Decoupling of a 3D-force flexible tactile sensor

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Abstract. Due to the frame structure of the three-dimensional force sensor which is made of pressure-sensitive conductive rubber, its output data is coupled seriously. To solve this issue, the force-applied model of the sensor is established based on the wire resistance model, which provides a theoretical basis for sensor dimensionality reduction and decoupling. In this paper, the Cartesian coordinate system is established to realize the judgment of the direction of the three-dimensional force applied on the sensor, and the sensor output data is decoupled using the least square method. According to the experiment result, the measurement error of the sensor is small and the decoupling method is proved to be suitable.

1. Introduction

Among the five senses of humans, the research on robot vision and hearing has made great progress. But other sensory research is still lagging behind, especially robotic touch. It is of great significance to install appropriate tactile sensors on the robot to enable it to have certain tactile awareness. It has always been a huge challenge for robot research and development to let humanoid robots have skins to get a sense of touch. There are many requirements for robot skins, such as being elastic, being able to cover a large surface area of the robot body, and being capable of sensing slight contact on the skin surface. Some of these requirements are in conflict with each other, which increases the difficulty of robot skin development.

At present, research in this field is very active. Researchers at home and abroad have successively carried out research work in this area for years and obtained many research results, mainly focusing on the three-dimensional force sensors which are based on piezoelectric[1,2], piezoelectric[3,4], capacitive[5,6], and photoelectric mechanisms[7]. However, most of the existing research results are in the laboratory stage, and there is still a big gap from practical application and commercialization.

In this paper, a multi-dimensional force flexible tactile sensor array based on conductive rubber is studied, it is able to detect three-dimensional force and has a certain degree of flexibility which is an important innovation of tactile sensors. Based on the previous research, this paper improves the decoupling method so that it can detect both the magnitude and the direction of the three-dimensional force.
2. Sensor structure
The sensitive unit of the three-dimensional force sensor studied in this paper adopts the integral frame structure. Two layers of electrodes and wires are embedded in the conductive rubber and parallel to each other. There is a 60° inclination angle between the two layers of wires [8]. The schematic structural view of a sensor sensitive unit is shown in Figure 1 and the top view of the double electrode layer is shown in Figure 2.

![Figure 1. Structural schematic diagram of sensor array](image1)

![Figure 2. Top view of double electrode layer](image2)

3. Sensor detection principle
According to previous research, if the incompressibility of conductive rubber is considered, the resistance variation is proportional to the square of its length variation, which can be described in below Formula:

$$\frac{R}{R_0} = \left(\frac{n_0 - \Delta n}{n_0}\right)^2$$ (1)

To simplify the derivation, the 1st node of i-th line $U_i$ of upper layer is marked as $U_{i,1}$, the rest of the nodes are described in the same way. In order to acquire the direction of the applied force, we take the projection of node $U_{1,1}$ on the lower layer as origin of the coordinate, and establish a Cartesian coordinate system which is shown in Figure 3.

Taking the lower layer node $U_{2,4}$ as example, the force-applied model of the three-dimensional sensor is derived in this section. According to the theory of parallel resistance, row-column resistance can be regarded as the parallel connection of multiple node resistances [9]. Therefore, in Figure 4, the resistance $R_{U2L5}$ which is between upper layer row $U_2$ and lower layer column $L_5$ can be expressed in Formula 2.

$$R_{U2L5} = R_{a_1} / / R_{a_2} / / \cdots / / R_{a_m} = \frac{1}{\sum_{i=1}^{r} \sum_{j=1}^{m} \frac{1}{R_{a_i}}},$$ (2)

In Formula 2, m is the number of electrodes in each row of the upper electrode layer. Considering that the unit resistance value of the conductive rubber is relatively large, the row-column resistance values output by the sensor circuit can be regarded as the parallel connection of the smallest and the next smallest resistance between the two nodes.
Because the piezoresistive characteristics of rubber materials are linear [10], combined with formula 1, $R_{U_2L_6}$ can be expressed as:

$$R_{U_2L_6} = N \times \left( \min\{|U_{21a_1}|, |U_{21a_2}|, \cdots, |U_{25a_4}|\} / \min\{|U_{21b_1}|, |U_{21b_2}|, \cdots, |U_{25b_4}|\} \right)$$

$$- \left( \min\{|U_{21a_1}|, |U_{21a_2}|, \cdots, |U_{25a_4}|\} \right)$$

(3)

Where $N$ is a constant and $N = \frac{R_0}{n^2}$. When the external force is applied within the measuring range, and tangential displacement is guaranteed smaller than $l/2$, we can know:

$$\min\{|U_{21a_1}|, |U_{21a_2}|, |U_{21a_3}|, \cdots, |U_{25a_4}|\} = |U_{24b_3}|$$

$$\min\{|U_{21a_1}|, |U_{21a_2}|, \cdots, |U_{25a_4}|\} - \min\{|U_{24a_1}|, |U_{21a_2}|, \cdots, |U_{25a_4}|\} = |U_{24b_4}|$$

(4)

Combined with Formula 3, there is $R_{U_2L_6} = N \cdot \left( |U_{24b_3}| + |U_{24b_4}| \right)^{-1}$.

According to the row-column resistance matrix collected by scanning circuit, row-column resistance between upper layer row $U_2$ and lower layer column $L_6$, $L_7$, $L_8$ can be respectively expressed as $R_{U_2L_6}$, $R_{U_2L_7}$, $R_{U_2L_8}$.

$$\begin{cases} 
R_{U_2L_6} = N \cdot (|U_{24c_3}|^2 + |U_{24d_4}|^2)^{-1} \\
R_{U_2L_7} = N \cdot (|U_{24d_3}|^2 + |U_{24d_4}|^2)^{-1} \\
R_{U_2L_8} = N \cdot (|U_{24d_3}|^2 + |U_{24d_4}|^2)^{-1}
\end{cases}$$

(5)

When a three-dimensional force $F = (F_x, F_y, F_z)^T$ is applied at node $U_{24}$, the conductive rubber will deform under the action of the force, the node will move to $U_{24}'$, which is shown in Figure 5. Suppose that the original coordinate of $U_{24}$ is $(x, y, z)$ and new coordinate after deformation due to applied force is $(x', y', z')$, then the displacement can be expressed as $\Delta x, \Delta y, \Delta z$, where $\Delta x = (x, x_0)\), $\Delta y = (y, y_0)$, $\Delta z = (z, z_0)$, and there is:

$$\begin{cases} 
|U_{24}'L_6| = \sqrt{(l + m - n \cot \alpha - \Delta x)^2 + (n + \Delta y)^2 + (h - \Delta z)^2} \\
|U_{24}'L_3| = \sqrt{(l - m - (k - n) \cot \alpha - \Delta x)^2 + (k - n - \Delta y)^2 + (h - \Delta z)^2}
\end{cases}$$

(6)
Figure 5. Sensor node displacement applied by 3D force

According to above formula, when an external force is applied at $U_{24}$, row-column resistance $R'_{U_{24}}$ can be expressed as:

$$R'_{U_{24}} = N \cdot \{(l + m - n \cot \alpha - \Delta x)^2 + (n + \Delta y)^2 + 2(h - \Delta z)^2$$

$$+ [l - m - (k - n) \cot \alpha - \Delta x]^2 + (k - n - \Delta y)^2\}^{-1}$$

Indicated as $R'_{U_{24}} = f_{U_{24}}(\Delta x, \Delta y, \Delta z)$.

In the same way, row-column resistance $R'_{U_{24}}$, $R'_{U_{24}}$ can be expressed as:

$$\begin{bmatrix} R'_{U_{24}} = f_{U_{24}}(\Delta x, \Delta y, \Delta z) \\ R'_{U_{24}} = f_{U_{24}}(\Delta x, \Delta y, \Delta z) 
\end{bmatrix}$$

Through the above analysis, the three-dimensional deformation $\Delta x, \Delta y, \Delta z$ of node $U_{24}$ under the action of three-dimensional force is obtained. Using the similar method, the three-dimensional deformation of other nodes can be achieved. As the relationship of applied force and deformation of conductive rubber satisfies the generalized Hooke’s law, combined with formula 8, the relationship between row-column resistance $R'_{U_{24}}$, $R'_{U_{24}}$, $R'_{U_{24}}$ and three-dimensional force $F_x, F_y, F_z$ can be expressed as:

$$\begin{bmatrix} R'_{U_{24}} = g_{U_{24}}(F_x, F_y, F_z) \\ R'_{U_{24}} = g_{U_{24}}(F_x, F_y, F_z) \\ R'_{U_{24}} = g_{U_{24}}(F_x, F_y, F_z) 
\end{bmatrix}$$

So far, the mathematical model of sensor node $U_{24}$ under the action of three-dimensional force has been established. Similarly, when other nodes are force-applied, their three-dimensional force information can also be acquired through analyzing their row-column resistances $R'_{U_{i,j}}$, where $i=1, 2, \ldots, K, j=1, 2, \ldots, T$.

4. Experimental verification

The thickness of the sensor used in the experiment is 5mm, the distance of upper layer nodes is $l=k=15mm$, and the distance between lower layer wires is $m=5mm$. The sensor output data is decoupled using the least square method in Matlab.

Taking the node $U_{24}$ of upper layer as example, we apply on it with different normal forces $F_z$ ($F_z \in [0N, 30N]$) in sequence, with the interval of 2.5N. The comparison between the actual output force information and the ideal data is shown in Figure 6, with a measurement error of 0.87%.

Then, a series of random three-dimensional forces are respectively loaded on the sensor nodes. Some experimental data are shown in Table 1. The decoupling results are shown in Table 2, and the measurement error surface is shown in Figure 7.
According to the results of above experiment, it can be concluded that the measurement error of the sensor is within an acceptable range, and the accurate detection of three-dimensional force information can basically be realized. In the meantime, this structure is able to reduce the number of wires in the lower layer, so that the sensor can have better flexibility. In addition, the complexity of sensor decoupling and the design difficulty of hardware circuits are also greatly reduced.

5. Conclusion
In this paper, the decoupling of flexible multi-dimensional force tactile sensor array is studied. A coordinate system is established to confirm the direction of the sensor's force, and sensor output data is decoupled using the least square method to obtain the three-dimensional force. The experimental result indicates that the measurement error of the sensor is acceptable, and the accurate detection of three-
dimensional force information can basically be realized.

Since the actual conductive rubber material has a variety of complex properties, there are still many performances to be studied, such as repeatability and hysteresis. Based on the research of this paper, there are still several topics that we need to further study in the later period, such as how to improve the decoupling algorithm, and how to reduce the measurement error caused by the non-linearity and hysteresis of the conductive rubber.

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