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Three-dimensional force simulation prediction of flexible sensor based on BP neural network

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Absrtact: When the robot grabs the object, the force information detection of the object is the basis for the smooth grabbing process. The force information of the object can be fully reflected by detecting the force in the three-dimensional direction. In this paper, with polydimethylsiloxane (PDMS) as the substrate and embedded into the sensitive unit prepared by conductive rubber, a new flexible sensor which can detect three-dimensional force is designed. Firstly, based on the piezoresistive effect of conductive rubber, COMSOL Multiphysics software was used to carry out multi-physical field simulation experiment for the sensor. Furthermore, based on the nonlinear approximation ability of BP neural network and the resistance of simulation output, the training sample set and the test sample set were constructed by using the 5-fold cross validation method, and the BP neural network model was constructed to achieve the accurate prediction of three-dimensional force. Finally, the number of hidden layer neurons was adjusted to optimize the BP network model. The results of cross-validation experiments show that the sensor designed in this paper can effectively detect the three-dimensional force information, and the optimized BP neural network can significantly improve the accuracy of the three-dimensional force prediction.

1. Introduction

Due to its excellent ductility and high sensitivity[1], flexible tactile sensors are widely used in medical diagnosis, robotics, electronic skin and other fields to complete sensory tasks[2].Saadatiz Mohammad Nasser[3] and Alireza Mohammad[4] et al. applied flexible sensors into the skin design of robots, making them more sensitive to the forces of the external environment. Wang Liangze, from Harbin Institute of Technology, took PDMS/ nano-graphite sheets as composite materials and proposed a design of a flexible piezoresistive sensor with a three-layer structure, which can effectively detect three-dimensional force information [5]. Hao Zhiliang et al. prepared a pressure sensor that can detect the position using carbon nanotubes as conductive filler and polyurethane as matrix [6]. Ge Weidong designed a three-dimensional fingertip tactile sensor [7], which realized the calibration and measurement of positive pressure, effectively improved the sensitivity of the sensor, and eliminated the coupling effect between the sensor's positive pressure and tangential force [8].

In this paper, polydimethylsiloxane was used as the substrate and conductive rubber as the sensitive unit. Four sensitive units were embedded into the PDMS substrate, and a flexible tactile sensor was designed. Based on the piezoresistive effect of conductive rubber, the multi-physical field simulation

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was carried out for the sensor, and the three- dimensional force was predicted and analyzed by combining BP neural network. The results show that the sensor can detect the three-dimensional force information effectively.

2. Material and Methods

2.1.Force analysis of the microstructure

Based on the piezoresistive effect and force sensitive characteristics of conductive rubber, a flexible tactile sensor was designed in experiment. The structural model of the sensor is shown in Figure 1, where 1 and 3 respectively represent the PDMS thin layer and the bottom layer, and 2 represents the piezoresistive layer. The microstructures of four cylindrical sensitive units of the piezoresistive layer studied in this paper are prepared from conductive rubber with a thickness of 1 mm and a diameter of 2 mm. PDMS is an inert polymer material with good chemical stability and good light transmittance [9]. PDMS thin film with thickness of 0.5 mm and length and width of 8 mm is used as the flexible substrate of the upper layer and the lower layer. The upper flexible matrix is mainly used to protect the sensitive unit from damage under the direct action of external forces. PDMS is also used around the sensitive units. Solidworks 2018 software was used to draw the sensor model with the size of 8mm× 8mm× 1.5mm.

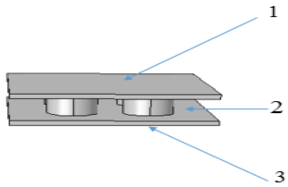

Figure 1. Sensor structure model

It is assumed that the conductive rubber adopted in the microstructure is a linear elastomer with incompressible volume and no hysteresis characteristics, and its strain law meets Hooke's law:

$$F = k \times \Delta l \quad (1)$$

Since the conductive rubber resistance R is proportional to its length L square, i.e.

$$R = \rho l/S = \rho l^2/V \quad (2)$$

According to Equation（2）, there is an mapping range:

$$R_i = \rho l_i^2/V_i \quad (i = x, y, z) \quad (3)$$

Because of the piezoresistive property of conductive rubber [10], that is, approximately satisfying the condition $F \propto \Delta l$, the mapping relationship between the three-dimensional force and resistance variation can be obtained:

$$F_i \propto (\sqrt{R_i'} - \sqrt{R_i}) \quad (4)$$

2.2. Multiple physical field simulation based on COMSOL

The finite element analysis software COMSOL Multiphysics 5.4 was used to conduct multi-physical field simulation of the flexible tactile sensor shown in Figure 1 to solve the coupling problem of solid mechanics module and current module, so as to accurately and rapidly analyze and calculate the simulation model. The process is shown in Figure 2.

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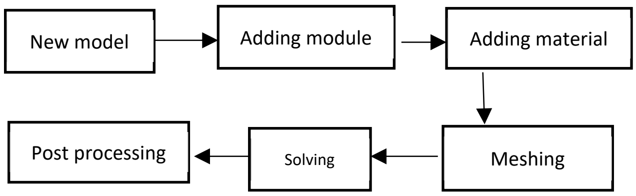

Figure 2. COMSOL solution process

Step 1: Creating a new model. First, three-dimensional space is selected, and then steady state is selected in the research module, because the experimental field variable resistance will not change with time. Finally, import the sensor model shown in Figure 1 into COMSOL.

Step 2: Adding materials. Conductive silicone rubber and PDMS with good chemical stability were selected. Coupling simulation of force field and electric field is required in the experiment. For conductive rubber and PDMS, material density, conductivity, young's modulus and other properties are set respectively, as shown in Table 1.

TABLE 1. Material attribute Settings

attribute	**variable**	**Conductive rubber**	**PDMS**	**Company**
density	Rho	293	970	kg/m^3
Young's modulus	E	$4e^6$	$7.5e^7$	Pa
Poisson's ratio	Nu	0.49	0.48	1
conductivity	sigma	0.0001	-	S/m

Step 3: Setting the boundary conditions. In the solid mechanics module, the lower surface of the sensor is taken as the fixed constraint, and the flexible substrate of the above layer PDMS is taken as the boundary load, and surface load is applied. Ideally, the solid model is isotropic. In COMSOL, solid mechanics module and current module are selected to carry out finite element simulation calculation. Due to the coupling of the two physical fields, a mobile grid interface needs to be added.

Step 4: Applying the load. In this simulation experiment, surface load is applied on the upper surface of the sensor to study the stress distribution of the sensor. When 1N pressure is applied in X direction, Y direction and Z direction simultaneously, the stress simulation results are shown in Figure 3. When a pressure of 2N is applied in X direction, Y direction and Z direction simultaneously, the stress simulation results are shown in Figure 4.

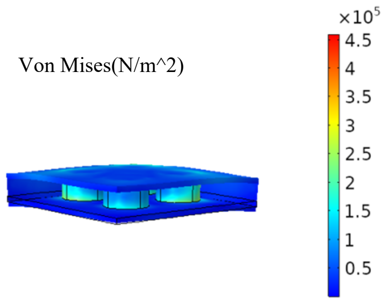

Figure 3. Stress distribution diagram of microstructure

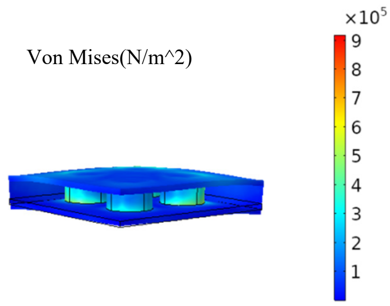

Figure 4. Stress distribution diagram of microstructure

Figure 3 and Figure 4 indicate that when pressure is applied to the sensor model, the darker the color of the micro-structure of the sensitive element is, the greater the force is exerted; On the contrary, it means that the force is less. As can be seen from Figure 3 and Figure 4, when the applied pressure increases, the deformation caused by the sensor also increases correspondingly, and it conforms to the Equation (1).

Step 5: The current is applied to the microstructure based on the surface load.The microstructural circuit diagram is shown in Figure 5, in which 1 and 2 respectively represent the electrode points at the center of the upper and lower end faces of the cylinder, 3 represents the cylinder prepared by conductive rubber, namely the sensitive unit, 4 represents the lower longitudinal conductor connecting the lower electrode points, and 5 represents the upper transverse conductor connecting the upper electrode points.

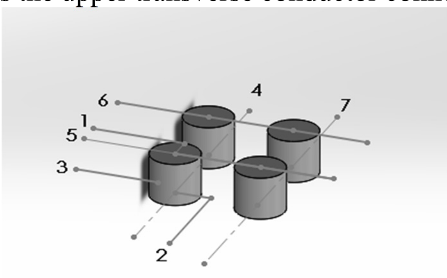

Figure 5. Microstructural array circuit diagram of sensitive element

When the external force is applied to the sensor, the conductive rubber cylinder will produce corresponding deformation. According to the piezoresistive effect of conductive rubber, the resistance of the column will be changed by deformation. Assuming that the resistance of cylinder 3 in Figure 5 is measured, the resistance can be measured by applying current to wire 4 and wire 5 respectively using the detection circuit. In the same way, other column resistances can be measured.

On the flexible substrate of PDMS on the upper layer of the sensor, 1N pressure was simultaneously applied in the X, Y and Z directions, and 0.01A current was applied on the microstructure. The potential simulation results were shown in Figure 6. The current remains unchanged and the pressure increases to 2N. The potential simulation results are shown in Figure 7.

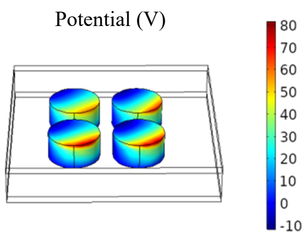

Figure 6. The potential diagram after applying 1N force

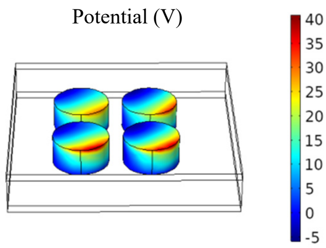

Figure 7. The potential diagram after applying 2N force

As can be seen from Figure 6 and Figure 7, when a load is applied on the sensor, the four sensitive elements are deformed by external forces, resulting in changes in the resistance. At the same time, with the increase of external force, the electric potential decreases and the resistance decreases accordingly.

3. Three dimensional force prediction based on BP neural network

According to the multi-physical field simulation results of the sensor, four sensitive units in the microstructure will generate different degrees of deformation when applied with the force, thus obtaining four resistors (R_1 R_2 R_3 R_4).In this paper, BP neural network is used to approximate the mapping relationship between the resistance value of the sensitive element and the external force.

3.1.Construction of three-dimensional force prediction model based on BP neural network

The forward feedback network was established in MATLAB, and the measuring resistances R_1, R_2, $R_3$and R_4 of the four sensitive units after the force simulation of the sensor were taken as the input vectors of the BP neural network, which was composed of four neurons. In other words, the input layer of the BP network constructed in this paper was 4 dimensions. The three-dimensional forces

F_x, F_y, F_z corresponding to each set of measured resistors, as the output vectors of BP network model, are composed of three neurons, that is, the output layer of BP network constructed in this paper is three-dimensional. Set the number of neural network layers as 3. The excitation function of the hidden layer of BP network constructed in this paper is the hyperbolic tangent S-type transmission function tansig, and the excitation function of the output layer is the linear transmission function Purelin. The maximum number of iterations was set as 1000, the mean square error (MSE) was set as 10^{-3}.and the number of hidden layer neurons was set as 3. Figure 8 shows the BP neural network schematic diagram established by using MATLAB neural network toolbox.

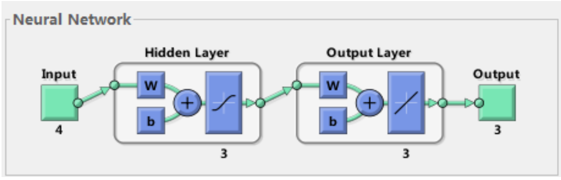

Figure 8. BP neural network established by Matlab toolbox

4. Results and analysis of three-dimensional force prediction based on BP neural network

4.1.Sample set construction based on 5-fold cross validation

Based on the piezoresistive effect of conductive rubber, for every force applied to the upper PDMS film layer of the sensor shown in Figure 1, the sensitive unit in the microstructure will output 4 resistors. The applied load range was 1N-50N, and 0.5N was used as incremental load to obtain 100 sets of samples.

In order to ensure the uniformity of samples, the 5-fold cross validation method was used to construct the training sample set and the test sample set. That is, the initial sample set was randomly divided into five parts, among which four parts were used as training samples and the remaining one part was used as test samples. The whole process was crossed for five times, and the average value of the results of the 5 cross verifications was finally taken as the prediction result of this experiment.

4.2.Evaluation indicators

The relative error delta δ is used to reflect the accuracy of the prediction. The smaller the relative error is, the higher the prediction accuracy will be. Where, the expression is as follows:

$$\delta = \frac{|F' - F|}{F} \tag{5}$$

Where,F represents the true value and F' represents the predicted value of BP network.

$$\delta_i = \frac{F_i' - F_i}{F_i} \quad i = x, y, z \tag{6}$$

In this paper, F_x , F_y , F_z are the real three-dimensional force outputs of training samples, while F_x' , F_y', F_z' are the predicted three-dimensional forces output by BP network, mean relative error $\bar{\delta}$ is defined as follows:

$$\bar{\delta}_x = \frac{1}{n}\sum_1^n(\delta_{x_1} + \cdots + \delta_{x_n}) \tag{7}$$

$$\bar{\delta}_y = \frac{1}{n}\sum_1^n(\delta_{y_1} + \cdots + \delta_{y_n}) \tag{8}$$

$$\bar{\delta}_z = \frac{1}{n}\sum_1^n(\delta_{z_1} + \cdots + \delta_{z_n}) \tag{9}$$

In the above equation, $\bar{\delta}_x$, $\bar{\delta}_y$, $\bar{\delta}_z$ respectively represent the average relative error of F_x, F_y, F_z,and n represents the total number of samples.

4.3.Results and analysis

Based on the method described in Section 3.1, five cross experiments were carried out. The variation trend of tangential force F_x and tangential force F_y is the same, so the experiment only studies and discusses the variation of F_x and F_z. The average relative error $\bar{\delta}_x$ of tangential force F_x and the average relative error $\bar{\delta}_z$ of normal force F_z .The prediction results are shown in Table 2.

TABLE 2. Average relative error table of F_x and F_z

	$\bar{\delta}_x$	$\bar{\delta}_z$
Training 1	21.7%	22%
Training 2	17.9%	17.9%
Training 3	28.1%	34.5%
Training 4	3.7%	3.7%
Training 5	14.5%	14.4%
average value	17.2%	18.5%

For the 5 training results shown in Table 2, the average value is taken as the prediction result. The average relative error of tangential force F_x and normal force F_z is 17.2% and 18.5% respectively. In the BP network constructed by experiments, a single hidden layer is adopted. In order to approximate the mapping relationship between input and output, the number of hidden nodes should be appropriately larger to increase the generalization ability of the network. On this basis, the training accuracy of the network is improved by increasing the number of neurons in the hidden layer. The average error prediction results of normal forces based on different node Numbers are shown in Table 3.

TABLE 3. Relative error table based on the number of neurons in different hidden layers

	3	4	5	6	7
δ_z	18.5%	16.9%	18.2%	20.1%	17.2%

By observing the results shown in Table 3, it can be found that the higher the number of neurons in the hidden layer, the higher the prediction accuracy. When the number of neurons in the hidden layer is too large, overfitting will occur, resulting in the decrease of prediction accuracy. In order to ensure the best accuracy, select number of hidden layer neurons is 4, normal force F_z reached the minimum, which was 16.9%. The average error $\bar{\delta}_z$ dropped 1.6 percentage points from 18.5 percent to 16.9 percent, compared with previous estimates. It is verified that the number of hidden layer nodes has an important effect on the prediction accuracy.

5. Conclusion

In this paper, based on the piezoresistive effect of conductive rubber, the flexible sensor combining polydimethylsiloxane PDMS and conductive rubber can effectively detect the three-dimensional force information through multi-physical field simulation experiments. Based on BP neural network technology, 5 - fold cross validation method is used to build the training sample and test sample sets, adjust the number of neurons, to optimize the BP neural network model, forecast the three-dimensional force simulation results, the results show that the BP network has good nonlinear approximation capability, and its output accurately reflect three-dimensional force.

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