Design of Multifunctional Touch and Slip Sensor System Based on PVDF Piezoelectric Film

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Abstract. A multi-functional touch slip sensing system is designed based on PVDF piezoelectric film. The piezoelectric sensor converts the pressure signal into electrical signal through piezoelectric effect, and the conditioning circuit further processes the electrical signal. After A/D conversion, the data is transferred to the upper computer to extract the information. In addition, based on the thermoelectric effect of piezoelectric film, the sensor can detect the thermal sensation signal and has the function of self-protection. The piezoelectric sensor adopts bionic fingerprint structure, which has high sensitivity and good flexibility. The conditioning circuit includes amplifying unit, filtering unit, voltage lifting unit and voltage following unit. These units are integrated on the circuit board of 11mm*10mm, which has high integration and easy application. The experiment verifies that manipulator equipped the sensing system can automatically judge tactile, slip and thermal sensation, and can grasp an egg and a paper cup with water, realizing the ability of soft grasping.

1. Introduction
In recent years, due to the rapid development of mechanical automation, manipulator gradually replaces human to complete a large number of work, which is applied to agriculture, machinery, electronics, automobile and other industries [1-3]. In order to better complete complex work, the manipulator must have some specific functions, such as touch, slip, thermal sensation, judging clamping force independently and so on. For this reason, multiple bionic sensors already have been studied by many researchers. Salehi et al. proposed a tactile sensor with a ridged fingertip structure that simulates human fingerprints [4]. The artificial finger embedded in the ridged tactile sensor can distinguish between different object shapes and surface curvature. Therefore, the structure of sensor plays a crucial role in the efficient operation of manipulator. W. Xu et al. proposed a prosthetic hand control system based on PVDF film sensor, which can provide force feedback signals of touch and slip sensation simultaneously to operate the prosthetic hand [5]. In addition, it is demonstrated that tactile signals are linearly related to contact forces. Based on bionics, Youssefian et al. designed a curved fingerprint sensor [6], and the detection system formed by the sensor and the robotic arm has a high spatial resolution and sensitivity.

This paper designs a fingerprint sensor based on PVDF piezoelectric film. The sensor is applied to manipulator, which can independently recognize tactile sensation, slip sensation and thermal sensation. In this paper, the response signals of PVDF film under tactile, slip and thermal sensation are compared and analyzed. PVDF film generates different signals under different conditions. According to the principle, the different states that exist between the object and the manipulator can be distinguished. As a sensing material, in addition to piezoelectric and thermoelectric properties, PVDF film also has
good biocompatibility, thermal stability, flexibility and other characteristics. What’s more, when the same pressure is applied, the output voltage of piezoelectric film is much higher than piezoelectric ceramic. The sensor has the advantages of simple structure, high precision and reliable operation. Experimental results show that the manipulator equipped with the fingerprint sensor can realize soft grasping and automatically bounce off when the temperature of the object exceeds 60°C.

2. PVDF Piezoelectric Film
PVDF film has been broadly used in tactile and slip sensors since Kawai discovered the piezoelectric of PVDF film in 1969. Piezoelectric effect includes positive piezoelectric effect and negative piezoelectric effect. Positive piezoelectric effect means that polarization phenomenon will occur in the internal when pressure is applied on the surface of PVDF film, and the upper and lower surfaces generate opposite charges, forming an electric potential difference. When the direction of the force changes, the polarity of the charge also changes. Negative piezoelectric effect means that PVDF film will undergo mechanical deformation when it is subjected to electrical signals, and when the electrical signals are removed, the mechanical deformation will also disappear [7]. Schematic diagram of positive piezoelectric effect is shown in figure 1(a). When the piezoelectric film is deformed by the applied force, the upper and lower surfaces of it generate the same amount of opposite charges, forming an electric potential difference.

![Figure 1. (a)Schematic diagram of normal piezoelectric effect (b) 33mode (c)31mode](image)

The working mode of piezoelectric film includes 33mode and 31mode. 31mode describes that the charge polarization occurs in the direction perpendicular to the force. 33mode describes that the charge polarization occurs in the direction in which the pressure is applied to the piezoelectric film. Studies have shown that 33mode is more easier to generate strain compared with 31mode, so the piezoelectric sensor in 33mode is more sensitive [8].

In addition, PVDF film also has pyroelectric effect. Pyroelectric effect refers to the phenomenon that when PVDF film is affected by temperature, the "frozen" polarization charge will be released. The pyroelectric coefficient can be expressed by the following formula:

\[
P_i = \frac{dP}{dT}
\]

Where \( P \) is the intensity of PVDF film spontaneous polarization, \( T \) is the temperature, and \( P_i \) is the pyroelectric coefficient.

What’s more, PVDF film also has the advantages of low cost, good flexibility, easiness to manufacture, biocompatibility and strong anti-interference ability[9].

3. Sensor Structure
The sensor based on PVDF film adopts bionic fingerprint structure, including a 20 µm thick PVDF film with aluminum electrodes, one copper foil and two layers of rubber membranes used to protect the sensor. As elastic substrate, copper foil has recoverability and electrical conductivity. In order to increase sensitivity, the fingerprint sensor is designed as an “arch” with a diameter of 20mm to mimic
human fingers. As proposed by Youssefian et al., the hemispherical shell structure was suitable for tactile sensors to detect forces in robot applications[6]. As a mechanical spring shaped like a dome, the outer surface of the copper foil is designed with many points arranged in the shape of a fingerprint to detect small triggering forces. According to fingerprints, the distance between two points is about 0.4mm. The "fingerprint" on the copper foil can further improve sensitivity of the sensor. The structure of the fingerprint sensor is shown in figure 2.

Figure 2. The structure of the fingerprint sensor

It can be seen from the front view of the sensor that the structure is similar to half period sine wave, so the structure of the sensor can be expressed in the following formula:

\[ f(x) = \sin \frac{\pi x}{d} \]  

(2)

Where \( d \) represents the diameter of the sensor. According to the electrode effective area of piezoelectric film and Gauss theorem, the relationship between the output charge \( q \) of the sensor and the applied pressure \( F \) is as follows:

\[ D_i = d_{ip} \sigma_p + \varepsilon^T \varepsilon P_i \]  

(3)

\[ D_i = D_s \]  

(4)

\[ q = \int \int_{s_y} F(x, y) D_s ds \]  

(5)

Where \( F \) represents the applied pressure, \( s_y \) represents the area bounded by \( f(x) \) and x-axis, \( E \) represents the electric field intensity, \( \varepsilon^T \) represents the dielectric constant matrix, and \( D \) represents the electric displacement and \( d_{ip} \) represents the piezoelectric coefficient. Since the structure of sensor conforms to the requirements of beam and follows Kirchhoff. G theory and the broad Hooke law. So \( D_s \) can be expressed as formula 6:
\[ D_3 = [d_{31}, d_{32}, d_{33}] \]

Where, \( u, v, \) and \( w \) are deformation values generated by the piezoelectric film in the x, y and z axes respectively. \( z_k \) represents a constant related to the thickness of the film. Therefore, the output charge \( q \) can be written as following formula:

\[
q = \int \int F(x, y) \left[ d_{31} \frac{\partial u_a}{\partial x} + d_{32} \frac{\partial v_a}{\partial y} + d_{33} \left( \frac{\partial u_a}{\partial y} + \frac{\partial v_a}{\partial x} \right) \right] dx ds - z_k \int \int F(x, y) \left[ d_{31} \frac{\partial^2 w}{\partial x^2} + d_{32} \frac{\partial^2 w}{\partial y^2} + 2d_{33} \frac{\partial^2 w}{\partial x \partial y} \right] dx ds
\]

(6)

In theory, compared with the deformation value generated by the piezoelectric film in z axes, the deformation value generated by the piezoelectric film in x and y axes can be ignored. Therefore, formula (7) can be rewritten as follows:

\[
q = -z_k \int F(x) d_{31} \int \frac{\partial^2 w}{\partial x^2} dx
\]

(8)

\[
q = -z_k d_{31} \int F(x) \frac{\partial^2 w}{\partial x^2} dx
\]

(9)

According to the above formula, it can be seen that the output charge of sensor is related to the deformation value generated by the z-axis, which indicates that the sensor based on PVDF film cannot measure static force, but is sensitive to dynamic force. It is similar to the sensing characteristics of human fingers.

4. System Circuit

The system processing circuit includes four modules: charge amplifier circuit, low-pass filter circuit, voltage lifting circuit and voltage following circuit. In order to improve the integration of circuit, OPA4347 chip is used. Four amplifiers are integrated into the chip. And it can be miniaturized with low cost and small volume.

As a pre-amplifier circuit, charge amplification circuit converts charge signal generated by PVDF into voltage signal. Because the output impedance of PVDF film is high, a 10M\( \Omega \) resistance is used to be the first impedance resistance according to the principle of impedance matching, which can improve the precision of the signal. The frequency of human body movement is generally less than 100Hz, so a low-pass filter circuit is used to eliminate the high-frequency interference signals. Then the power frequency interference signal is filtered by 50Hz power frequency trap circuit. Since micro-controller (MSP430F149) recognizes and processes positive voltage signals, a boost circuit is necessary to raise the output negative voltage to positive voltage to ensure that the micro-controller can normally process signals. The schematic diagram of the system processing circuit is shown in figure 3.
Figure 3. Schematic diagram of system circuit

5. Experiments and Application

5.1 Sensor Sensitivity Test

The sensitivity of sensor was tested using the schematic diagram of experiment as shown in figure 4. The sensor is under three different states of tactile sensation, slip sensation and thermal sensation, and its response signal is measured by oscilloscope respectively. Origin software is used to process the signal, and the response curve is shown in figure 5.

In tactile experiment, a force of 5N was applied in the direction perpendicular to the sensor to obtain the response curve as shown in figure 5(a). The response of the fingerprint sensor to the tactile signal is a continuous electrical signal, which is generated by applying pressure on the sensor and has a peak value. The slip sensation signal is obtained from the transverse shear force generated by the relative sliding between the object and the sensor. In slip experiment, an object with a mass of 500g fell freely and the friction coefficient was 0.47. The response curve includes a series of peaks, all of which are smaller than the tactile response peak, as shown in figure 5(b). In thermal sensation experiment, the fingerprint sensor was placed on heating plate at 20°C, 40°C, 60°C, 80°C and 100°C respectively. The output voltage increases with the increasing of temperature. The response curve of sensor on 60°C heating plate is shown in figure 5(c). The response signal is a step signal, which slowly returns to stable state. The curve peak is between the tactile signal peak and the slip signal peak.
Therefore, the fingerprint sensor is sensitive to tactile, slip and thermal sensation. The three kinds of signals can be distinguished by Labview software according to the threshold method. First of all, Labview can further remove the noise interference signal by filtering the acquired signal. Then, the mean value and variance of the output signal of the low-pass filter are calculated. The mean value is taken as the eigenvalue of the tactile signal and the variance as the eigenvalue of the slip signal. The tactile and slip sensation signals are judged through setting the threshold interval by Labview. The thermal sensation signal is judged by setting the frequency threshold and the amplitude threshold. In order to protect the fingerprint sensor, the maximum temperature of the object grasped by manipulator is controlled at 60°C by setting the threshold value. The overall design block diagram of Labview is shown as figure 6.
5.2 System Test and Application
Labview software was used to process the output signal of hardware circuit. The serial port of debugging software was selected as COM6, baud rate was 9600, data bit is 8, and the 1.0 stop bit was selected. The indicator will light up when the sensor recognizes tactile, slip and thermal signals and the signal amplitude is displayed. As shown in figure 7, at room temperature, when the sensor recognizes the slip sensation signal, the indicator lights up and the signal amplitude is displayed in real time. The two indicators will light up at the same time and the superposition of the two signals are shown when the sensor identifies two kinds of signals (touch and thermal sensation, slide and thermal sensation).

The fingerprint sensor is applied to manipulator for soft grasping experiment to verify the sensitivity of sensor. In the soft grasping process of the manipulator, the sensor collects the signals between the manipulator and the object, and the signal type is judged by the upper computer. The master controller controls the corresponding actions of the manipulator according to different sensory signals. The specific control strategy block diagram is shown in figure 8.

![Labview working interface](image-url)

**Figure 6.** Labview overall design block diagram

![Display window of signal](image-url)

**Figure 7.** Display window of signal
Manipulator grasps object
Sensor collects tactile signals
Sensor collects thermal sensation signals
Judge object temperature

Yes
The set threshold has been exceeded
Sensor collects the slip signal

No
Reached the critical point of tactile and slip

Object is grasped

Start
Program initialization
Manipulator grasps object

Figure 8. Control strategy block diagram of manipulator soft grasping

At room temperature, an egg and a paper cup with water were used as test subjects. As shown in figure 9, the manipulator can grab an egg without any damage and can grab a paper cup with water. The manipulator was actuated to close to the paper cups with hot water of 40°C - 70°C to test the thermal sensation function of the manipulator. The experimental results show that when the hot water temperature is close to or exceeds 60°C, the manipulator will automatically bounce off. Therefore, the manipulator can recognize the thermal sensation and has the function of self-protection.

Figure 9. Picture of sensor application (a) grab an egg, (b) grab a paper cup containing water, (c) manipulator with the fingerprint sensor
6. Conclusion
A fingerprint sensor based on PVDF film is proposed in this paper, which can be applied to a manipulator. The sensor adopts bionic fingerprint structure with high sensitivity and good flexibility. As for processing circuit, OPA4347 chip is used, which has high integration, small volume and simple application. Experiments show that the fingerprint sensor is sensitive to tactile, slip and thermal sensation. In addition, manipulator equipped with the fingerprint sensor achieves soft grasping, which can perfectly grasp an egg and a paper cup with water. When the object temperature is close to or over 60°C, the manipulator will automatically bounce off to realize self protect.

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