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Editorial

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Editorial

Developing materials is basic in wearable technology. The materials had better be stretchable, comfortable, bendable, portable, light and flexible enough to move with the users. That's why flexible materials are widely used in health diagnosis, sports monitoring, rehabilitation and entertainment.

Sensors are devices that detect some types of input from the physical environment and respond to them. Sensors in wearable technology are also wearable, and they are widely used in measuring health-related symptoms.

In this issue, we will see some articles about the technique involved in smartwear materials and sensors. Two of our editor board members offered articles on this topic.

Prof. Shufang Li from Beijing University of Posts and Telecommunications discussed the different realization methods and performance index requirements of wearable antenna (a new form of wearable devices), introduced the research situation of the wearable antenna in China and other countries in recent years and analyzed the development trend of wearable antenna. Prof. Liping Xie from Northeastern University summarized the development of flexible sensors in recent years, discussed how to construct high-performance flexible stress sensors based on deep analysis and investigation of the working principle and structural design of flexible stress sensors, pointed out the existing problems and looked forward to the development trend of flexible stress sensors.

A lot of other interesting papers were collected on this issue as well, such as the research on the real-time acquisition of multi-channel sensing systems by Yuehui Hu lab from Hefei University of Technology.

Managing Editor
Dr. Yina Xu

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ORIGINAL RESEARCH ARTICLE

Functional requirements analysis and design of wearable multi-channel sensing system

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ABSTRACT

In recent years, a large number of wearable devices have emerged; and users have higher and higher functional requirements for wearable devices. However, the realization of complex functions of wearable devices often depends on the real-time acquisition of multi-channel sensing signals. Taking the wearable 8-channel PVDF sensor system as an example; this paper studies the functional requirements of this kind of system. It is found that the flexible ultra-thin and long endurance time are two obvious characteristics of this kind of equipment. The key technical problems of the system are completed, such as the selection of MCU, the coding design of multi-channel sensing data, the transmission mode design of multi-channel sensing data and the low power consumption design of the system. A practical design scheme of reliable wearable multi-channel sensor system is designed. This scheme also provides a reliable reference for the design and development of wearable multi-channel sensor system.

Keywords: wearable equipment; system design; demand analysis; multi-channel; PVDF sensor; coding method; mode of transmission

1. Introduction

In recent years, a large number of wearable devices have emerged, such as Google glasses, Codoon bracelet, iWatch and so on. Wearable devices generally refer to electronic communication intelligent devices embedded in clothing or in the form of accessories, which can be worn comfortably by users and play the role of expanding perception and monitoring all kinds of signs. It is essentially an intelligent design of daily equipment such as glasses, watches and shoes[1], so that it has a friendly human-computer interaction function. The market demand for wearable devices is growing rapidly; and users have more and more functional requirements for wearable devices. However, the realization of complex functions often depends on the real-time acquisition of multi-channel sensor signals. Multi-channel sensor system is an important component of wearable devices and a source of information for wearable devices. It has the functions of monitoring data; transmitting data and so on. For a wearable device, it generally includes two parts: Sensor and data computing chip. The update frequency of sensor is low, and there may be no major upgrade in a few years. The replacement frequency of the computing

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chip is very high, so the hardware device itself should be more regarded as a super sensor system, and the computing part should be handed over to the mobile phone or cloud computing independently. Therefore, it is necessary to study the wearable multi-channel sensor system.

Wearable device users require comfortable wearing and good flexibility. PVDF (polyvinylidene fluoride) piezoelectric sensor just meets the characteristics of good flexibility and light weight[2]. Therefore, taking the wearable 8-channel PVDF sensor system as an example, this paper studies the functional requirements of this kind of system, designs a set of evaluation and selection system, and puts forward a practical and reliable design scheme of multi-channel sensor system.

2. Functional requirements analysis of wearable multi-channel PVDF sensor system

Wearable multi-channel sensor system needs to collect multi-channel sensor data, simply process and package it, and transmit it to other devices in real time and reliably[3]. Due to the wearable characteristics of this kind of equipment, that is, the equipment needs lightweight and low power consumption, as well as the real-time and reliability of data transmission, the wearable multi-channel sensor system has special requirements for the MCU part, data coding mode, data transmission mode and low power consumption of the system[4].

2.1. System MCU demand analysis

The data of the wearable multi-channel sensor system needs to be transmitted to other devices, which are often Android system or IOS system. If the system does not have this MCU, the system needs to be directly connected with the ARM chip of Android system or the microprocessor of other systems, which will cause a lot of inconvenience. Taking the sensor system as the lower computer and the ARM chip of Android system as the upper computer as an example, the inconveniences are as follows: The target signal collected by the sensor system is the human physiological signal, such as the motion signal generated by the muscle when the human wrist or ankle moves. The sensor signal output by the system is weak and has strong interference. If there is no preprocessing such as amplification, it cannot be directly connected with the arm of a droid system. Therefore, the pre signal preprocessing circuit is needed. The designed pre amplification circuit includes amplification, filtering and other functions. Even if the ARM chip of Android system has an amplification module, it cannot meet the requirements. Amplifying such sensor signals generally requires instrument amplifiers with high performance requirements. If 8 sensors in the sensor system collect 8-channel sensing signals, at least 8 signal lines need to be input into MCU. Considering the reliability and convenience of the system, it is not convenient to connect directly with the ARM chip of Android system. For the consideration of modular design, it is also necessary to use this MCU in the multi-channel sensor system. To sum up, we can find that the selected MCU needs to complete the functions of signal transceiver, A/D conversion, integration and serial output, and connection with the preprocessing circuit of sensor signal in the early stage.

Therefore, for the selected MCU, it is necessary to have at least 8 A/D conversion channels in function and meet certain accuracy requirements. In terms of hardware structure, considering the portability of wearable devices, the size of MCU should be small and the thickness should be thin. In addition, low power consumption is a key feature of portable electrical equipment. In order to achieve this goal, the power consumption of MCU should be low.

2.2. Demand analysis of system data coding mode and transmission mode

The most important and final function of wearable multi-channel sensor system is to provide a set of sensor data containing various information. The format of these data can match the data format of some mainstream communication protocols. The data can be easily and reliably transmitted to the Android system in real time.

The wearable 8-channel PVDF sensor system designed in this paper mainly collects human physiological signals. These signals are mainly concentrated in 0-100 Hz, that is, the frequency range of each channel signal of the sensor system is 0-100 Hz, and the maximum of 8 channels is 800 Hz. During A/D conversion in engineering application, the sampling frequency is at least 10 times the maximum frequency of the input analog signal, so the sampling frequency we adopt is 10 KHz, which meets the requirements of signal processing in digital domain in the later stage. Considering the requirements of real-time data transmission, the data frame is set to 10ms, that is, the lower computer sends a frame of data to the upper computer every 10ms. In fact, the data received by the upper computer each time is the data sampled by the lower computer in the first 10ms. When the sampling frequency is 10 KHz, a total of 100 data are sampled in 10ms. Because the resources and processing capacity of MCU are not enough, it is necessary to send the collected data to the host computer for processing in real time. However, if the data is sent directly after data collection, the packet will be lost due to the large amount of data collected in real time and the small buffer. Therefore, appropriate coding protocol and communication protocol are needed to ensure the reliability of communication. In this case, the lower computer is mainly responsible for collecting and packaging, which can meet the requirements of simplification, accuracy and real-time. The data to be calculated is handed over to the host computer for processing. At the same time, considering the slow updating of sensors and the fast updating speed of host computer processing chip, this scheme can also reduce the cost to a certain extent.

For the system data coding method, what we need is a real-time and reliable coding method and communication protocol. In addition, the transmitted data format should match the mainstream communication protocol data format. At the same time, the coding mode and transmission mode also need to consider the requirements of low power consumption.

2.3. Low power consumption demand analysis of the system

For wearable devices, the endurance time must be considered. The endurance capability is mainly determined by two factors: battery capacity and power consumption. The higher the battery capacity, the better, and the power consumption needs to be minimized. Unfortunately, before the emergence of new battery technologies or materials, the space for battery capacity improvement was very limited, and the size requirements of wearable devices were relatively strict, so it was impractical to increase the battery life by replacing large capacity batteries. Therefore, the pressure almost falls on how to reduce power consumption, which requires low-power design to meet the needs of users.

The low-power requirements of the system mainly include the following aspects. Firstly, try to use products with low voltage and low power consumption in the hardware development of sensor system[5]. For example, the amplification, filtering and preprocessing circuit of the sensor system generally selects a low-power chip. At the same time, in the selection of main control chip, we generally choose the main control chip with power-saving mode. Secondly, as the main controller of the system, MCU also needs low-power design. The work of MCU mainly includes A/D conversion of multi-channel sensor signals, simple processing and packaging of data and data transmission. Finally, it is required to have flexible low-power management mode and simple and fast sleep wake-up mechanism, so that MCU can quickly switch to different depths of sleep state in idle period and wake up in time. We can choose the way to wake up the main control chip or related modules. That is to optimize the software algorithm according to the demand of low power consumption while realizing the basic functions.

3. Design of wearable multi-channel PVDF sensor system

According to the above demand analysis and research on the system, it is found that the most significant characteristics of this kind of wearable devices are flexible, ultra-light weight and long service life. Therefore, wearable multi-channel PVDF sensor system should be designed around these two remarkable characteristics.

3.1. System MCU selection

According to the functional requirements analysis of wearable multi-channel sensor system, focusing on the two characteristics of low power consumption and high integration of wearable multi-channel PVDF sensor system, this paper compares and analyzes some mainstream MCU products in the market, and finally obtains the appropriate MCU selection.

Table 1 and **Table 2** select the mainstream MCU products in the current market, and compare their power consumption parameters and system indicators. Firstly, the wearable 8-channel PVDF sensor system needs at least 8-channel A/D conversion channels, and the MCU in **Table 1** meets the requirements. However, because the collected target signal is human physiological signal, the general signal is very weak, so the higher the accuracy of ADC, the better. The two MCU with high ADC accuracy are STM32. Compared with STM32F1 series, stm32L1 series has lower sleep power consumption, wider working voltage range and more A/D conversion channels. Secondly, according to the strict requirements for the size of the wearable system, the size of the tfbga64 package of STM32L151R6 is only 5 mm*5 mm*1.2 mm, the size fully meets the requirements. Finally, STM32L151R6 is a 32 bit core MCU of Cortex-M series, but its power consumption level is equivalent to that of traditional 16 bit low-power MCU, but its processing capacity is better than that of 16 bit MCU. Moreover, the price of STM32L151R6 is also moderate[8]. STM32L151R6 also has a great advantage in that STM company has a perfect system scheme based on STM32 and finished software and hardware modules, which has formed a relatively perfect ecosystem, low development threshold, rich reference resources and direct experience sharing[6]. The various advantages of STM32L151R6 prompted us to finally choose STM32L151R6 as the MCU of the wearable 8-channel PVDF sensor system in this paper.

3.2. Coding design of multi-channel sensing data

Because the collected 8-channel PVDF sensor data needs to be transmitted to the host computer in real time and accurately, the collected data needs to be encoded and simplified. In this paper, ADPCM coding is selected to compress the data, and then CRC_16 and convolutional coding are used to error correct the data. The target signal we collected is very similar to the voice signal.

Table 1. Comparison of typical microprocessor system indexes

Manufacturer model	Bus width (bit)|	Kernel architecture	Core efficiency (coremark/mhz)	Core efficiency (coremark/mhz)	Number of A/D conversion channels	ADC accuracy (bit)	Dimension (mm) × mm × mm)	Price (yuan)
RL78/Renesas RL78G13[10]	16	RL78	0.89	1.6-5.5	20	8/10	QFP64 sealed 14x14x2.25	22.5
PIC24F/Microchip PIC24FJ256GB110[11]	16	PIC24	0.93	3.0-3.6	16	10	TQFP100 sealed 12x12x1	57.2
MSP430F/TI MSP430F5229[12]	16	MSP4 30	1.11	1.8-3.6	16	10	VQFN64 sealed 9x9x1	45
STM32F1/STM STM32F103R8[7]	72	Cortex -M3	1.2	2.0-3.6	20	12	LQFP 64 10x10x1. 4/ TFBGA 64 5x5x1.2	13
STM32L1/STM STM32L151R6[9]	32	Cortex -M3	2.61	1.65-3.6	42	12	LQFP 64 10x10x1. 4/ TFBGA 64 5x5x1.2	19.2

Table 2. Comparison of absolute power consumption of typical microprocessor

MCU series	Maximum dominant frequency (mhz)	Operating power consumption (UA/mhz)	Sleep power consumption (UA)	Wake up time (US)
RL78/Renesas	32	66	0.24@Stop	>18-65
PIC24F/Microchip	32	150	0.42@LVS	70
MSP430F/TI[15]	25	195	1.2@LPM3	3.5-4.5
STM32F1/STM	72	373	1.7@Stop	50
STM32L1/STM	32	185	1.2@Stop	8.2

The correlation between the data is relatively strong. There is a lot of redundancy, and the final use of the sensing signal is mainly to analyze the shape of the signal, rather than obtain accurate values. ADPCM algorithm comprehensively uses the algorithm principle of differential pulse coding (DPCM) and Adaptive Incremental coding (ADM). On the premise of ensuring the speech quality of PCM, the rate of speech data is only half of that of PCM, and has better anti error performance. The core idea of ADPCM is: 1) use the adaptive idea to change the size of quantization order, that is, use the small quantization order to encode the small difference, and use the large quantization order to encode the large difference. 2) The predicted value of the next input sample is estimated using the past sample value, so that the difference between the actual sample value and the predicted value is always the smallest[13]. ADPCM compression algorithm is adopted in this paper, and the compression ratio of data can reach 4:1.

In order to improve the reliability of data, some error detection and correction coding should be carried out after data compression and coding. Although cyclic code CRC can only detect errors and cannot correct errors, it has low computational complexity, strong error detection ability and less redundant bits[14]. The convolutional code has strong error correction ability. Although the computational complexity is high, the computational complexity can be greatly reduced by looking up the table. In this paper, $CRC_1 6$ check coding and (2,1,4) convolutional coding are selected for error detection and error correction coding. Cyclic redundancy check (CRC) algorithm is one of the commonly used error detection methods. It is evolved from the branch of block linear code. Its main application is binary code group. The coding is simple and the error probability is very low. Using CRC algorithm for data at the receiver can effectively eliminate the error code in data transmission. CRC16 coding adopts look-up table method in algorithm implementation. The CRC16 code consists of two bytes. At the beginning, each bit of the CRC register is preset to 1, and then XOR the CRC register with 8-bit data. Then, the CRC register is shifted from high to low and zero is filled in the position of the highest bit (MSB). If the lowest bit (LSB, which has been moved out of the CRC register after shift) is 1, XOR the register with the predefined polynomial code, otherwise if the LSB is zero, no XOR is required. Repeat the above shift from high to low for 8 times, and the first 8-bit data is processed. Use the value of CRC register at this time to XOR with the next 8-bit data, and perform 8 shifts like the previous data. After all characters are processed, the value in the CRC register is the final CRC value. Every shift division operation of $CRC_1 6$ coding is replaced by look-up table method, which has low computational complexity. Every time a frame of data is encoded by $CRC_1 6$, a 16-bit check code is obtained. The 16 bit CRC algorithm can ensure that there is only one undetected error in 1014 bit symbols. Convolutional code is a kind of error correction coding. It compiles the input K information bits into n bits for output. It is especially suitable for serial transmission with small delay. It includes: an input shift register composed of N segments, each segment has k segments, a total of NK registers, a set of N modules 2 and adders, an output shift register composed of N stages, corresponding to the input sequence of k bits per segment, outputs n bits[16]. (2,1,4) convolutional code is to encode the 2-bit information input each time into 4 bits. Convolutional code has a large amount of computation and high complexity. In this paper, the look-up table method is used for convolutional coding of data. Firstly, the coding table of (2,1,4) convolutional code is generated by using convenc (msg, t) function in MATLAB. The size of the coding table is 2^8*16 bits, and then the table is directly looked up in the MCU of the lower computer for coding, which greatly improves the coding speed, reduces the complexity of the algorithm, and reduces the running power consumption of MCU.

The specific coding method of 8-channel sensing data is shown in **Figure 1**: It can be seen from the above that the data frame is sent every 10ms, and there are 100 original sensing data in each frame. Since the ADC accuracy of STM32L151 single chip microcomputer is 12 bits, the collected data is actually 100*12 bit, accounting for only the lower 12 bits of a word. The highest bit, i.e. the 16th bit, is set as a control bit. When the control bit is 0, it means that the current data is a data signal, when it is 1, it indicates that the current data is a control signal. The channel number code of 8 channels is 000-111, occupying the 13^{th}-15^{th} bits, and 100 data occupy 200 bytes in total. Firstly, ADPCM code the 200 bytes of data, and compress the encoded data to only 100*4 bit, occupying 100 bytes. Then the data is combined into an 8 bit. The data frame has been compressed to 50*8 bit, occupying only 50 bytes. Secondly, the data frame is encoded by CRC16, that is, a 16-bit check value is obtained. When the check value is added, the data frame is 52 bytes in total. Finally, the data frame is (2,1,4) convolutional coded, and the convolutional coded data frame has a total of 104 bytes.

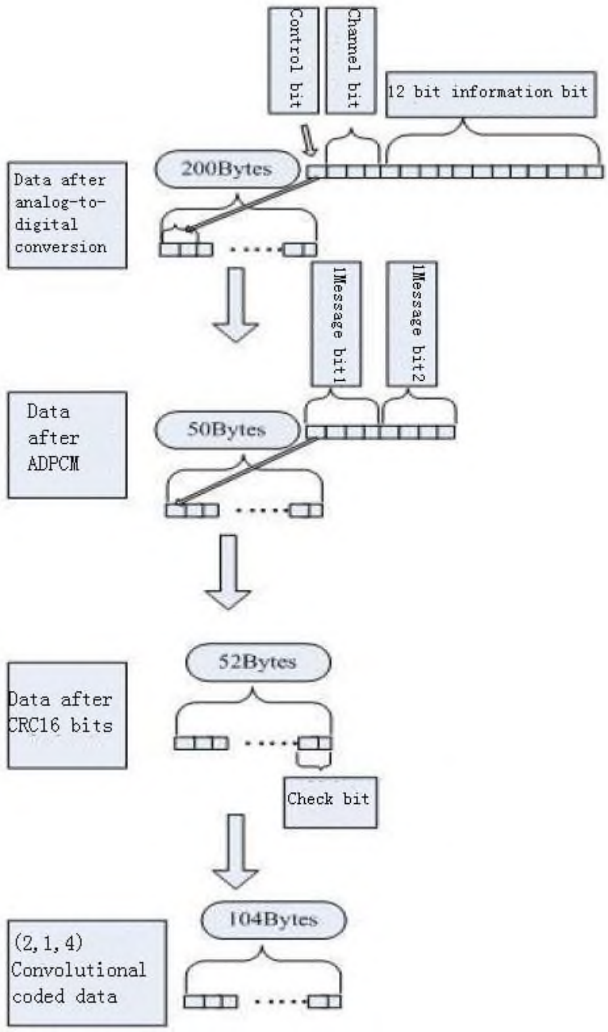

Figure 1. Flow chart of data coding scheme.

3.3. Design of sensing data transmission mode

Real time and reliable data transmission, in addition to relying on a real-time and reliable data coding method, the data transmission method is also very important. Considering the compatibility and application of the wearable multi-channel sensing system, two sensing data transmission methods are designed in this paper. One is wired transmission and the other is wireless transmission.

Design of wired transmission mode of sensing data

As for the choice of wired transmission scheme, we select four common transmission schemes such as I2C, USB, SPI and RS232 for comparison. By analyzing and comparing these common wired transmission modes, we finally choose I2C as the wired transmission mode of the system. I2C has the following significant advantages: 1) simple hardware and less resource consumption. There are only two bus lines: A serial data line (SDA) and a serial clock line (SCL), which save line space and increases the stability of the system. Therefore, in terms of size, since USB and SPI have four wires, RS232 has nine pins. Compared with I_2C, which has only two bus lines, it will inevitably lead to the problem that the connection and peripheral circuits occupy too much space. In terms of size, I2C should be our ideal choice in these wired transmission modes. 2) It is a real multi host bus, which locks the slave device through the address information on SDA. If two or more hosts initiate data transmission at the same time, the data can be prevented from being destroyed through conflict detection and arbitration. SPI bus has only one master device, and the master device determines the slave device through CS chip selection. 3) The 8-bit bidirectional data transmission rate of I2C serial can reach 100 Kbit/s in standard mode, 400 Kbit/s in fast mode and 4.4 Mbit/s in high-speed mode. In this scheme, at least 104 bytes are transmitted every 10ms, and the transmission mode adopted is at least 83.2 Kbit/s. The transmission speed of I2C fully meets the requirements. 4) Compared with RS232, I2C has another outstanding advantage: I2C sampling synchronous communication and RS232 asynchronous communication. The overhead of synchronous communication control characters is small and the transmission efficiency is high, in the asynchronous communication character frame, assuming that there are only start bits, 8 data bits and stop bits, the overhead of control bits in the whole character frame reaches 20%, and the transmission efficiency is low. 5) It is widely used. Now almost all IC manufacturers have integrated I2C on their chips[17].

Design of wireless transmission mode of sensing data

As for the selection of wireless transmission schemes, we choose ZigBee, NFC, infrared, Bluetooth and other four common transmission schemes for comparison[18,22]. In terms of service distance, infrared transmission is a point-to-point wireless transmission mode, which cannot be too far away, should be aligned with the direction, and there should be no obstacles in the middle, so it is almost impossible to control the progress of information transmission[23]. Bluetooth can transmit about 10 meters. After strengthening the signal, it can be up to 100 meters. It can detour, misalign, and cannot be in the same room. The maximum number of links can be up to 7, and the hardware can be distinguished at the same time. ZigBee is a cheap, low-power short-range wireless networking communication technology. However, due to the low transmission speed of ZigBee, it is not suitable for the application of multi-channel PVDF sensor system with high data volume. At the same time, due to the high cost of hardware resources when using ZigBee[24], mobile phones are not supported in the short term, which is not conducive to the promotion of products. NFC has the advantage of simple configuration. However, due to the short use distance and the ultra-thin size of the wearable device we use, NFC will produce high-frequency skin effect[25], and there may be some potential health and safety problems. And the compatibility of NFC is not very good at present. Many mobile phones do not support NFC. These problems prompted us to choose the final wireless transmission mode for Bluetooth, the specific scheme is the i484e-s module. This product integrates two chips: the Bluetooth chip is CSR8811 (based on Bluetooth 24 GHz radio and baseband chip system) and STM32F401 (32-bit RISC based on high-tech ARM Cortex-m4). The size is only 15.7*12*2.3 mm. It supports Bluetooth standard 4.0 low-power mode and downward compatibility. It can be switched to Bluetooth mode through I2C wired mode. The speed can reach 32 KByte/s, i.e. 256 KBit/s. When transmitting data at full speed, the power consumption is only 2 mA, and the standard button battery can run for one or even several years.

3.4. Low power design

The power consumption of a sensor system is determined by many factors. The overall power consumption depends on many factors, such as product performance, power supply voltage and so on. In practical application, the higher the dwelling frequency, the greater the power consumption, the higher the voltage, the greater the power consumption. For the design of low-power detection system, we should mainly consider the selection of chips and devices, the technical indicators of the system and the working mode of the system.

Selection of devices and chips

For low-power systems, the selection of devices and chips used in the circuit is very important, which directly affects the power consumption of the system from the hardware circuit. Therefore, in order to reduce power consumption, devices and chips must be selected reasonably. 1) Selection of power supply part. Due to the high-energy conversion efficiency of lithium battery, the power supply used in wearable devices is generally lithium battery. The battery selected in this scheme is polymer lithium battery, the specific model is 803040, the capacity is 1,000 mAh, and the size is only 40*30*8 mm. A 200 mA, low IQ, low noise and low voltage drop regulator chip for portable equipment is selected. The model is TLV707 and the size is only 1*2 mm[26]. 2) Low power microprocessor is selected. In this paper, STM32L151R6 with low power consumption is selected, which has a compact and efficient CPU core, so as to maintain the balance of performance, power consumption and cost. CMOS circuit technology, low voltage power supply system, power supply voltage of 1.65-3.6V. Flexible low-power management mode and simple and fast sleep wake-up mechanism enable MCU to quickly switch to sleep states with different depths during idle period and be awakened in time. Independent peripheral clock control switch, multiple internal and external clock sources. The operating power consumption is only 185 uA/MHz, and the sleep power consumption is only 1.2uA. 3) For the preprocessing circuit of sensor signal, MAX9618 operational amplifier of Meixin company is selected to build the preprocessing circuit of each channel sensor signal, including amplification part and low-pass filter part. Max9618 is a low power, zero drift operational amplifier, which provides space saving. It adopts 2 mmx2 mm, 8-pin SC70 package design and supports full swing CMOS input and output. The power supply current is only 59 μA in the whole time and temperature range, and the maximum offset voltage of zero temperature drift input is only 10 μV. It is not often suitable for wearable devices[27].

Selection of working mode of low-power system

The MCU of wearable 8-channel sensor system is a low-power device, and has various working modes to reduce power consumption, such as sleep, power failure and so on. When designing a low-power system, we should make full use of these characteristics to make the system work in these working modes as much as possible. 1) MCU uses the lowest clock frequency for A/D conversion and coding to reduce power consumption. The coding algorithm is the simplest. CRC16 and (2,1,4) convolutional coding adopt look-up table method, which shortens the execution time of each program. 2) When the wearable multi-channel sensor system in this paper is used as the lower computer, whether it collects data or not is controlled by the upper computer. When the upper computer sends a command, the MCU is awakened, and the system starts to work again to collect data.

4. Overall system design scheme

The overall scheme of the wearable multi-channel PVDF sensor system designed in this paper is shown in **Figure 2**. Firstly, multi-channel sensors collect human physiological signals. The collected data are amplified and filtered and sent to STM32L151 single chip microcomputer for A/D conversion, and the analog signals are converted into digital signals that can be easily processed[28]. STM32L151 single chip microcomputer encodes and packs the 8-channel data obtained after A/D conversion, and then sends it to the upper computer. Due to the compatibility of transmission mode, the upper computer can be Android platform or IOS platform.

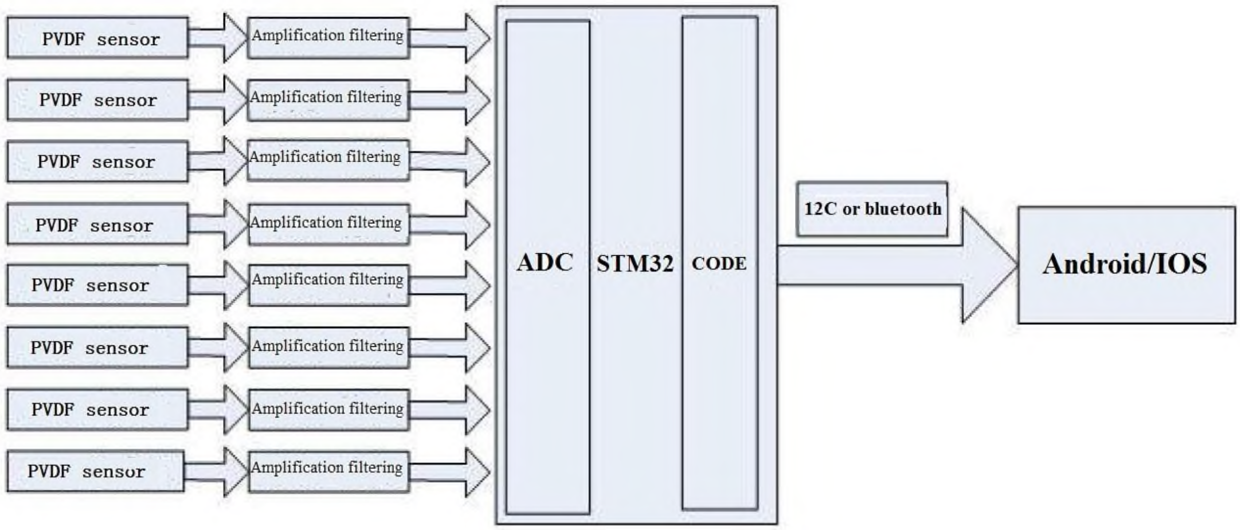

Figure 2. Overall system block diagram.

5. Conclusions

Since several scientists at MIT put forward the concept of wearable devices in the 1960s, people began to explore the application of wearable technology to design and develop daily wearable products in order to develop wearable intelligent devices. With the progress of technology and the change of user needs, the form and application hotspots of wearable intelligent devices are also changing. In this context, it is of great practical significance to analyze and design the functional requirements of wearable multi-channel sensing system. Taking wearable 8-channel PVDF sensor system as an example, this paper studies the functional requirements of this kind of system, and finds that flexibility, ultra-light weight and long service life are the characteristics of this kind of equipment. Based on this, a set of evaluation and selection system is designed to complete the MCU selection of the system; the coding mode of sensing data A practical and reliable system design scheme is obtained. This scheme also provides a reliable reference for the design and development of wearable multi-channel sensor system.

Conflict of interest

The authors declare no conflict of interest.

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ORIGINAL RESEARCH ARTICLE

Wearable grain silo working environment sensing and safety alarm system

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ABSTRACT

A set of wearable granary working environment sensing and security alarm system is developed to ensure the safety of granary staff. The gas sensor, piezoelectric ceramic chip, infrared transmitting and receiving tube and photosensitive resistance are used as the core components of each circuit module to collect the gas concentration signal, human respiration intensity signal, pulse intensity signal and light signal in the granary. AD0809 module chip is used to convert analog data into digital data and send it to MCU for information processing to make alarm judgment. At the same time, PTR2000 module is used to transmit the sensor data to the upper computer. The upper computer determines whether to alarm through data comparison, and transmits the alarm signal to the mobile phone through Wi-Fi in real time. Each module cooperates with each other, information real-time transmission to complete the detection of granary environment and danger alarm. The test results show that the system can meet the safety operation requirements of large and medium-sized state-owned grain depot.

Keywords: sensor; alarm system; AD0809 chip; Keil C51

1. Introduction

With the expansion of grain storage in grain depots and the wide application of chemical fumigation agents, grain depot workers often face the dangers of landslides, hypoxia, poisoning of harmful residual gases, etc. when entering the warehouse[1]. In order to address these issues, this project designs and develops a portable granary working environment and life activity sensing system for workers and other dangerous situations. The sensor itself and the connected wireless transceiver module can be used to implement automatic alarms inside and outside the warehouse, maximize the safety of workers entering the warehouse, and achieve part of the grain condition detection function.

2. System overall structure

The overall structure of the system is shown in **Figure 1**, including various sensors, signal acquisition, conditioning circuits and local alarms. Generally, it can be divided into four modules: gas detec-

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tion, respiratory and pulse monitoring, illumination detection and wireless communication[2]. The signal acquisition and conditioning circuits then process the data collected by the sensors and after preliminary amplification, conditioning, shaping and digitization of the signal, transmits the signal to the communication host of the monitoring center in the current limited transmission mode through the communication extension where it is connected with the host computer through the RS232 interface. The host computer then receives the signal sent by the communication host and conducts a real-time online analysis. Once the signal value is found to exceed the safety standard, the host computer will send an alarm command to the lower computer to trigger the local alarm. As a result, the sounding of the room alarm will go off and at the same time, the emergency situation will be reported to the relevant personnel in the form of a short message through Wi-Fi.

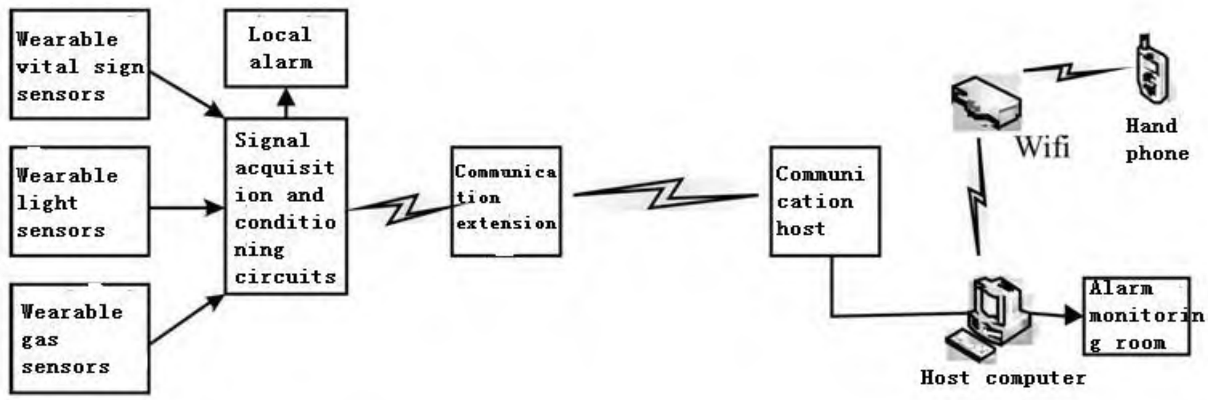


Figure 1. General diagram of system structure.

3. Hardware system design

3.1. Gas detection module

The gas detection module is divided into a fumigation gas detection module and an oxygen and carbon dioxide gas detection module[3].The design ideas of these two modules are the same, and the structure diagram of the gas detection module is shown in **Figure 2**.The gas detection module consists of gas sensors[4] and an AD0809 analog-to-digital conversion chip. The gas sensor can collect and analyze the concentration of fumigation gas or oxygen and carbon dioxide gases in the granary in real-time. When different gas concentrations are collected, outputs of different voltages and currents values will be sent by the sensors. At this point, the micro controller is unable to recognize the analog values and hence, it is necessary to convert the analog value output by the sensors into a digital value by selecting the use of AD0809 chip during the analog-to-digital conversion which will be activated by the microcontroller. After the activation of the chip AD0809, the analog voltage or current value is converted into a digital value. After the conversion, the AD0809 chip sends an interrupt request to the microcontroller where the microcontroller responds to the interrupt request reads these digital values in real-time, and compares the read digital values with the standard digital values to determine the gas concentration.

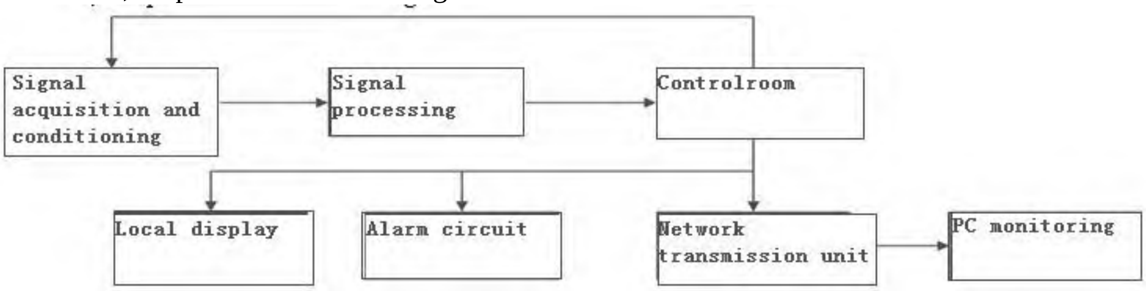


Figure 2. Working diagram of gas concentration detection module.

3.2. Respiration and pulse monitoring module

Design of respiratory monitoring module

The breath detection sensor is designed with a piezoelectric ceramic sheet as the core. When exhaling, a certain pressure will be applied to the piezoelectric ceramic sheet which will generate a signal output. When inhaling is performed, the pressure is then removed and the piezoelectric ceramic sheet will have no signal output. This way, the time length of one breath can be determined by measuring the output signals of two adjacent piezoelectric ceramic sheets and calculating the breathing frequency of a person.

The block diagram of the respiratory monitoring module is shown in **Figure 3**[5]. When the piezoelectric ceramic sheet senses exhalation, a rising edge pulse signal will be generated, and the rising edge will generate a timer interrupt for the microcontroller. At this time, the microcontroller starts timing. As the exhalation continues, the piezoelectric ceramic sheet continues to output a high-level signal. When inhaling, no force is applied to the piezoelectric ceramic sheet. During this time, the piezoelectric ceramic sheet continues to output a low-level signal until the next exhalation where the output signal of the piezoelectric ceramic sheet changes from low to high again. The change is then detected by the microcontroller and generates an interruption to the timer, and the timer is turned off. The microcontroller then determines the breathing frequency according to the time recorded by the timer and compares it with the normal breathing frequency set in the program. When the calculated breathing frequency is no longer in the normal range, the microcontroller will then start the alarm.

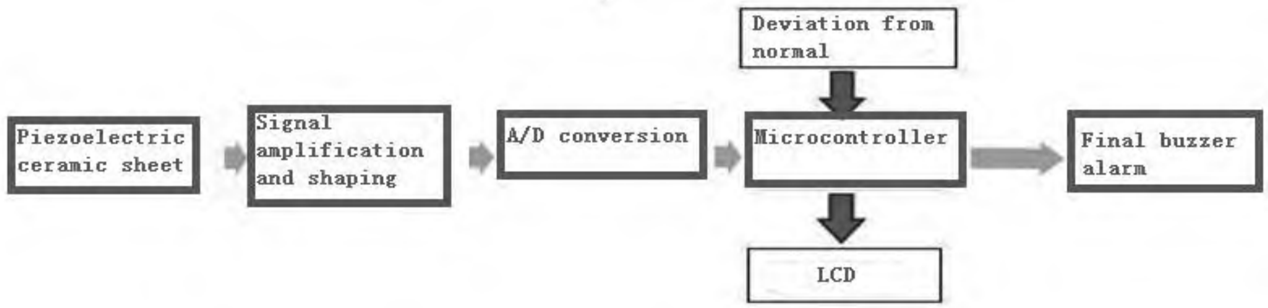


Figure 3. Structure diagram of the respiratory monitoring module.

Design of pulse monitoring module

The pulse measurement uses a reflective photoelectric switch sensor, which consists of an infrared emitting diode and a receiving diode. Measurement is made when a finger is placed between the transmitting diode and the receiving diode. When the blood flow changes, the intensity of the light received by the receiving diode also changes, and this change is consistent with the beat of the heart. The receiving diode converts the received light signal into an electrical signal, which is collected and processed by the microcontroller to calculate the pulse rate of the person.

The structure of the pulse monitoring module is shown in **Figure 4**[6]. The pulse sensor uses a reflective photoelectric switch as the core device. The device is a device that can convert between optical and electrical signals. After the optical signal reflected by the finger sensor is photo-electrically converted, it outputs about 2mVof electrical pulse information that is first filtered by an RC low-pass to filter out clutter and interference, then amplified by the integrated operational amplifier module and shaped by the NOT gate shaping circuit. Finally, the input is sent to the input and output ports of the microcontroller.

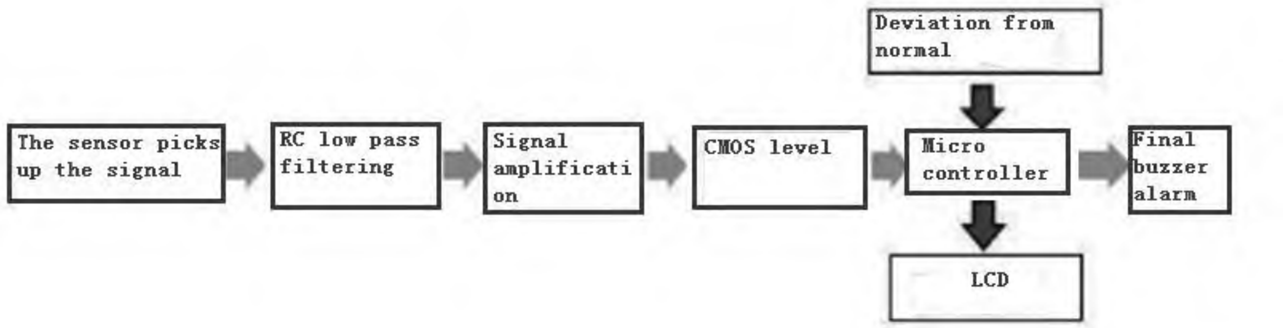


Figure 4. Structure diagram of the pulse monitoring module.

The microcontroller performs related processing on the input, calculates the number of human pulse beats per minute, and displays it through the LED light, while the other channel is input to the timing counting module for real-time and intuitive display. If the detected data deviates from the data range of the normal value, a real-time alarm will be given to the buzzer control through the microcontroller.

3.3. Illumination detection module

After entering the granary, the staff will work in a brightly lit environment. If the body is caught in the food, the chest and abdomen are compressed, and the person cannot breathe normally and if the time passed is too long, they will suffocate and die. This means that if the person were to fall into the food, the personnel do not immediately lose consciousness or even die. Since there is still some oxygen left in the body when it is just immersed, the body generally does not have symptoms within a minute. The people outside must also try to rescue the trapped people in the shortest time possible. This requires that when the sensor cannot receive the light signal, it will immediately send an alarm to the outside world. Sometimes if the staff works at night and encounters a power outage, the sensor will also not receive light at this time. If the alarm is issued again at this time, a false alarm will occur. Therefore, a drivable light source can be added to the original system, so that when there is sudden darkness, the microcontroller can drive the light source to emit light after receiving several light and dark data and continue to receive several additional data. If it is still light and dark, it will immediately issue an alarm.

This avoids false positives. The illumination detection module is mainly composed of illumination acquisition, microcontroller, A/D conversion, and three light sources, as shown in **Figure 5**[7]**.**

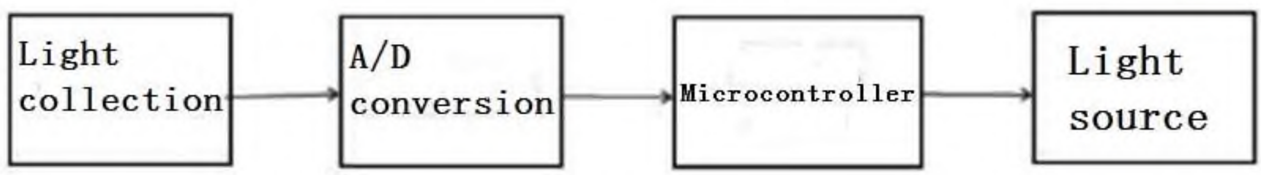


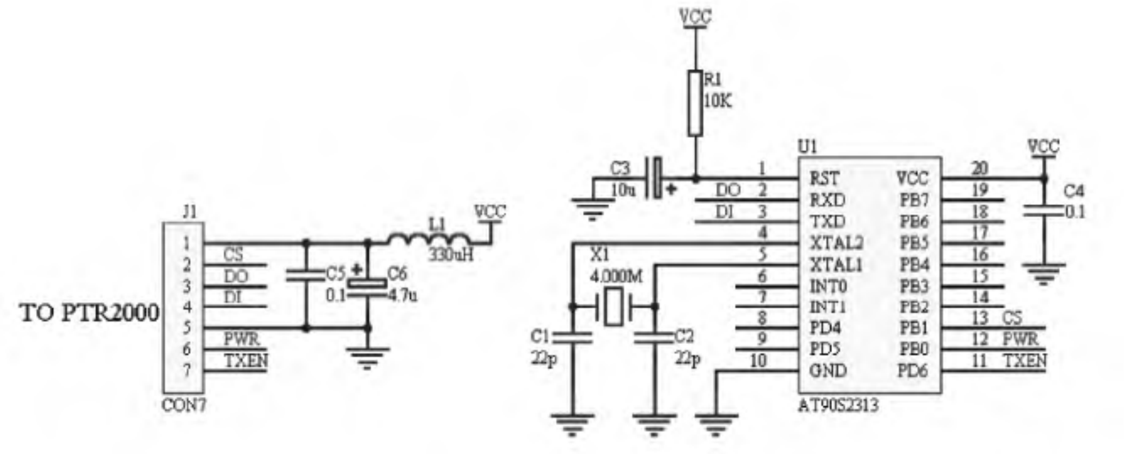
Figure 5. Overall block diagram of the illuminance sensing system.

The light collection uses a photo resistor as the light collection element, together with a diode and 555 timers to form a collection amplification voltage regulation circuit. Two transient steady-state outputs in the circuit are used to generate an analog signal output to the next module. In addition, the resistance value of the photo resistor will change with the intensity of the light, which in turn makes the multivibrator in the circuit generate different clock cycles. At the same time, the output waveform frequency will also change. After that, the digital-to-analog conversion is performed and the microcontroller handles the calculation.

3.4. Wireless communication module

PTR2000 is an ultra-small, ultra-low power, high-speed 19.2k wireless transceiver and data transmission MODEM with receiving and transmitting features. The operating frequency is the international common data frequency band 433MHZ using DDS+PLL frequency synthesis technology. The frequency stability is excellent and can be directly connected to the CPU Serial port use (such as 8031). Additionally, it can also be connected to the computer RS232 interface, which makes software programming more convenient. The PTR200 is mainly used in remote control, telemetry, industrial data acquisition systems and other fields[8].

A signal is transmitted to the communication host of the monitoring center in an infinite transmission mode through the PTR2000 wireless communication module, and the communication host is connected to the host computer through the RS232 interface. The host computer then receives the signal sent by the communication host and conducts real-time online analysis. Once the signal value was found to exceed the safety standard, the host computer will send an alarm command to the lower computer to stimulate the local alarm. At the same time, the alarm in the monitoring room which is directly connected to the upper computer alarms, reports the emergency to the relevant personnel in the form of short messages through Wi-Fi. The interface circuit between the PTR2000 series and microcontroller is shown in **Figure 6**.



Note: (1) The first pin of AT90S2313 is the reset pin (low-level reset). (2) The second pin of AT90S2313 is the serial input pin; the third pin of AT90S2313 is the serial output pin. (3) PWR, TXEN, CS of the wireless module can be connected to any I/O of AT90S2313 for control. (4) It is recommended to use tantalum capacitors for C6.

Figure 6. PTR2000 series and microcontroller interface circuit.

Figure 7 shows the connection circuit between PTR2000 and the computer serial port.

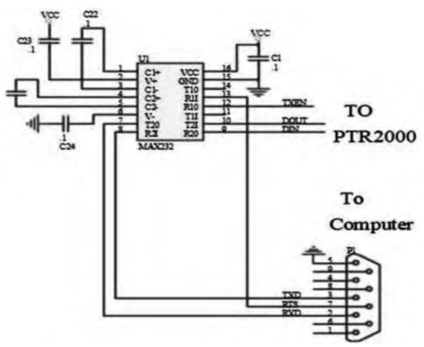


Figure 7. The connection circuit between PTR2000 and computer serial port.

Description: PTR2000 will send the received data to the computer serial port after 232 level conversion. Although it is permissible to connect the PTR2000 to a PC after 232 level conversion, it may take up a large amount of computer resources. Hence, in the actual design process, it is possible to consider adding a single-chip microcomputer between the PTR2000 and the computer. The working block diagram of the wireless communication module is shown in **Figure 8**.

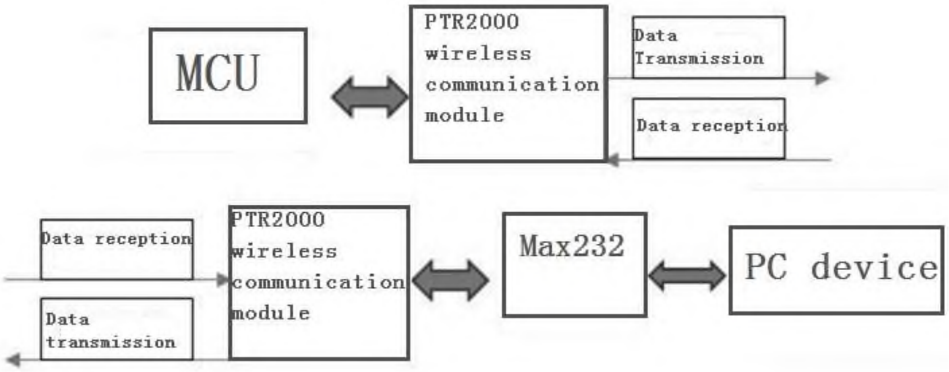


Figure 8. Working diagram of the infinite communication module.

4. Software programming

The design mainly adopts the programming of STC89C52, in which the system adopts modular design where each functional module collects information, converts it into a digital signal and inputs it into STC89C52 microcontroller and uses the microcontroller to perform analysis and calculation.

The modules include pulse respiration detection module, oxygen and carbon dioxide sensor module, illuminance sensor module and fumigation gas transmission module. Each module collects information and transmits the data to the STC89C52 microcontroller for analysis and calculation. If the signals exceed the safety range, it will drive the alarm module and notify the host computer. The program flow chart is shown in **Figure 9**.

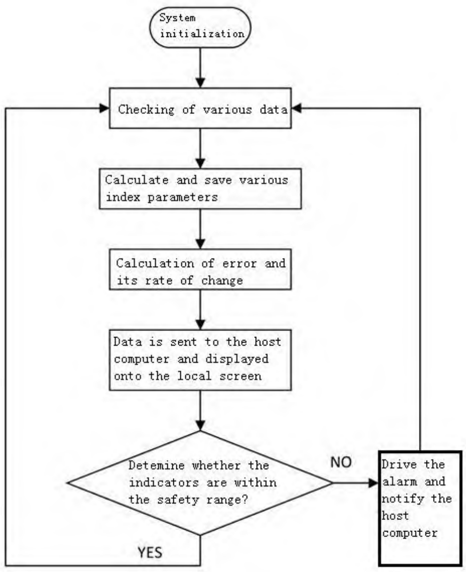


Figure 9. Program flow chart.

When the system starts, it first initializes and programs each module to ensure smooth operation, starts the timer interrupt and external interrupt, ensures the reception and response of data are in the working mode, records data changes at any time, determines whether the field situation is safe under the data analysis program of each module and sends the data to the host computer if necessary.

System software is mainly written in C language. Compared with assembly language, C language has better readability, structure, maintainability and portability, which is conducive to the modular design. Keil C51 is a 51 series compatible microcontroller C language software development system produced by American Keil Software. Keil provides a complete development solution including a C compiler, macro assembler, linker, library management and a powerful emulation debugger. These parts are combined through an integrated development environment (μVision)[9].The software part of this system adopts Keil uVision4 integrated development environment for program design, compilation and debugging. Since the microcontroller used is the STC89C52RC, the download programming and burning software of the microcontroller uses the STC-ISP designed for the STC series microcontroller.

5. System Test

After the design is completed, the wearable granary working environment sensing and alarm system is tested through experiments, and the results showed that the system has a good effect in detecting the granary environment. Before the test, the hardware is repeatedly checked whether there are problems such as short circuit, multi-line, and low line, and check whether the performance indicators of the components and the selection of components meet the range requirements. After the hardware inspection is completed, the source program is burned to the microcontroller to detect whether each function meets the basic requirements of the system in the environment. If it deviates from the expected result, the system is debugged until the expected result is reached.

5.1. Detection of oxygen and carbon dioxide detection sensor system

The detection was carried out by placing the O_2 and CO_2 sensor system into a sealed box filled with inward oxygen and carbon dioxide and continuously adjusting the molar mass density ratio of oxygen and carbon dioxide, and observing that when the ratio of oxygen and carbon dioxide reaches a preset value, the system can give off an alarm.

5.2. Detection of illuminance detection sensor system

The light sensor system was placed in an environment with adjustable light intensity constantly adjusted. When the light intensity reaches a preset value, the system will give off an alarm, indicating that the light intensity detection sensor alarm system can meet the basic requirements.

5.3. Detection of pulse and respiration detection sensor alarm system

According to the exhalation of the human body, the exhaled gas will produce a certain pressure on the piezoelectric ceramic sheet, while inhalation does not affect the piezoelectric ceramic sheet. The two processes then prompt the piezoelectric ceramic sheet to produce different output signals, which determines the passing of the test. The signal output of the piezoelectric ceramic sheet was measured to calculate the time length cycle of one breath of the human body and then through the calculation, the breathing frequency rate of the human body per minute is measured. When the respiratory rate exceeds the preset value range, the system will give off alarms, indicating that the pulse and respiration detection sensor alarm system can meet the basic requirements.

5.4. Detection of fumigation gas detection sensor alarm system

The phosphine fumigation gas and air were filled into the sealing device and the concentration ratio of fumigation gas and the air was continuously adjusted. When the value reaches the preset value, the system gives off an alarm, indicating that the internal power of the fumigation gas detection and sensing alarm system meets the basic requirements.

6. Conclusions

The safety and reliability of the working environment of the granary have always been an important issue. As people have increasingly higher requirements for the working environment, a reliable safety system is naturally required to ensure the safety of the staff.

The wearable granary working environment sensing and safety alarm system is therefore developed to solve this issue. Through the division of labor and cooperation of the team members as well as through the analysis and discussion of different technical issues, the design of this system has been completed. A lot has been gained throughout the design process where some important conclusions were finally reached.

Aiming at the possible existence of harmful fumigation gas in the granary, we have carried out the research and design of the detection and sensing system of harmful fumigation gas. In this, it is difficult to completely remove harmful gases through exhaust ventilation, but if the concentration is low, no alarm signal will be generated which indicates that the accuracy of the sensor is particularly high. However, the detection of harmful gases is still very important. Thus, when designing the gas sensor and processing circuit, we chose a more reliable detection device and optimized the processing circuit to solve this problem. The concentration of oxygen and carbon dioxide in the granary is also a very important index, as the concentration of oxygen will be directly related to the storage of grain. Since the oxygen concentration in the granary has been in a stable fluctuation range, the cost of the sensor can be reduced by selecting an instrument that allows some errors in measuring the concentration of oxygen and carbon dioxide. In the research and design of wearable sensing systems, we aimed to be more functional and more portable, while at the same time paying more attention to the real-time nature of wearable devices. Having considered the real-time requirements of the system, wireless communication was used in data transmission, which also reduces part of the cost and brings more portability to people in use.

This design realizes real-time monitoring of gas concentration and vital sign sensors in the granary and reliable transmission of information through wireless communication technology, which greatly improves the safety of the granary, improves work efficiency, and is more conducive to scientific grain storage, which is also a trend in the future development of the warehousing industry.

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ORIGINAL RESEARCH ARTICLE

The design and realization of flexible wearable wireless music controller

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ABSTRACT

By using flexible sensors and micro-control units, a wireless controller that can be integrated into clothing for cross-platform music control has been designed and implemented, providing a new idea for making a simple and low-cost flexible wearable sensing system. The design and implementation of a wireless controller that can be integrated into clothing for cross-platform music control provides a new idea for the preparation of a simple and low-cost flexible wearable sensing system. Based on the flexible fabric sensing material, a simple structured sensor piece is proposed as a button for the controller with good wearing comfort. The sensor element is capable of sensing finger presses up to 15kPa. ESP32 is used as a micro-control unit for sensing signal acquisition and data processing. Using the Bluetooth chip integrated inside the ESP32, the controller can be connected with terminal devices of different platforms for wireless data transmission. The results show that the prepared wireless music controller can be stably connected with both Windows computer terminal and Android cell phone terminal, and the sensor recognition accuracy of finger press is 99.7%, which indicates that the flexible fabric sensor has a broad application prospect in the field of wearable devices.

Keywords: flexible sensors; wearable devices; ESP32; wireless music controller

1. Introduction

With the development of technology, wearable devices are widely used in medical, human-computer interaction, motion capture and other fields[1–6], and the wearable devices market is growing at an explosive rate. According to the *2020 Global Wearable Devices Third Quarter Data Report*[7] issued by IDC in December 2020, the number of wearable devices shipped worldwide increased by 35.1% year-on-year to 125.3 million units, and the number of wearable devices shipped worldwide in 2019 was 336.5 million units. Although the number of wearable devices shipped has increased compared to previous years, the top three wearable devices with the highest market share are headphones, watches and bracelets, according to IDC's research. Generally speaking, the main functions of wearable devices are to monitor human physiological signals (such as heart rate, pulse, pressure, step count, etc.) and to control cell phones and computers through human-computer interaction with wearable devices. In order to achieve these functions, wearable devices usually use rigid sensors as sensing units and thermoplastic silicone vulcanizate (TPSIV) or thermo-

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plastic polyurethane (TPU) rubber as the housing for the wearable device to fit well on the body. In contrast, flexible fabric materials[8–11] have good flexibility and have promising applications in the field of wearable devices. However, the characteristic that flexible fabric materials are not easily integrated with circuits due to their inherent intolerance to high temperatures also makes it difficult for sensors made of flexible fabric materials to be integrated into clothing.

Commercially, Levi's has cooperated with Google to launch the Commuter Trucker Jacket[12] in 2016, which incorporates conductive fibers in the left cuff and encapsulates Bluetooth, battery and other modules through an "electronic tag" on the side. This smart jacket account can be controlled by finger operation in the conductive fiber area, such as adjusting the volume, switching songs, answering phone calls, etc. The material used in this smart jacket is a kind of conductive fiber, which can sense the user's finger movements. However, its production process is complicated, which makes the smart jackets expensive and greatly limits their industrialization and practical application. The domestic smart clothing has many functions such as electric heating and magnetic therapy, and smart clothing products with information processing functions are still blank. In order to explore the application prospect of combining flexible fabric sensing materials and computer technology to make wearable devices, this paper designs and implements a flexible wearable wireless music controller based on flexible fabric sensors and ESP32 microcontroller unit, which has the characteristics of simple structure and easy fabrication and cross-platform use.

2. System Function and Structure

The flexible wearable multimedia wireless controller designed in this paper is a wearable multimedia control device that can be integrated into clothing and has good wearing comfort. It can be connected to cell phones and other terminal devices via Bluetooth, and can control the music playback in cell phones without taking out the cell phone. The main functions and structure of the system are shown in **Figure 1**.

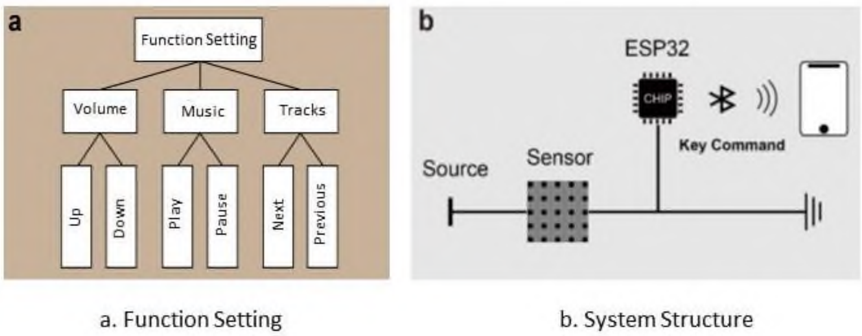


Figure 1. System Function and Structure.

In terms of function setting, the music controller designed in this paper can control the volume up and down, music play and pause, and track switching when the finger taps on the flexible fabric sensor. The system structure consists of two parts: The flexible fabric sensor and the micro control unit. The flexible fabric sensor generates electrical signal changes under the action of external forces. The micro-control unit detects this signal change in real-time and at high speed through circuitry, and then processes the signal data. When a finger tap is detected, a corresponding key command is sent to the terminal device via Bluetooth.

3. System design and implementation

3.1. Design and implementation of flexible fabric sensing structure

Sensing structure design

In order to fit the human body structure and achieve better comfort, this paper uses a flexible fabric sensing material to make a flexible sensor. The structure of the sensor is shown in **Figure 2**.

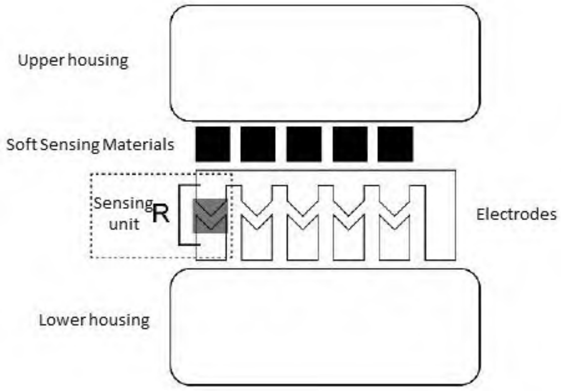
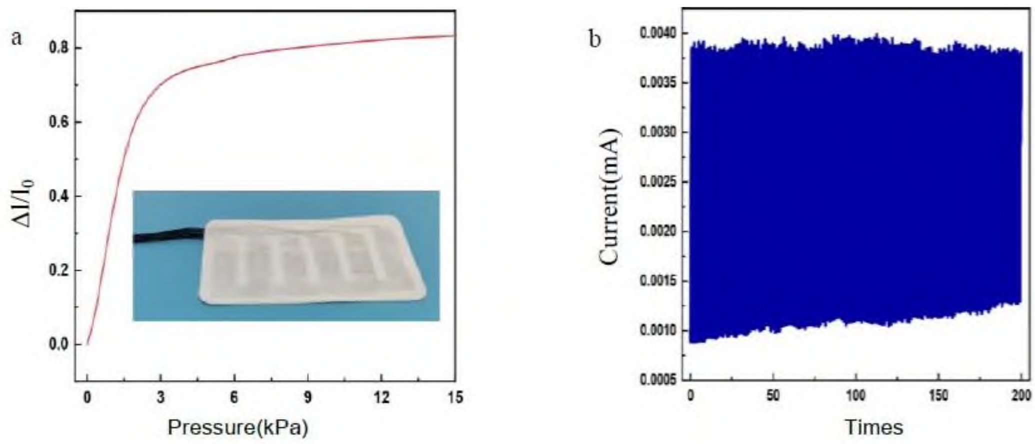


Figure 2. Sensor structure.

The structure of the sensor is divided into four parts, the uppermost and lowermost layers are the outer shell, and the middle two parts are the electrode layer and the sensing layer. The upper and lower housings of the sensor are made of smooth and comfortable white knitted fabric. The material used for the electrodes is a flexible conductive fabric (3 Ω/cm), and the sensing unit uses a flexible fabric sensing material with a knitted structure. As shown in **Figure 2**, there are five sets of flexible sensors as five function buttons, which correspond to the volume increase and decrease, music play and pause, and track switching. Each sensing unit will change its resistance under the action of external stress, and the state of finger tapping on the sensing unit can be obtained by detecting the change of resistance.

Sensor fabrication and performance testing

The performance of the prepared sensor was tested by using a force meter and CHI650 electrochemical workstation. The electrical flow through the sensor was continuously collected at different pressures (< 1s5 kPa) with a voltage output of 0.5 V at both ends of the flexible fabric sensor and plotted; the sensor was pressed repeatedly 200 times at a pressure of 3 kPa, and the electrical flow s was recorded and graphed. The corresponding test results are shown in **Figure 3**.



a. Sensor sensitivity test with physical picture of the sensor

b. Cyclic stability test

Figure 3. Physical and performance testing of sensors.

Figure 3(a) shows the sensitivity test results of the sensor and the physical picture of the sensor. The test results show that the current variation of the flexible fabric sensor subjected to pressure in the range of 4 kPa-15 kPa accounts for 20% of the overall variation, but when the pressure is within 4 kPa, the current variation accounts for 80% of the overall variation. The cyclic stability results are shown in **Figure 3(b)** for 200 tests. The results show that the maximum and minimum values of the current flowing through the flexible fabric sensor fluctuate after several taps. The fluctuation range of the maximum value is within 0.0004 mA. Since the flexible fabric sensor uses the fabric structure, after repeated knocks in a short time, the minimum current will gradually increase due to the lack of timely rebound of the fabric structure, but the increase is limited, about 0.0006 mA, which has little effect on the knock determination.

3.2. Hardware circuit design

ESP32 Introduction

ESP32 chip is a dual-mode 2.4 GHz Wi-Fi and Bluetooth integrated chip solution from Loxin. The ESP32 is powered by the Xtensa® 32-bit LX6 single-core processor with 200 MIPS of computing power. In addition, the ESP32 has an integrated 12-bits SAR ADC supporting a total of 18 analog channel inputs with a sampling frequency of 200 ksps.

Signal Acquisition

When a flexible fabric sensor is subjected to external stress, it deforms electrically in the form of a change in electrical resistance. In order to detect the pressure signal of the sensor, the signal can be acquired through the principle of resistive voltage division in a series circuit. The signal acquisition principle and circuit diagram are shown in **Figure 4**.

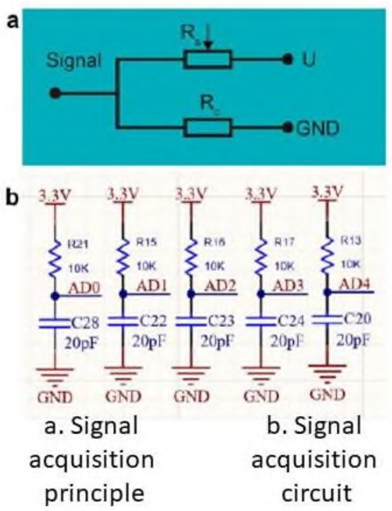


Figure 4. Signal acquisition principle and circuit diagram.

In **Figure 4(a)**, U is the total voltage in the circuit, R_s is the resistance of the sensor, and R_c is the fixed value resistor used for voltage dividing. When the resistance of the flexible fabric sensor changes, the voltage divider U_c at R_c will also change accordingly, and the voltage acquisition point is at Signal, and the change of sensor resistance R_s can be obtained by collecting the change of voltage at Signal. The voltage signal is calculated by the following formula:

$$Singnal = UR_c/(R_s + R_c)$$

Figure 4(b) shows the signal acquisition circuit, which contains five signal acquisition channels, each of which connects a flexible fabric sensor in series with a 10 K fixed-value resistor and connects to the analog-to-digital converter interface of the ESP32. In order to reduce the noise interference in the circuit, a 20 pF capacitor is added in front of the fixed resistor.

3.3. Software Programming

Software Structure

Since the underlying driver of ESP32 is not open source, the hardware needs to be initialized using the official driver functions provided by Loxin. Loxin provides the corresponding software development kit, ESP-IDF, which allows users to easily add their own libraries or other functions and integrates with the FreeRTOS operating system. The program execution flow is shown in **Figure 5**.

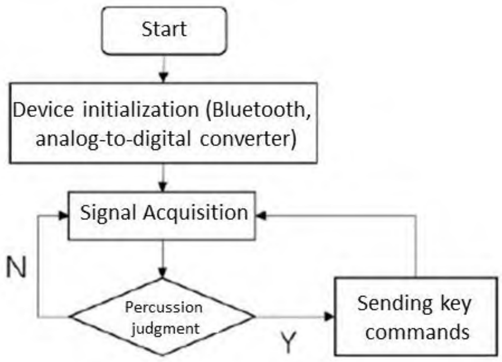


Figure 5. Program execution flow.

After the hardware is powered up, the main program is executed. The main program initializes the hardware, which includes the Bluetooth and analog-to-digital converter modules of the ESP32. After the initialization is completed, the signal is collected in real-time by the analog-to-digital converter. Whenever the signal data is collected, the data collected is evaluated. If the keystroke is valid, the corresponding key command is sent via the Bluetooth module. After the command is sent, the next round of acquisition is performed. If there are no taps, the signal will continue to be collected.

Bluetooth wireless communication

To send key commands to terminal devices, Bluetooth needs to be driven. The Bluetooth protocol stack supported by ESP32 includes Classic Bluetooth and BLE protocols. In order to send multimedia control commands via Bluetooth, the HID (Human Input Device) protocol is implemented using the GATT protocol of BLE. GATT (Generic Attribute Profile) is a low-power Bluetooth device communication protocol. The GATT protocol is used to implement the USB HID protocol, which allows the terminal device to recognize the Bluetooth device as a keyboard. The execution flow of the program is shown in **Figure 6**.

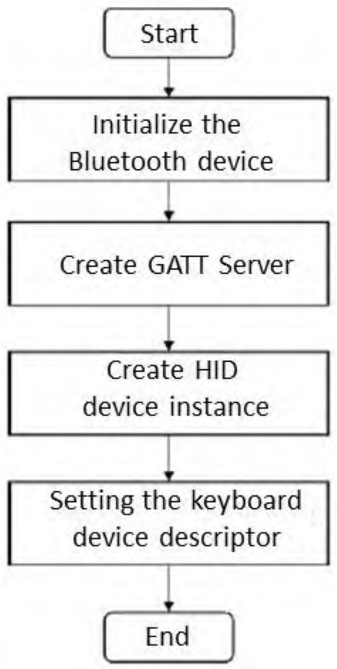


Figure 6. Bluetooth communication operation flow.

Firstly, the program needs to initialize the Bluetooth device, then create the GATT Server instance and set up the callback function. Next, the HID device instance is created, which contains the definition of the device type, manufacturer, HID information, etc. Finally, the HID keyboard descriptor property needs to be provided to the GATT service so that the end device can parse the data transmitted by Bluetooth into keyboard commands. Some of the main descriptions of the HID keyboard descriptors are shown in **Table 1**.

Table 1. HID keyboard descriptor

Content	Meaning
0x09,0x06	Device usage for keyboard
0x05,0x07	Usage page for buttons
0x09,0xb5	Next song
0x09,0xb6	Next song
0x09,0xcd	Play/pause
0x09,0xe9	Volume increase
0x09,0xea	Volume reduction

Analog to Digital Converters

In order to collect the signal data of the flexible fabric sensor, it is necessary to drive the analog to digital converter for signal acquisition. The ADC of ESP32 has two working modes, namely ADC-RTC and ADC-DMA modes. The ADC-RTC mode is controlled by the RTC controller, which is suitable for the application scenario where only low-frequency acquisition is required. ADC-DMA mode allows data to be directly copied from one storage space to another without CPU processing. Therefore, in signal acquisition, the acquisition frequency can be greatly accelerated. This paper uses ADC-DMA mode for signal acquisition, analog to digital converter driver process as shown in **Figure 7**.

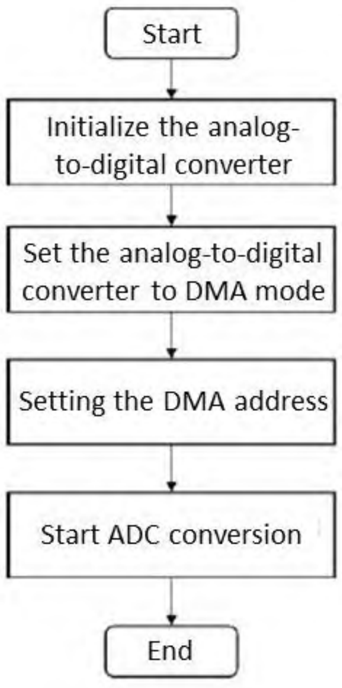


Figure 7. Analog-to-digital converter driver flow chart.

3. System Testing

In order to verify the functional effectiveness and reliability of the design, cross-platform compatibility tests and functional tests were conducted.

3.1. Cross-platform compatibility testing

The flexible wearable wireless music controller connects to the end device via Bluetooth, which includes the Windows desktop and Android mobile terminal. The connection effect is shown in **Figure 8**.

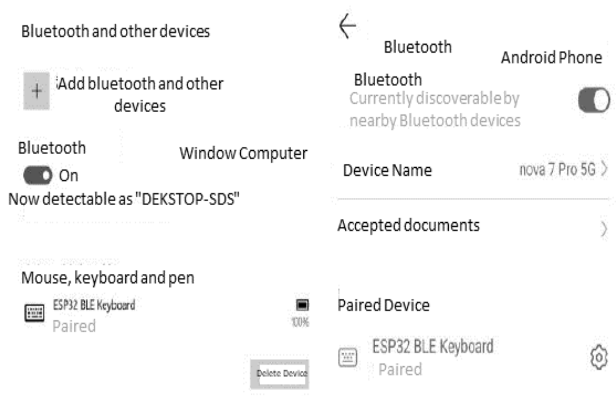


Figure 8. Effect of different terminal connections.

During the test, different types of terminal devices were used to connect to the flexible wearable wireless music controller designed in this paper, and the connection was maintained for an hour. A successful connection was considered when the connection could be maintained for an hour without dropping the connection. Windows desktop devices include Windows desktop and laptop computers, while mobile devices are mainstream cell phones, such as OnePlus, iqoo, Meizu, Xiaomi, and Huawei.

3.2. Functional Testing

After the compatibility test, the functionalities were also tested in this paper. After the end device was connected to the flexible wearable wireless music, each of the five function keys was hit 20 times and the corresponding function was recorded. The success rate of the function test is shown in **Figure 9**.

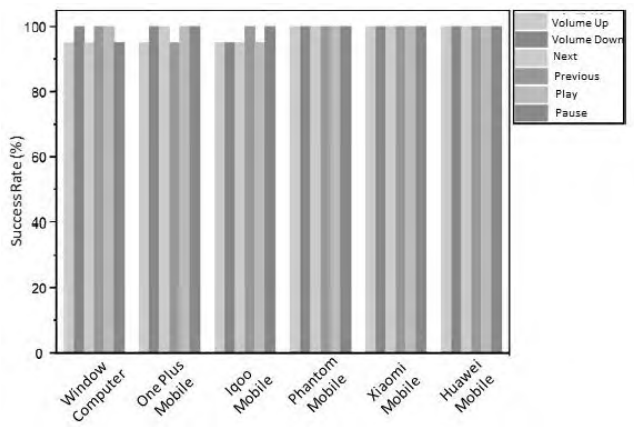


Figure 9. Functional test success rate.

In **Figure 9**, in addition to Windows computers, one plus mobile phones, iqoo mobile phones, other types of mobile phones on the key function trigger rate can reach 100%. The trigger success rate of Windows computer, one plus mobile phone and iqoo mobile phone is slightly lower, more than 96.7%. The reason for this phenomenon may be that these devices themselves are not perfectly compatible with ESP32 Bluetooth. The test results show that the comprehensive accuracy rate of the flexible wearable wireless music controller designed in this paper is 99.7% in different end devices.

4. Conclusions

This paper uses a flexible sensor to create the keypad of a flexible wearable wireless music controller. Through ESP32 signal acquisition and knock judgment, the Bluetooth module of ESP32 is used to connect the terminal equipment and send key instructions. The test results show that the flexible wearable music controller can be used cross-platform, and the success rate of connecting to different platforms is 100%. In terms of functionality, the five key functions work well on different terminals, and the overall success rate of key recognition is 99.7%. The design of this paper combines the disciplines of material, textile and computer to explore the prospect of applying cross research of different disciplines in the field of wearable devices and provide research cases and ideas.

Conflict of interest

The authors declare no conflict of interest.

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REVIEW ARTICLE

Research progress of fabric electrodes in wearable electronic clothing

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ABSTRACT

Aiming at the application requirements of fabric electrodes in wearable electronic clothing, the current materials and structure types of fabric electrodes are introduced respectively, the influence of fabric electrodes materials and structure parameters on the stability of ECG signal acquisition is analyzed, the use principle of fabric electrodes and the relationship between signal acquisition stability and comfort are summarized, and the application prospects and development direction of fabric electrodes in wearable electronic clothing are prospected in the future.

Keywords: fabric electrodes; wearable electronic clothing; biosingnals; comfortability; stability

1. Introduction

In recent years, the proportion of human patients with chronic diseases (such as cardiovascular and cerebrovascular diseases) has been increasing, resulting in frequent accidental sudden death. In order to understand the accumulation degree of chronic diseases, patients need to carry out long-term monitoring of physiological signals in the hospital, resulting in long registration and waiting time and crowded queue in the hospital (such as ECG, B-ultrasound and other monitoring departments). In order to alleviate this phenomenon, the new concept of modern medical treatment is to move the monitoring of chronic diseases from hospitals to communities and families. Patients monitor on demand at home, transmit physiological signals to hospitals through Internet of things technology, and doctors give diagnosis and treatment suggestions in time according to the signals. This idea has greatly promoted the research and development of wearable electronic clothing[1], and also promoted its application research in deep diving, military, aerospace, fire protection and other fields. Electronic clothing combines fabric and clothing technology, microelectronics technology, communication technology and cloud technology. It can monitor human physiological signals for a long time, give early warning before the occurrence of emergency conditions, and enable patients to be rescued at the first time.

As the sensing material of electronic clothing, the signal acquisition electrodes mostly adopt the adhesive electrodes (the core component is Ag/AgCl)

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in the early stage. During the detection, it is necessary to apply conductive paste between the electrodes and the skin. However, the conductive paste is easy to dry and is not suitable for long-term monitoring. Continuous use will also cause skin allergy, itching or inflammation[2].

Fabric electrodes is a kind of flexible dry electrodes which can monitor physiological signals for a long time. It uses fabric processing technology to process conductive materials into functional fabrics, which can collect the weak potential (bioelectrical signal) on the skin surface. Compared with wet electrodes, fabric electrodes are more suitable for monitoring physiological signals for a long time. This paper summarizes the research and development of material, structure and performance of fabric electrodes in wearable monitoring system, and analyzes the relationship between its comfort and monitoring signal stability.

2. Fabric electrodes material

The traditional Ag/AgCl gel electrodes is shown in **Figure 1.** Fabric electrodes can replace the traditional Ag/AgCl electrodes. Through wireless transmission technology, it can monitor physiological signals for wear, long-term, continuous and undisturbed. Compared with gel electrodes, the advantages of fabric electrodes are its wearability, softness, breathability, comfort and real time acquisition, as well as the good experience it brings to guardianship objects.

The materials of fabric electrodes can generally be divided into polarized metal, non-polarized metal, polymer coating metal, conductive polymer, nano silicone and carbon black[3]. At present, the research focuses include new conductive polymer (modified polymer polyimide), micro precious metal, graphene, modified conductive rubber, dry foam electrodes and so on. As far as the fabric electrodes is concerned, the new conductive polymer is the easiest to weave into the electrodes structure. At the same time, it has attracted people's attention because of its flexibility, light weight and strong weavability. According to different structures and preparation methods, conductive polymers can be divided into composite type, ionic type and structural type. The conductivity of the three structural types varies greatly due to different materials and structures[4].

Figure 1. Ag/AgCl electrodes and its fabric composite electrode.

In addition, compared with the current common porous carbon coated electrodes, polypyrrole/cotton fabric electrodes not only have incomparable flexibility and mechanical properties, but also has the characteristics of light weight, low cost and non-toxicity, and has high conductivity, which can meet the requirements of flexible wearable fabric electrodes. For example, Yue[5] used ordinary cotton fabric to prepare polypyrrole coated fabric through in-situ chemical polymerization (CP), vapor deposition polymerization (CVD) and interfacial polymerization. After repeated high-strength stretching, the polypyrrole coated fabric can still maintain high electrochemical properties, be suitable for stretching during human movement, and realize the softness and lightness of fabric electrodes. It can be applied to wearable monitoring electronic clothing.

Xin et al.[6] used the method of first chemical synthesis and then electrochemical plating to coat the polypyrrole conductive layer on the substrate of the fabric surface to prepare a fabric electrodes for ECG acquisition. This fabric electrode has good conductivity and good soft, breathable and moisture permeability. It can directly contact the skin surface of the monitoring object for long-term ECG acquisition.

For some fabric electrodes, the composite structure of conductive materials and conventional fabric materials is mostly used, or the conductive materials are attached to the yarn or printed and dyed to the fabric through various coating processes. The materials used in the composite structure of the latter include base materials and conductive materials. Common base fiber materials include animal and plant fibers and some chemical fibers. Acrylic and polypropylene fibers in chemical fibers are not suitable as substrates because of their poor moisture absorption, comfort and dimensional stability; The polyester fiber and its fabric in the chemical fiber have good wrinkle resistance, good elasticity, wear resistance, poor moisture absorption, easy washing and quick drying, and are not easy to moth and mildew. On the contrary, it is suitable to be used as the base material of conductive fabric. Also suitable for base materials are nylon filament, viscose yarn, cotton, carbon nanotube, polyethylene, polyamide and other fibers[7]. For the materials of conductive parts, they need to be selected according to the base materials. For example, nylon filament is generally silver plated, viscose yarn is generally made of core spun yarn with 30% stainless steel filament, conductive fabric is copper plated, polyester is blended with stainless steel wire, carbon nanotube is coated with Ag/AgCl, polyethylene is deposited with titanium and copper, polyamide and other chemical fibers are silver plated, etc.[8]

3. Fabric electrodes structure

Fabric electrodes mostly adopt the interleaving structure of conductive materials and conventional fabric materials, or attach conductive materials to yarns or printed and dyed fabrics through various coating processes, so as to form various types of fabric electrodes.

3.1. Common fabric electrodes assembly forms

The properties of the fabric electrodes are different according to the manufacturing method and structure. Catrysse et al.[9] used stainless steel filaments to make knitted structure electrodes as shown in **Figure 2**. The advantage of the electrodes is that it does not stimulate the skin and can be integrated into the clothing. The disadvantage is that the interface between the fabric and the skin has a large impedance, resulting in too weak or unstable ECG signal acquisition. In addition, knitted fabrics are prone to curling and de edging in the manufacturing process, and have large deformation in the use process. When stressed, the resistivity will also change, resulting in the instability of ECG signal.

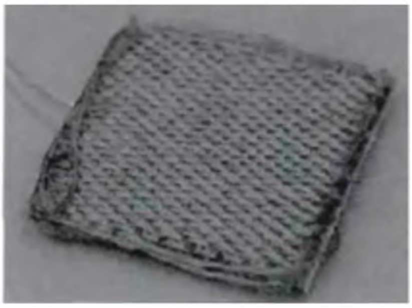


Figure 2. Soft electrodes made by steel fiber knitted fabric.

Huang[10] laid the carbon fiber lead wire on the conductive hydrogel, and then pressed the three parts by pressing the non-woven fabric. A disposable ECG monitoring electrodes was invented. He et al.[11] developed a non-contact ECG sensor and its wearable multi-channel ECG sampling underwear. In the underwear, a three-dimensional shielding cavity is formed through a hole, a shielding ring and a shielding layer, which can collect excellent ECG signals under the interference of daily electromagnetic environment.

Cai et al.[12] designed a new type of ECG monitoring electrodes. The conductive elastomer is placed in the concave cavity of the anti-mucous membrane, and the surface is connected with the sensing electrodes. The conductive elastomer uses a protruding sponge block to impregnate the conductive paste. Compared with the traditional coating conductive paste, its cost is reduced and its conductivity is improved. Qu and others[13] invented a new conductive hydrogel electrodes material, which is mainly composed of polymer and deionized water, electrolyte, water retaining agent and so on. It shows excellent biocompatibility, strong adhesion to skin, good environmental stability and excellent electrical conductivity.

Chen et al.[14] took graphene as the substrate, placed the metal seed layer between the metal electrodes and the flexible graphene substrate, and the electrodes lead is connected to the metal electrodes on the flexible substrate. The electrodes are arranged coronally, which increases the contact area with the skin and enhances the stability of ECG acquisition; At the same time, because its texture is soft and flexible, it can adapt to people of different shapes. Wu et al.[15] invented a similar electrodes structure. At the same time, several electrodes are connected in series, which are directly used for skin dressing, and complete the test and monitoring of 12 leads at one time.

Zieba et al.[16] designed a wearable system for ECG monitoring. As shown in **Figure 3**, the electrodes of the system is woven fabric of silver plated wire, and the interior of the electrodes is filled with elastic sponge.

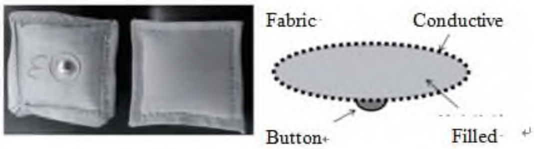


Figure 3. Electrodes model of woven fabric.

The electrodes in **Figure 3** can be well attached to the skin. The silver plated yarn improves the information conductivity of the electrodes and will not stimulate the skin if worn for a long time.

According to the weaving method, the conductive fabric of fabric electrodes can be divided into four structural forms: woven, knitted, nonwoven and other fabrics. **Figure 4** shows the fabric morphology of different fabric electrodes.

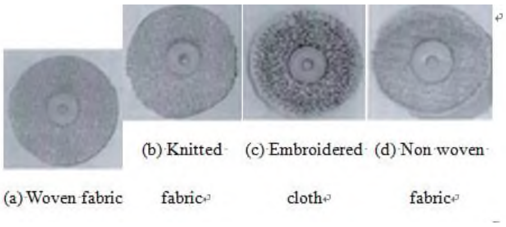


Figure 4. Fabric electrodes.

3.2. Fabric electrodes of woven structure

The fabric electrodes of woven structure is made of warp and weft conductive yarn, which has stable structure and high uniformity and consistency. Guo[17] used silver plated polyester filament as the conductive fiber of woven structure, wrapped sponge in the fabric of woven structure, and used sponge elasticity to ensure full contact between conductive cloth and skin; at the same time, hard sponge and support pad are applied to the outer ring to further improve the support force of fabric electrodes and slow down the impact in the wearing process. The structure and real object of fabric electrodes are shown in **Figure 5** and **Figure 6.**

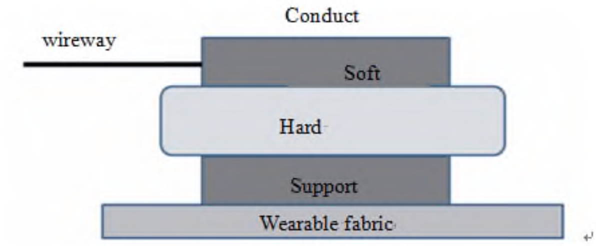


Figure 5. Structure illustration of a woven electrodes.

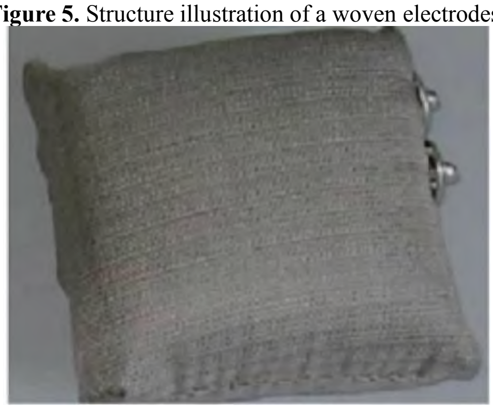


Figure 6. A real woven electrodes.

In addition, the fabric electrodes of woven structure can be made by coating conductive materials with woven fabric as the bottom layer. For example, Zhang[18] compounded polypyrole/cotton fabric ECG electrodes through electrochemical polymerization to measure the ECG signal of human body in static state. Li et al.[19] studied the effects of different woven structure parameters on the electrical conductivity of polypyrrole fabrics. Using 37 tex polyester cotton staple yarn, four kinds of plain fabric, through-hole fabric and 1/3 right twill fabric with different weft density were prepared by changing the crimp speed and weft density of the loom. The conductive materials were compounded on the fabric by chemical oxidation synthesis. It is found that the greater the weft density or linear density of the fabric, the smaller the surface specific resistance of the fabric and the stronger the conductivity; When the critical value is exceeded, the conductivity will decrease.

Zhang et al.[20] designed a flexible wireless bioelectric electrodes, including conductive layer, adhesive layer, flexible layer and conductive part of woven structure. The conductive part passes through the flexible layer and adhesive layer and is connected with the conductive layer. The conductive layer is woven by several conductive yarns in woven structure, the woven conductive fabric is adhered to the adhesive layer, and the signal collection and transmitting device is placed on the flexible layer and connected with the conductive part, This design avoids the wear of the conductive layer on the yarn surface in the process of fabric shuttle, ensures that the electrodes has good conductivity, reduces the attenuation of signal and increases the wearability of flexible electrodes.

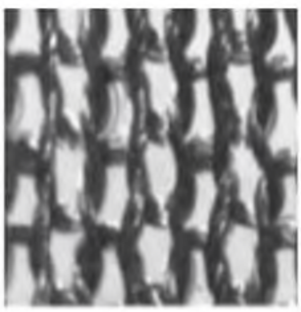
The fabric electrodes of woven structure can also be obtained by jacquard process. The jacquard structure of the jacquard weaving machine of the Korean University[21] uses the physiological signal of the jacquard weaving machine of the Korean university to detect the tissue of the human body. The fabric uses 82.5 dtex/36 F and s twisted polyester filament as warp yarn, silver plated yarn as weft yarn to make the bottom layer, and then silver plated yarn weaves the sensing layer on the bottom layer, so that the silver plated yarn becomes a double-layer structure. The fabric electrodes size of the woven jacquard structure is 50 mm×50 mm.

3.3. Fabric electrodes of knitted structure

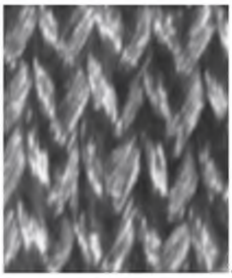
In the process of using knitted fabrics, due to repeated stretching, there will be problems such as looseness and deformation, fuzzing and hook wire, so the signal acquisition of this kind of fabric electrodes will also be affected. In addition, when weaving the knitted electrodes, the fabric can be coated with conductive materials, or the fabric electrodes can be obtained by weaving conductive yarn with other materials.

Yang et al.[22] developed a kind of knitted wool flexible ECG electrodes, which overcomes the problems that the existing flexible fabric ECG electrodes cannot contact with the skin stably and the contact impedance increases due to the growth of stratum corneum, and can effectively avoid the skin allergy caused by conductive paste.

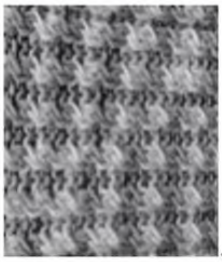
Liu[23] used coated carbon fiber and its conductive composite silk thread, selected weft flat weave and 1+1 rib structure to make fabric electrodes with knitted structure. It is found that the stability of 1+1 rib structure is better than that of weft flat structure; However, when simulating the washing process, it is found that with the increase of washing times, the overall resistance increases, and the change of resistance becomes more and more unstable. Wang et al.[24] prepared four kinds of fabric electrodes as shown in **Figure 7** by weft knitting. Comparing the sensitivity of four kinds of fabric electrodes to collect physiological signals, it is found that the signal sensitivity of vertical stripe double rib knitted fabric is higher than that of horizontal stripe double rib knitted fabric, and higher than that of silver plated yarn weft flat knitted fabric; From the repeatability of double rib resistance, it can meet the requirements of sensor repeatability and stability, and can be used to develop monitoring devices for heartbeat, respiration and cardiopulmonary function.



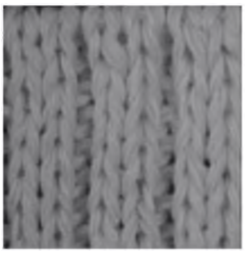
(a) Silver plated yarn weft flat knitted fabric



(b) Silver plated yarn spandex double yarn interwoven weft flat knitted fabric



(c) Silver plated yarn and wool yarn horizontal double rib knitted fabric (1, 2-way wool yarn, 3, 4-way silver plated yarn)



(d) Double rib knitted fabric with vertical stripes of plated yarn and wool yarn (1 and 3 are wool yarn, 2 and 4 are silver plated yarn)

Figure 7. Four knitted structure of fabric electrodes.

3.4. Fabric electrodes of nonwoven structure

Nonwoven structural materials have good mechanical properties such as breaking strength and breaking elongation, short production process and low cost, so they are widely used. Xu et al.[25] used magnetron sputtering to form a layer of deposited nano silver film on the surface of nonwovens, so that nonwovens can conduct electricity and be used to manufacture fabric sensors. The nano silver film of the fabric has good combination with the substrate, and the film has the characteristics of high purity, good compactness, uniform film formation and no chemical pollution of the fabric electrodes.

Ninane et al.[26] designed a nonwoven fabric electrodes, which can monitor human physiological signals for a long time. This electrodes adopt multi-layer three-dimensional structure, has superior hydrophilicity, can store a certain amount of solution, leach and wet the contact surface between skin and electrodes during extrusion, and reduces the impedance of the interface between electrodes and skin. Kang et al.[27] formed conductive lines and conductive layers on the surface of nonwovens by hand drawing or screen printing, and prepared nonwovens active electrodes. The results show that this kind of active electrodes have improved air permeability and more flexible skin adhesion design.

3.5. Fabric electrodes with embroidery structure

It is more flexible and convenient to weave fabric electrodes by embroidery. Peng Xiaohui et al. [28] embroidered silver plated fiber to produce fabric electrodes according to the designed structure, and used it as a pressure sensor for respiratory monitoring. In addition, in order to improve the sensitivity and repeatability of the sensor, the contact resistance can be connected in series and silica gel can be coated at the contact point, as shown in **Figure 8**. In the manufacturing process, 11.1 tex silver plated filament yarn is selected to be twisted into sensing materials (18 pieces/strand, two strands twisted, strand twist 8 twist/dm), which are sewn at 6 cm×6 cm polyester base cloth. Experiments show that the electrodes have the feasibility of physiological signal acquisition.

Figure 8. Embroided fabric electrodes covered with silica gel.

Zhang et al.[29] used Ag/AgCl composite yarn prepared by silver plated yarn electroplating as sensing material, and adopted the structure of embroidered Terry to prepare a circular fabric electrodes with Terry height of 3 cm, needle pitch of 1 mm and diameter of 3 cm. The utility model has the advantages that the terry structure can pass through the body hair, the skin adhesion is better, the physiological signals can be measured more accurately, and there is no need to process the skin in the process of use. In addition, in the process of connecting the fabric electrodes with the outside, the electrodes buckle is nailed in the middle of the fabric electrodes, and the male buckle is connected with the female buckle to realize the detachability of the electrodes.

4. Conclusions

Compared with traditional medical electrodes, fabric electrodes have the characteristics of softness, air permeability, stability, comfort and long-term wearability from the perspective of material and structure. Therefore, they play a more and more important role in the application of human physiological signal monitoring[30]. With the rapid development of microelectronics and information technology, fabric sensing will become a research hotspot of life and health materials and technology.

Conflict of interest

The authors declare no conflict of interest.

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Review article

Progress in the study of enzyme-free glucose electrochemical sensors

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ABSTRACT

The detection mechanism of enzyme-free glucose electrochemical sensors, the research progress of enzyme-free glucose sensors based on composite materials such as noble metals, transition metals and doped carbon nanomaterials, and the latest progress of new wearable enzyme-free glucose detection devices are reviewed. With the development of science and technology, enzyme-free glucose sensors will potentially be applied to the in vivo detection of animal and plant species, which will become a hot spot for new research.

Keywords: enzyme-free; glucose sensor; electrode modification; in vivo detection

1. Introduction

Glucose is an important component of carbohydrates in plants and animals. The development of new devices and instruments for the quantitative determination of glucose in living organisms is of great importance for advancing research in the field of in vivo glucose detection. The development of new and efficient enzyme-free glucose sensors is a key issue in the field of sensor development. The development of new and efficient enzyme-free glucose sensors is a key issue in the field of sensor research and development. However, research into the real-time monitoring of glucose levels in living plants and animals is still in its infancy and is the focus of research and development by scientists.

In 1962, Clark and Lyons first introduced the concept of using glucoamylase electrodes in electrochemical assays and prepared the first glucoamylase electrode[1]. After decades of development, glucose sensor technology has become more mature and is widely used in clinical medicine and phycological testing, for example, in the detection of blood glucose levels during the treatment of diabetes. According to Grand View, a leading global research institute, the market for Continuous Glucose Monitoring (CGM) sensors in China will reach US$55 million by 2024. Therefore, the development and application of glucose sensors is of increasing interest to researchers.

This paper provides an overview of how electrochemical glucose sensors work, discusses their current status and recent developments, and outlines

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the main challenges and opportunities for their further development and use, with a focus on the application of enzyme-free glucose sensors for in vivo detection.

2. Development of glucose sensors

2.1. Enzyme-based glucose sensor

For the classification of glucose sensors, the common electrochemical glucose sensors can be divided into enzyme-based glucose sensors and non-enzymatic glucose sensors (NEG), depending on whether enzymes are used. Depending on the type of electronic medium used, enzyme-based glucose sensors can also be subdivided into three generations of sensors. Throughout the development of glucose sensors, the first to third generations of sensors have been based on the principle of bio-enzyme catalysis as the core of the reaction, with improvements focused on increasing the electron migration rate at the reaction interface.

The first generation of enzyme-based glucose sensors used the immobilisation of an enzyme on an electrode enzyme[2]. Glucose Oxidase (GOx) uses Flavin Adenine Dinucleotide (FAD) as a carrier for the redox reaction. Oxidation of glucose to gluconolactone and hydrogen peroxide, while obtaining the reduced form of the enzyme GOx ($FADH_2$). GOx ($FADH_2$) reacts with dissolved oxygen to produce hydrogen peroxide. The concentration of glucose in the initial sample can be determined by measuring the consumption of oxygen or the production of hydrogen peroxide[3,5].

Equations involved in the catalytic reaction of the first generation of glucose sensors:

$$GOx(FAD) + glucose \rightarrow GOx(FADH_2) + gluconolactone$$
$$GOx(FADH_2) + O_2 \rightarrow GOx(FAD) + H_2O_2$$

There are two main problems with first generation glucose sensors: Firstly, the presence of many electroactive interfering substances in the blood that can be oxidised, and the relatively high detection potential of H_2O_2, at which the interfering substances are co-oxidised, leading to interference with the experimental results; and secondly, the reliance on free oxygen as a catalytic medium. The former produces interference effects that reduce the selectivity of the sensor, while the latter makes the sensor ineffective in detecting defective oxygen samples[3,5]. Therefore, the first generation of sensors is not suitable for analysis of practical applications[5].

The researchers have improved on the first generation of sensors by replacing the biological mediator oxygen with an artificial mediator to develop a second generation of glucose sensors. The second-generation glucose sensor technology uses a non-physiological artificial medium to speed up the electron transfer process and overcome the interference problems of the first generation[4]. The reaction equations involved in second generation glucose sensors are as follows:

$$GO_x(FAD) + glucose \rightarrow GOx(FADH_2) + gluconolactone$$

$$GOx(FADH_2) + Med_{(ox)} \rightarrow GOx(FAD) + Med_{(red)}$$

In the reaction equation, $Med_{(ox)}$ is the oxygenated medium and $Med_{(red)}$ is the reduced medium.

The electron transfer rate between the enzyme and the electrode is increased due to the replacement of the artificial medium, but the medium is still required. The media may still react with interfering substances in the blood, affecting accuracy and efficiency. It is very difficult to maintain the presence of the mediator near the surface of the electrode and enzyme[5]. Therefore, scientists set out to study new glucose sensors that do not require the introduction of external media.

With the further development of new nano-functional materials, direct electron transfer (DET) between enzymes and electrodes becomes possible, and the third generation of glucose sensors emerges as the times require. This type of sensor immobilizes the enzyme directly on the electrode surface, which further improves the free electron transfer rate between the electrode and the enzyme.

No medium is the main advantage of the third-generation sensor. There is no interference from electroactive substances during the reaction process, and there is no dependence on dissolved oxygen. At the same time, the interference effect caused by the competition between the dissolved oxygen and the electrode to regenerate enzymes is greatly reduced[5].

The reaction equation involved in the third-generation glucose sensor is as follows:

$$glucose + FAD \rightarrow gluconic\ acid + FADH_2$$

The principle of the third-generation enzyme-based glucose sensor is shown in **Figure 1**. Although the enzyme-based glucose sensor occupies the main market in the glucose sensor industry, it still cannot get rid of the influence of environmental factors on the activity of the enzyme, such as ambient temperature, humidity, pH value, etc., because its sensitivity depends largely on the activity of the enzyme[4]. The stability of the enzyme has also become a great obstacle in the development and application of enzyme-based glucose sensors.

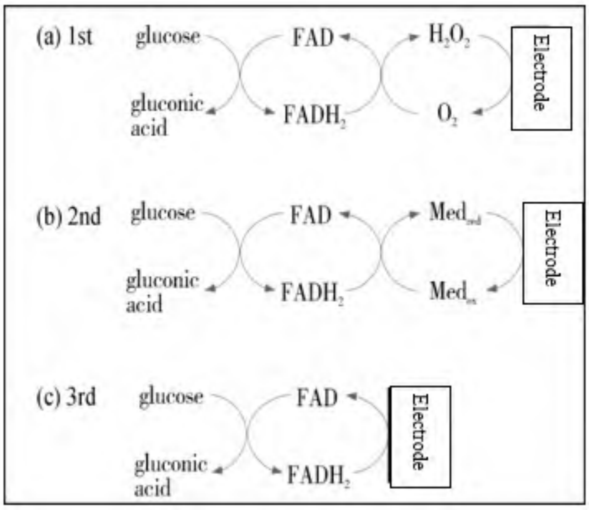

Figure 1. Principles of the first, second and third generation enzymatic glucose sensors[2].

2.2. Enzyme-free electrochemical glucose sensor

Enzyme-free electrochemical glucose sensors are based on electrodes or modified materials on electrodes to replace biological enzymes to generate electrocatalysis. Compared with enzyme-based glucose sensors, its biggest advantage is that it is easy to achieve long-term and stable target detection, breaks through the limitation that biological enzymes are susceptible to failure due to environmental temperature, pH value and other factors, and provides an optimized interface for rapid electron migration. It can provide support for high-performance continuous monitoring application scenarios.

Currently, two models exist for explaining the mechanism of non-enzymatic electrochemical glucose sensors: The activated chemisorption model (**Figure 2**) and the Incipient Hydrous Oxide Adatom Mediator (IHOAM) (**Figure 3**). The former proposes that the electrocatalytic reaction requires the adsorption of the substrate (glucose) to the catalyst surface (electrode surface) to form bonds with the unfilled d orbitals of the catalyst. The latter is a model proposed by Burke, demonstrating that the formation of a monomolecular front layer of hydroxide is one of the keys to the electrocatalytic process of glucose. The active hydroxide ions generated after the dissociation of water on the electrode surface are involved in the electro-oxidation process of glucose and many organic small molecules, so the enzyme-free glucose sensor can show high sensitivity under alkaline conditions[2,4,6].

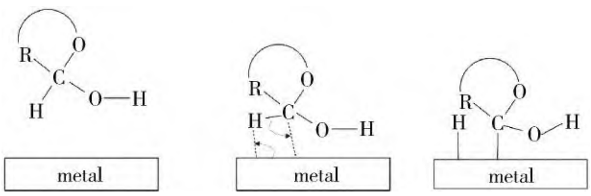

Figure 2. Activated chemisorption model[4].

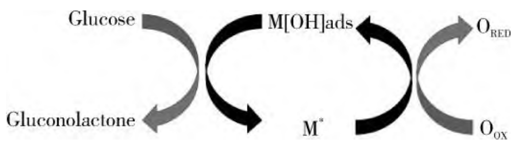

Figure 3. IHOAM model[4].

The emergence of non-enzymatic glucose sensors has provided more choices in the selection of materials for glucose sensors, and the way to increase the effective surface area is no longer limited to the stacking of enzymes. Due to the advantages of high catalysis and high sensitivity for the oxidation of glucose, such as noble metal materials, transition metals and composite materials doped with carbon nanomaterials, etc. Therefore, their selection as modification materials to modify the electrodes of glucose sensors has also become an effective way to enhance the effective area of the glucose sensor reaction and the interfacial electron migration rate. The catalytic ability of the working electrode is also no longer limited to biological enzymes, and the application of noble metals, transition metals and doped carbon materials will lead to further enhancement of the detection performance of glucose sensors.

3. Research progress of electrode modification methods

At present, in the field of electrochemical sensors, carbon electrodes are widely used because of their advantages of good chemical stability, wide electrochemical stability window, and low background current. Commonly used carbon electrodes are glassy carbon electrodes and carbon paste electrodes[7]. However, due to the defects of bare electrodes, modifiers are required to improve performance. This paper mainly describes the research progress of modified electrodes synthesized by noble metals, transition metals, and composite materials doped with carbon nanomaterials. These modification methods provide reliable ideas for the application of enzyme-free glucose sensors in in vivo detection.

3.1. Sensors decorated with precious metal materials

Platinum (Pt), gold (Au) and other noble metal materials have excellent catalytic properties, and their nanoparticles are often used to modify electrodes to promote the catalytic oxidation of glucose. Pt has high catalytic activity for compounds such as glucose and hydrogen peroxide. Porous nano-Pt has the characteristics of high sensitivity and strong anti-interference ability, and has excellent selectivity and catalytic activity to glucose[8]. Wesley et al.[8] used $H_{14}Cl_{16}O_6Pt/CuSO_4$ solution as electrolyte and used cyclic voltammetry to electrodeposit porous nano-Pt films on screen-printed carbon electrodes for the fabrication of glucose sensors. As shown in **Figure 4**, it has good chemical stability, a wide linear range (up to 13 mM, as shown in **Figure 5**), and a short response time (less than 5 s).

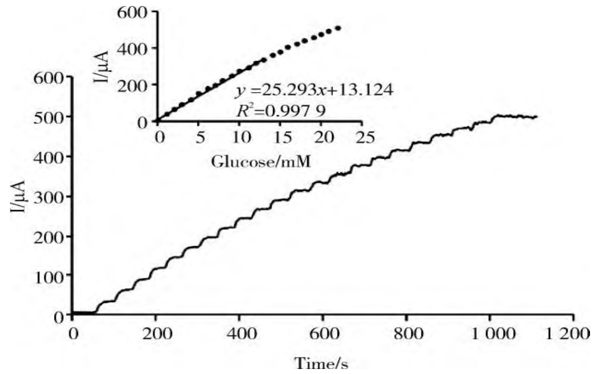

Figure 4. The current response of the nanopore electrode to the continuous addition of 1 mM glucose (0.4 V) to PBS buffer (0.1 M). Insert: Calibration curve for amperometric response[8].

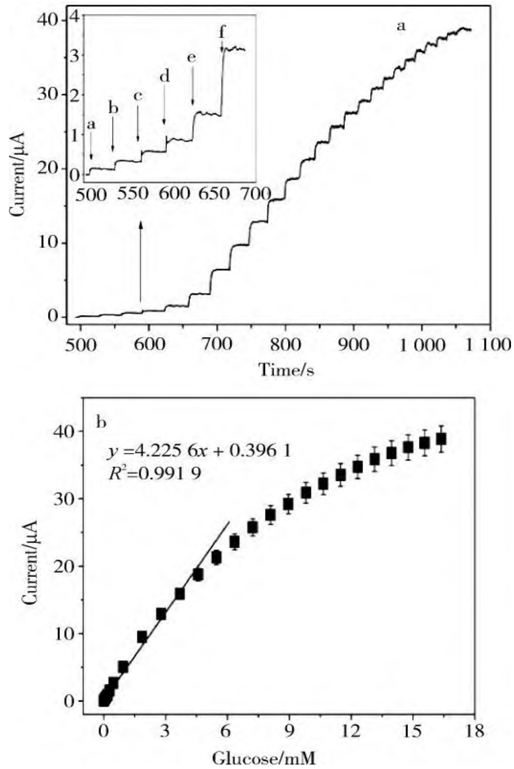

Figure 5. (a) GO-COOAu/GCE at + 0.35 V on grape Amperometric responses of sugar additions of 0.02 (a), 0.04 (b), 0.06 (c), 0.08 (d), 0.1 (e) and 0.2 mM glucose (f). **(b)** Calibration curve of the amperometric glucose assay[9].

In alkaline medium, the rate of Au catalyzing the oxidation of glucose is better than that of other Group VII noble metals such as Pt. Therefore, Au is also an excellent modifier for the preparation of enzyme-free glucose sensors[9]. Yusuf et al.[9] deposited Au nanoparticles on carboxylated graphene oxide (GO-COOH) and modified them on glassy carbon electrodes as working electrodes for glucose sensors. The sensitivity of the sensor prepared by the GO-COO-Au glassy carbon electrode reached 20.218 μA/(mMcm2). As shown in **Figure 5**, in an alkaline environment, the linear range is 0.02 to 4.48 mM under the condition of + 0.35V, which broadens the Linear range with detection limits down to 6 μA. However, the sensor showed almost no response in neutral glucose solution, and only showed excellent performance under alkaline conditions, which would be limited for in vivo detection of plants with a pH value of less than 7.

3.2. Sensors decorated with transition metalsand their oxides and hydroxides

The transition metals Cu, Ni, oxide Cu_XO, NiO and hydroxide materials all have good selectivity and stability for the catalytic oxidation of glucose, and they have a very large price advantage. Therefore, such modified materials are widely used in electrode modification of glucose sensors at this stage. Cobalt oxide has good bio-compatibility, wide band gap, high stability, low cost and good reproducibility. At the same time, the electrochemical performance of cobalt oxide and its selectivity to glucose can be improved by doping Since its porous with other nanomaterials[10]. The preparation cost of nickel is low and the preparation is simple. Under alkaline conditions, it has a high electrocatalytic ability for glucose[11]. Xu[10] used a hydrothermal method to fabricate 3D Co_3O_4/Ni heterostructures on porous Ni materials, as shown in **Figure 6**.

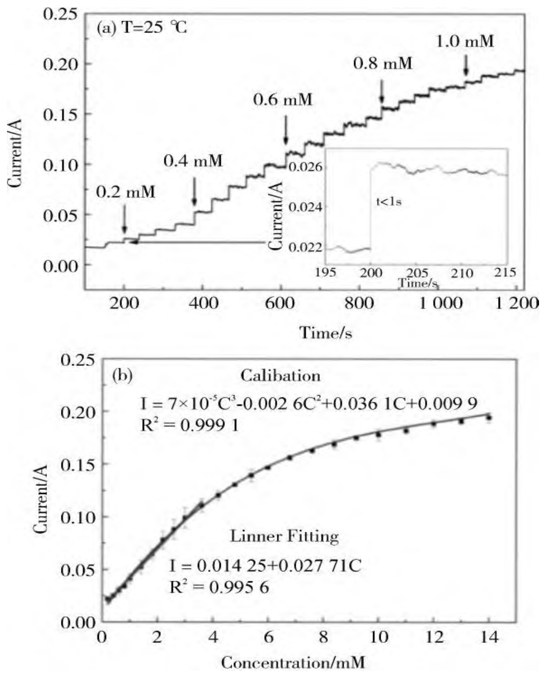

Figure 6. (a) The current responses of the glucose sensor based on the 3D Co3O4/Ni heterostructure sensing electrode to different glucose concentrations at room temperature. Inserted is the response time of the sensor to changes in glucose concentration. **(b)** Measured data and the amperometric response calibration curve of the sensor to glucose concentration. Each concentration was repeated three times, and error bars indicate deviations[10].

Since its porous structure provides multiple electroactive sites, it is favourable for the oxidation reaction of the electrode surface with glucose. The sensor has a sensitivity of 13,855 μA/(mMcm2). The detection limit was reduced to 1 μM. The detection limit is an important performance parameter of the sensor, and how to optimize the detection limit has always been a focus of researchers in the sensor field. Moreover, metallic nickel has the characteristics of non-toxicity[11], so it is expected to be used in the detection of living organisms. However, since nickel only exhibits excellent catalytic activity under alkaline conditions, how to apply it to the in vivo detection of acidic fruits and vegetables requires further exploration by scientists.

CuO has received extensive attention from scientists due to its good electrochemical activity and low overvoltage during electron transfer[12]. In 2019, Cheng et al.[12] applied transition metal-containing porous organic frameworks (MOFs) to the construction of enzyme-free glucose sensors, and constructed the MOF structure of porous CuO polyhedrons on carbon cloth. The sensor has a sensitivity of 13,575 μA/(mMcm2) and a detection limit of 0.46 μM, which further reduces the detection limit. In 2020, Ashwini et al.[13] used gold nanowire electrodeposition to modify the CuO nanoelectrode on the basis of the same use of CuO nanomaterials to catalyze glucose. This structure further increases the specific surface area of the electrode, improves the catalytic activity, the sensitivity is 1,591.44 μA/(mMcm2), and the detection limit is greatly reduced to 0.3 μM. In the same year, Luo et al.[14] used Cu-MOF microcrystals as raw materials to prepare a porous nanolayered CuO structure as a catalytic material for the working electrode of an enzyme-free glucose sensor. The sensitivity of the sensor is 1,806.1 μA/(mMcm^2), the linear range is 0–6.535 mM, and the detection limit drops to 0.15 μM, which reduces the detection limit of the sensor again. The optimization of these properties benefits from its porous hierarchical structure.

3.3. Composite-modified sensor doped with carbon nanomaterials

Carbon nanomaterials have become one of the latest research hotspots in the field of glucose sensors due to their excellent performance in glucose catalysis. According to its morphology, it can be divided into one-dimensional (such as carbon nanotubes) and two-dimensional (such as graphene oxide). Carbon nanotubes have large specific surface area, excellent electrical properties and good biocompatibility[15]. Zhao[16] et al. used carbon nanotubes to prepare a carbon nanotube-nickel/boron-doped diamond composite electrode (CNTs-Ni/BDD), Ni nanoparticles themselves can catalyze glucose, and the composite carbon nanotubes increase the specific surface area and electrode active sites of the BDD electrode, and at the same time, the carbon nanotubes enhance the electronic conductivity. Therefore, using the composite material to modify the electrode greatly improves the catalytic activity of the electrode to glucose, and its sensitivity is 0.005–0.02 mM, 0.02–1 mM, 1.0–5.5 mM, respectively, at the glucose concentration. The linear range of mM was 475, 42, 19 μA/(mMcm2), respectively, and the detection limit was 0.42 μM. Hun et al.[17] developed a 3D material based on nitrogen-doped graphene-carbon nanotubes and gold nanoparticles and applied it to an enzyme-free glucose sensor. The introduction of carbon nanotubes between graphene nanosheets can avoid the problem of large charge transfer resistance of graphene, good dispersion of carbon nanotubes can avoid the aggregation of graphene, and graphene nanosheets as "surfactant" can disperse carbon nanometers tube, forming a network structure with large specific surface area and excellent electrical conductivity. As shown in **Figure 7**, the modified electrode has excellent performance, with a linear range of 2 μM to 19.6 mM, a sensitivity of 0.9824 μA/(mMcm2), and a detection limit of 500 nM, which further improves the sensitivity and reduces the detection limit.

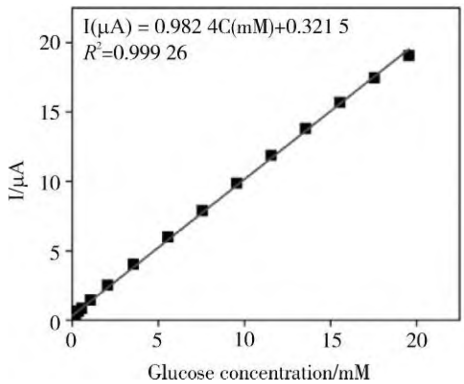

Figure 7. The relationship between current and glucose concentration[17].

The two-dimensional nanomaterial graphene has good electrical conductivity, large specific surface area, and its honeycomb two-dimensional structure can increase the electron transfer rate.

Graphene oxide also has the characteristics of being easy to combine with other materials, so that it can be prepared into functional composite materials with good comprehensive properties[18,19]. For example, Xue[20] et al. prepared persimmon tannin-reduced graphene oxide-platinum-palladium alloy (PT-RGO-Pt-Pd) nanocomposite. graphene oxide is easily combined with other materials, combined with persimmon tannin to form a thin film, wrapping metal particles, enhancing the stability of the composite material, and graphene oxide itself has excellent electrical conductivity, so it improves the catalytic conductivity of the electrode. The sensor modified by the composite material has high stability and fast response (<3 s), with a detection limit of 1.43 μM and a linear range of 0.01 to 0.40 mM, as shown in **Figure 8(a)**. The electrode is suitable for a neutral detection environment with a pH of 7 to 8. As shown in **Figure 8 (b)**, at pH=6 (Curve a), pH=7 (Curve b), and pH=8 (Curve c), pH=9 (Curve d), pH=10 (Curve e) in the PBS solution using time amperometric method to detect glucose, the large current value appears between Curve e and Curve d, that is, the pH value is between 7 and 8.

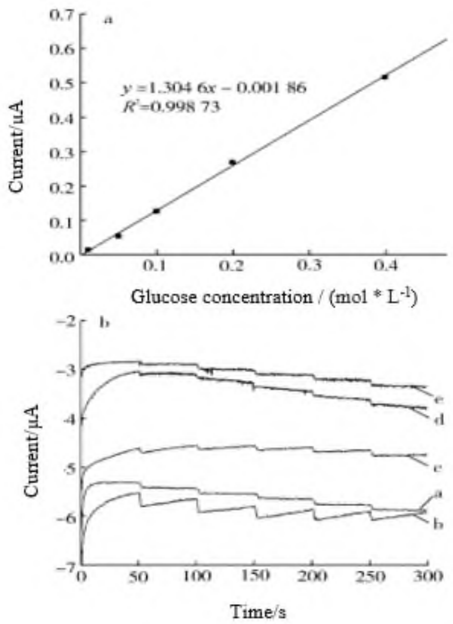

Figure 8. (a) Effects of different pH on the performance of persimmon tannin-reduced graphene oxide-Pt-Pd enzyme-free blood glucose sensor. **(b)** Glucose standard curve[20].

This is a major breakthrough compared to previous sensors, many of which only showed excellent performance under alkaline conditions. There are organic acids in the fruits of many crops, and the juice is acidic. Therefore, the application of non-enzymatic glucose sensors to the in vivo detection of plant fruits needs to overcome the limitation that many current electrodes are only suitable for alkaline environments. The development of an enzyme-free glucose sensor that can be used in acidic conditions will further promote its application in vivo detection.

Carbon nanomaterials are easy to combine with other materials, and composite materials doped with carbon nanomaterials have many advantages for modifying non-enzyme glucose sensors, such as enhancing electrode specific surface area, enhancing current, etc. Therefore, there are many studies on doping carbon nanomaterials in modified materials to improve the performance of sensors. In the modification process of composite materials, attention should be paid to how to make various materials compatible with each other to form a stable structure, and some materials will be difficult to modify on the electrode. For example, Zhao et al.[16] needed to overcome the difficulty of co-modifying BDD with Ni nanoparticles and carbon nanotubes when preparing carbon nanotube-nickel/boron-doped diamond composite electrodes (CNTs-Ni/BDD).

4. Application of non-enzymatic glucose sensor in vivo detection

Enzyme-free glucose sensors have a series of advantages, such as high specificity, fast detection speed, portability, low cost, and low power consumption. In recent years, glucose sensors have developed rapidly and have deep applications in agriculture, biotechnology, medicine and many other fields. At the same time, scientists have gradually developed new sensor structures for the detection of living organisms, such as minimally invasive painless devices, wearable flexible devices, etc. The above-mentioned various electrode modification methods provide ideas for in vivo detection. Most of them use carbon electrodes or metal electrodes as electrode substrates, and on this basis, modify the materials to improve their performance. Difficulties encountered in applying non-enzymatic glucose sensors to in vivo detection of animals and plants. For example, how to replace the base electrode in the existing research to make it suitable for living body detection, how to make the sensor fit with the living body, and how to ensure that the sensor living body detection is not toxic to the living body, etc., are the research hotspots of scientists.

4.1. In vivo detection in animals

In 2015, Lee et al.[21] developed a new patch-type enzyme-free biosensor for painless continuous blood glucose monitoring, which used a platinum black sensing electrode layer micro-needle array. Micro-needle arrays were fabricated using micro-machining techniques and 316 L commercial stainless steel. They inserted the sensor part into rabbits and performed blood glucose monitoring experiments in rabbits. The sensor was able to operate normally for four days, with a sensitivity of 1.62 μA/mM and a linearity of 0.9939. In 2018, Li et al.[22] established an enzyme-free Online Electrochemical System (OECS) for the first time, as shown in **Figure 9**. The sensor can be used for the continuous determination of glucose in animal brain systems, an in vivo application of an enzyme-free glucose sensor. In the same year, Yoon et al.[23] developed a wearable enzyme-free glucose detection system, and through two animal experiments, proved that the system has good bio-compatibility. With the further in-depth research, more and more wearable devices for animal live detection are gradually being developed.

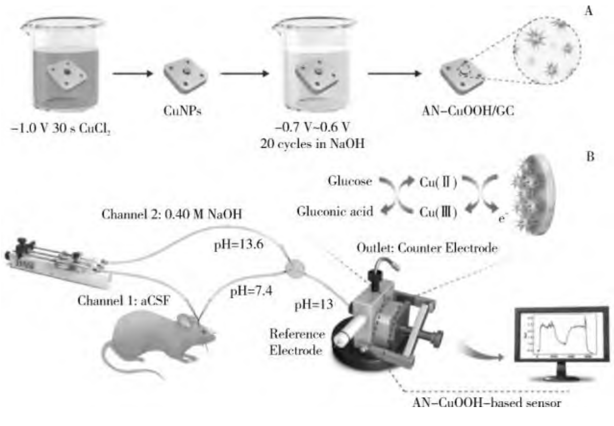

Figure 9. Schematic diagram of continuous monitoring of rat striatal glucose by non-enzymatic electroanalysis system based on OECS[22].

4.2. Human wearable enzyme-free glucose sensor

In the medical field, the application of sensors in blood sugar detection of diabetic patients is one of the hotspots. Diabetes is a disease caused by insufficient insulin production or ineffective use of insulin in the body, and its incidence has continued to rise in recent decades. Currently, there are two drawbacks to the traditional glucose monitoring methods on the market. One of the disadvantages is that most blood glucose monitoring systems on the market rely on enzymes to catalyze glucose oxidation, and the disadvantage of enzymatic sensors is that their performance is easily affected by the environment, such as pH, temperature, humidity, etc. This disadvantage has been mentioned above, and it is very disadvantageous for patients to monitor their glucose levels in real time. The second disadvantage is that the traditional glucose monitoring method usually samples the blood from the fingertip of the patient first, and then tests the blood glucose of the sample, which will cause certain damage to the physical and mental health of the patient.

For the first disadvantage, compared with enzyme-based sensors, enzyme-free sensors are not constrained by the constraints brought by enzymes, and have many advantages, such as high stability, simple preparation, strong reproducibility, and no oxygen limitation. Therefore, an enzyme-free glucose sensor is more beneficial for diabetic patients to monitor glucose levels stably in real time. For the second disadvantage, non-invasive biosensors currently under development can solve this problem. To address the above shortcomings, researchers are focusing on combining non-invasive and non-enzymatic glucose sensors.

Wearable biosensors are non-invasive sensors that have attracted much attention due to their ability to provide continuous, real-time physiological information through dynamic, non-invasive measurement of biochemical markers in biological fluids such as sweat, tears, saliva, and tissue fluids[23]. Most of the current wearable glucose sensors require the use of enzymes (mainly glucose oxidase), there are still few mature wearable non-enzymatic glucose sensors for human blood glucose detection, and there are many studies on in vivo detection in animals, and wearable sensor devices are gradually being developed.

In 2017, Munje et al.[24] studied a sweat-based wearable diagnostic biosensor made of room temperature ionic liquid, which used a ZnO thin film deposited on a nanoporous polyamide film. It is demonstrated that ionic liquids can enhance the stability of wearable sensor devices. With the birth of wearable sensor devices, it has also been applied in the detection of glucose, which has replaced the method of fingertip blood collection to a certain extent. Sampling in a non-invasive way can avoid damage to the stratum corneum, the outermost protective layer of human skin, and avoid direct contact between the device and blood. Therefore, the non-invasive detection method brings less harm and less risk of wound infection in patients.

In addition, the breakthrough in the development of flexible electrodes combined with non-invasive glucose detection is also conducive to further reducing the discomfort caused by patients during the glucose detection process. Through the use of advanced materials and sophisticated design, wearable devices have certain flexibility and stretch-ability to achieve patient body compliance and reduce wearer discomfort[23].

In 2018, Zhu et al.[25] prepared a wristband-type wearable enzyme-free glucose by covering fluorocarbon-based materials on gold electrodes. The sensor, shown in **Figure 10**, is used to monitor the glucose concentration in human sweat in real time and upload the detection results to a smartphone app via Bluetooth. During monitoring, multiple different potentials are used on the Au electrode corresponding to different uses. Among them, the high negative potential is used for sample pre-treatment, which generates alkaline conditions on the local surface of the electrode; the medium potential is used to detect the glucose concentration in the sample, and needs to be used in the sample. carried out in an alkaline environment. A positive potential is used to clean the electrode surface. The detection limit is 15 μM, and the sensitivity can reach 114 μA/(mMcm2). The birth of the wearable glucose sensor has greatly influenced the home blood glucose monitoring method of diabetic patients.

Figure 10. (a) Sweat glucose analysis during physical activity using a wristband-based electrochemical sensor. (b) physical image of the wrist-worn electrochemical sensor used to analyze glucose in sweat. (c) An application of a smartphone for analyzing glucose in sweat, the sensor is connected to the smartphone via Bluetooth[25].

In 2019, Ali et al.[26] used chemical methods to synthesize Ni-SnOx, PANI and CuO nanoparticles on the surface of cotton fabrics to prepare a flexible and high-performance enzyme-free glucose sensor. The sensor has a wide linear range from 0.001 to 10 mM, a detection limit as low as 130 nM, long-term stability and re-usability, and excellent performance.

In the application of living body detection, wearable glucose sensor technology has developed rapidly in the past few years, and a lot of research work has been done on flexible sensors that apply it to human blood glucose level monitoring. The application of glucose sensors in the medical field has only just started, and its application in physiological research needs to be further developed, and the performance of flexible wearable glucose sensors needs to be further improved. In general, due to the current need for such technology in medical or biological detection, this technology still has great potential for development, and more new non-enzymatic glucose sensor devices will also be developed[27].

5. Conclusions

In this paper, the development of glucose sensors in past generations is discussed, and the research results of non-enzymatic glucose sensors in electrode modification materials, new sensor structures and their in vivo detection applications in recent years are reviewed. Enzyme-free glucose sensors are increasingly the focus of attention due to their excellent properties. The working electrode modification materials of the enzyme-free glucose sensor are mainly nanoparticles such as noble metals, transition metals, and composite materials doped with carbon nanomaterials. It has also become a research direction for scientists to improve the performance of the sensor around the modified materials. The research on electrode modification of glucose sensor also provides ideas for its application in in vivo detection. In terms of in vivo detection, glucose sensors are mostly used in the detection of human blood sugar levels. New flexible electrodes are still to be developed. After the technology is further matured and popularized, it will become a great boon for diabetic patients. Moreover, there are few studies on non-enzymatic glucose sensors applied to agricultural living detection, which still requires further exploration by scientists to promote the development of agricultural intelligence.

Conflict of interest

The authors declare no conflict of interest.

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REVIEW ARTICLE

Overview of smart masks and research on new technology

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ABSTRACT

The smart mask is a new type of mask with active air supply and breathing. It adopts an external electric fan-forced air supply system, which can effectively reduce the user's breathing load and achieve the purpose of improving comfort and user experience. However, in the current market, the function of smart masks is relatively simple with weak practicability and limited application. Based on these situations and in the research of a large number of smart masks and other types of masks, their application scenarios, advantages and disadvantages of the current technologies used in smart masks are analysed and compared to demonstrate their advantages in comfort and functionality. In terms of application prospects, new technologies can be integrated into the research and development of smart masks, providing new ideas for the research and development of new masks, which is crucial to the future market development of smart wearable products.

Keywords: smart mask; motor wind wheel; sensor; fit; functionality; wearable technology

1. Introduction

Portable active air supply type smart mask, its interior is designed with a motor wind wheel, which can effectively solve the shortcomings of insufficient air supply of ordinary masks, especially when compared with ordinary protective masks. Smart masks have better facial fit and a more obvious filter effect. At present, there is only one type of mask design on the market. Apart from special industry, personnel being unable to find suitable masks in the mask market, ordinary consumers to find masks suitable for daily wear in the market also face the difficulty. The multi-functional air supply and exhaust smart mask not only improves the wearing comfort of the user, but also protects special types of work according to the user's environment and external climate. Smart masks will become one of the main development trends of the mask market in the future[1].

2. The origin of smart masks

At the beginning of the 20th century, masks became a necessity for public life. In 2013, the northern regions of China PM2.5 air hazards have become serious, and hence masks have become more popular and functional due to frequent haze weather. Over time, masks no longer simply play a role in preventing dust and air pollution. In addition

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to medical masks, activated carbon masks, air filter masks, etc.[2] are also relatively common in life, and smart masks are also appeared owing to smog. Due to the shortage of masks during the epidemic, smart masks are becoming increasingly popular.

2.1. Analysis and comparison of smart masks and ordinary masks

Masks can be divided into three types from the perspective of users: Civilian masks, medical masks and industrial protective masks. These three types of masks are also different from each other due to different implementation standards. Among them, civilian masks are further divided into cotton masks, decorative masks and thermal masks. Medical masks are divided into medical protective masks, medical surgical masks and general medical masks. Industrial protective masks are a branch of industrial protective facemasks. According to the protection level, they can be divided into 90 (90% protective power), 95 (95% protective power), etc. According to the classification of protective objects, they can be divided into dustproof and oil fume proof. Aside from the above three types of masks, smart masks as a new contemporary product, have gradually entered the public eye. The following is an analysis and comparison of smart masks and other masks from three aspects: Functional advantages and disadvantages, specifications, and application scenarios. First of all, it is necessary to clarify the specifications and standards of the above three types of masks, see **Table 1**.

Table 1. Comparison of specifications and standards of three types of masks

Type	Area	Executive standard	Filtering efficiency %		
			Low-level standard	**Intermediate standard**	**Advanced standard**
Daily protection masks	CHN	GB/T 32610—2016 *Technical Specifications for Daily Protective Masks*	Level III≥ 90.00	Level II≥ 95.00	Level I≥ 99.00
		TAJ1001—2015 *PM2.5 Protective Masks*	Level 2 F90 ≥90.00	Level 1 F95 ≥99.00	Level 1 F95 ≥99.00
Medical and healthcare masks	CHN	YY 0469—2011 *Medical Surgical Masks*	BEF≥95.00	BEF≥95.00	BEF≥95.00
		YY/T 0969—2013 *Disposable Medical Masks*	BEF≥95.00	BEF≥95.00	BEF≥95.00
		GB 19083—2010 *Technical Requirements for Medical Protective Masks*	Level I≥ 95.00	Level II≥ 99.00	Level III≥ 99.97
	EU	EN14683—2014	TYPE Ⅰ BEF≥95.00	TYPE Ⅱ BEF≥98.00	TYPE Ⅲ BEF≥98.00
	US	ASTM F2100—2004	BEF≥95.00	BEF≥98.00	BEF≥98.00
Labour insurance masks	CHN	GB 2626—2006 *Respiratory Protective Equipment Self-priming Filter Anti-particulate Respirator*	KN90, KP90 ≥90.00	KN95, KP95 ≥95.00	KN100, KP100≥99.97
	EU	EN149: 2001+A1—2009	FFP1≥ 80.00	FFP2≥94.00	FFP3≥99.00
	US	NIOSH Standards （Title 42 CFR Part 84）	N90, P90≥ 90.00	N95, P95≥ 95.00	N100, P100 ≥99.97

Function advantages and disadvantages

PM2.5 masks can deeply filter and block smog, effectively filter bacteria and viruses, car exhaust, second-hand smoke, formaldehyde, air pollution poisonous gases, etc. However, due to the large breathing resistance of PM2.5 masks, it is not suitable for people with heart or respiratory difficulties (such as asthma and emphysema), pregnant women, etc. Meanwhile, medical surgical masks can prevent the spread of blood, body fluids and splashes during invasive operations, and have strong resistance to bacteria and viruses. However, the filtration efficiency of particles is limited, and most of them are rectangular designs that do not provide the same tight-fitting to the face as that of medical protective masks.

Compared with ordinary masks, smart masks have the advantage of reducing breathing resistance, effectively preventing suffocation, greatly reducing the user's breathing load and are more suitable for people with poor lung capacity such as the elderly and children. However, smart masks are not suitable for use in high-risk environments such as hospitals. Smart masks are powered by electric motors and used for a short time after each charge, which will bring restrictions and inconvenience.

Specifications

The group standard of *PM2.5 Protective Masks* (TAJ1001-2015) was implemented on March 1, 2016, and is the first group standard for PM2.5 protective masks in China[3]. Before the introduction of this standard, most protective mask products implemented *Respiratory Protective Equipment Self-priming Filter Type Anti-particulate Respirator*, GB 2626-2006 standard or individual enterprise standards, with some implemented the American NIOSH standard and the European FFP standard. However, these standards are industrial mask standards. In fact, for civilian anti-fog products, these standards are not very applicable and thus, there is the TAJ 1001-2015 group standard[4].

On December 31, 2011, National Food and Medical Products Administration issued the YY0469-2011 *Medical Surgical Masks*[5] YY 0469-2011 is an industry-standard for the pharmaceutical industry and it is also a mandatory standard[6]. The standard clearly stipulates the technical requirements, test methods, signs and instructions for use of medical surgical masks, as well as packaging, transportation and storage requirements.

The safety items of smart masks are tested according to *Safety of Household and Similar Electrical Appliances Part 1: General Requirements*[7] GB 4706.1-2005, while the performance of smart masks is tested according to *Electric Anti-haze Masks*[8] T/CAQI 63-2019. This standard provides a method for the testing of electric anti-haze masks. The standard mainly emphasizes the main performance indicators such as material, structural design, protective effect, internal quality, air supply volume, noise and microbial filtration efficiency, anti-allergen, antibacterial and mildew resistance. At present, there is no standard for smart masks, and the relevant standards are only in the tests.

Application Scenarios

The application scenarios of different masks are different and the comparison of application scenarios of several types of masks is shown in **Table 2**.

Table 2. Application scenarios of several masks

Type of mask	Particle type	Application scenarios
Smart mask	Smog, pollen, industrial powder, etc.	Haze weather and suitable for people with poor lung capacity
PM2.5 mask	Smog, viruses, bacteria, dust mites, pollen, etc.	Widely used in the medical and health industry, public places
Medical surgical mask	Bacteria, viruses, blood, body fluids and splashes, etc.	Generally used in medical clinics, laboratories

Medical protective mask	Particles in the air, blocking droplets, blood, body fluids, secretions, etc.	For preventing respiratory infections
Activated carbon mask	Organic gases, acid volatiles, pesticides, SO_2, Cl_2 and other irritating gases	For anti-virus, deodorization

2.2. Advantages of smart masks under the epidemic

Under the COVID-19 epidemic, with the comprehensive promotion of resumption of work and production, the daily demand for masks in the country is expected to reach 530 million with strong market demand[9]. However, in the process of wearing masks, people will experience poor breathing and discomfort[10]. During the epidemic, medical staffs wear medical surgical masks for long periods, which lead to prolonged pressure on the skin and hinders the evaporation of water vapour, thereby causing device-related pressure injury[11], which endangers the health of medical staff to a certain extent. The emergence of new smart masks with active air supply has improved user experience.

Most of the smart masks use silicone or latex materials in the parts, which come into contact with the face[12]. They have strong deformation adaptability and strong recoverability, which can meet the airtight requirements of different facial features and give the wearer a sense of comfort. In addition, some smart masks use adjustable ear straps and adjustable nose clips in the design[13] ,where users can make appropriate adjustments according to their face shape to reduce the pressure on the bridge of the nose and ears.

Additionally, a smart mask with an active air supply appeared on the market. It adopts 5 layers of composite filters to achieve a 99% high-efficiency filtration effect with excellent air permeability. The air outlet of the main unit is designed according to fluid mechanics. Fresh air is circulated and supplied to both sides and then enters the nasal cavity after the wind is moderated. The flexible gill valve and exhaust valve are closed when inhaling and opened, when exhaling to discharge turbid air and condensed water, increasing air permeability and making breathing smoother. Meanwhile, the folded cavity of the silicone mask allows water vapour to flow out along the inner wall of the cavity, preventing water vapour from flowing to the face and causing discomfort. There are also smart masks with various functions such as making calls and listening to music. To improve the quality of people's calls when wearing masks, a high pickup microphone and high-quality headphones are embedded outside the mask. In addition, the main control board STM32, battery, Bluetooth, wireless charging ring, temperature and humidity measuring instrument are installed inside the mask, while an OLED display is installed on the wall of the mask to display real-time data. A dust-measuring instrument is also hung on the same side, which provides the monitoring of the environment and the transmission of data, allowing users to have a better experience.

3. Analysis of the current situation and functional design of smart masks

3.1. Status of relevant patents

By retrieving keywords such as smart masks, the research situation of patents related to smart masks in the CNKI database was counted, as shown in **Figure 1**. As can be seen from **Figure 1**, the first patents related to smart masks were issued in 2001, and in the following 13 years, only a few patents were issued. However, the number of related patents has increased sharply since 2014, which shows that due to the haze weather, smart masks have received widespread attention while a sharp falling number was seen in 2019. It is speculated that the current domestic smart mask field may be in a bottleneck period. In short, the distribution of patents related to smart masks shows an overall growth trend.

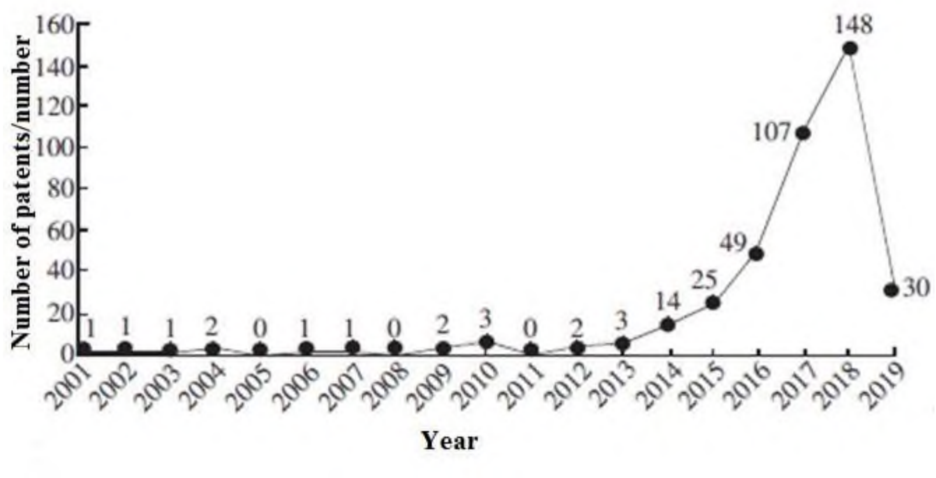

Figure 1. Number of patents related to smart masks in CNKI database.

Selected main patents retrieved from CNKI along with compared main functions and features is shown in **Table 3**. It can be seen that there are many types of patents for smart masks in China and the functions are relatively complete.

Table 3. Comparison of related patents of several smart masks

Patent name	Application time	Main features
Hidden detachable smart mask	Jan. 30, 2018	The hidden detached smart mask is composed of a mask, a host and a trachea. The main unit is placed on the inside of the jacket, does not appear when wearing the mask, and the air temperature can be adjusted.
Intelligent anti-smog mask for traffic police	Apr. 28, 2018	An electric exhaust structure and a Bluetooth communication module for Bluetooth speaker communication are set on the anti-fog mask to make breathing smooth where traffic police can conduct effective traffic command without taking off the mask.
Solar smart mask	Aug. 30, 2018	The mask includes the mask body, the fresh air module and the solar module. The battery of the fresh air module is charged through the solar module to improve the battery life.
A type of smart mask	Nov. 26, 2018	The mask includes a mask body, controller, temperature and humidity sensors. There are LED lights at the front of the body and a processing module at the lower end, which can heat and humidify the air and serve as a night warning.
Smart mask	Dec. 17, 2018	The smart mask includes a front cover, a filter body frame and a silicone mask. There is a sound-absorbing structure, which can effectively reduce noise and improve the overall comfort of the smart mask.

3.2. Current situation of commercialized smart masks

Generally, the smart masks sold on the market are roughly divided into three types: Fan-type masks, masks with external air purifiers and masks with built-in air purifiers. The three brands of electric masks are listed, as shown in **Figure 2**. The comparative analysis of smart masks and ordinary masks is shown in **Table 4**.

(a) DNC Dongyan fan type mask **(b)** Purely external air purifier type mask **(c)** TCL built-in purification device type mask

Figure 2. An example of an electric smart mask.

Table 4. Comparison of smart masks and ordinary masks

Mask Category	Function	Applicable Scope	Degree of comfort
Fan type mask	Anti-haze and sterilisation	High dust concentration	Easy to adjust and comfortable
External air purifier type mask	Anti-haze and deodorization, effectively purify toxic substances	High dust concentration	The quality is heavy and wears on the ear, not easy to wear for a long period.
Built-in air purifier type mask	Anti-haze and deodorization, effectively purify toxic substances	High dust concentration	General comfort, inconvenient to wear for a long period
Ordinary mask	Anti-haze, dust-proof	Low dust concentration	Average comfort, poor breathing, not suitable for long-term wear

Compared with ordinary masks, the biggest advantage of smart masks is that they reduce the breathing resistance and can effectively prevent suffocation. Taking the familiar N95 mask as an example, the N95 mask with a valve produces filtering protection by controlling one-way air intake. It works, but if you wear it for a long time, you will feel a sense of suffocation, which is not good for breathing.

3.3. Design elements and functionality of smart masks

Design

a. Material and shell

The whole smart mask uses healthy and harmless materials and does not produce toxic and harmful substances. Meanwhile, the tightness of the mask and the face directly affects the protection effect[14].

Most smart masks use silicone or latex materials[15], which can satisfy both airtight conditions and comfort. To adapt to the face shapes of different people, an adjustable ear strap design has appeared on the market. The material of the ear buckle part can be made of food-grade silicone, which is non-toxic, odourless, environmentally friendly, soft, elastic, non-cracking, and has a long life with high tear strength.

b. Filter element

The 4–5 layer filter design can make the filtration effect reach 95%–99%[16], mainly using sterilisation paper, activated carbon, HEPA filter and non-woven fabric. Sterilisation paper can sterilise and prevent bacteria from growing on the surface of filter paper while activated carbon can absorb and eliminate various odour molecules in the air as well as absorb formaldehyde, ammonia, benzene and other harmful gas molecules. The HEPA filter used is

PM2.5, which is a good medium for effective filtering of smoke, dust, bacteria and other pollutions. The non-woven fabrics can inhibit the growth of bacteria and protect the filter paper.

c. Electric air supply device

According to the design principle of fluid mechanics, the main air outlet should avoid problems such as facial spasms caused by wind directly hitting the human skin while the flexible air discharge gill valve and exhaust valve increase air permeability to reduce the feeling of dampness to make breathing easier[17].

Additional functions

On February 19, 2020, according to foreign media reports, the United States Patent and Trademark Office granted Xiaomi a patent for a smart mask. The smart mask features an embedded computing unit that includes a processor, a memory module, a battery, and a connector. In addition to filtering the air, this smart mask can also calculate the intake of pollutants and record the total wearing time of the mask. The smart mask compares this data with the filtration efficiency of the mask air filter and estimates the air quality the user is breathing in the user's environment and can even help the user determine changes in lung capacity. Finally, the onboard processor will initiate a wireless connection with other devices (such as smart phones) to send data about the air the user is breathing to an App. After sharing the data with the device, the smart mask can request air quality data from the central server to inform the user of the air quality of the city in real-time.

From the breakthrough of Xiaomi smart masks in digital science and Bluetooth devices, we can see the application of high-tech technology and the development of other functions in the current smart masks. In addition, many patents have made progress in other functions, such as temperature and humidity sensors, solar cells, and communication equipment[18]. This has greatly promoted the development of smart mask functions. It is believed that smart masks will be more diversified and intelligent in the future.

3.4. The main factors restricting the market popularisation of smart masks

Firstly, the price is expensive. The average price of smart masks on the market is 200–300 yuan, some of which are even more expensive. Apart from that, the most critical part inside the smart mask is the filter element, which needs to be replaced regularly. Hence, the long-term purchase of the filter element alone will also be an additional expense. Secondly, in the large quality of the mask, due to the presence of multiple components such as motors and batteries, which make the mask relatively heavy. As such, the long-term wearing of the mask will have adverse effects on the head. Thirdly, the battery life is short, where the current average battery life of smart masks is observed to be mostly 4–6 hours, which can't satisfy long-term travel. Fourthly, the motor and fan will generate noise, which makes people feel anxious. Fifthly, the air intake of human breathing is non-linear such as the gap between walking and running. It is very large, and the instantaneous air intake of some electric air supply masks is insufficient, which makes this type of smart mask only suitable for use when walking or light exercise.

4. Function development and new technology application

The development prospects of smart masks are huge. In future research and production, people will no longer be satisfied with the single function of active air supply of smart masks but put forward higher requirements for the versatility and practicability of smart masks. Therefore, we need to develop and perform research towards the trend of multi-functional smart masks according to different application scenarios, user groups, etc., combined with new technologies in the digital age.

4.1. Flexible wearable electronic devices

Flexible wearable electronic devices have the characteristics of thinness, low energy consumption, good biocompatibility, and tuneable mechanical properties. In addition, small size, bendability, and portability are also the reasons why the products are favoured.

Flexible wearable electronic devices are one of the main forms of flexible electronics. Based on flexible materials, combined with micro-nano processing and integration technology, we designed and manufactured products that possess functions such as logic amplification, filtering, data storage, signal inversion, digital computing, and sensing. Flexible functional materials have unique physical and chemical properties such as light, electricity, magnetism, heat, and force, which can be widely used in intelligent electronic systems such as flexible display, data encryption, and wearable perception. Therefore, the application of flexible electronics in electrically driven masks can greatly improve the experience of using masks and enhance the practicability of electrically driven masks. Using microelectronic printing technology, the various printed components are combined to obtain the electric device required for the electric drive mask, which can reduce the volume of the mask and realize portability.

4.2. Bluetooth module

Bluetooth technology is an open global standard for wireless data and voice communication. It is based on low-cost short-range wireless communication and provides a communication technology with special connections for the communication environment of fixed and mobile devices[19]. The survey shows that answering the phone or listening to music while wearing a mask has a certain impact, whether it is a Bluetooth headset or a wired headset, they all have their disadvantages. Based on Bluetooth technology, a high pickup microphone and high-quality earphones are embedded on the outside of the mask, allowing users to enjoy high-quality music and calls. For example, the low-cost and cost-effective BEKEN BK8000L chip is used to provide higher-quality music and compatibility for the Bluetooth module of the smart mask. Using Bluetooth 5.0, the low-power mode will not have a great impact on sound quality[20] and can greatly increase battery life[21].

4.3. Detection sensor

Detection of PM2.5

PM2.5 air quality detector refers to a special detection instrument specially used to measure the value of PM2.5 in the air. It is suitable for the measurement of public places, atmospheric environment and indoor air, and can also be used for the evaluation and analysis of the purification efficiency of air purifiers. The PM2.5 air quality detector can monitor the concentration of PM2.5 particulate matter in the air in real-time, digitise it, and display the dynamic curve of the concentration on the digital display.

In order to make people understand the surrounding environment more clearly in haze weather, the value changes of PM2.5 are monitored in real-time using sensors added to the masks which are connected to the Internet[22] or mobile phone software, so that people can use it no matter where they are. The mobile phone can check and understand the changes in the air quality at any time. According to the current technology, mobile phone software based on Java programming language is designed[23] to combine with the haze detector and GPRS module data transmission of the atmospheric haze monitoring system[24] as well as an intelligent wireless communication and detection function within built-in masks. The chip finally transmits the real-time monitoring of the local haze situation to the mobile phone software. The terminal records and analyses the acquired data, integrates the data and displays it to the user, and can generate a smog map, while providing a variety of personalized health services for mask wearers, playing a role in smog monitoring and responding to bad weather in advance.

Detection of the breathing signal

The respiratory rate can reflect the health status of the human body[25], so the detection of human respiration is not only applicable to the medical industry, but also of great significance to the health of the general population. In recent years, increasingly more wearable devices have emerged on the market with gradual improvement in the comfort of the devices[26]. Their applications in the field of biomedicine have also become more and more extensive. The detection of breathing signals is embedded in the mask to monitor human respiration.

There are many different methods for detecting respiratory signals in the current literature. The main methods of wearable respiratory monitoring include nasal airflow method, electrical impedance plethysmography technology and induction plethysmography technology[27]. The breath detection element uses a semiconductor thermistor[28] as a sensitive element and uses the principle of detecting the airflow temperature differences between exhalation and inhalation to produce data analysis[29]. To directly monitor the amplitude and frequency of people's breathing activities, the fibre rapid condensation and evaporation system[30], as well as the fibre micro-conduction technology, are used[31]. Additionally, remote monitoring can also be achieved, which is of great significance for reducing the risk of infection among medical staff.

5. Conclusions

At present, the research on smart masks shows great potential. This paper sorts out the research and development status of smart masks and discusses the feasibility of new technologies in the design and development of smart masks. Currently, high-tech textiles have become a competitive point in the international textile market and also as a new growth point for the textile industry to improve economic benefits. In this context, there is a huge market space for the research and development of smart masks[32]. The research and development of mask performance for the epidemic are one of the hot spots in the current market. Therefore, the development of smart masks will tend to be digital and multi-functional, which is more in line with the needs of different users.

In the international market, functional textiles are widely used. Whether in daily life, industrial production, or military equipment, the usage has been greatly increased in recent years and the prospects for high value-added textiles are bright[33]. As a part of that, the development prospect of smart masks is self-evident. In the future research and development of smart masks, there are two main aspects: Firstly, many applications of smart masks in medical treatment, in complex medical environments or how to prevent the spread of viruses are a major problem in the design and development of smart masks; secondly, how to correctly and appropriately integrate new scientific and technological elements into the research and development of smart masks so that the protective performance and versatility of smart masks can be improved, and the usability needs of consumers can be met from many aspects. The research and development of smart masks increase the added value of mask products, can arouse people's interest, promote consumption, and help to promote the development and revitalization of the textile industry[34]. At the same time, with the mutual penetration of various disciplines, the performance of functional textiles has been continuously optimised and gradually tends to be multifunctional[35]. Therefore, in the future development of the industry, researchers are required to grasp the basic needs of the public, so that smart masks can truly serve users.

Conflict of interest

The authors declare no conflict of interest.

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REVIEW ARTICLE

Research progress of flexible sensor and its interaction technology in force feedback electronic clothing

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ABSTRACT

The sense in simulated reality is the key of human-computer interaction technology. Force feedback interaction technology is an important factor to realize simulated force sense in virtual reality. It can truly reproduce the physical information such as the mass, inertia and hardness of things in the virtual world. This paper summarizes the flexible sensors commonly used in force feedback technology and the development and research status of virtual reality wearable electronic clothing equipment based on force feedback technology, summarizes the principles of several force feedback structures, analyzes and compares their characteristics and main application fields. This paper briefly describes the prospect of force feedback technology, summarizes the trend of high-precision, multi-modal and multi-point interaction of force feedback equipment in the future, and puts forward some suggestions on miniaturization, softness and authenticity of force feedback technology in combination with the application characteristics of wearable electronic clothing.

Keywords: wearable electronic clothing; force feedback technology; virtual reality; human computer interaction; flexible sensor

1. Introduction

Virtual reality technology refers to the technology that simulates the virtual world by computer, and uses interactive equipment to immerse people in the virtual world through intuitive perception (such as hearing, vision, touch, force, etc.). Force sensing technology is a major difficulty in virtual reality interaction technology, and force feedback technology is the decisive factor to realize simulated force sensing. According to the principle, the force feedback system can be divided into bionic manipulator feedback, magnetorheological hydraulic feedback, aerodynamic feedback, electromagnetic force feedback and exoskeleton force feedback. This paper analyzes the principles of different force feedback systems, and summarizes the current research status, application and development prospect of force feedback technology in wearable electronic clothing, in order to provide new ideas for the research of force feedback technology in wearable electronic clothing.

2. Commonly used flexible sensors for force feedback structure

In wearable smart clothing, how to efficiently

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and sensitively convert various external stimuli into electrical signals and measure and transmit them timely and accurately is the key problem of sensor application in force feedback structure. Flexible sensor refers to the sensor made of flexible materials, which has good foldability and changeable structure, and can adapt to the spatial position change of flexible materials such as fabrics. Therefore, flexible sensors are usually used for information measurement and transmission of force feedback structures in wearable devices.

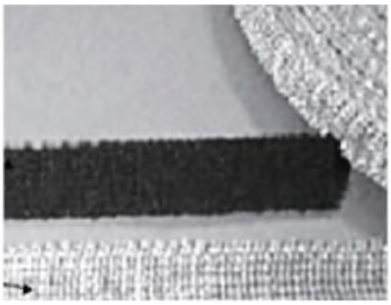
According to the signal conversion mechanism, flexible sensors can be divided into the following five types: piezoresistive sensors, piezoelectric sensors, capacitive sensors, optical fiber sensors and inductive sensors.

2.1. Piezoresistive sensor

The piezoresistive sensor acts on the elastic sensor through external force, which changes the resistance of the sensor, and then changes the electrical signal output by the detection circuit to indirectly perceive the change of force. The earliest piezoresistive sensors were made of semiconductor materials silicon and germanium, and later made of conductive elastic composites (such as polymer composite conductive fiber filled with carbon black, composite conductive fiber filled with graphene, etc.). The resistance change of the piezoresistive sensor is directly proportional to the square root of the external force. Therefore, the piezoresistive sensor made of textile composite materials has the advantages of softness, high resolution, simple signal readout mechanism and equipment, easy combination with fabric and so on. It is a common sensor for the force feedback structure of wearable clothing.

Figure 1 is a knitting flexible sensor. Philips laboratory invented a flexible sensor[1] which is made of carbon fiber and elastic fiber by knitting (see **Figure 1 (a)**). The length of the fabric will change with the force, and its equivalent resistance will also change with the elongation of the fabric. Using the "plating structure" in knitting technology, the conductive fibers and tracking materials are arranged in parallel and formed in the same loop forming system to form interconnected sensors and transmit electrical signals (see **Figure 1 (b)**).

(a) Schematic diagram of knitting structure of fabric elongation sensor.



(b) Knitting sensor and conductive tracker.

Figure 1. Knitted flexible sensor.

De Rossi et al.[2] invented a piezoresistive sensor that combines the polypyrrole part of the sensor with Lycra cloth. When pressure is applied to the sensor, the size of the Lycra fabric will also change, and the resistance of the sensor will decrease due to the increase of the conductive cross-sectional area of the material. However, with the deepening of the experiment, it is found that this type of sensor has many problems, such as long signal transformation time, poor response sensitivity, difficult manufacturing process, rigid cloth and so on.

Carbon black conductive material is a potential sensing material for flexible sensors. Feng et al.[3] made a piezoresistive sensor with nano-carbon black/silicone rubber composite on a ceramic substrate with interdigital electrode. The test shows that the sensor has positive piezoresistive effect at 0.1–100 kHz, and the sensor has fast response and recovery performance. However, with the increase of frequency, the polarization intensity of space charge will be reduced and the piezoresistive effect of the sensor will be reduced.

Park et al.[4] developed a stretchable electronic skin with multi-directional force sensing capability. The piezoresistive interlocking micro circular array is used in the flexible sensor sensitive to stress direction. Two CNT (carbon nanotube) composite films with micro circular pattern are connected on one side of the pattern to form the interlocking geometry, as shown in **Figure 2**. When stimulated by various mechanical forces such as shearing, bending and torsion, etc. this pressure sensor has high-sensitivity detection ability. Due to the unique geometric structure of the array, it shows different degrees of deformation in different applied force directions, so it can distinguish various mechanical stimuli. The response time of microstructure device is about 18 ms and the recovery time is about 10 ms. It is a piezoresistive sensor with high accuracy and stretchability.

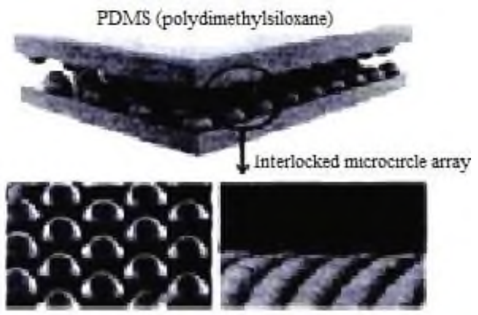


Figure 2. Flexible pressure sensor with interlocked micro-circle array.

2.2. Piezoelectric sensor

Under the action of external force, the crystal structure of piezoelectric material deforms and produces electric dipole distance, which forms a potential difference at both ends of piezoelectric material. After connecting external circuits, electrical signals can be generated. Piezoelectric sensor is a sensor with piezoelectric effect made of piezoelectric materials. In order to meet the demand of wearable electronic products, some new piezoelectric materials are gradually introduced to replace brittle ceramics and quartz in the existing market, including polyvinylidene fluoride trifluoroethylene copolymer P (VDF-TrFE), lead zirconate titanate (PZT) and zinc oxide (ZnO). Polyvinylidene fluoride trifluoroethylene copolymer flexible P (VDF-TrFE) has good chemical inertia, simple processing technology and large piezoelectric coefficient. It has become a new piezoelectric material attracting much attention at present.

Shirinov et al.[5] used piezoelectric polyvinylidene fluoride (PVDF) as the sensing element to prepare a flexible piezoelectric sensor with an area of 25 mm^2, which can be used normally between 40–125 ℃, with a detection range of 10–2,000 kPa and a response delay time of 1 ms. The pressure sensor has the advantages of simple manufacturing method and low cost.

Drean et al.[6] integrate PVDF conductive material into the outer layer of automobile seat and the inner layer foam, and transfer the current change brought by the piezoelectric effect to the amplifier and the impedance phase analyzer. The results show that this change is linear and can be used in the automotive field to detect the pressure applied to the car seat.

Liu et al.[7] developed a monitoring system integrating textile materials and piezoelectric materials, which can collect angular acceleration, vertical acceleration and piezoelectric data. The monitoring system can feed back and record the gait stability of people with motor disabilities in real time. The monitoring system embeds piezoelectric sensors, printed circuit boards, microcontrollers and other electronic components into the clothing to collect signals, and transmits the piezoelectric data to the designated location through Bluetooth, so as to identify and distinguish people with movement disorders.

Persano et al.[8] developed a fiber array with independent three-dimensional structure by electrospinning using polyvinylidene fluoride-Co-trifluoroethylene. This material has good piezoelectric characteristics, and can sense pressure less than 0.1 Pa, and has high sensitivity. It can be used in micro sensors with high sensitivity requirements, such as sensitive collision detector.

2.3. Capacitive sensor

Flexible capacitive sensor generally takes flexible material as capacitor plate and elastic material as spacer, which is equivalent to a device that converts the changes of various forces into capacitance. The flexible capacitive sensor is combined with textiles to make intelligent textiles. It has the characteristics of high sensitivity, high spatial resolution, soft and stretchability of textiles.

Sergio et al.[9] designed a capacitive fabric pressure sensor that can be integrated into clothing. The conductive wire matrix (16 × 16 capacitance matrix formed by warp and weft conductive yarn)) is covered on the elastic foam. When the pressure is applied to the substrate, the foam sandwiched in the middle is extruded and deformed, resulting in the change of the distance between the conductive yarn matrices on both sides, thus causing the capacitance to change. The external circuit can scan the capacitance change of the sensor and draw the signal change curve, and get the fabric pressure change. Due to sandwiching elastic foam in the middle, the sensitivity of the sensor decreases, and the flexibility of the fabric sensor decreases with the sandwich structure, and the comfort of the fabric is also affected.

Meyer et al.[10] optimized the model on the basis of reference[9]. The structure of the optimized fabric pressure sensor is shown in **Figure 3**. The measurement of the fabric sensor in **Figure 3** is 0–10 N/cm^2, the average error is less than 3–4%, and it can be integrated into clothing to measure the pressure of the human body. For example, there is a 6mm thick spacer fabric in the middle of the fabric sensor and it is used as a dielectric layer. At this time, the capacitance before applying force to the sensor is 3.5 pF (no load), and the capacitance after applying pressure is 5.8 pF (pressure 5 N/cm^2). However, due to the friction between the sensing band of the sensor and the human skin during relative movement, the pressure distribution measured when the muscle bends to the front arm is uneven. This kind of fabric pressure sensor can be applied to the situation where high local resolution is required.

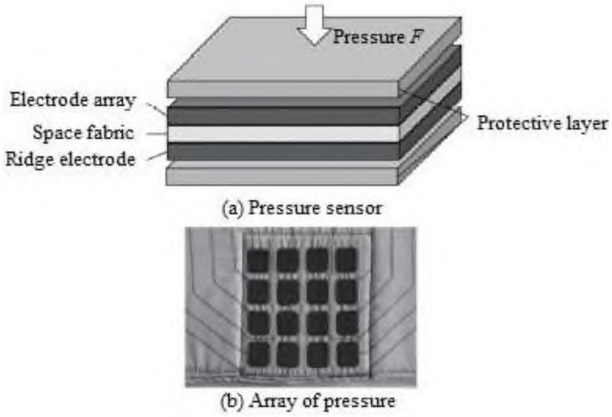


Figure 3. Structure of textile pressure sensor.

Donselaar et al.[11] invented a sandwich structure intelligent pressure pad with insulator wrapped in upper and lower conductive fabric layers. The pressure pad is composed of 64 pressure sensors and supporting test software. It is mainly used to collect the pressure of each part of the baby's limbs on the protective pad in the incubator to ensure the safety of the baby.

2.4. Other types of flexible sensors

Optical fiber sensor

Optical fiber sensor is a kind of sensor that uses the optical transmission characteristics of optical fiber to convert the measured optical signal into optical characteristics (intensity, phase, polarization state, frequency and wavelength). Many scholars at home and abroad weave optical fibers into optical fiber sensors, which can measure signals such as pressure, acceleration, temperature and electric field without affecting the softness and wearability of the fabric itself.

Rothmaier et al.[12] woven plastic optical fiber into the elastic knitted fabric by embroidery to make optical fiber pressure sensors, as shown in **Figure 4**. When pressure is applied to the sensor, due to the deformation of the fabric, the intersection position of elastic yarn in the area with optical fiber will change, resulting in the change of transmitted light intensity. Therefore, the change of fabric stress can be detected.

Figure 4. Textile sensor with optical fibers inductive sensor.

Inductive sensor

Using the principle of electromagnetic induction, the change of measured non-electric physical quantity is converted into the change of coil self-inductance coefficient or mutual inductance coefficient, and then the measured circuit is converted into voltage or current output. This device is called inductive sensor, which is usually made of textile materials such as conductive fiber or yarn. Compared with ordinary metal coils, this sensor is softer, more comfortable to wear and more suitable for use in combination with textiles. At present, inductive sensors have been used in the fields of sleep quality monitoring and motion capture.

Wijesiriwardana[13] integrated elastic Lycra fiber, conductive copper wire and ordinary fiber into the fabric, arranged conductive fibers with different conductive levels in the spiral path to form a coil, and developed a tubular inductive sensor (also known as fabric transducer). When the sensor is worn on the chest, breathing can lead to small fluctuation changes in the chest, so that the inductance of the sensor also changes and is converted into voltage signal output. The monitoring of respiration can be completed by using this principle.

Liu et al.[14] embedded the inductive sensor into the fabric and designed a digital rip breathing monitoring belt based on body area network technology to monitor the subjects' daily activities such as sitting, walking, running, 6 h sleep breathing and so on. The results show that the average measurement accuracy of respiratory rate of this product can reach 95%, and can be applied to the collection and analysis of daily physiological signal changes of human body.

3. Force feedback technology based on flexible sensor

3.1. Bionic manipulator feedback (piezoresistive force feedback)

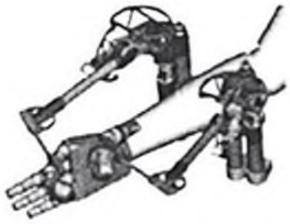
The finger structure of bionic manipulator studied by Lin et al.[15] adopts tendon transmission structure. The five finger knuckles are equipped with light-weight pressure sensors. When the bionic manipulator is used to hold the object, the resistance value of the pressure sensor will change, and the pressure is inversely proportional to the resistance value. The pressure value generated by holding the object will be transmitted to the force feedback data glove through the pressure sensor. After receiving the signal, the glove can control the micro electromagnet. The electromagnet will produce attraction. Because the pawl is connected with the electromagnet, the pawl will also approach the ratchet wheel with the electromagnet, so that the ratchet wheel and the pawl can complete the work together.

The force feedback data glove is shown in **Figure 5**. Virtual technologies designed a commercial force feedback data glove "CyberGrasp" (see **Figure 5 (a)**) based on CyberGlove glove[16]. It is driven by the force generated by the motor and transmits the force through the steel wire rope, so it can generate up to 16 N force on the finger; however, the glove also has many disadvantages, such as the large mass, and users will feel tired after wearing it for a long time.

Frisoli et al.[17] used brushless DC motor as power source to make a force feedback data glove with human hand tactile interface structure (see **Figure 5 (b)**). The base of the structure is installed on the forearm. Due to the tendon transmission arrangement, the gloves can feed back the movement of the thumb and index finger; however, the whole system is heavy and bulky, and the integration is not high.

The advantages of bionic manipulator are: It can not only grasp objects accurately and stably, but also can replace human hands to do some high-risk actions; however, it also has the following defects: The mass is large, so it will feel tired to wear it for a long time, and its system takes up a large space larger and less integrated.

(a) CyberGrasp data glove



(b) Force feedback data glove based on current liquid

Figure 5. Force feedback data gloves.

3.2. Magnetorheological fluid feedback

Magnetorheological fluid is composed of magnetic particles, carrier fluid and stabilizer. The fluidity of magnetorheological fluid is related to the existence of additional magnetic field. The existence of additional magnetic field can enhance the fluidity of MR fluid; on the contrary, after the additional magnetic field disappears, the magnetorheological fluid can change from liquid to solid immediately. This process can be realized in only 1 ms and is reversible. Therefore, the state of MR fluid or its viscosity and yield stress can be controlled by changing the magnetic induction intensity. Dai et al.[18] proposed a driver, which is realized by the above magnetorheological fluid principle. The driver structure is shown in **Figure 6**. The driver uses the electromagnetic pure iron with high permeability to make the shell, fixed disk and other main parts, and uses the magnetic insulation material to make the magnetic insulation ring and shaft, so as to improve the use efficiency of the magnetic field energy generated by the coil and make it mainly used in the fluid of the working gap of magnetorheological fluid.

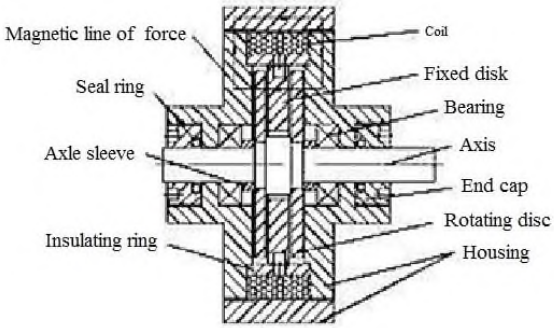


Figure 6. Crosssection of drive profile.

The performance of magnetorheological fluid will change under electric field, so that it can meet the requirements of flexibility and hard object contact force at the same time in specific environment[19]; in addition, if different viscosity and yield stress need to be changed, it can be realized by changing the magnetic induction intensity on the magnetorheological fluid.

A force feedback data glove developed by Southeast University[20], as shown in **Figure 7**. This kind of glove is based on Cyberglove number driven glove. The difference is that it adds electrorheological fluid (ERF). Electrorheological fluid is composed of basic fluid (such as oil) and suspended particles. The size of suspended particles is 0.1–10 μm.

Figure 7. Force feedback data glove based on electrorheological fluids.

With the change of electric field, the liquid viscosity changes sharply, the electric field strength increases, the viscosity increases, and the performance of ER fluid finally changes. Under the action of electric field, ER fluid has shear resistance under static state, which is due to the change of mechanical properties of ER fluid, and this force is the source of force in force feedback gloves[21]. Compared with most existing force feedback data gloves, the force feedback structure has the advantages of stability, safety, small friction, large force feedback range, light weight, easy to carry and strong continuous force.

3.3. Aerodynamic feedback

Wang et al.[22] conducted a more in-depth study on the structure of micro low-friction cylinder, and its structure is shown in **Figure 8**. This structure is an elastic sealing device. The piston is equipped with a one-way sealing ring of nitrile rubber. The sliding resistance is very small, but the resistance will increase with the increase of air pressure.

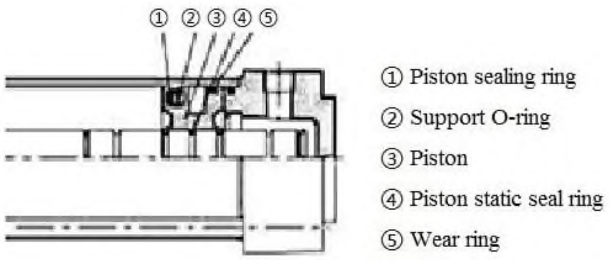


Figure 8. Low friction cylinder structure.

In the above low-friction cylinder experiment, the angle sensor and displacement sensor are used to measure the movement degree of the cylinder and the position change of the piston rod respectively, so that the experimental data can be used to calculate the bending angle of each joint. Once the virtual hand touches the real object, the piston rod will send force to the virtual finger under the condition of air supplied by the cylinder, so that the hand can feel the existence of force and complete the force feedback.

Based on the principle of aerodynamic feedback structure, Rutgers Master Glove[23] designed by Rutgers University in the United States can bend, stretch, abduct and retract fingers through the coaxial design of cylinder and spherical joint, as shown in **Figure 9**. The executive structure of the glove is fixed. Users can adjust the Velcro on the glove according to the size of their hands to adjust the size of the glove and achieve the best state. The gloves have the advantages of low friction, simple structure and light weight. The disadvantage is that the movement space of fingers is limited. In terms of the overall performance of gloves, this Rutgers Master Glove is superior to the CyberGrasp.

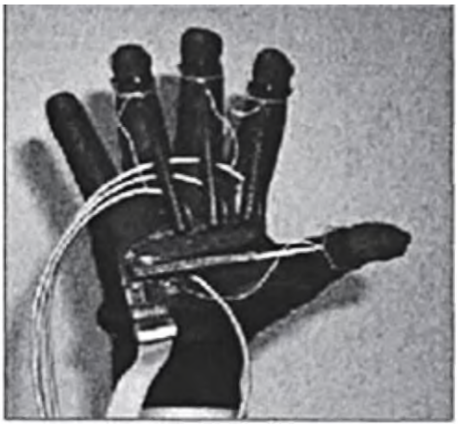


Figure 9. Rutgers Master force feedback data glove.

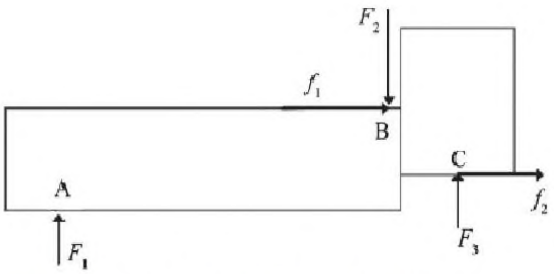
Kopecny[24] realizes force sensing through pneumatic muscle. The principle of pneumatic artificial muscle device is that the push and pull force is provided by external compressed air. It is not only light in weight, but also can provide relatively large driving force. One end is fixed on the support and the other end is fixed on the sleeve of the finger. The magnitude of its transverse force can be controlled by the magnitude of pressure.

Sun et al.[25] developed a force feedback data glove based on pneumatic artificial muscle, but the difference is that it uses a micro low friction cylinder as the source of force and can measure the bending and extension angles of fingers and joints. This kind of gloves has small quality and can provide great tactile force to make the touch more real. The maximum tactile force can reach 30 N.

3.4. Electromagnetic force feedback

The principle of force feedback through electromagnet is: When the glove does not receive the signal, because the electromagnet is attached to the finger, it will move with the finger, and the friction resistance is small at this time. When the glove receives the signal, the electromagnet will provide a feedback force and stop moving. The feedback force can be set by adjusting the current.

According to the above principle, two different types of circular tube push-pull electromagnets are used as the braking device. The stress of the electromagnet is shown in **Figure 10**. Among them, the stop electromagnet can achieve instantaneous braking, and produce resistance to the thrust electromagnet to stop sliding. With the help of the friction between the electromagnet itself and the inner wall of the sleeve to complete the braking, the braking can be completed more efficiently and more energy-saving. At the same time, the stiffness of the device can be enhanced.



F_1 is the positive pressure at point A of the electromagnet that generates the thrust;
F_2 is the positive pressure at point B of the electromagnet that generates the thrust;
F_2 is the positive pressure at point B of the electromagnet that generates the thrust;
f_1 and f_2 are the friction force between the electromagnet and the inner wall of the conduit.

Figure 10. Force diagram of electromagnet after tilting.

Asamura et al.[26] designed a force tactile system. The system uses the electromagnetic principle to fix four magnets on the user's finger or palm skin respectively, as shown in **Figure 11**. The upper magnet controls the attraction or repulsion of the magnet by opening or closing the electromagnet and controlling the direction of the current, so as to stimulate the skin of the finger or palm. The biggest feature of the system is that the structure is simple and the principle is easy to understand. The final force feedback can be adjusted according to the force of the manipulator, and the adjustment is more convenient.

The point-based finger force feedback system developed by Yuan et al.[27] is a force feedback device composed of an outer skeleton driven by a proportional electromagnet. When applying force to the device, it can not only inhibit the joint movement of the hand, but also prevent the virtual hand from embedding into the virtual object. Through the electromagnet to realize the braking, it can brake immediately while receiving the force. It has the advantages of simple structure and strong controllability. Compared with the traditional mechanical braking device, this feedback system has better control effect.

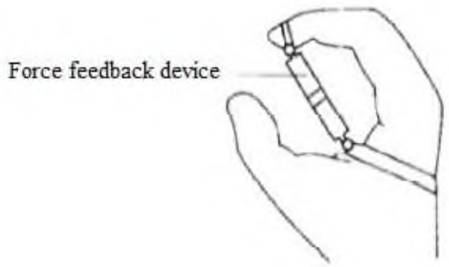


Figure 11. Force feedback diagram.

4. Application of intelligent wearable force feedback structure

Intelligent wearable force feedback structure can be applied to all fields of life. For virtual reality system, force sense can significantly enhance the sense of reality of the participants, and improve the execution efficiency and success possibility of task objectives in human-computer interaction. Intelligent wearable force feedback structure is entering various fields such as education, entertainment, tourism, medicine, aerospace and so on.

4.1. Application of traditional mechanical force feedback structure

The mechanical force feedback structure has a small range of motion, and the force only acts on the joint position of the finger. After the control device captures the specific movement of the finger, the appropriate force is applied to the finger to imitate the human grasping action. CyberGrasp is a finger type force feedback device driven by a motor and transmitted by a steel wire, which can generate a force of about 12 N[28]; its disadvantage is that it has large back impulse and friction, and is not suitable for wearing for a long time. Master-II-ND is a feedback device built in the force feedback structure, which can provide large feedback force. Its disadvantage is to restrict the movement of fingers.

4.2. Application of force feedback structure in education and learning

In mathematics, physics, architecture and other disciplines, the force feedback structure constructs a real experience from concrete to abstract for teachers and students in the virtual world, which helps to improve the learning efficiency of users. Stanford University and Johns Hopkins University introduced the force feedback technology into the primary dynamic system course of college students to guide students to personally experience mechanical movement, and the teaching effect is quite remarkable[29].

4.3. Application of force feedback structure in health care

In medical treatment, virtual surgery is a concrete presentation and application example of force feedback interaction technology. This technology constructs virtual surgical objects through three-dimensional modeling technology. Doctors can wear force feedback equipment, simulate real surgical scenes, and practice surgery with virtual objects to improve the success rate of doctors' surgery. In recent years, with the development of force feedback technology, doctors can operate by manipulating virtual force feedback surgical equipment and synchronously reflecting its actions into real surgical equipment by means of signal transmission. This technology has become an important auxiliary prop and real-time recording tool for modern surgery[30]. The force feedback surgical equipment can reduce the action of the doctor's hand in the same proportion, and has the correction function. It can filter out the shaking of the hand, so as to eliminate the small errors caused by physical factors, ensure the flexibility and accuracy of the doctor's operation, and improve the accuracy of surgical operation. At the same time, some external frame force feedback equipment can be applied to rehabilitation training and realistic simulation of the disabled and some special patients.

In traditional Chinese medicine, it is often said to "looking, listening, asking and pulse-feeling". Understanding the specific situation of the patient's pathological part will help doctors better diagnose the patient's condition. Doctors can train their professional ability through the palpation system with force feedback structure and sensors as the main components. The palpation system can reflect the doctor's palpation action on the display screen in real time. The doctor can feel the change of hand force when pressing different examination parts with the help of force feedback equipment, and judge the patient's disease. This kind of training is more real, accurate, simple and efficient. It provides a large number of practical cases for medical staff, saves the training cost and training time to a certain extent, and provides the possibility for doctors to diagnose patients' condition remotely.

4.4. Application of force feedback structure in space technology

The combination of force feedback and sensing structure with virtual reality technology can be used to simulate the real feeling of human body in the scenes of outer space and deep sea, and study the shape, temperature, hardness and other information of objects that people feel in this scene. Moreover, in the immersive environment, the remote command can be carried out with the human body feeling similar to the real situation, which can greatly improve the safety of scientific research team members in harsh and dangerous situations[31].

4.5. Outlook and prospects

With the progress and development of visual reproduction technology, the demand of human society for force feedback technology will be more and more complex. High-precision position detection, real multi-simulation state force tactile reproduction system and multi-point interactive force tactile reproduction system will be the main development direction of force feedback technology in the future[32]. At the same time, the research on how to reduce the manufacturing cost of wearable electronic clothing equipment will have a great impact on the promotion of virtual reality interaction technology.

5. Conclusions

As a key technology in the field of virtual reality, force feedback technology combines visual, auditory, tactile and other senses in the process of virtual reality interaction, making the interaction experience between users and the virtual world more realistic and more engaging. In recent years, interactive devices with force feedback technology as the core are developing rapidly all over the world, and the research on this technology is further deepened in various countries. At present, although force feedback equipment is a key factor affecting the authenticity, experience, timeliness and accuracy of virtual reality interactive system, its development is still restricted by many aspects. In the field of clothing, in the process of combining force feedback technology with intelligent electronic wearable clothing, how to realize the miniaturization, softness and authenticity of equipment is still a problem to be solved.

Conflict of interest

The authors declare no conflict of interest.

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REVIEW ARTICLE

Research progress of fiber-based organic electrochemical transistors

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ABSTRACT

Organic electrochemical transistors are flexible in design with characteristics such as miniaturization, biocompatibility and amplification and are one of the rapidly developing research topics in recent years. As an excellent flexible material, fiber has unparalleled advantages in weaving and compatibility with the human body. Combining fibers with organic electrochemical transistors is a promising research direction that has the high sensitivity of organic electrochemical transistor testing and the human body compatibility and flexibility of wearable electronic products. This paper introduces the relevant operating principles, working modes and commonly used channel materials of organic electrochemical transistors. Based on the basic device structure of organic electrochemical transistors, the development and changes of organic electrochemical transistors in recent years are discussed, and the research results of fiber-based electrochemical transistors by researchers focusing on the application of fiber-based organic electrochemical transistors in chemical sensing, bio-sensing and other application explorations are summarized. Finally, this paper visioned the future development trend of fiber-based organic electrochemical transistors.

Keywords: fiber; organic electrochemical transistor; flexibility; wearable

1. Introduction

Organic thin-film transistors are the core components of organic electronics, and their comprehensive properties are comparable to those of commercial amorphous silicon products. At the same time, the advantages of low cost and high function have shown broad development prospects and industrialization value[1].Organic electrochemical transistors (OECTs) are a kind of organic thin-film transistors, which were invented by White et al.[2] Organic electrochemical transistors have the advantages of flexible design, low operating voltage, and good biocompatibility. They also have dual functions of sensing and amplification and can be widely used in light sensing[3], artificial skin[4], environmental monitoring[5], food safety testing[6], drug release[7] and medical diagnosis[8].In previous studies, most of the reports on OECTs are based on planar structures, and there are few studies on flexible OECTs, so OECTs are often unable to adapt to complex curved environments in practical tests, and the application is limited. Fiber-based organic electrochemical transistors are a major emerging re-

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search direction in recent years. Fiber is a common material in daily production. It is closely related to people's lives and is also a popular material in scientific research. It has the advantages of lightweight, good flexibility, able to be weaved, and low cost. Many studies have been carried out to use it as a substrate to prepare electronic materials and devices. Fiber-based organic electrochemical transistors creatively combine the sensitivity of OECTs with the flexibility and weavability of fibers that can adapt to complex test environments while effectively testing, and have a wider range of applications such as wearable sensors. The broad development prospects have been acknowledged by the majority of scientific research workers. This paper discusses the working principle, mode and materials of OECTs device channel and briefly introduces the development of OECTs technology focusing on the recent development of fiber-based organic electrochemical transistors and their applications in biological and chemical sensing. The application of fiber-based electrochemical transistors and the future development direction of fiber-based electrochemical transistors are also reviewed.

2. The working principle, mode and material of OECTs

2.1. The working principle of OECTs

OECTs consist of an organic semiconductor channel in contact with the electrolyte and three electrodes, where the channel is between the source and the drain. The channel is covered by an electrolyte and the gate is an external electrode immersed in the electrolyte. The source and drain are in contact with the organic semiconductor film and define a channel for holes or electrons to flow from the source to the drain. It works as follows: The source is grounded, and a constant voltage bias on the drain drives a current through the semiconductor channel between the source and drain. This channel current is defined as the output current of OECTs, which is modulated by the input voltage on the gate electrode. This modulation is caused by the interaction between electrons and ionic carriers. Charge carriers (holes) carry channel currents in OECTs. On the other hand, ionic charge carriers provide charge balance for holes, thereby regulating the concentration of holes and thus the electron conductivity of the transistor channel. OECTs rely on the implantation of ions from an electrolyte into an organic thin film, thereby changing its doping state and thus its conductivity, controlled by the voltages applied to the gate (gate voltage, VG) and drain (drain voltage, VD). The VG controls the ion implantation channel and thus the doping state (i.e. redox state) of the organic film. The VD induces a current (drain current, ID), which is proportional to the amount of mobile holes or electrons in the channel, and this mechanism probes the doping state of organic thin films. Similar to organic thin-film transistors, OECTs work like switches, where the VG (input) controls the ID (output). They can also be thought of as amplifiers, where the power of the input signal is amplified on the way to the output.

In contrast to the thin interfacial regions in field-effect transistors, the distinguishing feature of OECTs is that doping changes occur over the entire volume of the channel. Therefore, for low VGs, large modulation of the ID can be achieved, which makes OECTs efficient switches and powerful amplifiers[9]. At the same time, the use of electrolytes instead of metal oxide semiconductor dielectrics greatly enhances the flexibility of OECTs in terms of device architecture and integration with various substrates. The inherent tunability of organic conducting polymers can also improve ion and electron transport and the convenience of bio-functionalization. Due to these characteristics, OECTs are widely used in research, including neural interfaces[10], chemical and biosensors[11], printed circuits[12] and neuromorphic devices[13]. In addition to the advantages of organic thin-film transistors, OECTs also have the characteristics of simple structure, low operating voltage, and the ability to work in a solution environment. First, OECTs can work in an aqueous medium, and their low operating voltage can effectively prevent hydrolysis. Second, OECTs gate electrode and channel can be prepared separately, and the biochemical sensor can be prepared by special treatment of OECTs gate electrode. OECTs can be successfully used in biochemical detection[14] such as lactate[15], glucose[16], dopamine[17], DNA[18], ions[19], bacteria[20] and antigens[21].

2.2. The working mode of OECTs and their channel materials

The working mode of OECTs depends on the doping level of the conjugated polymer in the original state, and its working modes are divided into depletion mode and accumulation mode. In depletion mode transistors, the current between the source and drain gradually decreases as the VG increases. For transistors operating in accumulation mode, the VG increases in correlation with the gradual increase of current between the source and the drain. Its working curve is shown in **Figure 1**[22]. In depletion mode, the conjugated polymer of OECTs is in the doped form in the pristine state and the device is turned on at zero gate bias. Applying positive gate bias results in the injection of cations or the expulsion of anions from the conjugated polymer network and shuts down the device. Most of the OECTs developed so far work in depletion mode because they are already present in the doped form when they are fabricated. The polyelectrolyte dissolves in the solvent and can ionize out ions that act as counterions to the positively charged formed in the backbone of the conjugated polymer upon doping. Therefore, the pristine conjugated polymer/polyelectrolyte exhibits high conductivity at zero gate bias. Taking the most common PEDOT—PSS as an example, when a positive gate bias is applied, the PEDOT is reduced to a neutral (non-conducting) state according to the following half-reaction PEDOT:

$$\text{PEDOT : PSS} + M^{+} + e^{-} \rightleftharpoons \text{PEDOT} + M : \text{PSS}$$

In the equation above, e^- is the electron, M^+ is the positively charged ion from the electrolyte. In accumulation mode OECTs, the conjugated polymer is in the de-doped semiconducting state in its original form, and the device is turned off at zero gate bias. Applying a negative gate bias causes the injection of anions from the active layer (or the expulsion of cations from the active layer), which turns the device on. Commonly used materials in OECTs channel are shown in **Figure 2**[22]—Semiconductor conjugated polymers, conjugated polymer composite materials and conjugated polyelectrolytes.

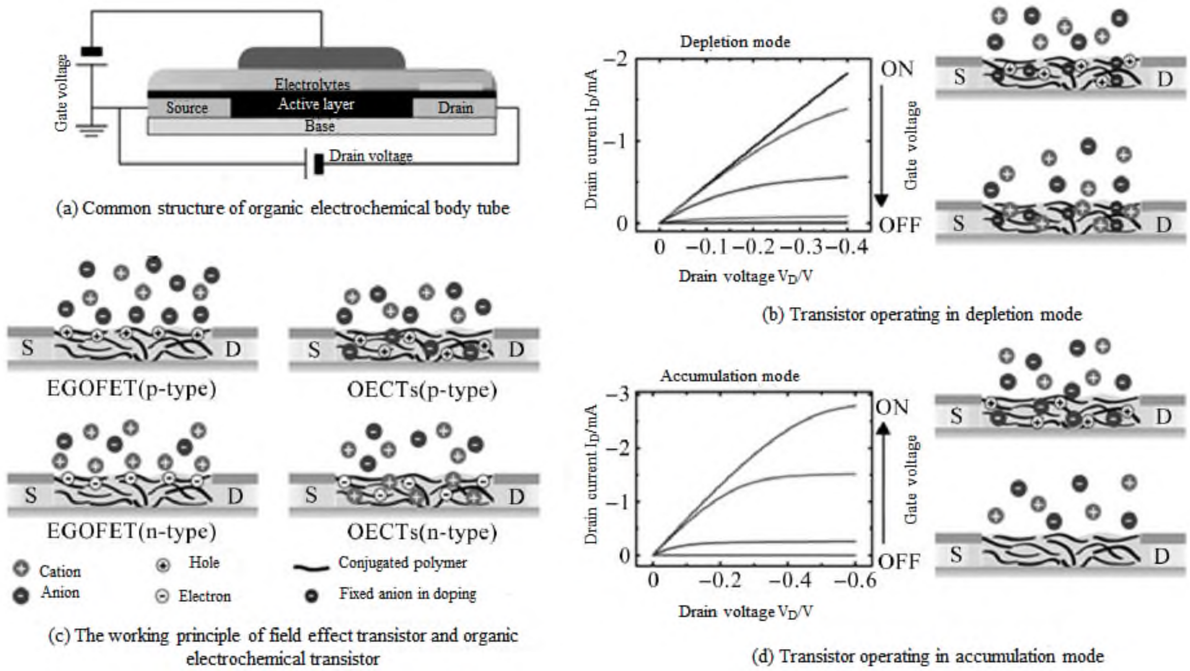


Figure 1. The working principle of organic thin-film transistors.

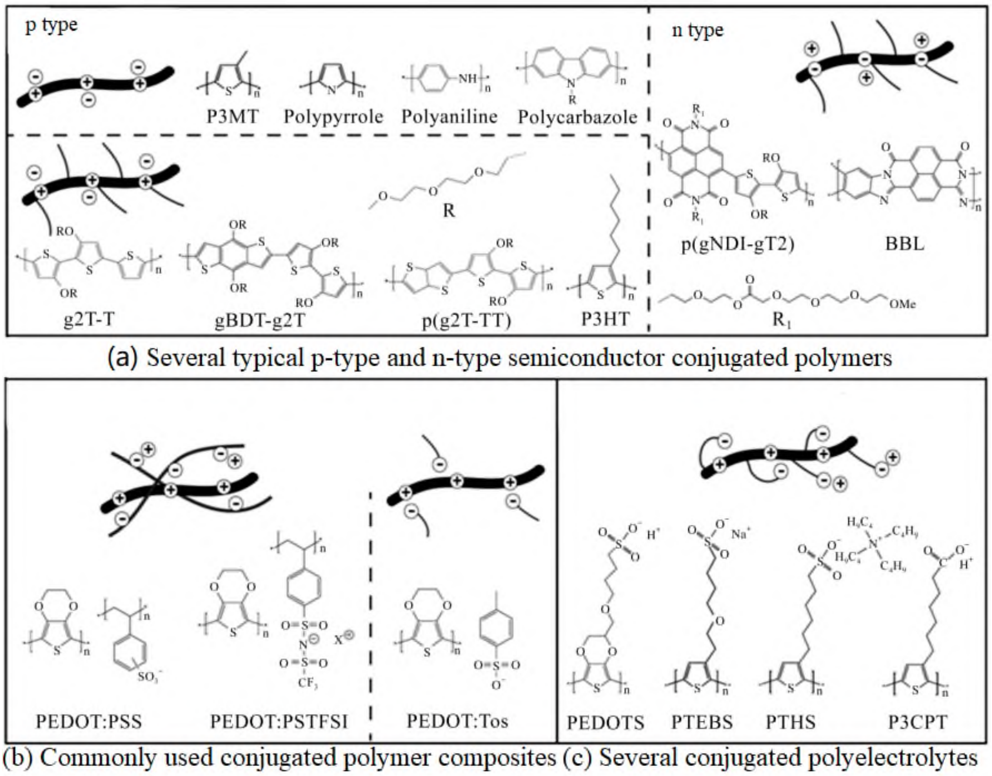


Figure 2. Common materials for the channel of organic electrochemical transistors.

Most of the organic semiconductors used in OECTs show p-type characteristics in air, such as PPy, PANI, PEDOT:PSS, etc. Therefore, most of the research on OECTs done so far worked with the depletion mode. The channel materials required for transistors operating in accumulation modes, such as BBL and P3HT, are difficult and expensive to prepare. Hence, there are not many studies on this aspect.

3. Development of OECTs

3.1. Development of OECTs device structure

The basic structure of OECTs is shown in **Figure 1(a)**. It is mainly composed of three electrodes: Gate, source and drain, as well as a channel and electrolyte. The electrolyte is separated, and the electrolyte covers the three electrodes, thus constituting a basic OECTs device. The use of an electrolyte as the gate dielectric allows great flexibility in the design of OECTs in terms of the placement of the gate electrode relative to the channel. In addition, the "long channel" effect can also be addressed. In organic thin-film transistors (OTFTs), charges are transported along accumulated holes or electron sheets and reside at the semiconductor-gate dielectric interface. In long channels, this often results in very low currents, limiting the ability to use the OTFT as a power-hungry driver. On the contrary, in OECTs, the entire volume contributes to charge transport, therefore, higher currents can be delivered for the same given channel length. At the same time, OECTs can be flexibly designed concerning the gate, electrolyte, channel size and relative position. In addition, different deposition and patterning techniques on a variety of substrates including flexible and stretchable substrates can be applied, paving the way for a host of new device architectures and form factors.

Bartlett et al.[23] reported on the electrochemical transistors fabricated by printing technology. Carbon-based source and drain electrodes and dielectrics were screen-printed on polyvinyl chloride substrates. The obtained devices had a channel length and width of 20 μm and 4.5 mm, respectively and were used as a microelectrochemical enzymatic transistor for glucose and peroxide sensing. Meanwhile, Rani et al.[24] reported on OECTs with 1MKCl electrolyte, thick paper as carrier and polycarbazole as channel material with a channel length of 0.5 mm and studied the effect of device electrode spacing on the transfer performance of OECTs. This study provided a good idea for the electrode design of subsequent OECTs.

In the early 1990s, poly-3,4-ethylenedioxythiophene (PEDOT) was used as electronic inks and conductive coatings for various conductive, electronic, and electrochemical applications[25,26]. PEDOT shows good redox stability and high electronic conductivity when combined with the dopant sodium poly (p-styrene sulfonate) (PSS) and can be incorporated into OECTs structures using printing techniques, where PEDOT:PSS can be used both as an active channel as well as an electrode for the gate, drain and source electrodes. As such, PEDOT: PSS has become the most common material for the preparation of OECTs.

Anderson et al.[27] used PEDOT:PSS to fabricate channel materials on coated paper by printing technology and combined the prepared OECTs with vertical electrochromic display units to form the main smart pixel and display. Wan et al.[28] used a 3D porous sponge of PEDOT:PSS to prepare OECTs as a sensing scaffold. Paper and plastic films as extremely widely used flexible materials with their use as substrates to prepare OECTs have attracted great attention from scientists. Several standard and modified printing techniques have been explored to produce OECTs devices and circuits using these techniques such as screen printing[29] and inkjet printing[30], of which both are commonly used for the preparation of planar flexible OECTs. The advantages of these methods are low cost, simple and flexible design. The preparation of OECTs based on these two technologies can design different circuit structures on their substrates. Hütter et al.[31] developed full-screen printed OECTs logic circuits on a polyethylene terephthalate (PET) substrate by screen printing. Textiles are also good carriers for OECTs and the preparation of OECTs based on textile fabrics has potential applications in the field of wearable electronics. For example, PEDOT-based transistors have been fabricated on Gore-Tex as gas sensors on “breathable” substrates, and have also been screen-printed on common fabrics such as woven cotton and Lycra for wearable sensors that were used for biological fluid sensing such as sweat, saliva, and urine[33]. In addition, PEDOT:PSS combined with nano-fibrillated cellulose (NFC) was also investigated as a coating around the fibers. This combination provides a scalable technology for both stand-alone and large-scale OECTs integration systems such as the reconfigurable OECTs tagging platform[34].

3.2. Device structure of fiber-based organic electrochemical transistors

With the development of medical technology, real-time monitoring is becoming increasingly important for modern medicine and patient health. The OECTs device structure has also begun to be studied by various research groups. A review published in 2018 briefly summarizes the different device structures of OECTs (**Figure 3**)[35]. Compared with rigid planes, the flexibility and practicality of wearable devices and biosensors based on flexible OECTs have improved greatly, which makes real-time monitoring possible.

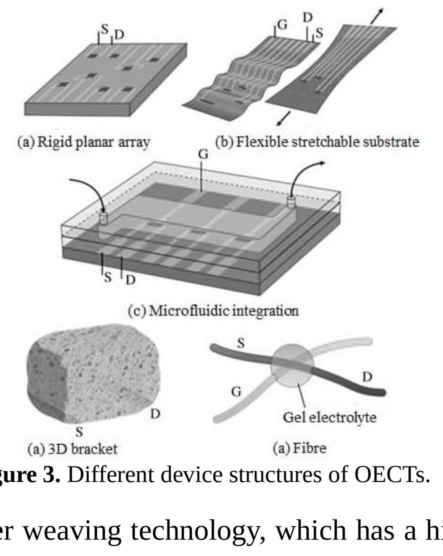


Figure 3. Different device structures of OECTs.

Fiber weaving technology, which has a history of thousands of years, provides a superior platform for the device development of OECTs. Integrating electronic functions within fabrics is an important approach to improve textile performance and extend functionality.

Fiber-based organic electrochemical transistors (FECTs) are a kind of smart material that has developed rapidly in recent years. Its advantage is that it can directly integrate electronic functions into ordinary fiber materials and achieve the design of integrated circuits on textile materials through weaving methods. The structure is simple to prepare and easy to weave into flexible fabrics. Fiber-based organic electrochemical transistors (FECTs) not only have the advantages of ordinary OECTs of low operating voltage, able to work in aqueous environments, good biocompatibility, high sensitivity, low production cost and simple preparation process, but also have the advantages of similar flexibility, bendability and weaving as fiber materials. Therefore, it can be applied to the fields of health care, biological intelligence monitoring and wearable sensing devices to effectively test human biomarkers[14]. Compared with other flexible platforms, textile fibers provide OECTs with superior flexibility, material diversity, and simple processability, enabling the efficient development of various designs. Due to the flexibility of fibers, the preparation method of fiber-based electrochemical transistors is very flexible where fibers are often used as carriers with conductive polymers attached to them. The methods of attaching conductive polymers include dip coating, in situpolymerisation, electrodeposition, and gas-phase polymerisation[36]. In addition, the gate preparation of OECTs is independent and the way of assembling and designing FECT devices is also very flexible and simple. The two most common assembly methods include the use of fiber coated with conductive polymer as the channel material as the source and drain, and the conductive fiber is used as the gate. The two fibers are separated by an electrolyte to form a cross (as shown in **Figure 4**)[37]. In another way, two fibers are placed in parallel at a certain interval[38], and the electrolyte is then dropped in the middle to coat the two fibers to prepare the OECTs. In addition to these two ways, there are many assembly ways to be explored.

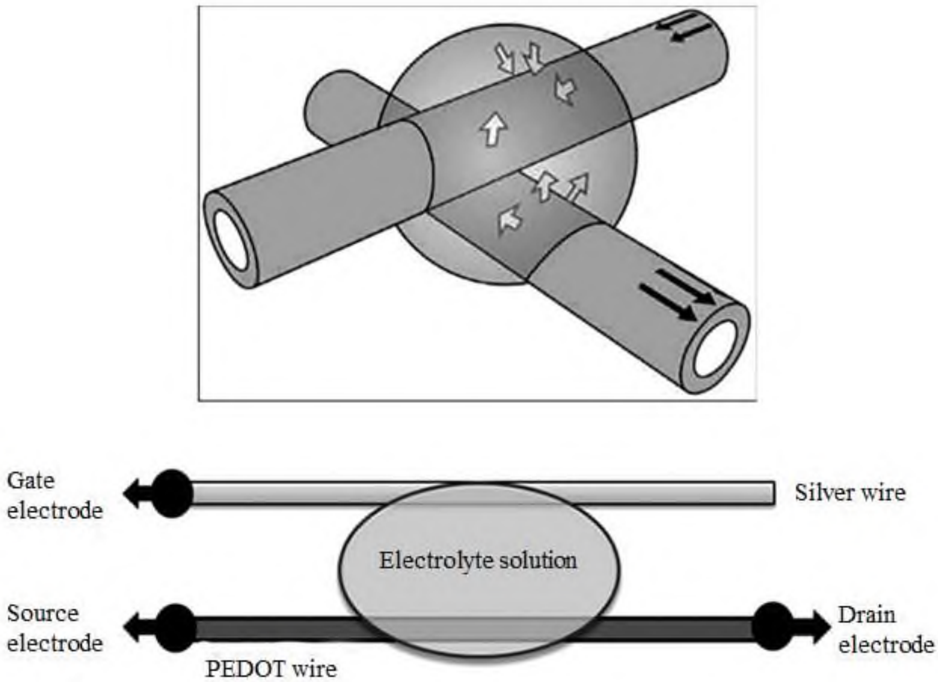


Figure 4. Two typical device structures of fiber-based organic electrochemical transistors.

4. Development process and application of fiber-based organic electrochemical transistors

In recent years, many researchers have begun to focus on the study of fiber-based organic electrochemical transistors. Since Hamediet al.[37] first reported fiber-based organic electrochemical transistors in 2008; many research groups have successively published relevant literature. Cotton, nylon and other fibers have been used as carriers to prepare various FECTs for different applications. In particular, in-depth research has been carried out on sensors based on FECTs. The sensing applications based on FECTs can be roughly divided into chemical sensing and biological sensing. This paper will introduce recent research on FECTs in these two fields. In addition, other researchers have explored and studied other properties and applications of FECTs, which will be briefly introduced below.

4.1. Application of fiber-based organic electrochemical transistors in ion sensing

Tarabellaet al.[38] used cotton fibers to functionalized cotton fibers by simply soaking them in a poly (3,4-ethylenedioxythiophene) (poly styrene sulfonate) (PEDOT:PSS) conductive polymer and directly used as channels for organic electrochemical transistors (OECTs) in contact with liquid electrolytes and silver wire gates (**Figure 5**). The prepared OECTs show stable and reproducible current modulation and demonstrate a very efficient electrochemical detection of sodium chloride concentration in water, which is simple and low-cost and has great potential in the development of wearable electronics in fitness and healthcare.

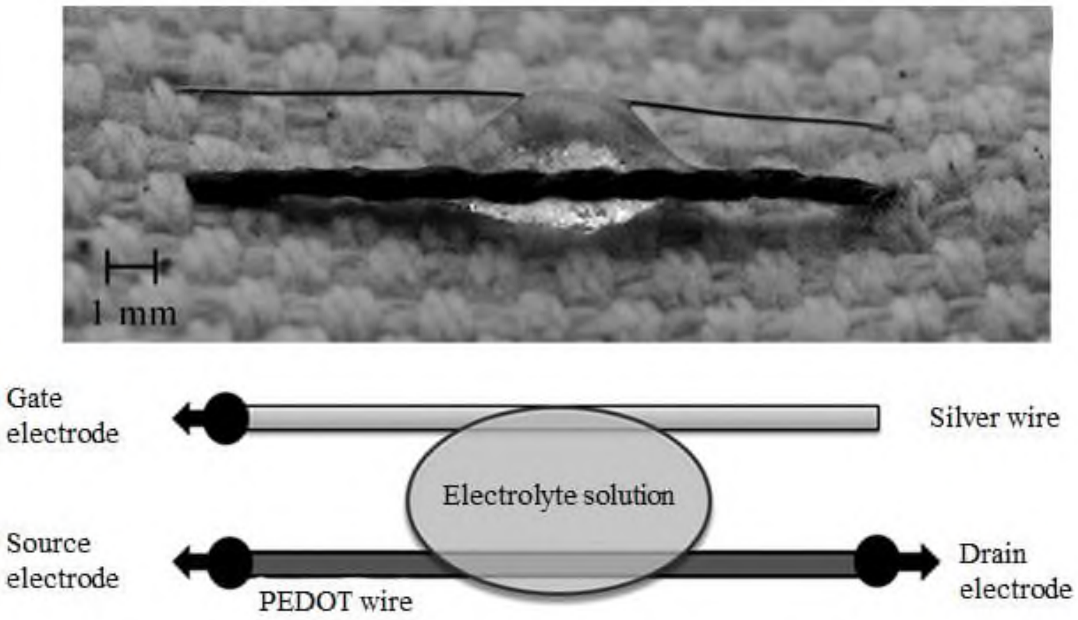


Figure 5. Optical photos and device assembly of FECTs devices.

Wang et al.[39] from Wuhan Textile University first prepared a fiber-based organic electrochemical transistor using polypyrrole and nanofiber materials in 2016, as shown in **Figure 6**. The FECTs exhibit excellent electrical performance with an on/off ratio as high as 100 and an operating voltage below 2 V. At the same time, the ion sensing behavior of FECTs was studied. The results showed that with the increase of cation concentration, the transfer curve of FECTs shifted to low gate voltage and the sensitivity reached 446 μA/dec in the range of 10^{-5} to 10^{-2} M lead ion concentration.

The ion-selective properties of FECTs were also systematically investigated (**Figure 7**) for the detection of potassium, calcium, aluminium, and lead ions. Devices with different cations show large differences in the response curves. Compared with other cations, transistor sensors are more suitable for selectively monitoring lead ions and are very efficient for lead ion electrochemical sensing, opening a path for wearable electronics in healthcare and biological applications.

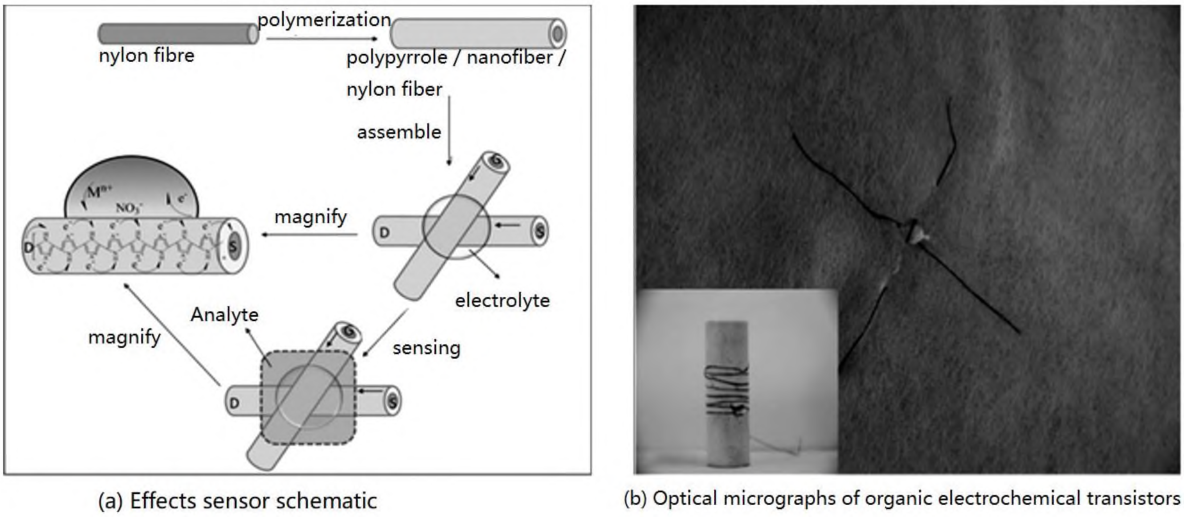


Figure 6. Assembly of nylon-based FECTs.

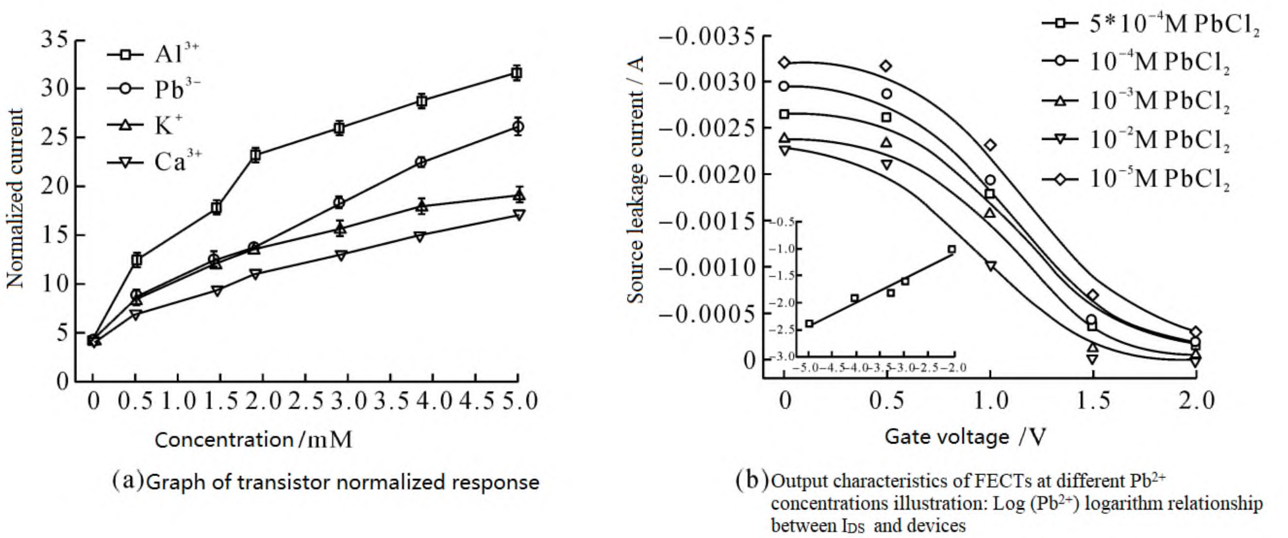
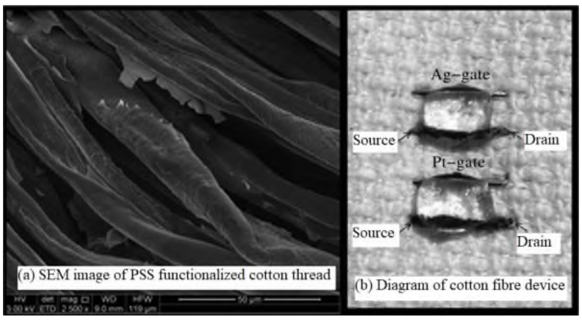


Figure 7. Sensing performance of FECTs sensor.

Copped et al.[40] studied organic electrochemical transistors as electronic textile biosensors and fully integrated PEDOT:PSS on a single cotton yarn as a channel material. **Figure 8** demonstrates the two different transistors that were fabricated using silver (Ag) and platinum (Pt) wires as gate materials, respectively.



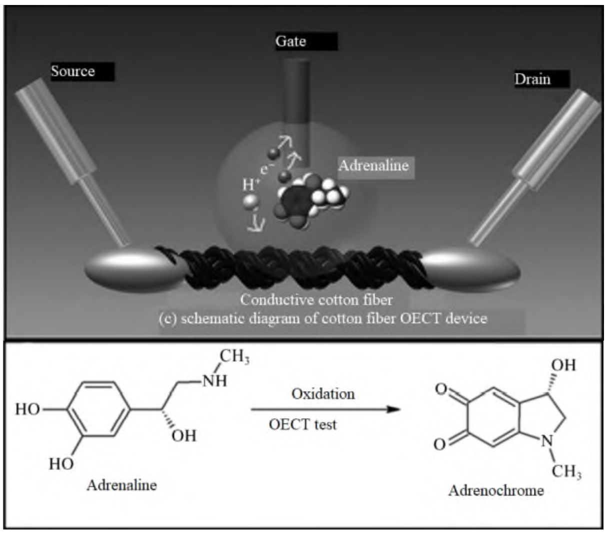


Figure 8. Assembly and sensing mechanism of cotton fiber-based OECTs.

The difference between the fabricated sensors is in the use of different gate electrode materials to detect saline and epinephrine concentrations in human sweat, respectively. Measurements performed in real-time detection mode confirmed the complete independence of epinephrine detection from sodium chloride, thus guaranteeing specific monitoring of epinephrine. The oxidation of epinephrine at different electrodes was studied by absorption spectroscopy. The findings confirm that the oxidation reaction driven by the Pt electrode results in the accelerated formation of adrenochrome, whereas for the Ag electrode, the oxidation is similar to the spontaneous oxidation that occurs in the air. This research opens up new avenues for healthcare, fitness and job security.

Kim et al.[41] from Korea reported conductive polymer microfiber organic electrochemical transistors (OECTs) and their application in single-strand fiber-based wearable ion concentration sensors. As shown in **Figure 9**, they used a simple wet spinning process using aqueous sulfuric acid as a coagulation bath to form PEDOT:PSS microfibers with excellent electrical conductivity and examined their electrical/electrochemical properties thereby achieving the fabrication of combined substrateless PEDOT:PSS microfiber OECTs devices. The novel characterization method presented in this study demonstrates that the current rate of change can be a reliable method for evaluating device performance as well as detecting ion concentration, regardless of actual channel dimensions. Finally, by introducing a source-gate hybrid electrode, single-strand fiber-type skin-mountable OECTs were developed and the resulting microfiber sensor was demonstrated to perform real-time repeated measurements of ion concentrations in human sweat.

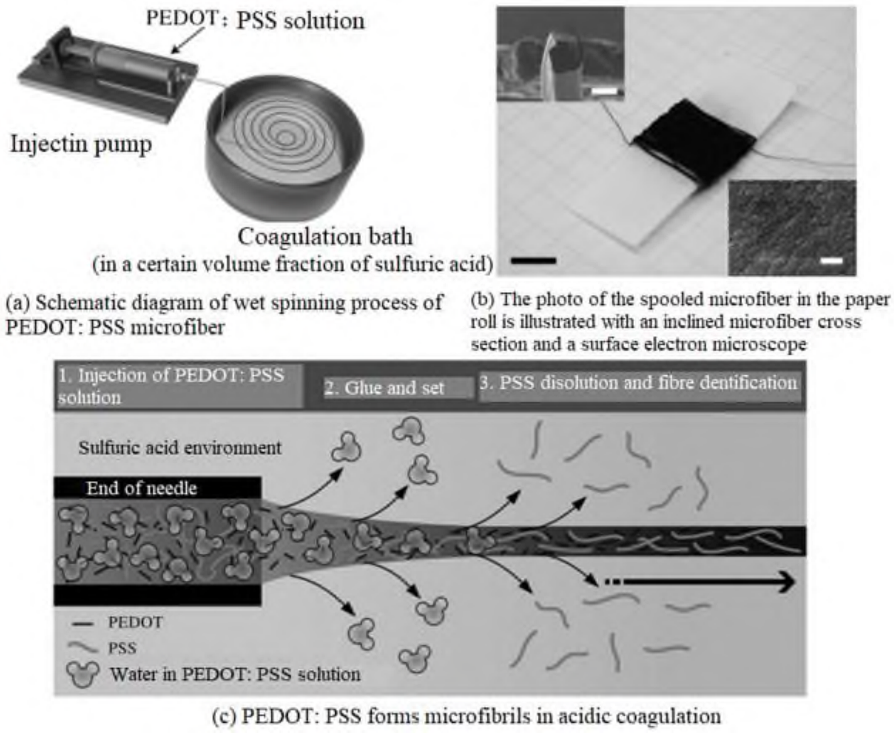


Figure 9. Spinning procedure and coagulation mechanism of PEDOT: PSS microfibers in a sulfuric acid environment.

4.2. Application of fiber-based organic electrochemical transistors in biosensing

In 2017, Wang *et al.*[42] used in situpolymerisation method to induce the generation of PPy nanowires on nylon fibers with reduced graphene oxide and prepared a new type of woven fiber organic electrochemical transistor (**Figure 10**). The experimental results showed that the introduction of rGO nanosheets can induce the growth of PPynanowires and increase their ratio. Moreover, it can enhance the conduction and electrical properties of the transistor. The fabricated transistors have a high on/off ratio, fast response time and long cycle stability. A glucose sensor based on fiber organic electrochemical transistors has also been studied, which has excellent sensitivity, a fast response time of 0.5 s, a linear range of 1 nM to 5 μM, low limit detection concentration and good repeatability.

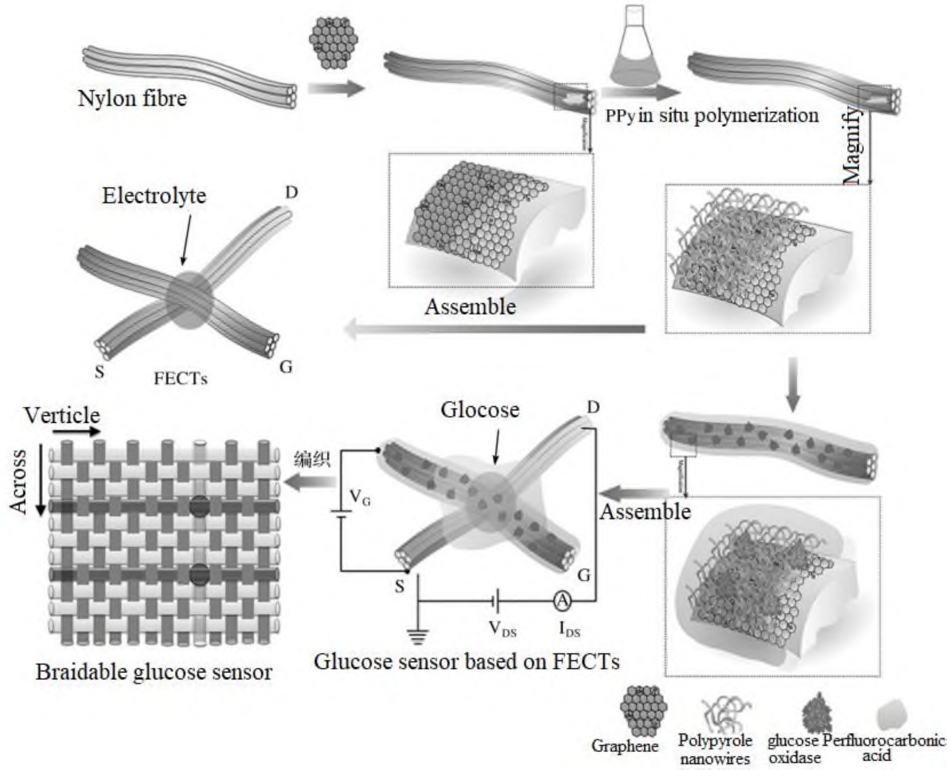


Figure 10. Schematic illustration of the glucose sensor of the fibrous organic electrochemical transistor.

In 2018, the research group[43] simultaneously fabricated another kind of fiber-based organic electrochemical transistors (FECTs), providing a new platform for achieving ultrafast and ultrasensitive biosensors. As shown in **Figure 11**, they pre-treated nylon fibers with PVA-co-PE nanofibers (NFs) to induce polypyrrole (PPy) nanofiber network on the fibers.

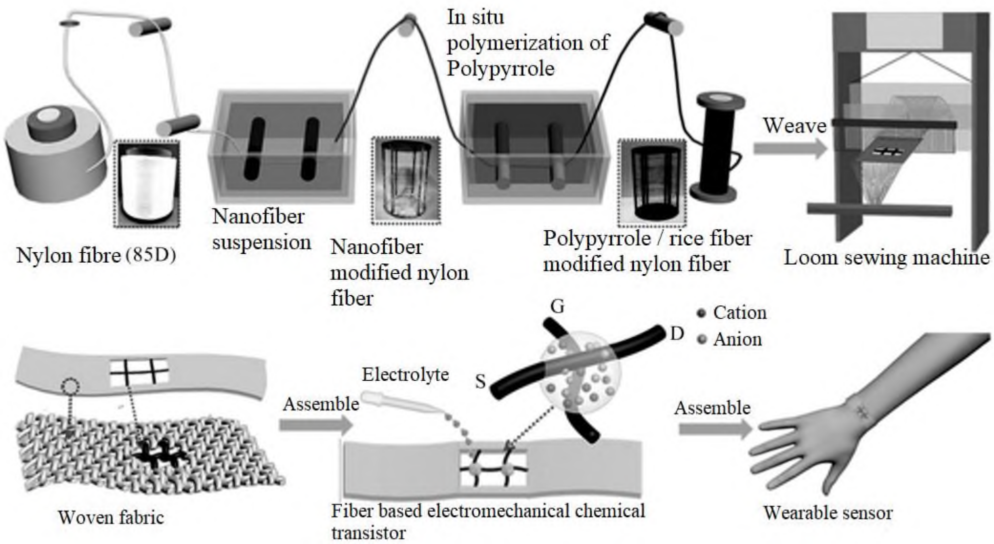


Figure 11. Fabrication and assembly of a wearable dopamine sensor based on FECTs.

The experimental results showed that the introduction of NFs significantly increased the specific surface area and hydrophilicity of nylon filaments, resulting in the formation of a large-area interwoven PPy nanofiber network. The PPy nanofiber network improved the electrical properties of the fibers and their electrical conductivity significantly. The device on/off ratio is as high as 100 with switching time between on and off states was as low as 0.34 s and exhibited good cycling stability. In addition, they also investigated the performance of FECTs-based dopamine sensors relying on different gate electrodes. The results showed that the fiber-based conductive polymer composite gate had the highest sensitivity while the device is highly selective and has excellent reproducibility in the presence of sodium chloride, uric acid, ascorbic acid, and glucose interferences. Moreover, it can also be woven into fabric products (**Figure 12**), which has strong application potential in wearable electronic sensors.

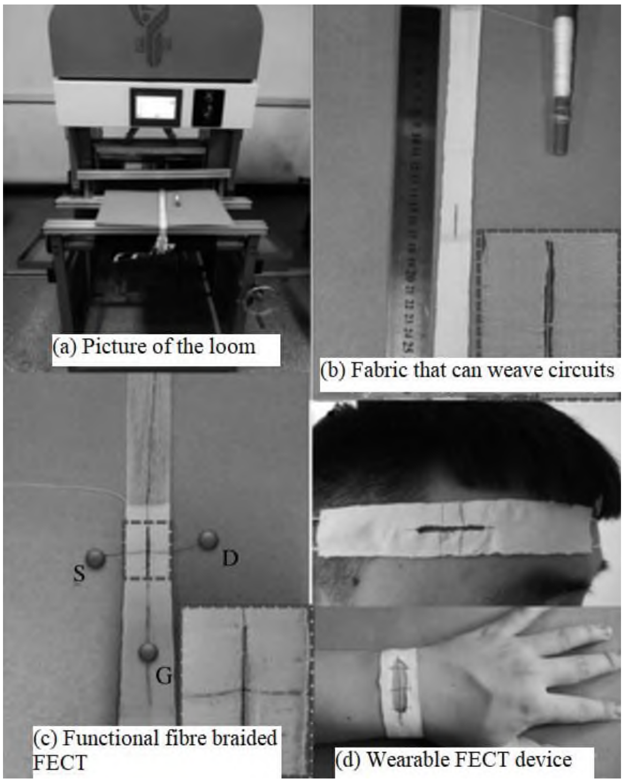


Figure 12. Practical weaving and wear of FECTs.

Yan Feng's research group[44] from the Hong Kong Polytechnic University used nylon monofilament dip-coat PEDOT:PSS as a channel material and deposited metal on the fibers as electrodes using magnetron sputtering. They also used the same method to deposit another nylon monofilament as a grid electrode and modified the electrode with enzymes and polyaniline. The two fibers were assembled in parallel into a transistor and its performance was tested (**Figure 13**).

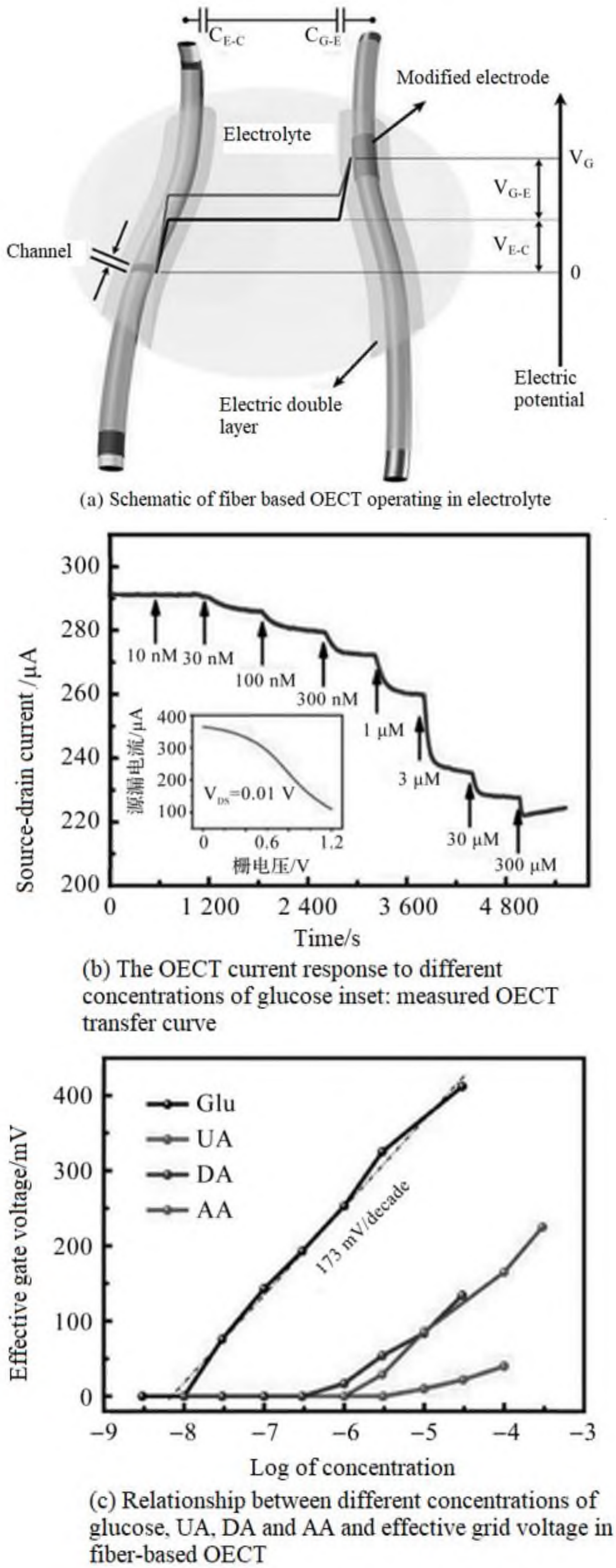
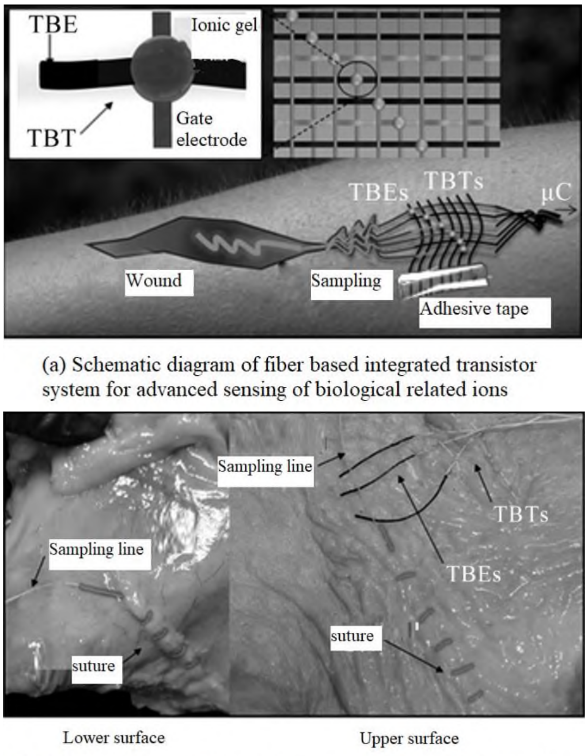


Figure 13. Schematic diagram of sensing mechanism and sensing performance of FECTs-based sensor.

Finally, the device was stitched on a diaper and monitored remotely in real-time with a mobile phone application, The highlight of their work was that by coating conductive polymers and metals with fiber coating, they studied the effect of the coating material on the mechanical properties of the fiber while investigating the degree of change in the electrical properties caused by the bending of the fiber before weaving. The studied fiber was then further integrated with a fabric-based wearable biosensor for the detection of human secretions, which paved the way for wearable devices and flexible electronics.

4.3. Other application exploration of fiber-based organic electrochemical transistors

Owyeunget al.[45] fabricated two different fiber-based electrochemical transistors using a gel composed of silica nanoparticles and 1-ethyl 3-methylimidazolium bis (trifluoromethyl sulfonyl) imide (EMI TFSI) ionic liquid as an electrolyte with assembled carbon nanotubes (CNTs) and poly3-hexylthiophene (P3HT) on a linen line as semiconductor channel materials as shown in **Figure 14**.

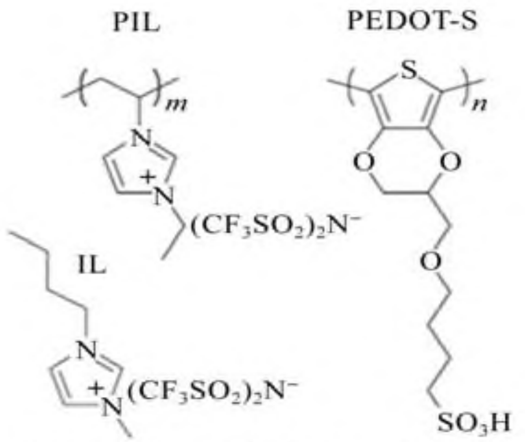


(a) Schematic diagram of fiber based integrated transistor system for advanced sensing of biological related ions

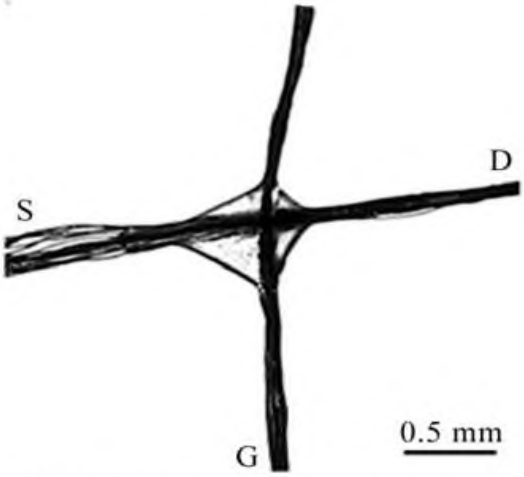
(b) Fiber based integrated transistor system stitched into chicken skin

Figure 14. Schematic of a fiber-based integrated transistor system.

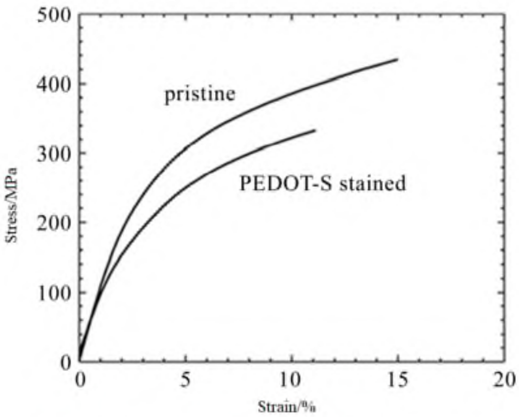
The thread-based electrochemical sensor (TBE) is interconnected, and a multi-channel diagnostic device based on a full thread was designed. Mlleret al.[46] reported a new method to demonstrate that a continuous film of conductive poly (3,4-ethylenedioxythiophene) can be coated on a textile monofilament with a diameter of 10–100 μm, and the monofilament can be coated with a continuous film of poly(3,4-ethylenedioxythiophene) for the preparation of microscale WECT on a single fiber. They also demonstrated inverters and multiplexers for digital logic. This paves the way for 3D polymer microelectronics to design large-scale circuits and integrate them directly into the 3D structure of woven fibers (**Figure 15**).



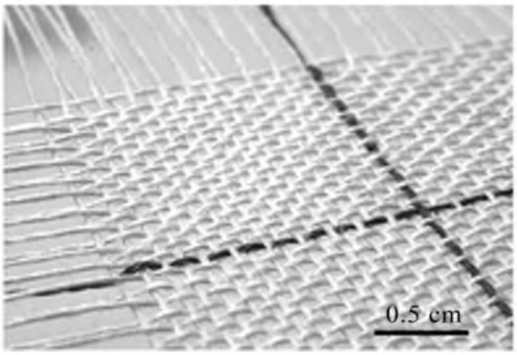
(a) Chemical structure of imidazole based ionic liquids



(b) Micrograph of FECT device of silk fiber with source (S), drain (D) and gate (G)



(c) Stress-strain curves of silk and silk fibers coated with PEDOT-S

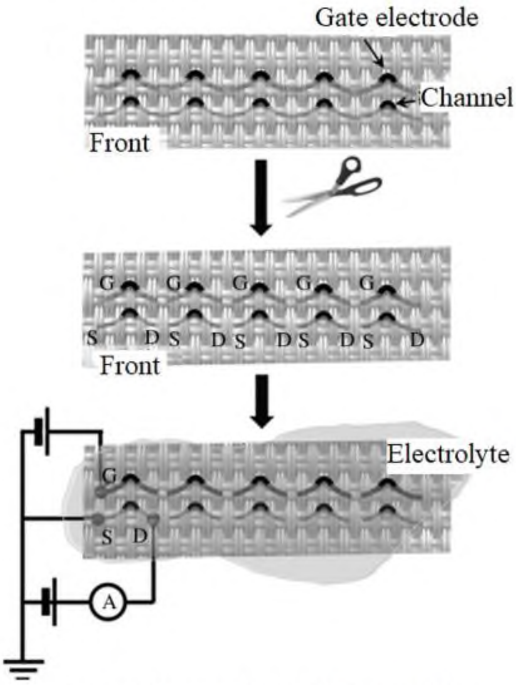


(d) Photo of silk woven fabric coated with PEDOT-S

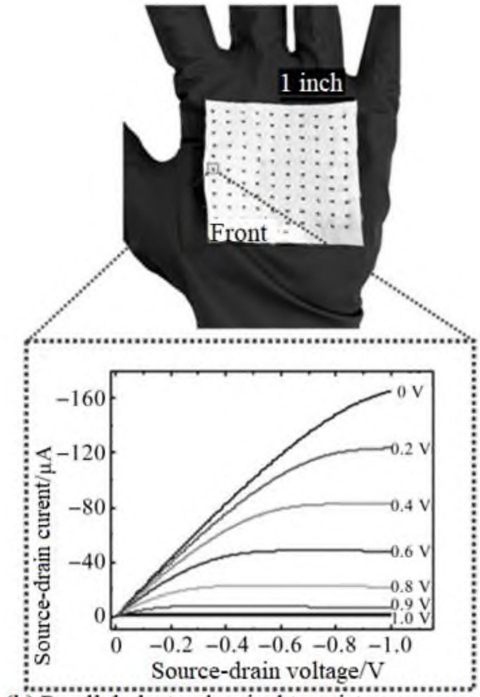
Figure 15. Stress-strain curves of silk conductive fibers and the actual weaving of the FECTs.

Zhang *et al.*[47] coated the conductive polymer PEDOT on nylon fiber monofilaments by gas-phase polymerization and demonstrated that fiber-based electrochemical transistors can be embroidered on fabrics for wearable and implantable bioelectronics devices.

Electrochemical transistors with fixed, micron-sized channel lengths were fabricated in parallel structures on hydrophobically treated silk fabrics with a high on/off ratio of 1,000, zero gate voltage and low applied drain bias (The transconductance value at 0.7 V) at 100 μS. Under these conditions, the device can then be incorporated into low-power integrated circuits. This demonstrates that large-area arrays of transistors can be rapidly generated by stitching monofilament fiber channels directly onto fabric substrates (**Figure 16**) and that a simple embroidery method can be used to fabricate spatially resolved electrodes for electrophysiology applications array.



(a) Process diagram of embroidering parallel electrochemical transistor array on silk backing



(b) Parallel electrochemical transistor array on a 2 × 2-inch fabric opticle picture of the array (top) and transistor output curves (bottom)

Figure 16. Construction of transistor arrays and performance testing on silk fabrics.

Tao et al.[48] used a new geometric pattern to fabricate OECTs by twisting PEDOT:PSS-coated monofilaments together, making it easier for transistors to be inserted into textile fabrics to enable mass production. Transistors can be up to several centimeters in length with an on/off ratio over 100 and a switching time that is close to 15 s. The inverter circuit and NOR gate control circuit were developed through a wire electrochemical transistor (WECT). An amplifier was also fabricated using a transistor to demonstrate the feasibility of an all-textile electronic circuit.

5. Conclusions

In short, fiber-based organic electrochemical transistors have been studied by a large number of researchers recently with accomplishments achieved by many research groups. The advantage of fiber-based organic electrochemical transistors is that they can combine high-sensitivity testing with wearable functions which is a very promising research topic. However, the research of fiber-based organic electrochemical transistors also faces some challenges. For example, most of the electrolytes used in FECTs are gel or water-based electrolytes and multiple difficulties are often encountered in practical tests, such as the uniformity of the sample preparation, the volatilization of the electrolyte, etc. In addition, the tests conducted using fiber-based electrochemical transistors are generally poorly repeatable and usually contain large data errors. Moreover, most of the fiber-based electrochemical transistors use p-type semiconductors and operate in the depletion mode and a few FECTs were found to operate in the accumulation mode. At the same time, in terms of applications based on FECTs, it can be seen that most of the research is mainly based on chemical or biological sensing and there is a lack of in-depth research on transistor mechanism as well as device structure-related exploration. The research direction is relatively narrow and it is not deep and detailed enough. Therefore, the future development direction of fiber-based electrochemical transistors may be the following: a) Study the operation mechanism of fiber-based transistors; b) solve the packaging problem of devices; c) study the relationship between structure and performance to improve the performance of flexible devices; d) research and explore the combination of n-type semiconductors and fibers as well as FECTs working in accumulation mode; e) explore more about the application of FECTs and conduct in-depth research.

Conflict of interest

The authors declare no conflict of interest.

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REVIEW ARTICLE

Flexible sensors in smart textiles and their applications

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ABSTRACT

Sensors are the core part of intelligent smart textiles, and flexible sensors play an important role in wearable smart textiles because of their softness, bend ability and stretch ability, and excellent electrical properties. Based on the working principle of sensors, the research progress of flexible sensors for smart textiles in recent years is reviewed, and the sensing mechanism, sensing materials and application status of different sensors are introduced respectively; the main research directions of flexible sensors for smart textiles are summarized: physiological parameter detection, pressure detection and motion detection, and the applications of the three research directions are reviewed. On this basis, the problems of intelligent flexible sensors and their development prospects are pointed out.

Keywords: wearable technology; smart textiles; flexible sensors; smart textile materials

Smart textiles refer to the integration of electronics, computers, biology, materials and other high technologies into textile garments, so that textile garments can simulate living systems with dual functions of sensing and reacting[1,2], etc., in which sensors are a key component of smart textiles that can sense and feedback changes in the external environment. With the increasing requirements for smart textiles, the expectations for the range, accuracy and stability of sensor measurements have been gradually increased, and it is also hoped that the sensors can also be flexible, ductile, easy to carry and fold. In recent years, the development of wearable flexible sensor technology has become a major hotspot in the research field of smart textiles[3], and the combination of flexible sensors and textile materials makes smart textiles intelligent while maintaining the softness and comfort of the fabric[4], which plays an important role in medical health monitoring, fitness sports, military, aerospace and other fields[5]. In this paper, the existing flexible sensors are classified into flexible pressure-electrical sensors and flexible strain-electrical sensors according to different sensing mechanisms, and the research progress of these two types of sensors and their latest applications in human physiological parameters, pressure, and motion monitoring are presented.

1. Classification and characteristics of flexible sensors

Smart textiles usually consist of three parts: Sensors, actuators, and control units[6,7]. As a wearable flexible monitoring device, the sensor needs to be embedded in the textile and can fully contact

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with the human skin surface to monitor a wide range of signs data without affecting the normal human activities and maintaining a certain wearing comfort. At present, there are many types of flexible sensors for smart textiles, with different classification methods. For example, according to the classification of signal conversion mechanism, flexible sensors mainly include capacitive, resistive, inductive, fiber optic flexible sensors[8]; according to the classification of fabric structure, flexible sensors mainly include flexible sensors based on knitted structure[9] and flexible sensors based on woven structure[10].

Effective conversion of external stimuli into electrical signals is a key technology for flexible sensor applications. According to the different electrical signal conversion mechanisms and operating principles of sensors, the common sensors with relatively mature technologies and a wide range of applications can be classified into four categories: Pressure-electrical-based flexible sensors, strain-electrical-based flexible sensors, flexible fiber-optic sensors, and flexible gas-sensitive sensors.

1.1. Flexible pressure-electrical sensors

Flexible pressure-electrical sensors include flexible capacitive sensors, flexible piezoresistive sensors, flexible piezoelectric sensors, etc., which indirectly detect changes in external pressure through changes in capacitance, current or voltage of the measured object under pressure. Flexible pressure-electrical sensors are widely used because of their high testing sensitivity and accuracy.

Flexible capacitive sensors generally use flexible materials (conductive films, fibers, yarns, fabrics, etc.) as capacitor pole plates and foam, rubber, etc. as spacer layers, and according to the principle of capacitor operation, the sensor will sense the amount of change in pressure or shear force to the user[11]. This flexible sensor can be combined with textiles to prepare smart textiles that can sense changes in external forces, have a simple structure, high sensitivity and are soft and easily deformable, and its greatest advantage is that it can achieve the detection of small static external forces.

Compared to capacitive sensors, flexible piezoresistive sensors are characterized by small size, various forms, high resolution and easy integration with textiles. Piezoresistive sensors are sensors made based on the piezoresistive effect of materials as well as integrated circuits[12,13], which, when subjected to pressure, generate electrical conductivity due to the transfer between metal particles within the sensing material, and infer the magnitude of the applied pressure by measuring the change in resistance. This sensor usually uses a composite material with a high sensitivity coefficient and good piezoresistive properties, such as a carbon-based material or graphene, as the piezoresistive material. Combining this sensor with textiles can be used to measure parameters such as pressure and acceleration acting on the fabric. However, pressure sensors based on piezoresistive and capacitive signal mechanisms suffer from problems such as signal crosstalk, which affects their measurement accuracy.

Flexible piezoelectric sensors are sensors made by applying pressure to piezoelectric materials to produce a piezoelectric effect[14]. The piezoelectric material is a special material that can generate an electrical charge under mechanical pressure, and currently most of the conductive material composite piezoelectric film with high piezoelectric coefficient and high sensitivity or bi-polyvinyl fluoride (PVDF) film. Intelligent textiles made of piezoelectric films can detect the pressure generated by the bending of human body parts, or detect the stability of human foot gait, etc. They have the advantages of high sensitivity, simple structure design and stable performance. Since the output is a voltage signal, the flexible piezoelectric sensor is relatively simple in circuit design and signal acquisition, with high sensitivity and high signal-to-noise ratio; however, these sensors can produce charge leakage and poor DC responsiveness of the output.

1.2. Flexible strain-electrical sensors

Flexible strain-electrical sensor is a kind of sensor with “strain-resistance effect”, such as pull-resistive sensors. Flexible tension-resistance sensors, also known as flexible strain sensors[15], are based on the same principle as piezoresistive sensors, i.e., the electrical signal of the sensor itself changes when the material or fabric is subjected to mechanical stress, which converts the local deformation of the object under test into an intuitively measurable electrical change. These sensors have low preparation costs, and the test principle and acquisition method are simple, with the advantages of good comfort and high sensitivity. In the field of smart textiles, these sensors are usually classified according to the preparation method and include mainly flexible coated strain sensors and flexible inlaid strain sensors.

The coated strain sensors are represented by polypyrrole-coated flexible sensors[16], which are made by coating the fabric surface with conductive polymers in the form of coating process (e.g., textile printing, collage). The coating material usually selects the carbon composite coating[17], and this polymer conductive coating has good adhesion on the fabric, as well as good sensitivity and linear correlation; however, there are problems such as coating process difficulties and easy to cause rough cracking of the surface coating.

The embedded strain sensor uses conductive fiber and yarn material as the main sensing element, and the corresponding conductive textile can be prepared by interweaving in woven or knitted form. The measurement is achieved by the deformation of the yarn coil structure under the action of the strain force, which affects the change in resistance. Commonly used textile conductive fiber materials include three types: metal conductive fibers, carbon fibers and organic conductive fibers[18]. Among them, the composite organic conductive fiber is the conductive properties of the yarn and other yarns through the core yarn and other composite conductive yarn, its comprehensive performance is the most excellent. The strain sensors prepared from conductive fiber yarns have the advantages of excellent sensitivity, easy measurement, and high wearing comfort; however, due to the special characteristics of the coil structure, the wash ability and repeatability for wearable textiles still need further improvement.

1.3. Flexible fiber optic sensors

The measured physical quantity is converted into a sensor for the change of optical characteristics[19]. Among the optical properties include characteristic parameters such as the amplitude, phase, and wavelength of the light wave. Compared with the traditional flexible resistive sensors, flexible optical fiber sensors have the advantages of light weight, high accuracy, fast response, good repeatability as well as high stability and low cost. The current domestic and international literature explores the weaving of optical fibers into textiles to constitute fiber optic sensors. In addition to sensing signals such as pressure, temperature, velocity, vibration and angle, fiber optic sensors can be used to measure tensile stress as well as changes in displacement. Such embedded fiber-optic flexible sensors can be used to measure small strain situations[20], such as measuring bending changes in human elbows and finger joints, or subtle strain signals associated with breathing.

1.4. Flexible gas sensitive sensors

Flexible gas sensors, also known as flexible gas sensors[21], are based on the measurement principle that when the sensor is in a gaseous environment, the conductivity of the sensor changes with the concentration and type of the gas being measured in the air, responding to the contact gas and converting it into an electrical signal. This sensor is widely used in environmental pollution detection, public safety and other fields, but also for medical diagnosis. The new gas-sensitive sensors currently used for wearable are generally constructed on a flexible stretchable substrate with polymer complex thin-film sensors, which have high gas-sensitive performance, small size, light weight, good stability, flexible and stretchable. The integration of flexible gas-sensitive sensors for detecting different gas types on textiles can be used to make smart textiles, such as clothing and multifunctional masks.

2. Application of flexible sensors

In the future development of wearable devices, flexible sensors will play a pivotal role. At present, the research of flexible sensors for smart textiles mainly focuses on the detection of human health conditions, such as the detection of basic human physiological parameters, pressure detection and motion recognition. The research on flexible sensors for smart textiles mainly focuses on the detection of human health conditions, such as the detection of basic physiological parameters, pressure detection and motion recognition.

2.1. Physiological parameters testing

Respiration, heart rate and pulse are important physiological parameters of the human body, which play an important reference value in the daily life monitoring of the human body. Therefore, when selecting sensors, try to choose flexible sensors with excellent sensitivity, high accuracy and high elasticity of the substrate.

The skin surface is deformed by stretching when the human body breathes, and physiological data such as respiratory rate and depth can be measured indirectly by detecting this deformation, so the sensors that can fit the skin, are portable and have high sensitivity and repeatability have obvious advantages. De Jonckheere et al.[22] made fiber-optic sensors by crocheting optical fibers into elastic fabrics to compensate for the effect of metallic materials on the detection signal in MRI in medicine. The stretching motion of the abdomen and chest caused by respiration leads to deformation of the fiber optic position in the fabric, and the change of the optical signal is measured to monitor the patient's respiratory status. Guo et al.[23] used six different materials of conductive yarns to embed the sensor into a seamless specimen in the form of partial yarn addition, and simulated the skin deformation caused by human respiration and heartbeat by performing tensile recovery experiments with different sizes of specimens at constant elongation. Huang et al.[24] studied three main factors affecting the fabric sensor: Yarn structure, textile structure, and fabric structure, and the detection of human respiration rate can be achieved by using single and double conductive yarns wrapped around the core fibers and woven into the fabric. In addition, due to the extended movement of human respiration, it makes the mutual pressure effect between the body surface and the intimate garment, and the respiratory changes can be easily detected by the pressure sensor. Kang et al.[25] used silver-plated elastic fabric and silver-plated non-elastic fabric as the two parallel pole plates of a capacitor, and through the contraction and deformation of the electrode plate under the action of external pressure, resulting in the capacitance between the two parallel pole plates. The change in capacitance between the two parallel plates was caused by the contraction and deformation of the electrode plates under external pressure, which indirectly monitored the human respiratory condition.

Due to the irregular and complex surface structure of the human body, the detection of weak heart rate and pulse signals requires sensors that are thin, light and extremely sensitive. In recent years, fiber optic sensors have been widely used to develop a variety of pulse, heart rate, respiration and other detection devices. Tian et al.[26] proposed a pulse detection method based on fiber Bragg grating sensor, which is implanted into the air layer of the fabric by cross-machine weaving, and uses the change in wavelength and amplitude of the reflection center of the fiber grating caused by heart vibration to achieve real-time online acquisition and analysis of pulse signals. Yang et al.[27] designed a new fiber-optic microbending sensor based on the fiber-optic microbending effect, using multimode optical fibers clamped to parallel strips to form a microbending structure, which is sewn together on an elastic base fabric for measuring human heartbeat and respiration rate when standing and sitting. In addition, fabric-based temperature sensors can also be used to sense human temperature changes, such as the use of wire cores in the weft direction and fabric integration to prepare a wearable temperature monitoring system, temperature sensors sense temperature, conductive yarn transmission data, so that the signal of body temperature changes can be obtained[28].

In practical applications, in order to optimize the sensitivity of the sensor, reduce the signal shift, and seek a more stable sensor structure, Peng et al.[29] improved the sensitivity of the contact resistance by coating silicone at the contact points between the wire yarns to increase the signal repeatability. However, the reliability and stability of flexible sensors are easily affected by external mechanical friction and water washing during the process of providing long-term sensing and feedback on human health conditions. Although Cai et al.[30] studied the performance stability of flexible sensors under a certain number of washes as well as temperature, they have not really been able to meet the performance requirements of actual consumers in their daily lives and work.

2.2. Pressure testing

Flexible pressure sensors have a wide range of applications in smart clothing and other applications, where they are mainly used to detect the pressure distribution generated by textiles on the human body.

The sensor resistance-strain principle was used to indirectly calculate the pressure values of various parts of human dressing. Wang[31] explored the relationship between the equivalent resistance of the flexible sensor and the tensile strain by analyzing the relationship between the equivalent resistance of the flexible sensor and the tensile strain of the knitted fabric, and integrated the correlation between the garment pressure and the tensile strain of the knitted fabric. According to the change of sensor resistance, the undergarment pressure distribution in the main parts of the human body and the influence of garment margin on the undergarment pressure were objectively evaluated. In addition, the flexible pressure sensor can be used to conduct static garment pressure test directly. Wang[32] prepared PVDF nanofiber membrane by electrostatic spinning method and designed and developed a flexible pressure sensor that can be used for human garment pressure testing and monitoring, and the complex human garment pressure can be measured realistically using its piezoelectric effect. Yi et al.[33] produced a conductive knitted fabric coated with carbon-based conductive composites with good piezoresistive properties and high sensitivity when the non-conductive surface is in contact with the indenter, which can be used as a sensitive element of the sensor for garment pressure and flexible human platform pressure measurement. Pang et al.[34] used a flexible pressure sensor to design and build a pressure sock pressure test platform, and the test obtained the pressure change values and pressure distribution on multiple parts of the circumference such as ankle and calf. In addition, in the study of dynamic pressure contact between clothing and human skin, Tang et al.[35] built a dynamic pressure testing system for sportswear based on flexible piezoresistive sensors, signal conditioning modules and graphical programming language to achieve the acquisition, processing and display of human dynamic pressure data.

In addition to measuring the distribution of garment pressure on the human body as well as the size of the intimate apparel, flexible pressure sensors can also be used to detect the distribution of plantar pressure[36]. Jin et al.[37] developed a piezoelectric test insole using PVDF piezoelectric film, and proposed the use of a multilayer sense core structure to improve the signal response of the sensor and improve the elastic hysteresis of the flexible sensor, which can record the distribution of plantar pressure under different states of motion, in response to the common frequency response problem of flexible sensors. In other textile manufacturing fields, Lee et al.[38] developed a textile structured fiber optic pressure sensor for car cushions, in which polymer optical fibers and yarns are cross-woven into a mesh structure, and the optical fibers produce bending deformation when the cushion is subjected to a large pressure load.

Flexible pressure sensors can be used not only in textiles directly, but also in the inspection of garment ready-to-wear. Jin[39] combined flexible pressure sensors with airbags and proposed an intelligent hanger as well as a mathematical model and control method to attach the flexible pressure sensor to the hanger, which can more directly detect the target deformation and eventually display the degree of fit of the clothes and the hanger, providing a fast and accurate method for garment inspection. In recent years, the research and development of flexible robotic pressure-sensitive skin further realized the intelligence of robots, and Tian et al.[40] integrated carbon black conductive material with a flexible substrate to develop a flexible robotic pressure capacitive sensor skin with a 3-layer composite structure, which can be attached to a robot hand for grasping, lifting and gripping application operations.

2.3. Motion detection

Currently, flexible sensors combined with existing wireless transmission technologies are widely used in the detection of human motion behavior. In addition to detecting subtle movements of the chest as well as the neck during breathing or speaking in human motion, the sensors can be used to capture a wide range of motion, such as the bending motion of hands, arms and legs.

Xie[41] used weft knitting technology to knit silver-plated nylon conductive yarn into a flexible knitted sensor, analyzed the electrical-mechanical properties of the sensor under bi-directional stretching and established a related theoretical model, and applied it to the recognition and monitoring of limb movements in a monitoring suit. Helmer et al.[42] tied a strain knitted sensor to the knee, and measured various movement postures of athletes' lower limbs when they played soccer at different times and with different movement amplitudes and speeds. Tognetti et al.[43] developed a strain sensor based on single-layer and double-layer knitted piezoelectric fabric KPF for measuring limb movement stretching and bending. The device measured knee movements at rest and in motion, respectively, and compared the measurements with those of a standard phase indicator, and the experiments confirmed the better performance of the double-layer knitted piezoelectric sensor. Zhang et al.[44] prepared three types of polypyrrole conductive fabrics by in situ polymerization method, and used these three conductive fabrics as sensing elements to fabricate posture monitoring fabric sensors, and performed quasi-static tests of upper limb motion states, respectively. By observing the changes of tensile resistance of polypyrrole conductive fabrics and their directional differences, the bending, rotation and their compound movements of the upper limbs could be accurately reflected.

In addition to the use of strain sensors to detect the deformation changes generated by the bending motion of the human body, Shi et al.[45] also proposed a pressure sensor-based human motion recognition method, which placed pressure-sensitive sensors in the insole and obtained the distance and time of human motion as well as the number of exercises based on the changes of the collected pressure data, and also extracted the motion intensity data such as the difficulty of the motion. Yang et al.[46] demonstrated the application of piezoelectric thin-film flexible sensors in table tennis motion detection by attaching DT1-028K piezoelectric film to the elbow of a table tennis suit, and when the paddle is swung, the elbow bends to make the voltage change between the two electrodes of the piezoelectric film, which can detect the number of single hits, frequency and total number of hits in real time.

With the rapid development of human-computer interaction and emotion technology, Su et al.[47] first proposed the concept of expression recognition through multi-channel analysis of piezoresistive flexible wearable electronic sensors. By attaching the flexible sensor to the human body skin, the response of human facial expressions under different environmental and psychological conditions can be monitored in real time.

At present, the data monitored by the flexible sensors applied to human motion detection is relatively single, mainly based on basic human flexion and extension movements, and the data analysis in the medical or fitness field is not fully matched with the actual needs, and the data mining, comprehensive analysis and utilization needs to be continuously improved. In addition, motion detection is a long-time output and feedback process, especially as a module to collect and transmit data information, the working mode of the sensor is often constrained by the battery energy, insufficient energy supply will affect the accuracy and stability of data acquisition.

3. Conclusions

Compared with traditional wearable sensors, flexible sensors have the characteristics of lightness and softness, outstanding electrical performance, good comfort and high integration, which influence the functional design and development direction of future wearable devices. However, the rapid development of intelligent flexible sensors is accompanied by some problems.

The current research and development of flexible sensors to conductive fabrics as the main sensing element, these sensors usually have a poor feel of the coating, the lack of wash ability, complex processing technology and processing costs and other shortcomings, cannot meet the design goals and use the performance requirements, it is difficult to adapt to the future of flexible sensors, large-scale, low-cost and high-efficiency production mode. In addition, the energy consumption and self-drive of flexible sensors is an important condition to ensure the stability of signal transmission, while the existing energy supply of sensors and the actual demand still exists a large gap.

The real development and application of flexible sensors also need to rely on more advanced research and development of new materials and the development of computer technology, with the recent years of printed electronics and 3D printing technology has received widespread attention to flexible sensors as the representative of the new printed electronic components, with its efficient and environmentally friendly, convenient and more customized advantages, and gradually to the advanced manufacturing of intelligent and flexible wearable products.

In terms of energy supply, considering the popularity of wireless charging technology in electronic products, it is possible to use relevant technologies or accept energy from the electromagnetic field in the environment or in the form of electromagnetic waves and convert it into electrical energy as a charging source. As far as battery technology is concerned, the development of electrochemical batteries with high energy and small size is a topic that researchers need to focus on.

While measuring the basic physical quantities of human daily physiology as well as activities, flexible sensors should also broaden the scope of their detection and combine with the data recording and feedback functions of mobile communication devices to meet consumers' needs for customization and personalization of smart textiles and adapt to different people and occasions. The integration of nanotechnology can integrate flexible sensors with different functions as well as other sensors in wearable textiles to realize highly integrated, tiny and diversified measurement functions of smart textiles.

Conflict of interest

The authors declare no conflict of interest.

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REVIEW ARTICLE

A review of wearable antenna research

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ABSTRACT

With the rapid popularization of IOT applications, wearable devices have been widely used in many fields such as sports and health, entertainment and medical assistance. In addition to the early wearable form, more attachment and implantable wearable devices are constantly developed, and the development of these new wearable devices is largely due to the development of miniaturization antenna technology. This paper discusses the different realization methods and performance index requirements of wearable antenna, introduces the research situation of wearable antenna at home and abroad in recent years, and analyzes the development trend of wearable antenna.

Keywords: wearable antenna; fabric antenna; button antenna; flexible antenna; specific absorption rate; multi-frequency multimode

1. Introduction

In recent years, the market for wearable devices has grown rapidly, and various forms of wearable devices continue to emerge, which has been widely used in entertainment and leisure, positioning and trajectory tracking, health management, medical assistance, and military fields[1]. Body area network communication and wearable devices have become one of the research hotspots in the field of scientific research. **Figure 1** shows the trend curve of the search quantity keyword "Wearable Technology" with Google search engine since 2013. It can be seen that from 2013 to 2015, the search popularity of wearable technology showed a nearly linear upward trend. With the increasing maturity of wearable technology, various wearable products pour into ordinary lives on a large scale. Wearable devices refer to the application of wearable technology to intelligently configure people's daily wear, and implanted various sensing, recognition, connection and cloud services into people's glasses, watches, bracelets, clothing, shoes and socks and other daily wear. Wearable devices are not only a traditional manufacturing hardware device, but also a kind of cross-border equipment that realizes data interaction and cloud interaction through mobile Internet. Its emergence will bring great changes to people's life and cognition.

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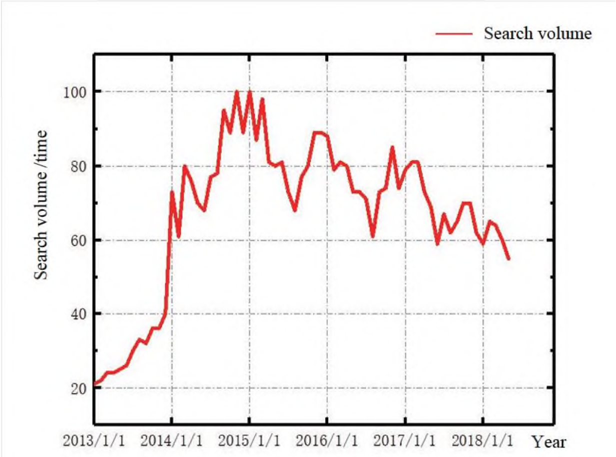

Figure 1. Search volume distribution map of "Wearable Technology" on Google since 2013.

In wearable devices, the wearable antenna plays a crucial role. Wearable antenna plays a role of data transmission, and the performance of the antenna directly affects the performance of the whole system. Wearable antennas originated from military applications, and the earliest individual soldier equipped antenna was the whip antenna. This antenna was exposed to soldiers' head, which could easily reveal the position of soldiers and was not conducive to combat. Subsequently, some antennas hidden in clothes or helmets are gradually removed whip antenna was replaced. Wearable antennas are antennas worn on the human body as the main component of wearable devices, it can be integrated into clothes, shoes, watches and other attachments. In addition to realizing the basic functions of transmitting and receiving electromagnetic waves, the wearable antenna needs to meet the comfort of the wearer to the greatest extent, and ensure the safety of the wearer[3].

This paper investigates the antenna performance, classification of wearable antennas, and future development trend of wearable antenna.

2. Wearable antenna performance

Compared with traditional antennas, wearable antennas have more special requirements in shape and size. When a wearable antenna is worn on the chest or back, it can be a little larger and not limited in shape. However, according to the appearance requirements, the thickness of such antennas should not be too thick. When the wearable antenna is worn at the back of the neck, arm and waist, the appearance can be designed in the form of belt and watch according to the different locations. At this time, due to the activities of the human body, high requirements are put forward for the bending characteristics of the antenna. When wearable antennas are applied in the motion field, the quality and bending characteristics of antennas are relatively higher. For applications in the medical field, wearable antennas require a more sophisticated design in the sensitivity of security and data transmission.

2.1. Antenna efficiency

Communication efficiency is seen as an important component in green radio and mobile communication environments, especially in telemedicine systems, and improving wearable antenna efficiency is expected to be a future research content. Firstly, the wearable device is equipped with light and small batteries to last for a long time. Secondly, when the wearable antenna is installed on the human body, the reflection coefficient and efficiency of the antenna will be affected due to the destructive nature of the human body. Improving the working efficiency of wearable antennas can be used to solve the above problems. Improving the efficiency of the wearable antenna is to reduce the loss caused by the antenna radiation. Choosing the substrate material with the appropriate dielectric constant will help to reduce the loss brought by the antenna material.

2.2. Robustness

Because wearable devices are worn on the human body, human activities will bend the antenna, which will cause the working frequency of the antenna deviation. Then in the design process, we need to consider the robust of wearable antenna nature. The robustness of the antenna is the property of maintaining certain performance when parameters such as structure and size are changed. Increasing the bandwidth of wearable antenna and compensating the frequency through reconfigurable design are the methods used in most studies now.

2.3. Specific absorption rate, SAR

In the process of body domain network communication, on the one hand, because the activities and posture of the human body will change, on the other hand, the position of the communication gateway relative to the device node is not fixed[3], therefore, the antenna is required to have a wide electromagnetic wave radiation angle. However, the radiation of electromagnetic waves is harmful to the human body, and the back radiation of its antenna is not the desired direction. Especially when wearable devices are worn on the human head, health considerations become more important. In the process of energy transmission of wireless communication, part of the energy of electromagnetic field in the transmission process will be absorbed by human tissue, producing a heating effect on the human body. Therefore, semi-omnidirectional radiation is a property pursued by wearable antennas. Wireless communication devices define the specific absorption rate to characterize how much of the radiation dose generated by the antenna is absorbed by the human body. At present, there are two international standards, one is the standard of 1.6 W/kg for 1 g of human tissue designated by IEEE, and the standard of 2 W/kg established by the International Commission on Non-lonizing Radiation Protection (ICNIRP)[4]. Its specific meaning is to take 6 minutes as the timing unit, per kilogram of human tissue absorption of electromagnetic radiation energy should not exceed 2 watts. In most current studies, good conductor ground or metamaterial structure is often used to reduce the back radiation of antenna, improve the main lobe gain of antenna radiation, and reduce SAR.

3. Wearable antenna classification

In recent years, in addition to traditional antennas, three new types of wearable antennas have emerged: Fabric antennas, button antennas, and flexible antennas.

3.1. Fabric antenna

Fabric antenna refers to a wearable antenna composed of fabric material, conductive patch and ground as the substrate plane. It has a planar structure and good integration, and it is a wearable antenna type with great potential. Fabric antennas can be integrated into clothing, furniture, or other fabric materials. Compared with conventional antennas, fabric antennas need to meet the additional requirements of drapability. Drapability means that it can be bent in any direction. Since the flexible substrate has only one specific bending direction, so that this characteristic of the fabric antenna is exactly in contrast with a standard flexible substrate. In addition, in wearable applications, the fabric antenna must be planar without affecting the wearer. Common fabric substrate materials include denim, wool, felt, etc. This material is light in quality, can be bent, similar to the material of clothes, and easy to integrate into clothes. Different types of fabric antenna characteristics are described in the literature[5]. In the wearable fabric antennas, the conductive materials are mainly woven, sewing, printed and copper-coated fabric cloth[3].

Joler et al. proposed an armband polarized wearable fabric antenna with a frequency band of 2.45 GHz, as shown in **Figure 2**[6]. The antenna consists of pure fabric material, which is small and thin enough to facilitate integration into standard armbands. The fabric antenna can reach 5.6% impedance bandwidth, gain 5.04 dBi at 2.5 GHz, and have a radiation efficiency of 55.3%[6], which can well meet the needs of wearable devices.

Figure 2. Plane diagram of sleeve antenna.

Typically, dual-frequency, dual-mode antennas are achieved by integrating two radiators, these radiators are powered by either single-port or two-port systems. Each radiator is operated at a different frequency and provides different radiation modes. Roy B. V. B. Simorangkir proposed a dual-frequency 2.45 GHz and 5.8 GHz dual-mode wearable antenna with the structure shown in **Figure 3**[7]. Two kinds of radiation characteristics are realized by using the inherent TM11 mode and TM02 mode of the circularly polarized patch antenna, namely, patch-like radiation for the external link and unipolar radiation for the internal link. The short pins and two arc grooves are used to tune the two modes to the desired operating frequency. This method can be used to implement a simple structured dual-frequency dual-mode antenna. Another advantage of the proposed antenna is that it uses a silver fabric integrated into a flexible polydimethylsiloxane substrate, making it more suitable for the wearable application[7]. Literature[7] simulated the performance of the antenna when attached to the human surface and showed that the human medium has little influence on the performance of the antenna. When placed on the mannequin, the 84 MHz and 247 MHz bandwidth were measured at the 2.45 GHz and 5.8 GHz frequency bands, respectively, and achieved gains of 4.16 dBi and 4.34 dBi, respectively, indicating their promising applicability to body area network communications.

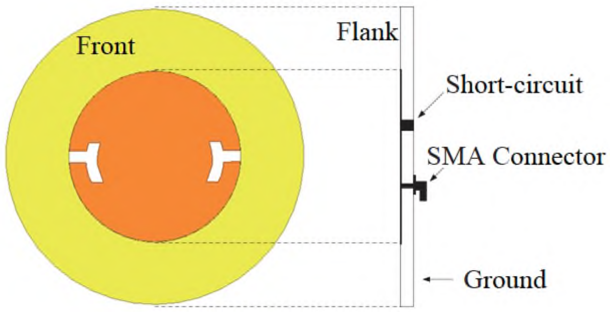

Figure 3. Wearable dual-frequency dual-mode fabric antenna.

Existing literature has disclosed a variety of design forms for wearable antennas, it mainly includes the dorsal cavity type[8] , microband[9] , fall F, flat surface[10], and with a vertical monopole antenna[11,12]. These antennas have narrow bandwidth, large area and high front-rear ratio (FBR), and are strictly affected by the body tissue repeat. Documents [13,16] propose using the electromagnetic band gap EBG structure in a 2.4 GHz metamaterial textile antenna. The introduction of an EBG structure in the wearable antenna design reduces the back-direction radiation, improves the front-rear ratio, and reduces the SAR in the tissue. However, such a structure has the obvious drawback that most EBG-based design sizes are relatively large[17]. Based on these features, Adel Y. I. Ashyap et al. proposed a 2.4GHz compact wearable antenna with a new miniaturized electromagnetic band gap structure, as shown in **Figure 4**[18]. The EBG structure reduces the dorsal radiation, increases the front and rear ratio by 15.5 dB, and separates the impact of the antenna on the human body. When the antenna is attached to the human surface, the antenna resonance characteristics are basically unaffected. The proposed antenna has a 27% (2.17 GHz–2.83 GHz) impedance bandwidth, with the gain increased to 7.8 dBi and a SAR reduction by more than 95%[18]. The resonant frequency and bandwidth are also largely constant in the bending test.

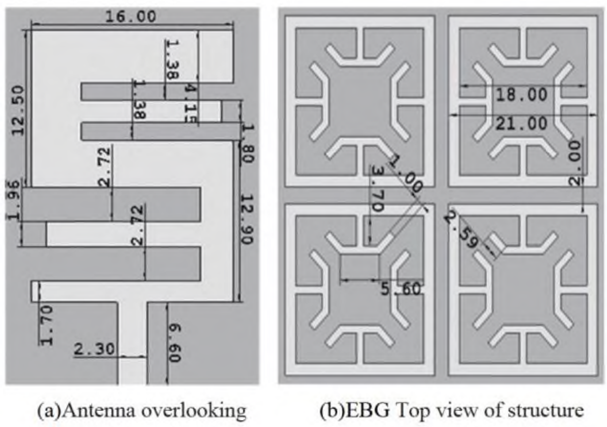

Figure 4. Antenna and EBG structure.

David Ferreira et al. introduced the influence of the bending of a rectangular textile patch antenna working at 2.4 GHz industrial, scientific and medical (ISM) frequency band on the performance. The substrate of the antenna is made of denim textile and conductive layers made of copper and nickel-coated polyester fabric. The substrate of the antenna is made of denim fabric, and the conductive layer is made of polyester fabric coated with copper and nickel. The antenna provides a maximum gain of about 4 dBi and a 70° half power beam width (HPBW) at the plane position. When subjected to wrist equivalent bending, the gain decreased by 2 dB, HPBW increased by approximately 25°, and the anterior-posterior radiation ratio decreased. On the other hand, the antenna shown in **Figure 5** bends in different directions, and the resonant frequency deviates to different degrees according to whether the antenna bends around its width direction or its length direction. When turning the antenna around its width in the bending of the direction, a shift towards low frequency is observed, while bending in the direction of the antenna length results in a frequency offset towards high frequency[19]. Therefore, when designing textile patch antennas for WBAN applications, research should be conducted according to the possible bending degree in the application scenario, as the resonant frequency offset relative to the curvature angle of the antenna may seriously affect the performance of the antenna.

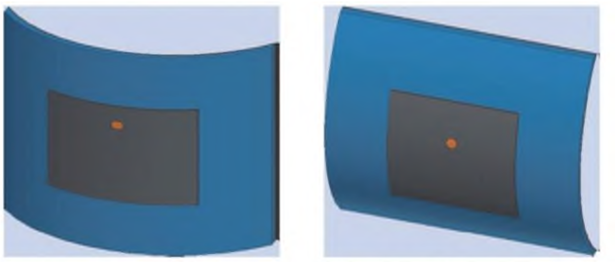
(a) Bending along antenna width (b) Bending along antenna length

Figure 5. Fabric antenna bending scenario.

It can be seen from the above examples that the research on fabric antenna is particularly important in the selection of substrate materials, and substrate materials have a great impact on antenna efficiency. At the same time, the influence of bending effect on antenna performance will also cause different degrees according to the change of direction. In terms of considering the impact of the antenna on the human body radiation, most studies choose a slightly larger bottom surface or EBG structure to reduce the back direction radiation of the antenna, so as to ensure the safety of the human body. Fabric antenna is a great type of antenna for wearable applications.

3.2. Button antenna

The button antenna is very practical. A hard, wearable antenna with a button-like shape that can be easily integrated into the wearer's clothing. Common button antennas include circular patch antenna and monopole antenna. By designing different sizes of radiation patch, the resonant frequency of the antenna can be adjusted, and multi-frequency characteristics can be obtained when multiple resonant structures are loaded.

Zhang proposes a dual-frequency dual-mode button antenna for human center communication with the structure shown in **Figure 6**[20]. The button antenna in literature[21,23] has only one omnidirectional radiation mode. Zhang designs a dual-mode omnidirectional radiation antenna structure consisting of spiral inverted F antenna and metal reflector. In the low frequency band, the inverted F antenna forms a radiation direction map parallel to the body surface, which can realize the communication between multiple wearable devices on the body surface. In the high-frequency band, the high-order mode forms the radiation direction map of the vertical antenna surface, thus realizing the communication between the wearable device and the in vitro device. At the low and high frequencies, the phantom-measured peak gain was 0.6 dBi and 4.3 dBi, respectively. The antenna has an efficiency of 46.3% in low frequency band and 69.3% in high frequency band. With the overall miniaturization, such button antennas can be integrated into the clothing, so it is expected to become the main form of wearable device antenna design in the future[20].

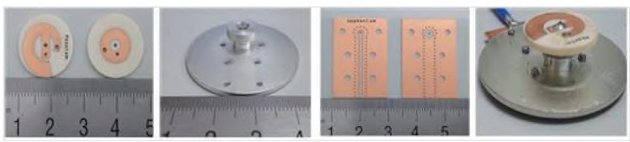
(a) Two-side metal of dielectric substrate (b) Metal wheel (c) Ground coplanar waveguide feed (d) Overall structure diagram

Figure 6. Button antenna figure.

Compared to the button antenna in the literature[21,28], Hu introduces a new wearable button antenna for wireless LAN. The antenna consists of buttons approximately 16 mm in diameter with patches mounted on the top of the dielectric substrate. The button is located on top of the textile substrate and conductive textile floor and will be integrated into the garment, structured as shown in **Figure 7**[29]. The main feature of this antenna is that it has two different types of radiation direction maps: Monpolar radiation for 2.4 GHz band for bulk communication and broadband radiation for 5 GHz band for in vitro communication. It achieves a radiation efficiency of about 90%, a result higher than the performance of other textile antennas in the literature[29].

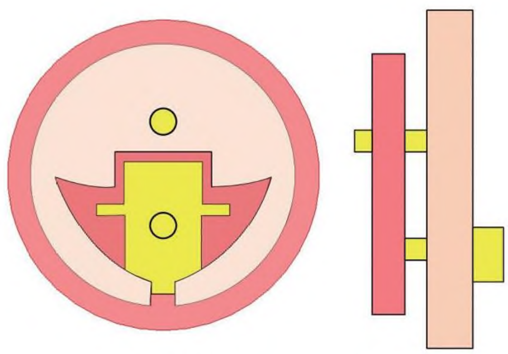

Figure 7. Structure diagram of button antenna.

Chen uses the antenna design concept of removable radiation units to provide the geometric refactoring of modules for wearable applications[30]. Different modular interchangeable microband patch units with snap buttons, whether as RF connections or mechanical fixing mechanisms, obtain specific operating frequency and radiation characteristics. A unique source of the design sharing a common feed structure for all configurations, the feed structure consists of a snap button, a ground plane and a double substrate coupled with the feed. Firstly, a removable patch is proposed that provides an interchangeable right-handed circular polarization (RHCP) and left-handed circular polarization (LHCP) at 5 GHz. Secondly, a planar inverted F antenna (PIFA) with an interchangeable resonance frequency of the 2.4 GHz and 5.3 GHz frequency bands used for the wireless LAN is presented. Finally, a patch module was designed for the 8GHz operation to show the versatility of frequency modularity. This antenna design has the advantage of low manufacturing and maintenance cost, realizing the dynamic configurable feature of multifunctional wearable systems in a passive way[30].

3.3. Flexible antenna

One of the main challenges for wearable electronic devices is to achieve flexible, ubiquitous, robust and low-cost wearable antennas, while exhibiting RF properties similar to rigid copper. With this in mind, flexible wearable antennas can address this challenge very well.

Roy BVB. Simorangkir proposed a new approach in 2018 to achieve a robust, flexible, and electronically tunable flexible wearable antenna. The conductive fabric forms a conductive part of the antenna on a polydimethylsiloxane (PDMS) substrate. The aggregate (active and passive) elements required for the antenna, electronic tuning, and RF choke control will be fully enclosed in the additional layer PDMS, as shown in **Figure 8**[31]. Close to the human model, continuous frequency tuning from 2.3 GHz to 2.68 GHz had an average bandwidth of 3.3% and an average peak gain of 2.6 dBi. After extreme bending (bending radius of 28 mm) and washing, the antenna can still maintain the overall antenna performance, including a good frequency refactoring from 2.3 GHz to 2.68 GHz[31].

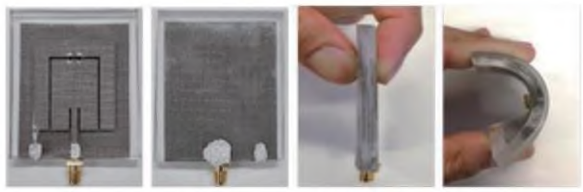

Figure 8. Reconfigurable antenna diagram.

Zahir Hamouda introduces an elliptic monopole flexible antenna fed by a coplanar waveguide that uses a kapton substrate and optimizes for frequencies from 1 GHz to 8 GHz[32] . Maximum gain as measured at 5.8 GHz is 1.86 dBi (without bending) and 3.1 dBi (under bending). Moreover, the conductivity of the polymer is changed by changing the MWNCTs concentration in the PANI matrix to adjust the gain of the proposed organoflexible antenna (PANI / MWCNTs)[32].

4. Future development trend of wearable antenna

The wearable antenna in the bud has large size, poor bending performance and other aspects. In recent years, the wearable antennas appearing in the market have been significantly improved in terms of wearability, intelligence and security, and have their own distinctive characteristics. “Wearable” indicate the need to have very efficient portability and comfort, as well as a stylish look that appeals to users. In the future, the following performance of wearable antenna still need to be studied and improved.

4.1. Small in size, light and convenient

The ideal state for wearable antennas is not to be perceived. When used for wearing occasions, the wearable antenna should be as small as possible, light and easy to carry. When integrating the antenna into clothes, the consideration needs the comfort of the original item and not destroy the comfort experience of the wearer. In particular, the implantable antenna, which has been studied more recently, has put forward new and higher requirements for its safety, digestibility and miniaturization.

4.2. Multi-frequency ultra-broadband

Because the wearable antenna is worn on the human body, the influence of human activities or external environment will affect the working frequency of the wearable antenna, and bending or distortion will shift the working frequency of the antenna, and cannot work normally. In order not to affect the comfort of the wearer, the position of the wearable antenna should be more reasonable, which should not affect the working performance of the system. Especially when the wearable antenna is conformal with the human body, which need the normal connection to the mobile terminal device despite bending to communicate with the data. Therefore, expanding the bandwidth of the antenna and designing wearable antennas that can work in multiple frequency bands are also a direction of concern for researchers.

4.3. Strong anti-interference ability

Wearable antennas are a medium for data transmission and exchange, whose workplace is anytime, anywhere. However, the interference of other radio waves, changeable weather, accidents in the use of waves, will affect the reception and transmission of electromagnetic waves; this requires a wearable antenna with a higher anti-interference capability. For example, waterproof and dust-proof, and not afraid about the interference of electromagnetic are the characteristics of the future wearable antenna pursuit.

4.4. Low SAR

Because the wearable antenna is close to the human body, the radiation of its electromagnetic waves will have a potential impact on the human health. How to reduce the back radiation characteristics of the wearable antenna as much as possible is an important indicator to be considered in the design of the wearable antenna. How to balance the contradiction between enhancing the communication ability of equipment and reducing the radiation to human body needs designers to study and optimize the design.

5. Conclusions

Wearable devices will still grow at a relatively high rate in the next few years, the research on wearable antennas will also continue to deepen and expand. The traditional communication antenna is further planar, miniaturization, and multi-frequency multi-mode design to make it more suitable for wearable devices and body sensor network applications. Combined with new metamaterials technologies, such as electric, magnetic and left-hand materials, you can obtain higher efficiency, better front and rear ratio of wearable antenna. And with the further research of electronic skin and implantable devices, the research of flexible antenna, fabric antenna and digestible antenna will be expected to become the hot spot of wearable antenna research in the future.

Conflict of interest

The authors declare no conflict of interest.

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REVIEW ARTICLE

Research and analysis of user needs for smart clothing for the elderly

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ABSTRACT

Following the principle of "people-oriented", we explore the user needs of smart clothing for the elderly and provide reference for the development of such clothing. The target consumers of smart clothing for the elderly are divided into two categories: The elderly and the young, and the needs of elderly users are investigated by means of literature analysis and interviews. The study showed that the needs of elderly users for senior smart clothing can be divided into five areas: Physiological, psychological, aesthetic, functional and consumer; the younger group is generally willing to buy senior smart clothing for the elderly and wants functional design to focus on physiological monitoring technology and aesthetic design to focus on loose fit design and dark shades of colour matching. The findings of the study will help companies to improve their design solutions and promote the healthy development of the senior clothing market.
Keywords: smart clothing for the elderly; demand analysis; consumer willingness; research methods

1. Introduction

China refers to people over 60 years of age as elderly people. According to statistics, at the end of 2019, China's elderly population had reached 254 million, accounting for 18.1% of the total population, far exceeding the standard value for judging the ageing of the population (10% of the total population aged 60 or above), and therefore, the Fifth Plenary Session of the 19th Party Central Committee for the first time elevated actively coping with the ageing of the population to a national strategy[1]. The elderly in this new era have undergone new changes: Such as longer life expectancy, better health, more income, greater ability, higher psychological expectations and richer needs[2], and are an important part of China's mega consumption potential[3]. The Guidance on Promoting the Development of the Elderly Products Industry states that by 2025, the overall scale of the elderly products industry will exceed 5 trillion yuan, and that the elderly clothing, which is the first of "clothing, food, housing and transport", is bound to occupy a larger market share.

However, the existing elderly clothing has fewer varieties and specifications, outdated styles, low fabric, lack of design and comfort[4], ignoring the actual needs and consumption characteristics of

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the elderly groups[5], making the supply and update of the elderly clothing market more lagging behind[6]. In particular, the smart clothing for the elderly, which is still in its infancy, still has many problems, although it gives the clothing intelligent functions to prevent potential risk factors in life from causing harm to the health of the elderly[7]. In addition, more and more young people, out of filial piety, will help their elderly family members to buy high-quality and high-priced medium-and high-end clothing[6], and the phenomenon of "buy and use" consumption has emerged, so as one of the target consumer groups, the children of the elderly, their demand for smart clothing for the elderly also deserves attention. Therefore, this study will analyse the real needs of elderly smart clothing consumers and make reasonable research and development suggestions to promote the healthy development of the elderly clothing market in China.

2. Overview of smart clothing for seniors

Smart clothing for the elderly refers to clothing designed specifically for the elderly group, under the condition of ensuring wearing comfort[8], solving the inconvenience of the elderly in their daily lives[9], sensing and responding to changes in the external environment and internal state in real time[10], and realizing the information interaction between the elderly, the clothing system and the mobile terminal, generally applying advanced textile and electronic information technology, and embedding miniature wearable electronic devices into the clothing to achieve this[11].

Scholars at home and abroad have rich research results on the two major directions of senior clothing and smart clothing, however, there is a considerable lack of research on smart clothing specifically for senior groups. In recent years, with the development of smart wearable technology, some design prototypes have started to appear in the field of smart clothing for the elderly, such as monitoring clothing for the elderly living alone[12], smart clothing for the elderly against wandering[13], and sleep monitoring clothing for the elderly[14]. However, most of these achievements remain in the laboratory research stage, and it is difficult to promote them on a large scale. The fundamental reason is that they fail to balance the technical and design aspects[11], resulting in the final results failing to meet the practical needs of the target group, and it is difficult to stimulate consumers' desire to buy.

3. Analysis of the needs of elderly users

As a new product combining traditional senior clothing and smart wearable devices, smart clothing for seniors is difficult to develop, as it has to meet the wearability of everyday clothing while achieving the usability and safety of the target functions. In order to avoid useless development, it is necessary to first find out where the needs of elderly users lie in order to design well and create value. This paper uses literature analysis and interviews with four local elderly people in Suzhou to understand the physiological needs, functional needs, aesthetic needs, psychological needs and consumer needs of elderly users of smart clothing.

3.1. Physiological needs

Due to changes in body shape, most elderly people experience varying degrees of hunchbackedness, a significant increase in back waist knot length and a significant shortening of front waist knot length[15], as well as an imbalance in the waist-to-hip ratio, making it easy to form a convex abdominal body and hip convex body[16], making it difficult for the elderly to buy clothes that fit well and restricting their daily activities. Therefore, when designing garment construction, the regular size should not be used only as a design reference, and a revised fit can be achieved by increasing the amount of slack in specific body parts and using elastic fabrics. In addition, the elderly in the interviews indicated that they would prefer natural fibre fabrics because in their consciousness chemical fibre fabrics are not breathable enough and are not good for the skin, so when new fabrics are used in smart clothing for the elderly, they may be accepted by the elderly as long as they are moisture absorbing and breathable and the electronic components integrated into the fabric do not produce an obvious foreign body feeling[17].

3.2. Functional needs

Functional needs refer to the requirement for smart services beyond the traditional function of keeping the body warm and sheltered. Compared to acute diseases, the health of older people is more vulnerable to chronic non-communicable diseases such as hypertension, diabetes and cardiovascular diseases[18], most of which can be monitored and prevented by wearable devices. Smart clothing can embed more sensors to achieve accurate positioning, extensive monitoring of daily activities, and timely collection of physiological signals for older people as it has more contact with the human body than other wearable devices[19]. Older people in the interviews expressed a willingness to try out health monitoring-type functions, especially finding the fall warning function valuable for promptly notifying family members or medical personnel, but also noted that they would be concerned about the occurrence of inaccurate test results and unsafe circuitry. Therefore, while implementing the pre-defined functions, smart clothing for the elderly should also focus on the accuracy of the test results as well as the safety and reliability of the system.

3.3. Aesthetic needs

Meeting the aesthetic needs of elderly users is crucial for elderly smart clothing, as the beauty of the garment can attract consumers' attention and make it easier for the elderly to accept smart clothing[20]. Although the elderly group pays less attention to fashion trends in clothing, it does not mean that there is no pursuit of beauty[21], and their needs for clothing aesthetics include the colour, style and pattern design of clothing. Older people interviewed said they did not like bright colours, preferred neutral colours, tended to favour casual and loose styles, and would be attracted to pattern designs that incorporated traditional elements. Therefore, in the process of using e-textile technology, the aesthetics of the garment should also be taken into account, through the use of conductive yarn blends, embroidery and weaving[22], so that the electronics are integrated into the garment, rather than the simple embedded combinations that currently exist.

3.4. Psychological needs

When faced with negative events such as an empty nest, the death of a spouse, or illness, older people can gradually change from being the independent, self-reliant, caring party to the cared-for party who needs to be accompanied and given care[4]. In reality, however, most older people are reluctant to rely on their children out of excessive self-esteem and a reluctance to be in a vulnerable position. The functions of smart clothing for the elderly, such as reminding medication and fall protection, can help the elderly to take care of themselves and meet their self-esteem needs. At the same time, the terminal of the smart clothing for the elderly can also be connected to the smart phones of the children of the elderly, so that the children can understand the health status of the elderly through the interactive interface and give them timely emotional care. Therefore, the application interface design of the smart clothing system for the elderly can be divided into two categories: For the elderly, the interactive interface should focus on simplicity and high visibility to minimise cognitive barriers; for the children, the user interface should facilitate the exchange of health monitoring information and give timely reminders and suggestions.

3.5. Consumer demand

The consumption level of the elderly in the new era is not low, the consumption concept is young, for the fashionable new products often with a review component, consumption is more rational, due to the usual exposure to a single information channel, they are more willing to experience in person than advertising and other publicity[23]. Although older people have a lower level of education, their enthusiasm for the pursuit of new things is undiminished[24]. After learning about smart clothing for the elderly, the interviewees said they were willing to try the products as long as they were good enough. In addition, when it comes to clothing consumption, older people attach great importance to offline service experience and have low trust in advertisements, especially for smart clothing, and only when older users can actually feel the beneficial effects of the product will they be inclined to buy it.

4. Analysis of the needs of young people

Consumer behaviour suggests that the decision maker, purchaser and user of a product can be different people. In addition to the elderly themselves, the children and relatives of the elderly will account for a large proportion of the purchasers of smart clothing for the elderly. This paper uses a random sampling method to distribute a web-based questionnaire to young people with older people in their homes. The questionnaire is divided into four sections: Basic information about older people in their homes, consumption behaviour of existing older people's clothing, preferences for design factors of older people's smart clothing, and knowledge of and willingness to consume older people's smart clothing. When investigating the younger group's satisfaction with existing senior clothing, a four-point scale was used, with scores from 1 to 4 corresponding to "dissatisfied", "average", "more satisfied" and "very satisfied" respectively. "The higher the score, the higher the satisfaction level. A total of 224 questionnaires were returned, of which 220 were valid, with an effective rate of 98.2%.

4.1. Basic information for older people in young group homes

The results of the study show that the age of older people in the younger households is mainly between 66 and 80 years old, accounting for 67.27% of the total number of older people. The majority of older people live with their children or partners, but 13.64% of older people live alone. In modern society, older people have more and more leisure activities, with the most popular form of leisure being walking, accounting for 89.09% of the total.

4.2. Analysis of consumer behaviour of existing senior clothing

As their standard of living improves, young people often help their elderly family members to buy clothes as a sign of filial piety. The frequency and satisfaction ratings of the younger group in helping the elderly buy clothing are shown in **Table 1**. More than half of those surveyed would help the elderly buy clothing one to two times a year, and even 26.62% of the younger group said they would buy more than two times a year. This shows that the younger group is a major consumer group in the senior clothing market that should not be taken lightly. Understanding their purchasing experience and consumption behaviour towards existing senior clothing can provide a valuable reference for the future senior smart clothing consumer market. As satisfaction ratings are mainly concentrated in the 2-point scale, i.e. "average", it is clear that young consumers are not quite satisfied with the current senior clothing market.

Table 1. Frequency and satisfaction of younger age groups in helping older people to buy clothing

Purchase frequency	Number of people/person	Ratio/%	Satisfaction rating/score
More than 2 years 1 time	28	12.73	2.14
1 to 2 times/year	133	60.45	2.03
3 to 5 times/year	42	19.09	2.05
More than 5 times/year	17	7.73	2.41

The price point and satisfaction of the younger group in helping the elderly purchase clothing is shown in **Table 2**. 39.55% would choose clothing priced between $200 and $500, which shows that the younger group has better spending power and is willing to spend money on mid to high end clothing for the elderly. Analysing the data from this research, 89.55% of the younger group said that the first factor in deciding to buy clothes for the elderly was comfort level, and that cheap prices did not drive them to spend. In terms of satisfaction scores, it is not the case that the higher the price of the garment, the more satisfying it is, suggesting that the mid-end to high-end senior clothing on the market is not well received by younger consumers and that there is room for improvement.

Table 2. Price points and satisfaction of younger groups helping older people to buy clothing

Clothing price point/$	Number of people/person	Ratio/%	Satisfaction rating/score
<100	33	15.00	2.00
100–200	83	37.73	2.16
200–500	87	39.55	2.05
≥500	17	7.73	2.00

4.3. Design factor preferences for smart clothing for older people

Functional design preferences for smart clothing for the elderly

It is understood that 54.55% of the younger group said that the elderly in their family had experienced falls, more than half of them said that the elderly had common chronic diseases such as high blood pressure, and about 75% of the younger group surveyed would express concern about the decline in the physical functions of the elderly. Therefore, smart clothing for the elderly with special features can not only help the elderly to age healthily, but also relieve the pressure of caring for the elderly from younger groups. As shown in **Figure 1**, when it comes to the functional design of smart clothing for the elderly, the younger group is most interested in real-time monitoring of physiological indicators such as blood pressure, blood sugar and heart rate, as well as early warning of falls and wandering that can often occur in the elderly, while not being too interested in the function of recording exercise. It can be seen that when designing the functions of smart clothing for the elderly, the immediate needs of the users should be identified to avoid homogenisation of design, and only really good functional design can impress young consumers.

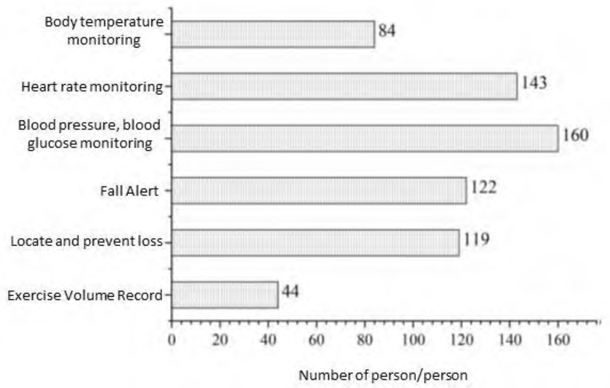

Figure 1. Functional design preferences for smart clothing for the elderly.

Aesthetic design preferences for smart clothing for the elderly

When helping older people to choose clothes, the younger group generally thought that how good the clothes looked depended on how well the fit was designed and how well the colours matched. As shown in **Figure 2**, 58.18% and 40% of the younger group thought that the fit of smart clothing for the elderly should be loose and fitted respectively, which shows that the younger group noticed the changes in the body shape of the elderly and their preference for the fit of clothing is basically the same as that of the elderly. Smart clothing for the elderly is used in their daily lives and has a casual, sporty style, so a loose fit, such as an H-shape, would be more appropriate.

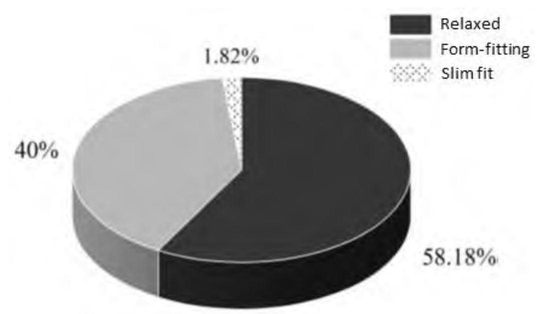

Figure 2. Percentage of pattern design preferences for smart clothing for older people.

As shown in **Figure 3**, 39.55% of the respondents thought that the colour scheme of smart clothing for the elderly was darker and more in line with what the general public would like, while 24.09% of the younger group thought that the colours of the clothing could be in brighter shades, indicating that young people want the elderly to try new colour schemes and break the stereotypes. This requires designers of smart clothing for seniors to cater to the aesthetic habits of the general public, while at the same time adding a sense of modernity and technology to the clothing through a small range of bold colour schemes to bring seniors closer to their children.

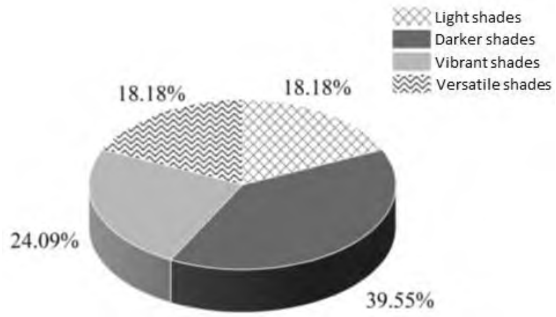

Figure 3. Percentage of colour design preferences for smart clothing for older people.

4.4. Analysis of knowledge and willingness to consume.

The level of understanding of smart clothing for the elderly among young people is shown in **Figure 4**. 57.73% of young consumers said they did not know about smart clothing for the elderly, and most of those who did know about it were still at the stage of having heard about it. This shows that smart clothing is still in the development stage and has not yet been industrialised, so its presence in the clothing consumer market is very low, inferior to other wearable devices, such as smart bracelets and smart watches.

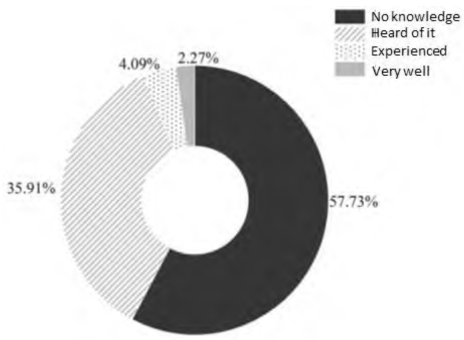

Figure 4. Percentage of people in younger age groups who are aware of the extent of smart clothing for older people.

According to the research data, it can be seen that the younger group's knowledge of senior smart clothing will have an impact on their willingness to consume. As shown in **Figure 5**, the proportion of younger groups willing to buy senior smart clothing does not become larger as their knowledge deepens, but rather young people who have heard of senior smart clothing will be more willing to buy it. This suggests that although young consumers' knowledge of smart clothing remains at a superficial level, their curiosity about new things will drive them to try new products. On the contrary, consumers who have had in-depth knowledge may have already used wearable products that are not yet mature in the current market and will be less willing to spend on smart clothing for the elderly as many aspects of them are not perfect and leave consumers with a bad user experience.

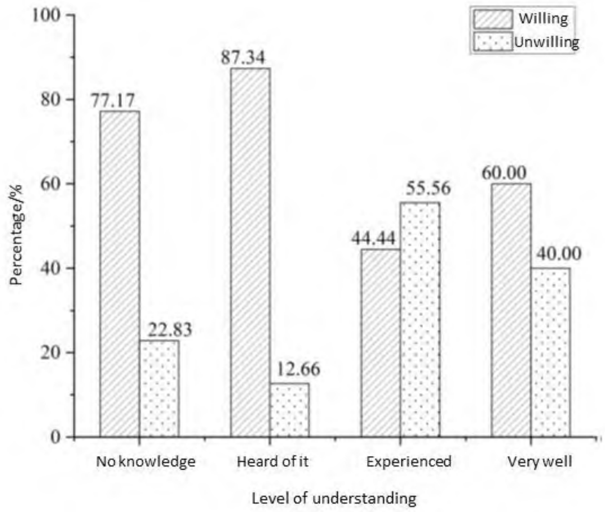

Figure 5. Comparison of the willingness to spend on smart clothing for older people among younger groups with different levels of understanding.

In this research, more than half of the survey respondents said they were willing to buy or use smart clothing for the elderly, with only 46 saying they were not, for the reasons shown in **Figure 6**, mainly because they were concerned about the inaccurate test results, overpricing and low safety of the clothing. There is a plethora of smart wearable devices on the market, especially in the smart bracelet category, but many users will find that the data from these devices is not accurate and does not give clear recommendations for treatment, and therefore does not provide substantial help to consumers. This may lead to the same concerns of the younger generation about smart clothing for older people, and places a higher demand on developers to develop products that can only be improved in order to allay the concerns of the younger generation and increase consumer willingness to buy.

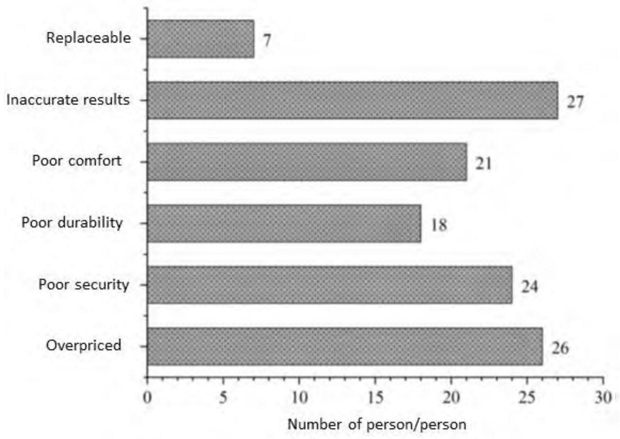

Figure 6. A comparison of the reasons for reluctance to buy smart clothing for older people among the younger age groups.

5. Conclusions

With the continuous advancement of technology, the development of smart clothing for the elderly is a development trend. In order to truly achieve "people-oriented" and demand-driven design, this paper conducts research and analysis on the needs of two major consumer groups. The results of the research show that: The elderly have high requirements for the comfort of clothing and the breathability of fabrics, and are more receptive to smart clothing that can play a safety and protection function and achieve self-care, in addition, smart clothing for the elderly should have a more exquisite appearance design and provide a good fitting experience in order to impress elderly users; most young people will help the elderly in their families to buy clothing, and the price is not low, and they have a basic understanding of the shape and colour design preferences of elderly clothing. Most young people will help their elderly family members to buy clothes, and the price is not low, and they have a basic understanding of the shape and colour design preferences of elderly clothing, but the elderly clothing currently on the market does not meet their consumption needs well.

Conflict of interest

The authors declare no conflict of interest.

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REVIEW ARTICLE

Research progress of flexible wearable stress sensor

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ABSTRACT

Flexible wearable pressure sensors are widely used in health diagnosis, sports monitoring, rehabilitation medicine, entertainment, and other fields due to some factors such as the stretch ability, bendability, light weight, portability, and excellent electrical properties. In recent years, significant progress has been made in flexible pressure sensors, and a variety of flexible pressure sensors that able to measure health status have been applied to the pulse wave, movement, respiration, and electrocardiogram (ECG) detection. However, there are still many problems to be solved in the development of flexible pressure sensors. This article summarizes the development of flexible pressure sensors in recent years, from the working principle to the structural design of the flexible pressure sensors; designs to build a high-performance flexible pressure sensors; discusses the problems existing in current flexible pressure sensors and envisions the development trend of flexible pressure sensors in the future. Flexible pressure sensors with excellent flexibility, good biocompatibility, rapid response, high sensitivity, and multifunctional integration have shown a broad application prospect.

Keywords: wearable; pressure sensor; flexible; sensor; health monitoring

1. Introduction

In recent years, the development of flexible electronics has made significant progress and has a broad market in personalized healthcare, movement monitoring, robotics, and human-machine interfaces. According to the authoritative view and statistical analysis of IDTechEx in the industry, the market share of flexible electronics will increase from USD 41.2 billion in 2020 to USDD 74 billion in 2030[1]. With the rapid expansion of the flexible electronics market, flexible electronics is expected to become an important strategic emerging industry of the country.

Monitoring of physiological health parameters is key to the prevention and diagnosis of disease. At present, the conventional rigid sensors are still being used in the monitoring of physiological signals clinically. Due to the poor strain sensing ability of conventional rigid sensors, it only suitable for flat surface measurement and unable to adapt to the curved surface of human skin, resulting in large errors during the measurement of human physiological signals and can be uncomfortable when wearing it for a long period of time. In addition,

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the bulk and weight of conventional rigid sensors limit the position and method for the measurement of physiological signals. Flexible pressure sensors have the characteristics of good flexibility, ductility, light, portability, able to be bent or even folded arbitrarily, and can adapt to complex curved surfaces during the measurement of physiological signals[2–4]. The light, portable, and flexible sensors are more convenient for people to monitor health, exercise, and other information at anytime and anywhere, and are conducive to the timely detection, prevention, or recovery of diseases.

At present, flexible wearable sensor technology has made significant progress, and a variety of flexible sensors have been widely used in the detection of pulse wave, movement, temperature, and biochemical parameters (such as glucose)[5–10]. However, there are still many problems to be solved for the development of flexible sensors. The conductive functional materials of flexible sensors can be divided into carbon-based nanomaterials, metal nanomaterials, liquid metals, conductive polymers, etc.[11] The preparation process of most conductive nanomaterials is complex, which increased the manufacturing cost of the sensors. Other than that, the production of high-performance sensors often involves complex and high-cost manufacturing processes, such as 3D printing, plasma metal deposition, silicon etching and other technologies, which made it difficult to achieve a production of large-scale, low-cost, and high-performance flexible sensors[12]. It is still an urgent problem to develop flexible pressure sensors with good mechanical compliance, light in weight, long life, high reliability, high sensitivity, rapid response, and low hysteresis that able to adapt to different applications.

The development of flexible pressure sensors in recent years is summarized from the working principle till the structural design of flexible stress sensors. The designation to build a high-performance flexible pressure sensors and the problems existing in current flexible pressure sensors are discussed, and the future development trend of flexible pressure sensors is prospected.

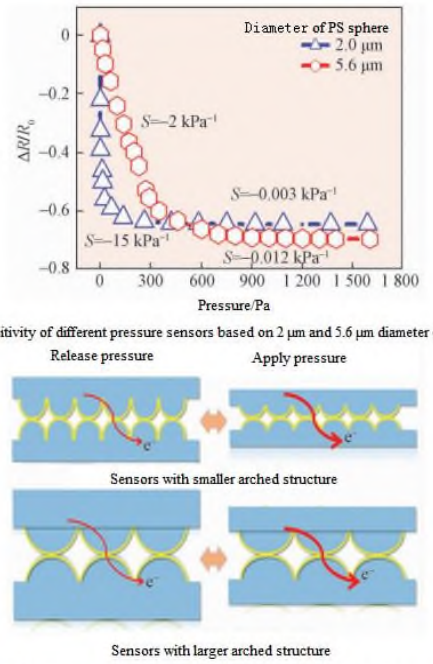
2. Classification of flexible pressure sensors

Generally, the working principle of flexible pressure sensors can be divided into flexible resistive sensors, flexible capacitive sensors, flexible piezoresistive sensors, and flexible field-effect transistors (FET) sensors.

2.1. Flexible resistive sensors

Flexible resistive sensors are flexible sensor which can convert the measurement into a measured resistive signal. Usually, the sensitivity of the sensors can be improved by changing the microstructure of the conductive layer. Through the designation of microstructure of the conductive layer, the changes in pressure to be measured causes the changes in the resistance of the sensor, thereby to achieve the design of high-sensitivity resistive sensor[13]. Zhang et al.[14] used a polystyrene (PS) microsphere-based template method to fabricate a double-layer resistive sensor with a microsphere array.

As shown in **Figure 1**, when the external pressure caused deformation to the sensor, it will change the structure of electrical conductors with microsphere then changed the contact area, which convert the pressure into a change in electrical resistance. The sensitivity of the sensor can be adjusted by changing the size of the PS microspheres and the sensor able to detect the pulse waves at our neck. Pu et al.[15] developed an electronic skin with pressure sensing and electromagnetic shielding capabilities by mimicking the epidermal and dermal layers of human skin. They used sandpaper as a template to form a polydimethylsiloxane (PDMS) film with rough surfaces, then the silver nanowires were spin coated on the rough surface of PDSM film, a silver nanowire conductive sensing layer with micro/nanostructure was obtained by annealing. At the same time, they used the smooth surface of conductive PDMS film with the silver nanowires that prepared via transfer method will act as the protective layer. The multifunctional resistive sensor was composed of a silver nanowire sensing layer and a silver nanowire protective layer relatively encapsulated. The sensor can accurately detect the pressure, and notably that the sensor can also act as an electromagnetic shield. Designing the micro-structure resistive sensing unit on conductive layer can improve the sensitivity of the sensor, but there are also some disadvantages. The pressure will cause direct contact with the microstructure of the sensing unit, and repeats contact friction will easily cause the instability of the device and lower the sensing performance, thereby reduced the service life of the sensor. Nie et al.[16] prepared a PDMS with micro-grid and filled the carbon nanotubes in the microgrids to produce flexible resistive strain sensors. The optical transparency of this strain sensor was as high as 87%, and the gauge factor (GF) can be up to 1,140, but the measurable strain range was only 8.75%. Currently, most flexible resistive sensors lack sufficient stretchability and exhibit a large hysteresis effect. During the measurement process, the hysteresis effect can cause large errors, which lead to inaccurate pressure measurement results. Chen et al.[17] produced a flexible pressure sensor by embedding the liquid metal eutectic Gallium-Indium (EGaIn) into a wave-shaped micro-channel elastomeric matrix. The microfluidic sensor can withstand strains up to 320%, and its hysteresis performance is also improved from 6.79% to 1.02%. Sophisticated structural tuning can improve the elastic range while increasing the fabrication complexity. Another strategy to increase the detection range of the sensor was synthesizing novel conductive materials and tuning their microstructure to improve the detection performance of the sensor. Yu et al.[18] constructed a MXene nanoparticle-nanosheet hybrid conductive network with unique Ti3C2Tx, and the sensitivity in the whole wide range (53%) can reach GF>178.4. They ingeniously designed the structures of nanoparticles and nanosheets to form a synergistic conductive network that allowed the continuity of the conductive paths to be maintained in larger strained regions. Wang et al.[19] reported the combination of vertically aligned gold nanowire films and elastomers to construct a bilayer pressure sensor that can be stretched to about 800% deformation and able to maintain stable electrical conductivity at the same time. 1Dconductive materials such as silver nanowires (AgNW), gold nanowires (AuNW), carbon nanotubes (CNTs) or 2D nanomaterials such as graphene and other electroactive materials are embedded in elastic polymers to construct resistive sensors, but high contact resistance and relatively high hysteresis effects limit the application of resistive sensors.



(a) Sensitivity of different pressure sensors based on 2 μm and 5.6 μm diameter of PS sphere

(b) Schematic illustration of changes of sensor when same external pressure is applied to the PS sphere in different diameter

ΔR is resistance variation; R_0 is initial resistance; S is sensitivity

Figure 1. Response of the pressure sensor[14].

2.2. Flexible capacitive sensors

Capacitive sensors usually consist of a three-dimensional multilayer structure formed by a dielectric layer and two parallel electrode plates. When the sensor is subjected to pressure, the parameters of the capacitive sensor changed, such as the distance between the electrode plates, the dielectric layer, or the relative area of the electrode plates, which caused the capacitance of the sensor to change. The sensitivity of capacitive sensors is mainly determined by two key factors: (1) Compressible patterned and micro-structured dielectric layers; (2) Conductive material used in electrode plates. At present, changing the microstructure of the dielectric layer is the main strategy to improve the sensitivity of the sensor. Many complex dielectric layer models, such as micro-scale pyramids, micro-porous structures, micro-domes, micro-pillar arrays, rough surface structures, can improve the sensitivity of flexible capacitive sensors[20]. He et al.[21] fabricated a capacitive pressure sensor using low-cost elastic nylon mesh as dielectric layer (**Figure 2**) and formed a single electrode plate with a flexible sandwich structure of dielectric layer/conductive layer/base through nylon mesh/graphene thin layer/ PDMS. The sensitivity of the flexible capacitive sensors can be adjusted by changing the number of the nylon mesh which can change the thickness of the dielectric layer. The sensor can manage to perform a high-sensitivity detection to tiny pressure, with a simple, fast, and low-cost production. Kang et al.[22] developed a capacitive pressure sensor based on a biomimetic porous structure. PDMS thin films with regular and uniform porous structure were prepared using polystyrene (PS) as a template and used as a dielectric layer. A highly sensitive porous structure capacitive sensor was constructed by a porous PDMS layer/indium tin oxide (ITO) (electrode)/ polyethylene terephthalate (PET). The pore size of the porous structure affects the sensitivity of the sensor and the compressible thickness of the dielectric layer. Capacitive sensors have a simple structure and are easy to implement, but the signal output of capacitive sensing devices often requires complex signal conversion circuits.

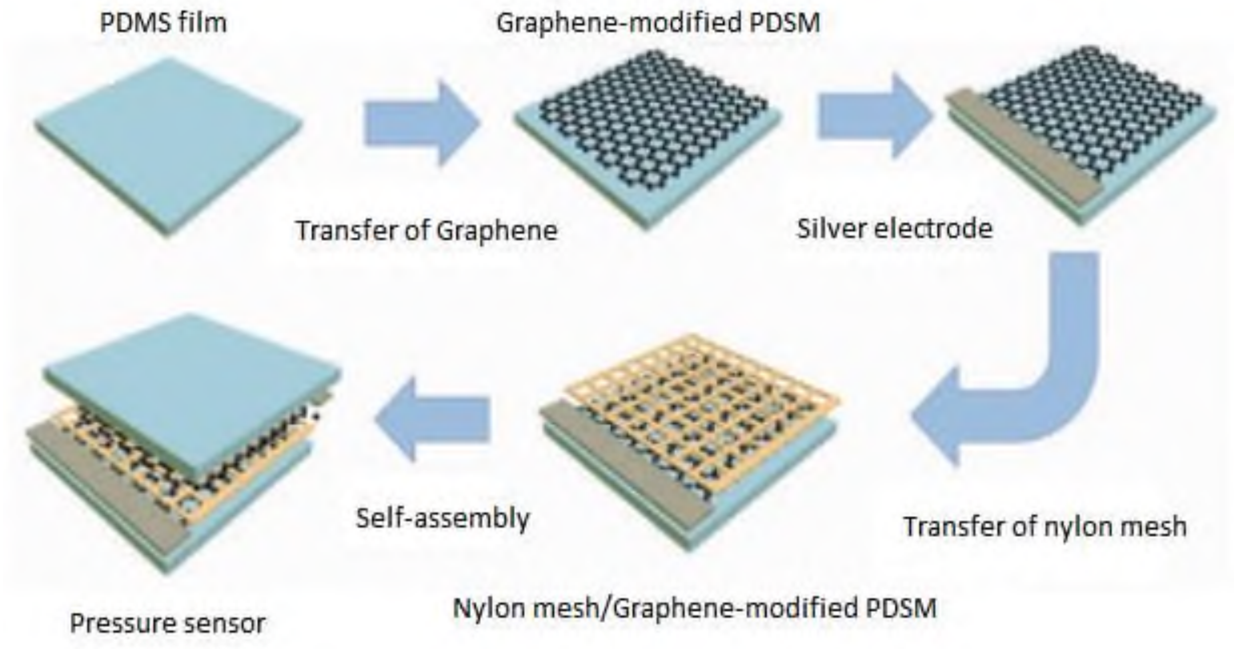


Figure 2. Fabrication steps of the sandwich-like pressure sensor based on low-cost nylon netting with numerous micro-sized square holes[21].

2.3. Flexible piezoresistive sensors

Piezoelectric sensor is a device that uses the piezoelectric effect of materials to convert the physical quantity to be measured into electric charge. Piezoelectric materials can directly convert the mechanical energy into electrical energy. When deformation occurred due to an external force, the surface of the piezoelectric material will generate an amount of charge that proportional to the magnitude of the external force, and the change in electrical polarization inside the dielectric layer will cause the potential of the upper and lower surfaces of the piezoelectric material to change. The charges on the two electrodes that contact with the surface of the piezoelectric material will be readjusted to balance the surface potential of the piezoelectric material, lead to a flow of charge in the circuit. The piezoelectric materials that commonly used include inorganic piezoelectric materials [such as lead zirconate titanate (PZT), aluminum nitride (AlN), zinc oxide (ZnO), quartz, and the like], and organic piezoelectric materials (organic polymers), composite piezoelectric materials, etc. In inorganic piezoelectric crystals, the internal polarization of the material changed with the applied stress, resulting in an electric field at the material boundary. There are some disadvantages on inorganic piezoelectric ceramic materials, such as high temperature is needed to reorient the polarity of the material, high fabrication cost, and poor flexibility. In organic piezoelectric polymers, the piezoelectric effect is caused by the molecular structure and orientation of the polymer[23]. Piezoelectric polymer materials have excellent mechanical flexibility, good formability, biocompatibility, and environmental friendliness. Therefore, piezoelectric polymer materials are widely used in piezoelectric sensors. Polymer nanomaterials, especially polyvinylidene fluoride (PVDF), PVDF copolymers and PVDF nanocomposites, are currently the most promising piezoelectric materials[24], which can meet the demands of dynamic sensing in flexible wearable electronic devices. PVDF nanofibers offer good flexibility as well as piezoelectric properties. Park et al.[25] used the electrospun nanofibers [copolymer polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE)] were sandwiched between two elastomer sheets with sputtered electrodes as the piezoelectric active layer, as shown in **Figure 3**. This piezoelectric sensor has the sensing ability to detect tiny stimuli (including deformations as small as 1 μm), enabling the detection of radial artery pulse waves. When the arrangement and orientation of PVDF fibers are more ordered, the piezoelectric properties of the material can be improved. PVDF nanocomposites prepared by electrospinning (such as PVDF/Ag[26], PVDF/carbon nanotubes[27], PVDF-TrFE[28]) have significantly improved piezoelectric properties. In addition, organic-inorganic composite materials can be used to improve the electromechanical properties of strain sensors, to overcome the brittleness of inorganic materials and the structural instability when compounded with organic materials, and the flexibility and conductivity of the device can be improved at the same time. Chen et al.[29] produced a flexible piezoelectric sensor (PVDF@ZnO) based on PVDF-TrFE fibers and ZnO nanowires. This device can withstand ultimate stretching with a stretch ratio up to 30% and exhibits excellent performance with high sensitivity (gauge factor of 4.59) and 150° change in bending.

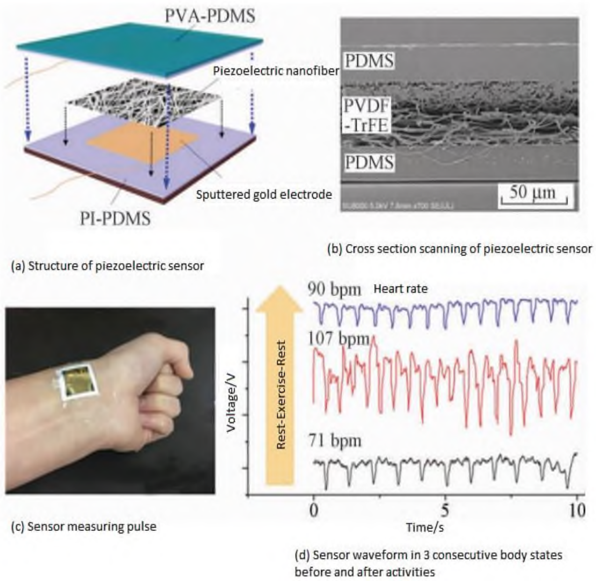


Figure 3. Structure and physiological signal measurement of the piezoelectric sensor[25].

Piezoelectric sensors have good stability, biocompatibility, low power consumption, fast response speed, simple device structure, and low-cost manufacturing process, and can directly convert mechanical energy into electrical energy without external circuit components. However, the limited stretchability constraints the application range.

2.4. Flexible FET sensors

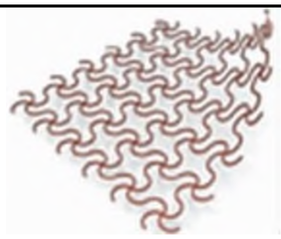
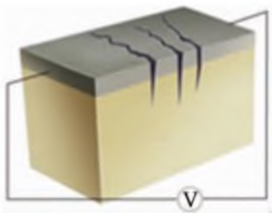
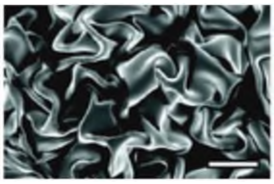
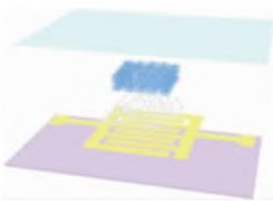
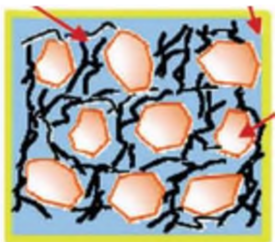
FET-based pressure sensors have received extensive attention in recent years due to their excellent signal amplification, high array uniformity, excellent stress monitoring, high spatial contrast, and convenience. FET is a voltage-controlled semiconductor device, metal oxide semiconductor field effect transistors (MOS-FETs) and organic field effect transistors (OFETs) are commonly seen in the field of FET sensors. There are several advantages of organic semiconductors properties, such as diversity in molecular design, low cost, light in weight, good flexibility, low operating voltage, and can be mass produced through low temperature inkjet printing. Due to its unique three-terminal structure, optimizing any single component of FET (e.g. gate electrodes, source and drain electrodes, dielectric layers, or semiconductor active layers) can significantly improve the sensing performance of FET devices. Liu et al.[30] proposed a new concept of the piezoelectric effect by replacing the gate voltage of FET with the piezoelectric potential energy generated by the mechanical response of the piezoelectric material, and the piezoelectric sensor perfectly combines the piezoelectric effect with the FET device. Wang et al.[31] developed a flexible piezoelectric sensor that can convert external mechanical force into voltage through PVDF nanowire arrays to drive OFET devices, which in turn can amplify the piezoelectric voltages, thereby can significantly improve the performance of piezoelectric sensors. Generally, FET-type flexible pressure/strain sensors are more sensitive than resistive and capacitive-type sensors due to their ability to adjust the conductance of the semiconductor channel material by controlling the gate voltage. Dai et al.[32] used the hydrogel "stamp" as a biometric module and graphene FET as a sensor module to form a module of FET biosensor. The sensor enables real-time, label-free detection of penicillin and urea using penicillinase and urease-encoded PEG hydrogels as biometric modules respectively. FET devices are widely used in the field of biosensing. At present, FET biosensors[33] have made progress in the detection of different biomolecules such as glucose, cholesterol, uric acid, urea, hormones, proteins, nucleotides, and biomarkers. In addition, related papers also reported its application in the detection of weak neuronal action potential[34]. However, high operating gate voltages limit their application in wearable electrical systems. Moreover, the toxicological properties of organic semiconductors restrict their application in invasive medical examinations.

3. Typical structure of a flexible pressure sensor

Scientific research on flexible sensors has shown that wide detection range, high sensitivity, rapid response, good durability, flexibility, and excellent stability are necessary conditions for high-performance flexible sensors. When the flexible sensor deformed by an external force, its conductive mesh structure also forced to deform at the same time, thereby generating an electrical signal output. Other than using advanced sensing materials with excellent intrinsic electromechanical properties, unique microstructures are also an effective strategy to fabricate high-performance flexible wearable sensors[35–36]. The conductive network can enhance the ductility and stability of the sensor, and effectively improve the sensitivity, response speed and detection range of the flexible sensor[37].

Table 1[38–43] summarizes several sensors with different conductive network structures. Commonly used conductive network structures including serpentine structures, porous structures, microcrack structures, and wrinkled structures. Various conductive network structures are used to improve the performance of flexible sensors[44]. Different conductive network structures produce different sensor performances[45,46]. The idea of the microcrack structure comes from the slit organ of spiders[39]. Yang et al.[47] fabricated a gold thin film flexible sensor with channel cracks for ultrasensitive strain sensing. The sensor has high sensitivity, good cyclicity and rapid dynamic response. Introducing weak interfacial interactions between metals and polymers can simultaneously achieve fracture geometry and reversible electrical responses. The sensor can reach a GF of 2 000 for 2% strain and can detect an amplitude of about 10 nm. However, due to the microstructure of sensor is easily damaged when a large deformation occurs, therefore problems such as limited detection range and easy peeling of the conductive layer on the surface can be occurred.

Table 1. Sensors with different conductive networks and their performance[38-43]

Structure	Structure	Image	Performance	Reference
Serpentine structure	Mixture of polyimide and 1-methyl-2-pyrrolidinone/Metal nanowires		Can measure up to 80% of the deformation, Electrocardiogram (ECG) and Electromyography (EMG)	[38]
Crack structure	Polyurethaneacrylate (PUA)/ Platinum film		GF = 2 000 (deformation ε <2%) Can detects tiny deformations up to 10 nm	[39]
Wrinkle structure	Ecoflex/Platinum/Gold film		GF = 42 (deformation ε <185%)	[40]
Kirigami structure	Silver nanowires/Ultrathin colorless transparent polyimide (PI)		0 to 400% tensile strain range, optical transparency greater than 80%, can measures EMG, ECG and EOG signals	[41]
Porous structure	Metal carbodes and nitrides (MXenes) sponge/Polyvinyl alcohol Porous structure (PVA) nanowires/Interdigitated electrodes		147 kPa^{-1} (pressure p <5.37 kPa) 442 kPa^{-1} (5. 37 < p <18. 56 kPa)	[42]
Isolation structure	PDMS/Electrically conductiveMulti-walled carbon nanotubes		GF = 142 (deformation ε <30%)	[43]

Liu et al.[48] fabricated a highly adhesive stretchable electrode using a novel nanostacks interlocking strategy. Nanofibers can significantly enhance the adhesion and redistribute strain in the film, enabling high stretchability. Nanostack electrodes can simultaneously monitor EMG signals and mechanical deformation. The wrinkle structure has a relatively broad detection range by using a pre-stretched flexible substrate, but the detection sensitivity was not as high as the microcrack structure. Other microstructures, such as three-dimensional porous structures and isolation structures enhanced the ductility of the conductive layer to a certain extent and expanded the detection range. However, its transparency and conductivity are limited. The design of these conductive structures enables the sensor to exhibit a dependence of external resistance force, which is mainly due to the change in the geometry of the sensitive element upon the application of external force. The kirigami structure shows good resistance to huge deformation[41]. Reference[48] proposed a novel fabrication method by using the art of kirigami to obtain highly stretchable electronic devices for various shapes, which have high electrical conductivity and high optical transparency (80%) and can be adapted to different curved surfaces of human body. The kirigami structure endows the electrode with adjustable elasticity, which can be adjusted in the range of 0-400% tensile strain and possess constant electrical properties.The design of the structure of highly conductive network is crucial to produce a sensor with high ductile and high-sensitivity.In practical applications, more suitable conductive structures can be designed according to the requirements of different application.

4. Challenges and development trends

4.1. Self-powered sensors

Suitable energy devices are important for the normal operation of flexible sensors. Conventional power supply modules are usually bulky and rigid, which are not compatible with emerging multifunctional electronic skin systems. Flexible self-powered systems are a promising alternative strategy, enabling self-driven sensor systems by harvesting ubiquitous energy from the environment or human movement[49–51]. With the continuous development of stretchable energy-harvesting active materials (carbon nanotubes, AgNWs, and graphene, etc.), and the emergence of various stretchable strategies (serpentine or self-similar), piezoelectric, triboelectric, and pyroelectric effects of dielectric elastomer-based energy harvesting devices have made some progress in wearable and stretchable electronics[52]. Frictional Electron Nanogenerator (TENG) have been shown to be a cost-effective and reliable method for the harvesting of environmental mechanical energy. The working principle of TENG is based on the periodic contact and separation of two materials with opposite triboelectric polarities. During the motion of contact and separation, a potential difference is created, which will help electrons to flow between the conductive electrodes and produce an electrical output. Although the operating principle of TENG is simple, but there are still some challenges exist in the development of TENG. Conventional TENGs usually work in contact or sliding mode, which mainly rely on unidirectional triggering. This would limit the application of TENGs in harvesting energy only from specific directions. Yang et al.[53] proposed a TENG device composed of paper-based substrate, polytetrafluoroethylene (PTFE) film and aluminum foil. The device fully utilizes the origami 3D structures to harvest mechanical energy generated by various human movement, such as stretching, lifting, and twisting. Ma et al.[54] reported a triboelectric pressure sensor composed of PDMS layers and carbon fiber electrodes (**Figure 4**). The device can be mounted on a finger or beetle and can achieve self-powered pressure sensing without an external power source, with a sensitivity of 0.055 nA/kPa and a strain detection limit of the sensor of 0.8 kPa. It had been reported that there are still some problems in the assembly and integration of the energy collection device currently, and the consistency, scalability, flexibility, long-term stability, comfort and energy conversion efficiency of the whole system still need to be improved.

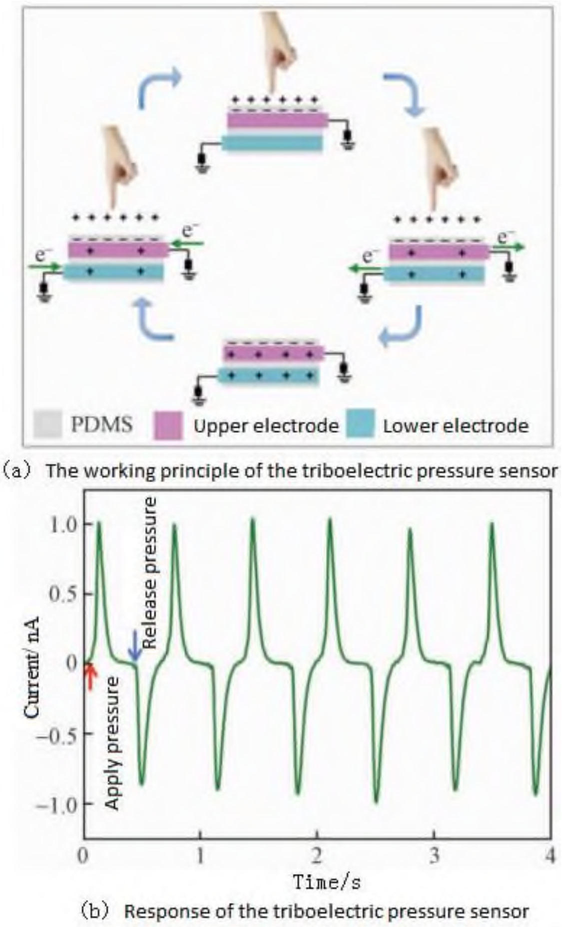


Figure 4. Working principle of triboelectric pressure sensor[54].

4.2. Biocompatibility

The good biocompatibility of wearable sensors to human body is thekey to prevent any adverse reactions[55]. Issues of safety and long-term stability must be considered during the designation of implantable flexible devices. Reference[56] designed and fabricated an implantable pressure and strain sensor that completely made of biodegradable materials, which showed excellent biocompatibility and good pressure and strain detection in a rat model, in which the healing in tendon can be monitored under real time condition.

Biocompatibility of flexible wearable devices requires consideration not only of the sensing elements but also other modules of the device. High-performance flexible nanogenerator with biocompatibility is an important part for flexible wearable devices, which can supply the required energy for the operation of wearable devices. Zhu et al.[57] proposed a flexible and biocompatible triboelectric nanogenerator with simple fabrication process and adjustable internal resistance. This nanogenerator exhibits good flexibility and biocompatibility for the applications of wearable devices. Li et al.[58] fabricated a nanogenerators based on polypropylene ferroelectrics (FENG), which is light in weight, flexible, foldable, and biocompatible as a power source for flexible wearable devices. FENG require some advantages such as of light in weight, flexibility, foldable, biocompatibility, scalability, low in cost, and strong flexibility, which make FENG as a promising alternative in the field of mechanical energy harvesting for various autonomous electronic devices. Due to the high impedance of FENG, the short-circuit current of the devices limits their applications.

Although scientists have now developed a variety of biocompatible and degradable sensors[59–60], they are still facing various problems. For example, there are some sensors without good sensing performance, or used materials with unproven biocompatibility.

4.3. Integration and multi-functionalization of devices

The human body is a complex living body, and it is difficult to determine the pathology by relying on only one or two physiological parameters. It is necessary to systematically and comprehensively collect a number of relevant physiological indicators of human body, such as blood pressure, blood sugar, blood oxygen, pulse, body temperature, ECG, etc. for accurate diagnosis. The development of multi-parameter and multi-function sensing technology has created favorable conditions for smart wearable medical devices. Sensor arrays or integrated platforms that simultaneously detect multiple physical signals are of great significance for personalized medicine. Reference[61] developed and designed a wireless, battery-free vital signs monitoring system for neonatal vital signs monitoring (**Figure 5**). The system consists of ultra-thin, lower modulus measurement modules, ECG, photoplethysmography (PPG), skin temperature, and wireless battery-free modules, which can accurately and non-invasively measure neonatal vital signs, such as heart rate, blood oxygen, temperature, respiratory rate and pulse wave. However, there are some problems occurred in the system, such as short wireless communication distance and brittle connection between modules. Reference[62] further improved and optimized the system to measure not only the physiological parameters such as heart rate, respiration rate, temperature, and blood oxygen, but also able to monitor the variability in heart rate, which can be used to predict changes in the clinical condition of infants before the apparent signs of disease. Wang et al.[63] fabricated a flexible temperature-pressure electronic skin sensor, using flexible and transparent silk nanofiber-derived carbon fiber membranes as electroactive materials, and integrated silk-based temperature and pressure sensors through a lamination strategy, to produce a sensor with high temperature sensitivity of 0.81%. The strain sensor shows extremely high sensitivity with a gage factor of 8,350 at 50% strain. The temperature and pressure sensors do not interfere with each other. Gui et al.[64] developed a sandwich-like sensing system capable of simultaneously monitoring temperature, light, and pressure signals without mutual interference of signals. The system employs skin-like epidermis, dermis, and subcutaneous structures to achieve multi-signal sensing properties, including ambient temperature, body temperature, pressure, and near-infrared light. Yamamoto et al.[65] integrated a skin temperature sensor, an ECG sensor, and an ambient ultraviolet (UV) light sensor with a printed triaxial accelerometer to demonstrate a multifunctional wearable health monitor. For sure there will be challenges in the future, and the reliability and overall performance of the functional circuit structure still need to be improved[66]. A complete wearable sensing system includes sensing unit, power supply unit, signal transmission, etc. How to integrate these excellent functional circuits into a single flexible system for flexible, high-sensitivity, multi-parameter, high-stability, real-time, and durable detection are the problems that needed to be solved.

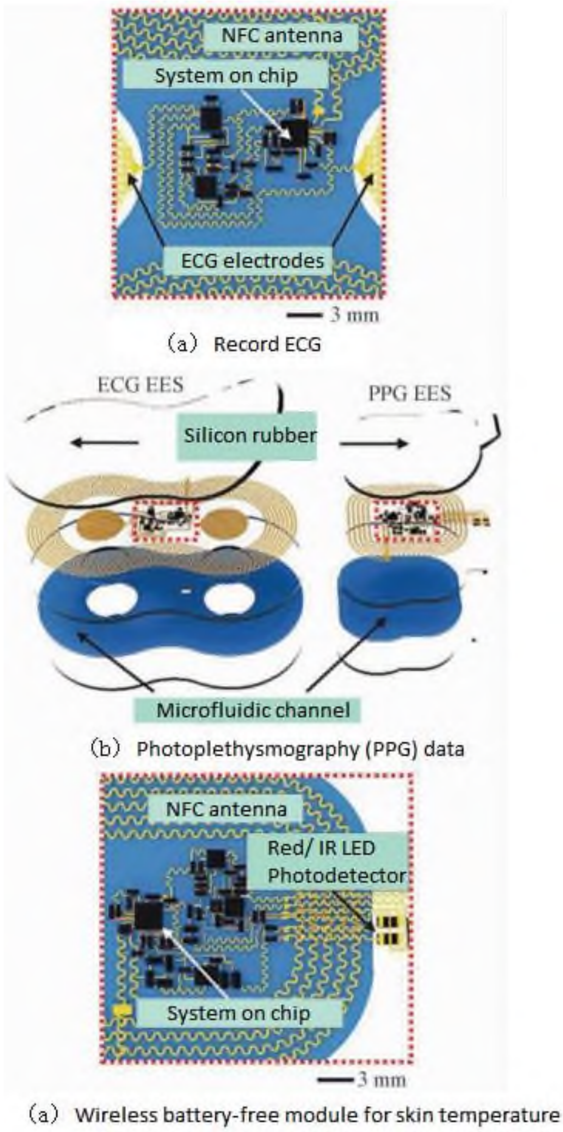


Figure 5. Flexible sensor for neonatal multi-sign monitoring[61].

5. Conclusions

The research progress of flexible wearable stress sensors in recent years is summarized in this review paper. According to the classification of working principles, the progress of resistive, capacitive, piezoelectric, and FET flexible sensors is analyzed and discussed, and the strategies for constructing corresponding types of sensors are discussed. In addition, a detailed analysis is made on how to improve the performance of the sensor from the aspect of structural design. Building highly integrated, high-performance, and muti-functionally flexible sensors is still the direction for future development. Although there are still many challenges in this field currently, flexible wearable stress sensors have shown excellent development potential and application prospects in the fields of biomedicine, robotics and entertainment technology.

Conflict of interest

The authors declare no conflict of interest.

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