Decoupling research on a flexible tactile sensor array with novel structure

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Abstract. This paper presents a flexible tactile sensor, which uses a novel structure and effective decoupling method to detect multi-point three-dimensional touch force. Firstly, the structure characteristics of the sensor are introduced. According to the theories of force-sensitive conductive rubber, the relationship between the resistance and the force exerted on the sensor is analyzed. Furthermore the mathematical model of the sensor based on finite element method is conducted. The simulation result is consistent well with the theory result. Then a decoupling method based on the RBF neural network is proposed in order to obtain the force from the resistance. The research indicates that the flexible tactile sensor with the novel structure and the decoupling method can accurately detect the three-dimensional force.

1. Introduction

Tactile as an important form of perception for the robots can directly perceive a variety of physical properties of environment and the target object. The flexible tactile sensor that can imitate human skin will play the key role in the robots[1,2], and be applied to other areas, such as surgery, rehabilitation, aerospace and so on. So the research of flexible tactile sensor is one of the hot spots in the field of robot sensors. The working principle of tactile sensor can generally be distinguished as pressure resistance, piezoelectric and capacitor, etc[3-6]. Koc. I. M et al.[7] use PVDF material to develop the piezoelectric tactile sensor with micro cylindrical structure, which can detect both force and force distribution at same time. Bao et al.[8] use PDMS material to create a highly sensitivity capacitive tactile sensor, which can clearly perceive the micro force produce by a fly or butterfly stay on the surface of sensor. F. Xu et al.[9] developed a three-dimensional force sensor based on conductive rubber, and the sensor with multi-layer array structure is similar to artificial skin tissue. The complex coupling relationship generally exists in the multi-dimensional force measurement of the tactile sensor. It will affect the accuracy and real-time performance of the sensor. For the early tactile sensor array there exists the complex coupling relationship[3,10]. We redesigned a new microstructural sensitive unit for three-dimensional detection. Its mathematical model is simpler, and also easier to construct a larger scale of the sensor array. Moreover, a decoupling method based on RBF neural network with high dimensional nonlinear ability [11] is used in order that the sensor can detect the three-dimensional force information accurately.
2. **Structural Design**

2.1 **Structure of Flexible Tactile Sensor Array**

In the model, the orderly microstructure unit array was adopted. It is the core component of the flexible tactile sensor. As shown in Figure 1, the microstructure unit is composed of three sections 1, 2 and 3, which denote the columns made of conductive rubbers, and 4, 5, 6 and 7 denote the electrode points on the surface of the columns.

![Figure 1. Microstructural unit](image1.png)

**Figure 1.** Microstructural unit

![Figure 2. Structure of flexible tactile sensor array](image2.png)

**Figure 2.** Structure of flexible tactile sensor array

Figure 2 shows the flexible tactile sensor array with 3×3 dimension of, in which, 1, 4 and 6 denote the columns made of conductive rubber; 2, 3, 5 and 7 denote the electrode points; 8 denotes the upper horizontal wire which connects the upper electrode points; 9 denotes the lower vertical wire which connects the lower electrode points. Insulating rubber is used to fill gap in the array.

When force is applied on the microstructure, the force can be decomposed into three different directions, \( F_x, F_y \) and \( F_z \). The resistance of each column is obtained by means of scanning, and then the resistance between the upper and the lower layer is detected one by one, so the resistance matrix \( R_x, R_y, R_z \) are obtained, and corresponds to the resistance changes of three different directions, respectively. Finally, according to state equations \( F_i = f(\Delta R_i) \), we can decouple the force of the sensitive unit.

2.2 **Force Analysis of Sensor**

When the force exerts on the surface of flexible tactile sensor, the relevant columns in the microstructure are deformed, resulting in change in the resistance values. According to the properties of hyperelastic material, volume of the conductive rubber remains constant when it is deformed. Therefore, the resistance values of the three conductive column in each microstructure satisfy the following formula:

\[
R_i = \rho \frac{l_i^3}{s} = \rho \cdot l_i^3 \quad i = x, y, z
\]  

(1)

For each microstructure unit, there are three resistance outputs, \( R_x, R_y, R_z \) respectively; They are consistent with three input of the three-dimensional force, \( F_x, F_y \) and \( F_z \) respectively. According to formula (1), there is a mapping equation:

\[
\Delta l_i = l'_i - l_i = (\sqrt{R'_i} - \sqrt{R_i})\sqrt{V_i}/\rho \quad i = x, y, z
\]  

(2)

The conductive rubber can approximatively satisfy the condition: \( F \propto \Delta l \) because of its piezoresistive properties, and then can be used to calculate the relationship between three-dimensional force and resistance of sensor.

\[
F_i = f_i (R_i) \quad i = x, y, z
\]  

(3)

Hence there is the following function relationship between the force exerted on the surface of tactile sensor and the resistance of conductive rubber.

\[
F_x = f_x (R_x) \\
F_y = f_y (R_y) \\
F_z = f_z (R_z)
\]  

(4)

It can be seen that the structure of the flexible tactile sensor reduces coupling relation and degree of nonlinearity.
3. Finite Element Analysis
Using COMSOL software, the numerical model of flexible three-dimensional tactile sensor is constructed based on the coupling simulation method[12]. Generally, the lower surface is considered as the fixed constraint in the simulation. When the three-dimensional force is exerted to the microstructure unit in the second row and the second column of the 3*3 sensor array, distribution of force can be seen in the variation stress chart. Figure 4 shows the displacement diagram when \( P_x=50\text{MPa}, P_y=50\text{MPa} \) and \( P_z=50\text{MPa} \). It illustrates that the deformation of microstructure unit in the force area is large, and the microstructure units of surrounding almost have no deformation.

In the experiment, the range of forces applied to the three directions is from 0 to 50MPa, with the increment of 4MPa. It will produce 1000 set of samples. Therefore, we get 1000 samples as training samples of RBF neural network, and 125 groups of samples are randomly generated as test samples of RBF neural network.

![Figure 3. Deformation of the sensor](image)

![Figure 4. Structure of the RBF neural network](image)

4. Decoupling of the flexible tactile sensor

4.1 Decoupling algorithm based on RBF neural network
RBF neural network has 3 layers, which are input layer, hidden layer and output layer. The network has the characteristics of simple structure and strong nonlinear approximation ability. As shown in Figure 5, the input layer is composed of three neuron nodes and transformation function of hidden layer is radial basis function, and the transformation function of output layer is linear function. The RBF neural network is used to decouple the three-dimensional flexible tactile sensor, its essence is that the complex pattern classification problem non-linearly is mapped to the high-dimensional space, and then is classified in the output layer.

There are kinds of radial basis functions in RBF neural network. In the paper, the radial basis function is mainly used in the form of Gaussian function as follows:

\[
\phi(x,x_j) = \omega_j \exp\left(-\frac{1}{2\sigma_j^2} \|x - x_j\|\right)
\]

Here, the vector \( x \) is the signal of the input layer; \( x_j \) is Gaussian function center of \( j \)-th input sample; \( \phi(\|x-x_j\|) \) is a collection which contains many radial basis functions; \( \|x-x_j\| \) is the center of the radial basis function; \( \sigma_j \) represents the basis function extension of \( x_j \) as a vector center. When the RBF neural network is used as a general function approximator, its output has following mathematical form:

\[
F(x) = \sum_j \omega_j \phi(x,x_j) = \sum_j \phi\left(\|x - x_j\|\right)
\]

Since the change in resistance resulted from pressure exerted on the tactile sensor is nonlinear, \( \{x\}_i \) is a collection of \( N \) different points, it can be sure that \( \phi \) is nonsingular matrix, which is reversible and has determination solution.
In the experiment, we construct 1000 sets of samples to train the RBF network, each sample contains two parts: The input vector is the 3-D matrix $R=[R_x, R_y, R_z]$, which is resistance matrix constituted by the three columns in the microstructure unit; The output vector represents the surface of the tactile sensor on which the three-dimensional force $F=[F_x, F_y, F_z]$ is exerted. Then use the trained RBF network model to decouple the three-dimensional force of the test samples, and solve the relative error. The result shows that the ability of the nonlinear mapping relationship based on the RBF neural network is very well, it can decouple the three-dimensional force information accurately.

4.2 Analysis of the decoupling results
In the RBF neural network, the most important factor affecting the performance of the network is the spread of the radial basis. The larger the spread is, the smoother the function fits, but the approximation error becomes large, the net requires more neurons, and it will lead to a large quantity of calculation. Conversely, the smaller the spread is, the more precise the decoupling results will be, but the approximation process is not smooth, the performance of network is poor, and there would produce over-fitting phenomenon, which is easy to produce larger training error. Therefore, we try to choose the different spread, as shown in Table 1, different mean square errors of the RBF neural network decoupling are given (the maximum number of iterations is 100).

| Spread | MSE   | Spread | MSE   |
|--------|-------|--------|-------|
| 1.0    | 0.0144011 | 6.0    | 9.03×10^{-7} |
| 2.0    | 3.21×10^{-4} | 7.0    | 2.89×10^{-6} |
| 3.0    | 9.79×10^{-7} | 8.0    | 1.35×10^{-6} |
| 4.0    | 3.60×10^{-7} | 9.0    | 1.87×10^{-6} |
| 5.0    | 3.74×10^{-7} | 10.0   | 6.81×10^{-6} |

In table 1, the MSE of the three-dimensional force trend to decrease as the increase of the spread of radial base expands. When spread = 4.0, the MSE is minimized. With the spread continues to increase, the neurons become less sensitive to the input, and the output signal of each neuron in the hidden layer tends to approximate value. even if increase the number of neurons, the error would not reduce significantly except increasing the amount of calculation. So we choose spread = 4.0, to construct the three layer RBF neural network.

![Figure 5. Training performance of RBFNN](image)

![Figure 6. Decoupling errors in three directions](image)

In the training process, we set the MSE of ideal target is $1\times10^{-7}$, Figure 5 shows the performance during the training process of the RBF neural network with spread = 4.0. As can be seen, when the training is finished, the final MSE is $3\times10^{-7}$, which satisfies the requirement of decoupling. Figure 6 shows the decoupling error of 125 sets of the samples with three different directions in the RBF neural network under the same conditions.

As shown in Figure 6, the decoupling effect of the flexible tactile sensor along the three directions is very good. The maximum absolute errors in directions of $F_x$, $F_y$ and $F_z$ are 0.029KPa, 0.0275KPa and
0.0377Kpa, respectively. Due to the maximum pressure we exerted on the sensor is 500KPa, it can be known that the relative error of the three-dimensional force satisfies the requirement of the precision of the actual needs. And we can see that the decoupling errors of the data points at right edge are significantly higher than the other part of data points. It is attributed to that the force is exerted at right edge, so the microstructure at the side would produce some interference signal during the process of the data acquisition.

5. Conclusions
Aiming at the complex nonlinear problem and difficult of decoupling the flexible tactile sensor has. In the paper, we designed the novel flexible tactile sensor, which can separate the three-dimensional force information from the structure, and reduce the difficult of decoupling method as far as possible. Combine with the RBF neural network, the three-dimensional force is decouple the optimized spread of the network and the faster speed of decoupling show that the RBF neural network can satisfy the need of real-time decoupling of the three-dimensional force.

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