Flexible Piezoelectric Tactile Sensor with Structural Electrodes Array for Shape Recognition System

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Abstract—This study provides an efficient and feasible solution to enhance the sensitivity of traditional piezoelectric tactile sensor based on introducing structural electrode upon the sensing material. A sandwich structure for flexible tactile sensor consists of top and bottom soft substrates made of Polystyrene, and in between of two soft substrates a piezoelectric thin film, PVDF, and a PDMS microstructures array are utilized as sensing material and microstructures, respectively. The experimental results showed the output voltage was linear with contact force from 10N to 0.5 N and good reliability within low frequency range 1 ~ 100 Hz. In addition, the shape recognition also can be achieved as the objective contacted with the 4 by 4 electrodes array. The effects of structural electrode on the enhancement of sensitivity were also numerically simulated by finite element method (FEM) and verified experimentally by dynamic measurement system, respectively. In general, the flexible tactile sensor developed in this study is not only applied for detecting contact force but also for the human physiology monitoring system, such as pulsation, heart rate and blood pressure, etc.

Keywords- Flexible Electronics, Tactile Sensor, Piezoelectric Material, Microstructure, Finite Element Method

I. INTRODUCTION

Better interfaces between humans and technology have become an important driving force for consumer electronics. Our sense of touch is a primary means of interaction with our environment, and for this reason, it is desirable to create interfaces between humans and technology that can communicate through force information about the magnitude, time-varying history, position, and force distribution. Tactile sensors, therefore, offer exciting possibilities in force-based interface through physical contact between sensor and object. Hence, an ideal tactile sensor is required following characteristics: First, a tactile sensor is thin, flexible and able to cover a large area like the human skin. Second, a distributed array of detectors is arranged with high density. Third, the durability to physical external force and chemical pollution is also needed. However, these requirements are difficult to achieve for a tactile sensor based on ceramic material like silicon, PZT and glass, etc. A number of researchers have developed a flexible tactile sensor based on piezopolymer PVDF (polyvinylidene fluoride) film [1-3]. Yu et al. [4] fabricated 8 × 8 distributed flexible tactile sensor by using PVDF film and flexible circuitry, however, the sensitivity was not satisfied to practical application. In order to enhance the sensitivity of PVDF-based tactile sensor, we introduced the so-called structural electrode to replace the thin-film electrode in the traditional design shown in the Fig. 1. The concept of structural electrode is to mimic the convex and concave surface in the human skin. On the contrary to thin-film electrode in the traditional tactile sensor, stress concentration can be generated in the piezoelectric material while contact force is transmitted through the microstructures instead of direct contact to the sensing material. The induced charge of piezoelectric material is, therefore, increased with raising stress nearby the microstructures underneath due to the contact surface is decreased. In this paper, the shape and size effects of structural electrode were evaluated by finite element analysis. A 4 × 4 distributed flexible tactile sensor with PDMS microstructures array was fabricated and characterized by MEMS technology and dynamic measurement.

II. SIMULATION

As an external force acting on the tactile sensor, the total force is shared by the distributed structural electrodes. In order to investigate the influences on introducing microstructures, a 3D model was established and analyzed by finite element software (ABAQUS) shown in the Fig. 2. The PVDF film is 200 µm in thickness and its material properties used in simulation were listed in Table 1. Three kinds of shapes and sizes for structural electrode on PVDF film were examined by applying a specific force 500N. As the size of electrode was 16 mm², the distributions of electrical potential on the surface of PVDF for different shapes were illustrated in Fig. 3. There is a plateau region corresponding to the structural electrode and the circle shape for structural electrode possessed slight higher electrical potential than the shape of square and rectangle. In addition, a peak value of potential was occurred at the edge of structural electrode due to the effect of stress concentration. On the other hand, the sensitivity, defined as the ratio of output...
voltage (mV) to applied force (N), is higher as the area of electrode decreases shown in the Fig. 4. Thus, the structural electrode effectively enhances the sensitivity of tactile sensor based on these numerical results.

### Table I. Material Properties of PVDF Film for Simulation

<table>
<thead>
<tr>
<th>Density (kg/cc)</th>
<th>Young's modulus (GPa)</th>
<th>Poisson ratio</th>
<th>Dielectric constant (Farad/m)</th>
<th>$d_{21}$, $d_{23}$ (m/Volt)</th>
<th>$d_{33}$ (m/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1780</td>
<td>3</td>
<td>0.35</td>
<td>$11 \times 10^{-10}$</td>
<td>$23 \times 10^{-12}$</td>
<td>$-33 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

Figure 2. 3D FEA Model for a cell of structural electrode, the PVDF film is 200 µm thick and 20 mm in square, the size of electrode area is 9, 16, 25 mm$^2$ with different shapes.

Figure 3. The electrical potential profile across the center of contact area and parallel in 1-direction, the area of electrode is 16 mm$^2$ but with different shapes.

III. Tactile Sensor Design and Fabrication

The structure of tactile sensor consisted of two parts, bottom layer was the sensing material PVDF (Measurement Specialties Inc.) patterned with distributed metal electrodes, the top layer was the PDMS microstructures array made by molding process shown as Fig. 5. The sensor was finally packaged with two polyester films for electrical insulation.

IV. Experimental Results

A. Experimental Setup

For a piezoelectric tactile sensor, it is difficult to measure a static force due to the charges induced by external force could not be well preserved and detected especially for the distributed sensor. Therefore, a dynamic test system was built to obtain the output characteristics of tactile sensor. The applied force was excited by a shaker (Data Physics) and calibrated by the force sensor (PCB209C02). The signals of 16 taxels were scanned sequentially by the analog multiplexer (MAX406, 16 channels) and amplified by a homemade charge amplifier with 60 Hz notch filter. The signal processing for force sensor and tactile sensor was controlled by PC-based LabVIEW programming. The processed signals of sensor output are visualized on a personal computer, the shape and force distribution of the contact object are also obtain in real time. The block diagram of signal processing flow and the experimental setup are shown in the Fig. 6 and 7, respectively.

Figure 4. The size and shape effects on the Sensitivity of tactile sensor.
B. Output Characteristics of Sensor

An example of the dynamic responses by the sinusoidal force of ±1.5 N under 2 Hz are shown in the Fig. 8. The tactile sensor output showed the time delay of 50 ms due to the signal processing and the slight noise from the AC power source at 60 Hz.

The relationship between the applied forces and the outputs of tactile sensor is shown in Fig. 9. The threshold of sensor is about 0.5 N and it has good linearity under 4 N. Fig. 10 shows the frequency response of tactile sensor, the horizontal axis is the frequency of applied 1 N force from 1 to 120 Hz; the vertical axis is the gain of the sensor output compared to the value at 1 Hz. For this sensor, the reasonable frequency should be limited under 50 Hz, because the variation of sensor output will increase in the higher frequency range. Hence, additional compensation is needed as measure an external force with higher frequency.

C. Sensitivity Enhancement by Structural Electrodes

According to the simulation results, the sensitivity can be enhanced by adding a structural layer upon the sensing electrodes. For quantifying the difference between with and without PDMS structures, a uniform loading on a specific contact area is necessary, therefore, a sinusoidal force of 1 N under 2 Hz was applied through a square piece of steel placed in the central four taxels. The output voltages for each taxel can be read out by LabVIEW program and visualized by MATLAB software as listed in the Table 2 and shown in the Fig. 11.
respectively. The average sensitivity for tactile sensor with structural electrodes is obviously larger than the value for conventional sensor with thin-film electrodes. However, the variation between each taxel is increased as the uniform loading transferred by PDMS structures array. This can be attributed to the fabrication error of PDMS structures and the misalignment between microstructures and electrodes.

![Figure 11. 3D images of the output voltages as uniformly applied 1 N external force on the central four taxels](image)

**D. Shape Recognition Results**

A human-machine interface was established by LabVIEW program shown in the Fig. 12. The signals of force sensor and tactile sensor can be graphically represented on the screen. Furthermore a color 2D image can be also displayed on the screen after the output voltage of each taxel was scanned sequentially by multiplexor.

![Figure 12. Human-machine interface constructed by LabVIEW program.](image)

An example of shape recognition is shown in the Fig. 13. We utilized two pieces of steel with different shapes to apply force on tactile sensor. As the results, the output voltages of contact taxels were 100 times higher than the other noncontact taxels. Consequently, the shape of object can be easily identified based on this distributed flexible tactile sensor.

![Figure 13. Two different object shape can be identified by 2D intensity images](image)

**V. CONCLUSIONS**

In this study, we introduced the concept of structural electrode in the PVDF-based tactile sensor for the enhancement of sensitivity. A 4 by 4 distributed flexible tactile sensor was designed and fabricated based on MEMS technology and Molding process. The experimental results shows the sensitivity can be increased roughly 30 % due to the microstructural effects, however, the contact condition between PDMS structures and metal electrode has to be improved for the accuracy of force detection. The human-machine interface based on LabVIEW programming is able to achieve the function of shape recognition and force measurement in real time.

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**REFERENCES**


