Modeling and Simulation Research of a Novel Artificial Skin Sensor

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Abstract: In this paper, a novel artificial skin sensor model with special structure based on the flexibility of Polydimethylsiloxane (PDMS) and the piezoresistive effect of Poly Vinylidene Fluoride (PVDF) piezoelectric fiber is proposed to solve the problems of structure design and complicated manufacturing process of skin sensor sensitive units. It has excellent piezoelectric effect and can detect the external force efficiently and precisely. The finite element analysis technology is used to simulate the deformation of the novel artificial skin sensor under external force from different aspects. Firstly, the crossing-mesh sensitive unit model and the three-layer configuration with three-layer of the artificial skin sensor are designed. Secondly, the external forces are applied to the sensitive units with different diameters by finite element analysis, and the sensitive unit with optimum diameter is figured out for the novel artificial skin sensor. After that, with the optimum sensitive unit, the performance of the artificial skin sensor model with the optimum sensitive unit is specifically simulated when it’s subjected to different stress. Finally, through seriously analyzing the experiment results, the mapping relationship between the deformation of the artificial skin sensor and the external force is obtained. Experiment results demonstrate that the novel artificial skin sensor has high sensitivity, not only can truly reflect the approximate linear relationship between sensor deformation and external load, but also can accurately detect the magnitude of external force applied to the sensor.

1.INTRODUCTION

With the rapid progress of intelligent robot and tactile sensing technology, research of the artificial skin sensor with high sensitivity takes a very important part in the intelligent robot field [1–4]. There is a huge challenge for the intelligent robot to judge the change of the external environment quickly and precisely from the deformation and external force loaded on the skin sensor, so as to make correct feedback and decision. The artificial skin sensor is very important to improve the intelligence of robots, it also can be known as flexible tactile sensor. It can help robots recognize objects, detect forces loaded on, and complete sorts of difficult tasks. It is required that the artificial skin sensor should have softness and flexibility as human skin, be suitable for surfaces with different roughness and shape, and can quickly and accurately capture the information from external environment [5]. In practice, the artificial skin sensor is supposed to be wearable and used as robot skin through which the external force loaded on can be detected precisely. The sensitivity of the artificial skin sensor is very crucial for ensuring the safe and efficient interaction
between robots and the environment. Therefore, the research of artificial skin sensors plays an irreplaceable role in the intelligent robot domain.

Many researchers have utilized different techniques, different structures and methods to improve the performance of tactile sensors and achieved the detection of stress with high precision. Hu et al. [6–7] introduced the structural characteristics of a 6-D force sensor based on an E-type membrane, analyzed the calibration results of each bridge, and determined the coupling relationship between bridges of a sensor. Rosle et al. [8] proposed the simple-structured soft fingertip sensitive to external force, the fingertip can estimate the grasping force and orientation of a thin rectangular object, and the contact state between the object and the environment based on magnetic flux density changes. Hao and Wang [9] designed a piezoelectric sensor which used pin module and spring to monitor the depth direction of the object surface, to improve the detection ability of the depth information of the object surface.

There are also many researchers have focused on special materials to produce the flexible tactile sensor, conduct the experiments, and to improve the performance. Lu et al. [10] proposed a new flexible tactile sensor array based on conductive rubber and PDMS, and took the advantage of flexible materials to make tactile sensors which can measure the contact pressure of a single curved surface. Shin [11] designed the haptic sensors based on piezoelectric sensor arrays with pin-type modules which have high responses and dynamic sensing capabilities, and studied for surface topography measurements. Park [12] presented a Depth Neural Network (DNN) based non-linear EIT algorithm to improve the reconstruction accuracy of tactile sensor based on EIT, which ensures the low calculation and provides superior measurement accuracy. As the coupling relation widely exists among the sensing signals of the tactile sensor, many researchers have focused on how to simplify the structure of the sensitive element to decrease the coupling effect and establish efficient method to decouple the relationship among the high-dimensional information of the tactile sensor. Wang et al. [13] presented a special structure of the sensitive unit which can decompose the tactile force loaded on the flexible tactile sensor, and efficiently decoupled the three-dimensional information of the tactile sensor by the BP algorithm under ideal conditions. Chen et al. [14] put forward a kind of data decoupling algorithm for the overvoltage sensor based on interphase coupling theory, and gained high precision. In order to solve the problem of poor consistency and low sensing range of piezoresistive tactile sensor, Chi [15] proposed the best organic solvent by comparing the dispersion performance of MWCNT and the stability of MWCNT / PDMS. Nag et al. [16] proposed a new method to realize the flexible transparent strain sensor, it combines the use of transparent conductive fabrics with PDMS through the simple and direct layer by layer assembly process.

At present, most flexible tactile sensors have complex structures and high costs of manufacture [17-19]. In view of those problems, a novel artificial skin sensor model with special structure based on PDMS and PVDF material is proposed in this paper. Simulation experiments are conducted to the sensitive element with different diameters for the novel sensor model by multi-physical field finite element technology from different aspects to optimize its performance and configuration. The simulation for the novel skin sensor figures out that the magnitude of deformation of the sensitive element increased or decreased is proportional to the increasement or decrement of external force. There is a positive correlation between deformation and external force, and their mapping relationship is approximately linear. This paper is organized as follows. Sec. 2 introduces the material characteristics of the novel artificial skin sensor. Sec. 3 describes and analyzes the modeling process of the artificial skin sensor structure. Sec. 4 elaborately analyzes the simulation process for the novel sensor under different stress and deliberately discusses the entire experiment results for the sensitive elements with different configurations. Sec. 5 presents the conclusions.

2. MATERIAL CHARACTERICS
Many flexible materials have been applied in the field of robot skin sensors. Especially, the flexible surface layer of the skin sensor plays a very important role in protecting sensitive elements of the sensor and transmitting pressure and deformation, so that the robot could get precise information from external environment and make a correct response or feedback to the surroundings. Simultaneously, the intelligence of the robot could be improved. It is required that the artificial skin sensor should be stable, soft, and
stretchable as human skin, appropriate for objects with different roughness and shape, and could acquire multi-dimensional information from the environment quickly and accurately.

The structure of the novel artificial skin sensor proposed in this paper is mainly composed of two parts: one is the flexible protection film layer made of PDMS and the other is the sensitive element layer made of PVDF piezoelectric fiber.

The protection film layer is also the surface layer, it is the component where the artificial skin sensor can get contact with the environment. It means that the material which is used to make the surface layer should be able to protect the sensitive element from being corroded by the external environment. PDMS is a kind of silicone rubber, as a polymer, it has great stability, flexibility, and low young's modulus properties [20]. In general, PDMS is chemically inert, non-toxic, stretchable, cheap, and difficult to burn. All of these properties make it very suitable to make the surface layer for the artificial skin sensor [21].

Although there are many materials that can be used to make the piezoelectric layer of the sensor, as a novel type of polymer piezoelectric material, PVDF piezoelectric fiber could be used as the sensitive elements of the piezoelectric layer [22]. It has excellent characteristics, such as, high piezoelectric constant, low density, light weight, good flexibility, high sensitivity, low acoustic impedance, wide frequency response, better stability, and easy portability and processing. In view of PVDF's excellent properties, it is widely used in the manufacture and processing of tactile sensors [23-24]. In this paper, PVDF piezoelectric fiber is selected to make the sensitive element layer for the artificial skin sensor.

3. STRUCTURE MODELING
A novel model for the artificial skin sensor is proposed and designed in this paper, and its basic architecture is shown in Figure 1. It is mainly consist of two components that are the sensitive element layer made of PVDF piezoelectric fiber and the protection film layer made of PDMS rubber [25]. The PVDF fiber should be put into a self-made artificial skin mold, then the PDMS silicone rubber is added to produce the artificial skin for the experiment. In order to simplify the specific analysis procedure, PDMS layer and PVDF piezoelectric fibers are drawn separately in Figure 1. Actually, PVDF piezoelectric fiber is embedded in the PDMS material in the real sensor.

In Figure 1, "1" and "3" represent the protection film layers (shown in Figure 2) made of PDMS, it is used to protect the PVDF piezoelectric fiber. The film layer makes the artificial skin sensor soft and flexible, and felt like human skin. In Figure 1, "2" represents the sensitive element (shown in Figure 3) made of PVDF piezoelectric fiber. The PDMS film layer shown in Figure 2 is laid to prevent PVDF piezoelectric fiber from being damaged under the effect of external force, and also prevent the PVDF fiber from being worn out by external force touching the surface of the artificial skin frequently. Some researchers have used single rows to deploy the PVDF piezoelectric fibers [29], but the structures are fragile and instable. In this paper, the crossing-mesh arrangement of the sensitive element made by the PDVF piezoelectric fiber is adopted to improve the stability of the model.
The novel structure of the PVDF piezoelectric fiber layer is shown in Figure 3. When the novel artificial skin sensor is subjected to external force, the piezoelectric fiber would be deformed, and the extent of the deformation corresponding to the magnitude of the force. Collecting electrical signals from the circuit when PVDF fiber is deformed by external force, the mapping relationship between electrical signals and deformation would be explored and constructed. Then, the magnitude of the external force applied on the artificial skin sensor could be computed and solved inversely. In the experiment, the PVDF piezoelectric fiber layer is meshed, and each mesh works as a sensitive unit.

PVDF piezoelectric fiber can be regarded as a simple beam structure, and the fiber is embedded inside the artificial skin sensor. As the PVDF piezoelectric fiber is covered by the thin PDMS film, it is supposed that the force or load applied to the surface of the artificial skin sensor is equivalent to applied directly to the PVDF piezoelectric fiber. The sensing signal of the artificial skin sensor is derived from the inductive signal produced by the PVDF piezoelectric fiber. The sensitive element model designed in this paper is the crossing-mesh structure, and there exists cross coupling effect among the sensitive units. If the force applied to the artificial skin sensor solved directly by detecting the change of electrical signal of the sensitive element, there would exist coupling errors. In order to reduce the degree of coupling effect among sensitive units, in the simulation, the external forces are retrieved by detecting the deformation of piezoelectric fibers. When the external force applied on the novel artificial skin sensor, the sensor sensitive unit will generate corresponding deformation due to the stress, and the magnitude of the deformation could be further deduced and calculated through detecting circuit signals. Finally, the extent of the external force could be calculated inversely by the state equation that relate to the relationship between the deformation and the external force.

4. ANALYSIS AND DISCUSSION

4.1. THEORETICAL BASIS

When the artificial skin sensor is subjected to external forces, the PVDF sensitive element would be deformed, and different deformations corresponding to different forces. The external circuit could be used to gather and deduce the deformation signal, then the force put on the skin sensor would be deduced in reverse.

In this paper, the PVDF piezoelectric fiber is meshed by the COMSOL software, and each mesh is a sensitive unit of the sensor. For each sensitive unit, its input signal is the three-dimensional force (corresponding to the three components Fx, Fy, and Fz), and its output electrical signal is the corresponding resistance components that are Rx, Ry, and Rz. According to the law of resistance, the resistance of PVDF piezoelectric fiber is proportional to the square of its length, that is as follow.

$$ R = \rho \frac{L}{S} \left( \frac{\rho L^3}{V} \right) $$

When force or stress is applied to the sensor, the deformation of the sensitive element can be calculated by detecting the corresponding resistance as below.
\[ L_i = \frac{(L \cdot \sqrt{R_i})}{\sqrt{R_i}}, \quad i = x, y, z \] 

(2)

\[ \Delta L_i = L_i - L_i = \sqrt{V}, \quad i = x, y, z \] 

(3)

\[ F_i \propto \frac{\rho \Delta L_i}{V_i} \quad |L_i^2 - L_i^2|, \quad i = x, y, z \] 

(4)

So, the relationship between force and deformation can be calculated by (3) and (4). It can be generalized as,

\[ F_i = g(\Delta L_i) = f(R_i) \] 

(5)

Therefore, the magnitude of the external force exerted on the sensor can be gained from the deformation of the sensitive unit.

4.2. SIMULATION FOR THE ARTIFICIAL SKIN SENSOR UNDER DIFFERENT STRESS

In order to truly and effectively simulate the deformation situation of the novel artificial skin sensor when it’s subjected to different stress, the COMSOL finite element simulation technology is utilized to carry out numerical simulation experiments for the skin sensor’s sensitive element (PVDF piezoelectric fiber) from different perspectives.

First, the source file of the artificial skin sensor model shown in Figure 1 is imported into the COMSOL software. After that, the material properties (as shown in Table 1 and Table 2) of the two important components of the artificial skin sensor model are set up respectively, to construct the basic finite element model for the sensitive element. Then, constraints are applied to the stress points which are the intersections and endpoints of the sensitive element. The finite element model has 4 stress points at the intersection of each sensitive element and 2 stress points at each endpoint, as shown in Figure 4. Therefore, the whole finite element model has a total of 718 stress points.

| Property                              | Value       | Unit           |
|---------------------------------------|-------------|----------------|
| Coefficient of thermal expansion      | 9e-4        | 1/K            |
| Heat capacity at constant pressure    | 1460        | J/(kg*K)       |
| Relative permittivity                 | 2.75        | 1              |
| Density                              | 970         | Kg/m^3         |
| Thermal conductivity                 | 0.16        | W/(m*K)        |
| Young’s modulus                      | 750         | Pa             |
| Poisson’s ratio                      | 0.49        | 1              |

| Property                              | Value       | Unit           |
|---------------------------------------|-------------|----------------|
| Density                              | 1780        | Kg/m^3         |
| Young’s modulus                      | 2500        | Pa             |
Figure 4. The sensitive units under constraints.

In the numerical simulation, external force of 2N is applied to the center sensitive unit of the PVDF piezoelectric fiber (where, the Fx, Fy and Fz are all 2N), and the result is shown in Figure 5 (a). Then, the force of 5N is applied to the center of PVDF piezoelectric fiber, and the result is shown in Figure 5 (b). The experiment results indicate that when the external force is applied to the sensor model, the brighter the point is, the greater the force is induced at the stress point, that means the greater the external force acts on the stress point, the more deformation is gained. If the color of the sensitive unit is less bright, it means that the force induced by the stress point is smaller and the deformation is less obvious. From Figure 5, it can be concluded that when the pressure loaded on the surface of the artificial skin sensor increases, the stress that the PVDF piezoelectric fiber felt increases correspondingly, and the extent of deformation become more obvious, vice versa. It implies that the novel artificial skin sensor has superior sensitivity and is sensitive to the changes of external force.

Figure 5. Stress distribution of the sensitive units.

4.3 DISCUSSION FOR SIMULATION RESULTS OF THE SENSITIVE ELEMENTS WITH DIFFERENT DIAMETERS

In order to analyze how different configurations of the sensitive elements act on the performance of the sensor when external force loaded on and build the optimum structure for the sensitive unit, this section focuses on the simulation for the sensitive units with different diameters and make sure which one would be best for the novel artificial skin sensor. For the sake of making the artificial skin sensor not only has superior flexibility, but also has thin and light characteristics that could be similar to real human skin, the diameter of the sensitive element is controlled within 2mm during the experiment. In the numerical simulation and research process, the sensitive units with diameters of 1mm, 1.5mm, 1.8mm and 2mm are carried out in detail, respectively. The three-dimensional force of 1N (Fx=Fy=Fz=1N) are applied to the corresponding sensitive elements. Meanwhile, the deformation (displacement) of 718 stress points generated by the PVDF piezoelectric fiber under external force are obtained, and the specific experiment results with different diameters are shown in Figure 6, respectively.
Figure 6. Deformation of PVDF piezoelectric fibers with different diameters.

Figure 6 (a) ~ (d) show the deformation of the PVDF piezoelectric fiber with diameters of 1mm, 1.5mm, 1.8mm, and 2mm, accordingly, their maximum displacements are 12.67cm, 2.638cm, 1.325cm, and 0.6381cm, respectively. The experiment results shown in Figure 6 indicate that when the artificial skin sensor is subjected to external force, the sensitive units with different diameters of the PVDF piezoelectric fiber produce corresponding deformation that could be the displacements generated by the stress points. From Figure 6, it is concluded that the sensitive unit which farthest from the spot where the force loaded on has the smallest displacement. With the distance from the spot where force loaded on decreases, the deformation generated by the corresponding sensitive element increases gradually and proportionally, and the experiment results are uniform and symmetrical.

In order to further study the best performance of the sensor, based on repeated experiments, the maximum displacement of PVDF piezoelectric fibers with diameters of 2.2mm, 2.5mm, 2.8mm, 3mm, 3.2mm, 3.8mm and 4mm under the 1N load are carefully analyzed and compared with those PVDF piezoelectric fibers with diameters no more than 2mm, the result are shown in Figure 7.

Figure 7. The maximum deformation of the sensitive element with different diameters.

Figure 7 shows that with the increase of the diameter of the piezoelectric fiber, the maximum displacement of the same stress point suffered by the same load decreased. In other words, if the diameter
of the sensitive units were different, the deformation of the PVDF piezoelectric fiber were different even if it is subjected to the same load.

After the comparison and analysis of the results shown in Figure 6 and Figure 7, it implies that when the diameter of PVDF piezoelectric fiber is 2mm, the differences of displacement among the stress points are small, which indicate that PVDF piezoelectric fiber with the diameter of 2mm has high sensitivity and would not do harm to the sensor structure due to the deformation generated by the external force. Especially, its thickness is quite suitable. Its performance is better than the others, and its proper thickness could improve the performance of the sensitive element. Therefore, the PVDF sensitive unit with a diameter of 2mm is optimal and would be studied in detail as below.

4.4. SIMULATION AND DISCUSSION OF THE PVDF FIBER WITH THE OPTIMUM DIAMETER
In order to deeply explore and verify the performance of the novel artificial skin sensor with the diameter of 2mm of the sensitive unit, the finite element analysis technique is used to apply different loads to the upper surface of the sensor. The external forces of 1N, 2N, 3N and 4N are loaded on the sensitive unit with the diameter of 2mm, respectively. The deformation of the PVDF piezoelectric fiber are gained and the results are shown in Figure 8.

Figure 8. The Deformation of the PVDF piezoelectric fiber with 2mm diameter under different loads.

Figure 8 (a)~(d) show that when external forces with different magnitude are applied, the sensitive units of PVDF piezoelectric fiber generate different deformations (displacements) which depend on the distance from the force point. The stress point near the central stress point where the external force exerted on produces the maximum displacement. The further the stress point from the spot where the force loaded on, the displacement or deformation decreases proportionally, the relation between displacement and distance is inverse proportional. For the sensitive unit of the diameter of 2mm, the deformation of the PVDF piezoelectric fiber are different when it is subjected to external loads with different sizes. The displacement of the stress point increases with the increaseamet of the external force, vice versa. According to Figure 8 (a) ~ (d), when the artificial skin sensor is subjected to external forces of 1N, 2N, 3N and 4N, the mapping relationship between external force and deformation (displacement) could be obtained, which shown is Figure 9.
By analyzing the mapping relationship between deformation and force for the PVDF piezoelectric fiber with the diameter of 2mm shown in figure 9, it is acquired that when the force applied to the sensor surface increases linearly, the maximum deformation or displacement produced by PVDF piezoelectric fiber also increases linearly, vice versa. At the same time, the deformation data of the stress points with non-maximum displacement are analyzed and it implies that the deformation also linearly changed according to the magnitude of the external force and the distance from the spot where the force applied to. That is, the mapping relationship between the change of the deformation (displacement) caused by the PVDF piezoelectric fiber and the change of force applied on the sensor surface is approximately linear. The experiment results show that the novel artificial skin sensor not only has superior piezoelectric effect, but also can detect and reflect the external force precisely.

5. Conclusion
In this paper, a novel artificial skin sensor model is designed based on the piezoresistive effect of PVDF and the flexibility of PDMS. Simulation experiments are conducted to the novel sensor model by multi-physical field finite element technology from different aspects to optimize its performance and configuration, and the experimental results are analyzed and discussed in detail. The simulation results show that the sensitivity of the sensitive element with the diameter of 2mm of PVDF piezoelectric fiber is much better than the others. At the same time, the sensor has excellent performance under different external forces. The simulation for the novel skin sensor figures out that the magnitude of deformation of the sensitive element increased or decreased corresponding to the increasement or decrement of external force and their mapping relationship is approximately linear. The novel sensor model proposed in this paper has stable performance, optimized structure, superior sensitivity, and excellent piezoelectric effect, which can detect and reflect the external force efficiently and precisely. It also has perfect practicability and application value in intelligent robot skin field. The research of this paper would provide both technical support and theoretical accumulation for the development of robot skin.

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