan	4.5	[25]
PAH/TA/PAA/Go/Glycerol	1.3	[26]
PAM/LMS	2.6	[27]
PAM/SA/$CaCl_2$·H_2O	2.9	[28]
PVA/$CaCl_2$/CS	3.6	This work

We have carried out a real time stretch-unload test using 10% as the deformation step, and Fig. 2 (f) shows a clear distinction between the rates of change of the sensor’s resistance under different deformations. This demonstrates that the sensor has a good step response at 0% to 100% deformation. In addition, the rate of change in resistance between loading and unloading of the sensor in 0% to 100% shape stretching is basically unchanged, indicating that our sensor has low hysteresis characteristics (Fig. 2 $(h)_{(i)}$). And we have performed error bars on the data for each deformation step, Fig. 2 $(h)_{(ii)}$ shows the error bars for stretching and unloading for 30% deformation. Their mean values in tension and unloading are 0.50056 and 0.48732, respectively.

In addition, our sensitive layer material, corn starch hydrogel, is also versatile, as shown in Fig. 3 (a). Initially, the strain sensor has a resistance of 3.86kΩ, which tends to infinity after being disconnected. When the sensor is connected, the hydrogel layer inside returns to 3.54 kΩ, indicating excellent self-healing property. Fig. 3 (b) shows that the hydrogel can adhere to a 50g weight, demonstrating the adhesion properties of our hydrogel. The logo of Soochow University covered with hydrogel can be clearly seen in the Fig. 3 (c), indicating good transparentness. Fig. 3 (d) represents the gradual decomposition of the spherical hydrogel after 5min of stirring in water and complete decomposition after 3h of continued stirring. These characteristics prove that our gels are degradable. Fig. 3 (e) shows the deformation of the hydrogel inside the Ecoflex 00-30 encapsulation layer from an initial 20mm to 120mm (500%), demonstrating the excellent stretchability of the hydrogel. In summary, our hydrogels are self-healing, adhesive, transparent, stretchable and degradable.

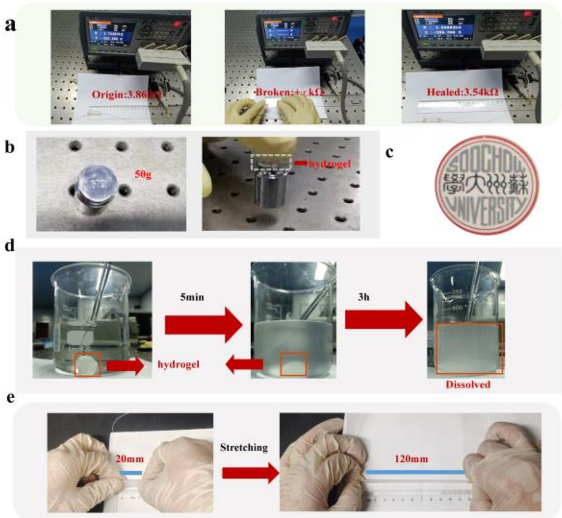

Fig. 3. Multifunctional properties of hydrogels. (a) Self-healing properties; (b) Adhesion; (c) Transparency; (d) Degradability; and (e) Stretchability.

B. *Design of HMI for Smart Gloves*

Fig. 4 (a) shows a sensor array of strain sensors, each of which is attached to the glove shown in Fig. 4 (b) by means of adhesive tape, with the sensor units corresponding to the finger. By evaluating the finger knuckle joints and the size of the fingers, we have designed a finger sleeve with multiple joints of the fingers, including top, middle and bottom (Fig. 4 (b)). A wearable glove is formed by connecting the edge of the finger glove to the palm of the hand via a wire. Four sensors arrays are connected to the glove via adhesive to form a smart glove. The assembly diagram and photo of the smart are shown in Figs. 4 (c–d), respectively.

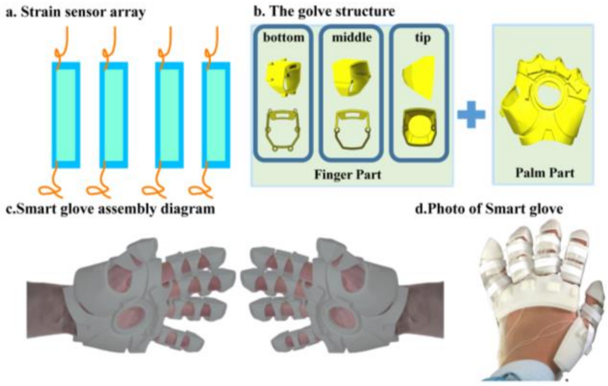

Fig. 4. (a) Strain sensor array; (b) glove structure; (c) smart glove assembly diagram; and (d) photo of Smart glove.

C. *Strategy and Characterization of Control Interface*

In order to study the application of this smart glove in human-machine interaction control, we designed a system for wireless control of UAV using smart glove. Fig. 5 (a) shows hardware and flowchart of a smart glove-based UAV control system. Firstly, the original analog signal of finger bending, after filtering and amplifying processing by peripheral pre-processing circuit, the high quality of voltage signal is sent to NI acquisition card. And then the digital signal is output, and the Labview-based program can convert the output digital signal into control command, which is recognized by Arduino to control the drone. According to the different voltage changes of the four-array strain sensors located at the thumb and index finger, different finger movements can be detected, based on the component vector control strategy. Combining the responses of the four-array sensors after different movements, the six directions of motion of the UAV can be controlled, as shown in Fig. 5 (b).

We have marked the strain sensors for the 4 channels (C1-C2-C3-C4) in the order of the left thumb, left index finger, right index finger and right thumb (Fig. 5 (c)). Finger flexion increases the length of the strain sensor, which results in an increased electrical output signal. Coupling the movements of the different fingers ultimately defines the direction of motion of the 6 drones.

Fig. 5 (d) shows the correspondence between the different finger bending movements and the different directional movements of the drone. When the volunteer bends the left index finger and the right index finger, the resistance of C2 and C3 changes, then the MCU controls the drone to fly towards the front. If the resistance between C3 and C4 changes when the volunteer bends the right thumb and index finger, then the MCU controls the drone to fly upwards. When the volunteer bends the left thumb, the resistance of C1 changes and the MCU controls the drone to fly to the left. When the volunteer bends the left thumb and the right thumb at the same time, C1 and C4 resistance changes and the MCU controls the drone to fly backwards. When the volunteer bends all four fingers at the same time, all four resistances change and the MCU controls the drone to fly downwards. When the volunteer's right thumb is bent, only C4 changes in resistance and the MCU controls the drone to fly to the right.

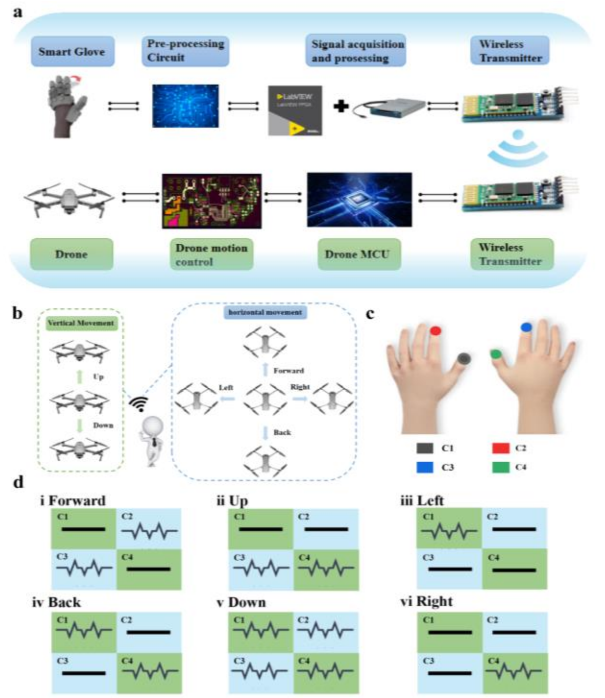

Fig. 5. Strategy and characterization of control interface: (a) Hardware and flowchart of a smart glove-based UAV control system; (b) The drone can achieve six kinds of movements in both horizontal and vertical planes; (c) Fingers corresponding to the four channels; and (d) working principle of wearable human-machine interface based on the strain sensors.

D. Demonstration of Human-Machine Interface for UAV Control Movement

The four-array strain sensors are directly connected to the signal processing module and NI USB multi-function I/O device (USB-6210) to capture the finger signal. Among them, the signal processing module converts the current signal into voltage signal, then filters and amplifies the voltage signal. And the output voltage signal is captured by the NI USB multi-function I/O device. The Labview-based program can convert the output electrical signals into control commands, which are recognized by Arduino to control the movement of the UAV. In this process. The acquisition frequency of the I/O device is about 10 HZ and the response time is about 0.1s.

The motion control of UAV was investigated through a smart glove human-machine interface based on a strain-sensing array (Fig. 6). The first and fifth rows show the direction of motion control of the drone. The second and sixth rows show the instructions for the four sensor arrays to control the flight of the drone. For accurate operation, a threshold value is set for the voltage output. The relative change in voltage within the threshold is set to 1 and the rest is set to 0. The third and seventh rows show a demonstration of the output signals from the corresponding strain sensor arrays controlling the six directions of flight of the UAV. The fourth and eighth rows show the signal waveforms of the strain sensor array. It is clear that the HMI can control the UAV in six directions (forward, back, left, right, up and down) in real-time.

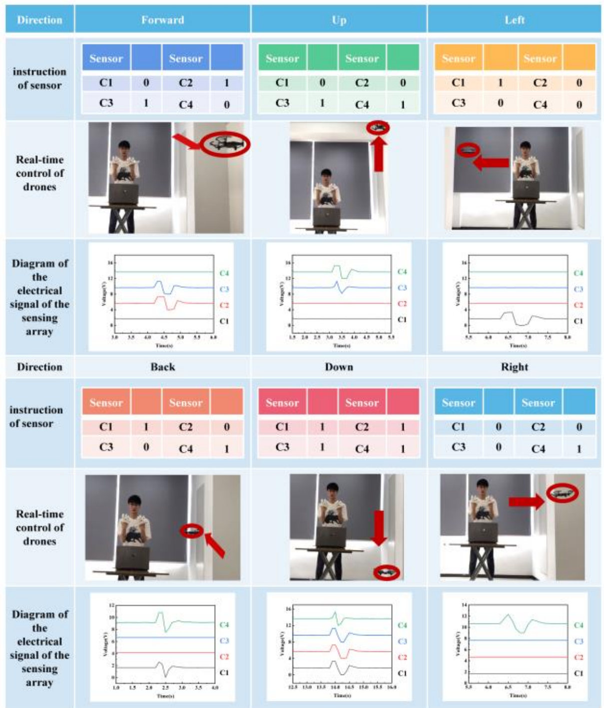

Fig. 6. The relationship between the fingers' motions and the curve of voltage when the UAV is controlled by the human-machine interface.

IV. Conclusion

In summary, we have designed a smart glove HMI, which has advantages over traditional gloves based on accelerometer and gyroscope in terms of manufacturing cost and simplicity. The smart glove was constructed using 3D structural design combined with the strain sensor array. The system utilized transparent, self-healing, degradable green starch-based strain hydrogel sensor with adhesion properties. The obtained sensor showed high sensitivity (GF_{max}=3.6), fast response time (110 ms), good stability, wide- detection range of 0-500%. This smart glove, could enable to control the UAV motions in six directions of forward, back, left, right, up and down. This work provided a promising solution for the development of advanced human-computer interaction interfaces with positive prospects in areas such as entertainment and industrial production.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ping Fang, Fengxia Wang and Yirun Zhu conducted the research; Ping Fang and Wenxiao Lu analyzed the data; Ping Fang wrote the paper; Fengxia Wang and Lining Sun provided technical guidance; all authors had approved the final version.

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