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Design of a Large-scale Three-dimensional Flexible Arrayed Tactile Sensor

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Abstract: This paper proposes a new type of large-scale three-dimensional flexible arrayed tactile sensor based on conductive rubber. It can be used to detect three-dimensional force information on the continuous surface of the sensor, which realizes a true skin type tactile sensor. The widely used method of liquid rubber injection molding (LIMS) method is used for "the overall injection molding" sample preparation. The structure details of staggered nodes and a new decoupling algorithm of force analysis are given. Simulation results show that the sensor based on this structure can achieve flexible measurement of large-scale 3-D tactile sensor arrays. *Copyright © 2011 IFSA.*

Keywords: Flexible tactile sensor, Three-dimensional, Array.

1. Introduction

Flexible tactile sensor is among many basic sensors for the development of advanced humanoid robots. Current researchers have tried for the development of three-dimensional tactile sensor based on capacitance, PVDF and optical waveguide etc. Z. Chu of Delft University of Technology, Laboratory for Electronic Instrument has proposed 3-D tactile sensor based on theory of capacitance [1]. Dargahi of Simon Fraser University of Canada analyzed the Piezoelectricity and thermoelectricity of PVDF, and proposed a piezoelectric tactile sensor with three sensing elements for robotic [2]. Scientist Yoji Yamada of Japan designed soft viscoelastic robot skin with a contact object-location-sensing capability [3]. Jin-Seok Heo of Korean National Academy of Technical Sciences proposed a 3-D tactile sensor with architecture of 3×3 arrays based on fiber Bragg grating technology [4]. Hefei Institute of Intelligent Machines, Chinese Academy of Science, produced three-dimensional tactile sensor array by MEMS technology in 1999[5] and multi-dimensional armor structure of flexible tactile sensor in 2005 [6]. Some of above sensors are not 3-D tactile sensor [7], some of these are not flexible enough to be used as robots' skin. On the other hand, the current sensor arrays based MEMS are designed with rigid silicon underlay. The sensor has great encapsulation volume with a great deal of discrete sensors, which have difficulty in obtaining more accurate continuous information, and the package cost for this kind of sensor is much higher than a discrete sensor.

To develop flexible tactile sensor, especially used as the skin of humanoid robots, conductive rubber has been applied widely [8-15] due to its good pressure-sensitivity and flexibility. Current conductive rubber based sensor is basically single-dimensional because of the bad forming processing of it. We propose the structure of 3D design consists of two 2D-scanning configurations based on conductive rubber. The widely used method of liquid rubber injection molding (LIMS) method was used, the conductive rubber is injected into the complex multi-layers nodes structure [16]. The LIMS based design can meet the need of flexible and multi-dimension of the tactile sensor. The nodes design together with its circuit design is described in detail in this paper. We solve the force-bearing point of the sensor with a new graphic algorithm. The decoupling algorithm and the simulation of the sensor under ideal situation are also described in detail in this paper. This skin liked flexible tactile sensor which is proposed in this paper can meet the urgent demand of the intelligent operation of humanoid robots. It can also be applied in many fields such as sporting training and rehabilitation biomechanics, etc., with a broad application potential.

2. Theory of the Flexible Tactile Sensor

Experimental sample composes of GD-401-type silicone rubber, CB3100-type carbon black, Hn-2002g-based nano-SiO2 and other supporting materials [17-18]. These filler groups are placed into a cylindrical model and mixed to full dispersed by ultrasonic instrument when added organic solvents. We disperse the filler again after the silicone rubber matrix is added. We can find with experiments that the conductive rubber of above components ratio has good pressure-sensitivity and piezoresistive properties that can meet the need of the flexible and other sensitive characters of the sensor.

A structure of two-layer wired nodes is selected in this tactile sensor, by which the conductive rubber is divided into three layers. The upper layer nodes are staggered with the lower layer nodes. The schematic diagram is shown in Fig. 1 and Fig. 2.

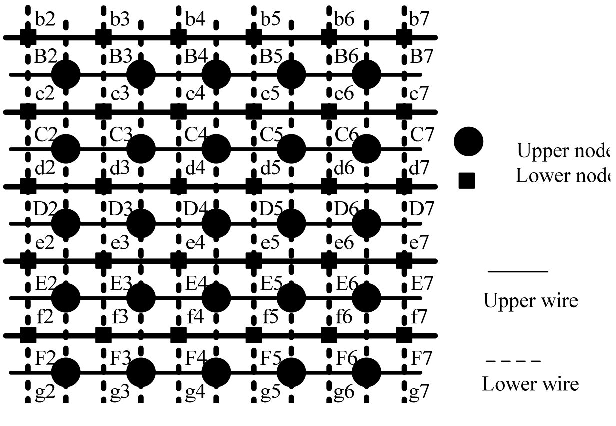


Fig. 1. Top view of the sensor.

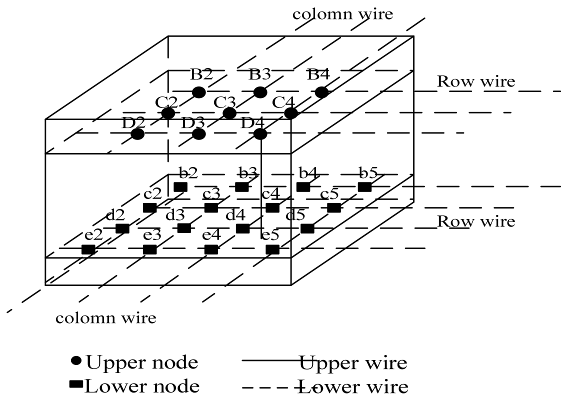


Fig. 2. Stereogram of the sensor.

Every node of the sensor has two identical nodes stick together by insulating cement, so that the two nodes pasted together is insulated to each other. Fig. 3 shows the details of arrangement of every node of the sensor. The upper nodes of the same layer are connected by the row conductors, while the lower nodes of the same layer are connected by column conductors as Fig. 4. Nodes are conductive to the wire, so nodes on the same row or column are electrical conductive to each others. The conductors are coated by insulating material and are insulated to the rubber.

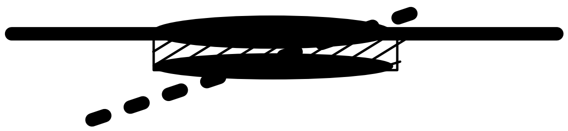


Fig. 3. Single node of the sensor: Two nodes are put together with insulating cement (expressed as shadow).

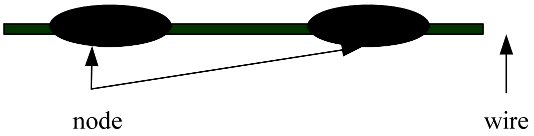


Fig. 4. Node of the sensor: The nodes are conductive to the wire which is insulating to the conductive rubber.

In order to satisfy the designing need we have the above and the bottom rubber layer of the sensor as thin as possible. Then it can be assume that the upper layer nodes are deformed by the force applied and the lower layer nodes are fixed. With this structure, resistance matrix can be measured by the digital circuit designed below. We design a sample with upper layer node matrix of 9 by 7 and lower layer node matrix of 10 by 8, The size of node is ignored. The full-scale of force: Z direction 20N, X, Y direction: 10N. The size of the conductive rubber: 40×50×5 mm.

3. Sample Circuit of the Sensor

The main function of circuit part of the sensor is to acquire signal from conductive rubber, hardware filtering of signal, and transfer signal to host computer. The circuit board consisting of two different parts, one is controller and interface circuit, which is responsible for the signal output to AD conversion, storage, and conversion results to host computer at a time when communications. Controller, memory and interface circuit is included in this part. The other part is for signal acquisition and it includes counters, encoders, multi-selection analog switches, as well as op-amp, etc, which responsible for the signal acquisition from conductive rubber, loading the voltage to the rubber, acquiring and amplifying signal. The circuit is shown in Fig. 5.

With the circuit board we measure the body resistances between the lines of the different layer in order. For example, we measure the resistance between the first row line of the upper layer and the first row line of the bottom layer and get the r11, and then we can measure resistance between the first row line of the upper layer and the second row line of the bottom and get the r_{12}, and so on. With these resistances we can get the arrays of R1 (row-row resistance), R2 (row-column resistance), R3 (column-column resistance), R4 (column-row resistance). The paper below will discuss the method to decouple the force pressed on the sensor with these resistance matrixes.

4. Decoupling Algorithm for the Sensor

The resistance arrays change when the sensor is subjected to external force, the force pressed on the sensor can be decoupled by analyzing these matrixes.

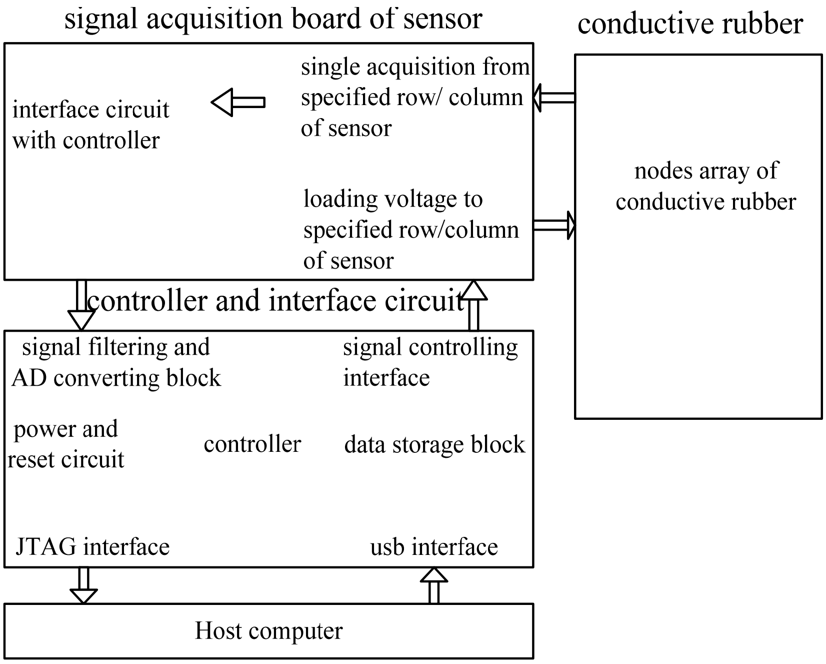


Fig. 5. Control circuit of sensor.

4.1. Assumption

For conductive rubber has the characteristic of a highly nonlinear material and usually possesses hysteresis effect. Tactile sensor based on the conductive rubber may face trouble if we take the nonlinearity and the hysteresis characteristic into account. To simplify the analysis process, we assume that the rubber characteristic is linear and isotropic. Artificial intelligence arithmetic will be used to correct the error in the post-processing of the decoupling.

Assume that the space between the adjacent nodes of same layer is s, the distance between layers is s too, and the space between the adjacent nodes of different layer is $s0=\frac{\sqrt{6}}{2}s$. We can set up the origin of coordinate system at every node of upper layer, point D4 for example. We rotate the coordinate system and show as follows (Fig. 6).

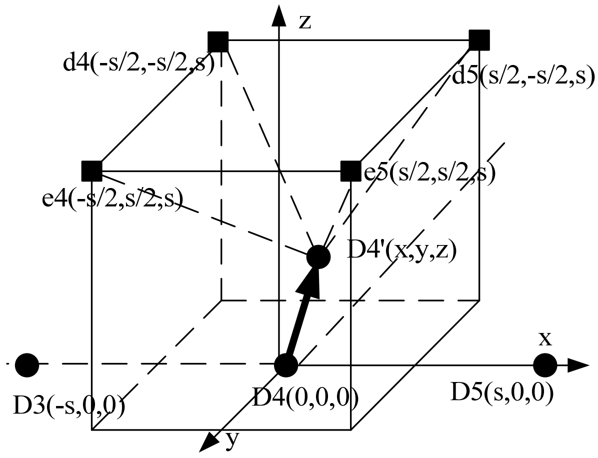


Fig. 6. Node D4 move to D4' acted by force.

We define the distance between the nodes of different layers. For example, we denote s1 as the distance between one upper node and its upper left node of lower layer, s2 as the distance between upper node and its lower left node of lower layer, s3, s4,……s12 etc. of all upper nodes. Specifically, we define s1, s2…… of A1 as A1(s1), A1(s2)……. The distance diagram of upper nodes is shown as follows. Similarly, s1, s2, s3, s4 of all nodes of the sensor can also be set as Fig. 7.

Under ideal condition, we make the following assumptions according to the characteristics of the conductive rubber: (1). Arbitrary resistance between two different nodes is proportional to the distance between two nodes; (2). Arbitrary resistance between two different lines is proportional to the shortest distance between nodes on two different lines as Fig. 8 shows.

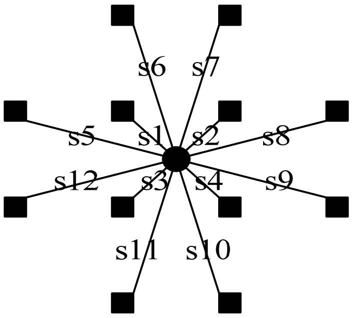


Fig. 7. Define of distance between nodes.

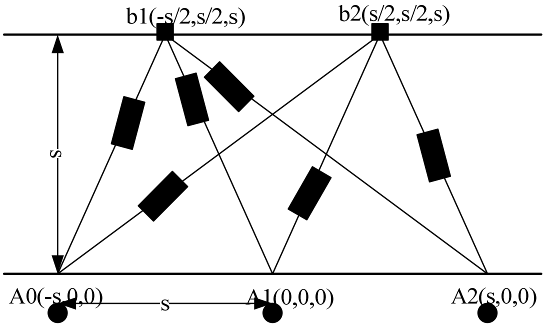


Fig. 8. The resistance between layers.

Assuming that nodes b0,b1,b2…… are on line $\overrightarrow{b_1b_2}$, nodes A0,A1,A2…… are on line $\overrightarrow{A_1A_2}$, the resistance between lines is shown as Fig. 8, then

$$R_{equ} = g\times\min(|A0b0|,|A0b1|,|A0b2|\ldots\ldots|A1b0|,|A1b1|,|A1b2|\ldots\ldots|A\,n\,b0|,|A\,n\,b1|,|A\,n\,b2|\ldots\ldots), \quad (1)$$

where g is the coefficient of the material between the resistance and the distant of lines of sensor.

Although conductive rubber belongs to viscoelastic material, the conductive rubber complies with the elasticity theory when the deformation of the material is not significant. That is to say, deformation of the flexible conductive rubber is compliance with Hook's law when being forced. The force is proportional to the deformation of the rubber:

$$F= k \times \triangle s, \quad (2)$$

which implies that:

$$Fx= k \times \triangle x,\ Fy= k \times \triangle y,\ Fz= k \times \triangle z. \quad (3)$$

4.2. Analysis of Location of the Force-bearing Point

Upper node D4 as an example, assume D4 is pushed to D4' when a force is exerted on the sensor as shown in Fig. 7, we denote that $|D_4'd_4| =$s1', $|D_4'd_5| =$s2', $|D_4'c_4| =$s3', $|D_4'c_5| =$s4'. We assume the maximum deformation of force is smaller than s. So we can conclude that s1', s2', s3', s4' cannot be larger than s0 at the same time. Set ss(i, j)= min(s1, s2, s3, s4) (i, j) be a measurement of deformation in an neighborhood of the i-j-th node, we then have that: if ss(i, j)=s0 then the node is free of the force; if ss(i,j)<s0 then force-bearing point F is detected at i-j-th node. The magnitude of force can be assured with the ss(F) at the same time.

We define matrix E, made by a number of sub-matrix e, each is corresponding to a node of upper layer, so there are 9 by 7 sub-matrixes in the E. Each sub-matrix has four elements, with initial value 0's, reflect line segments s1, s2, s3, s4 of one node the possibility of less than s0.

$$E=\begin{Vmatrix} \begin{vmatrix} e_{s1}, e_{s2} \\ e_{s3}, e_{s4} \end{vmatrix}_{A0}, \begin{vmatrix} e_{s1}, e_{s2} \\ e_{s3}, e_{s4} \end{vmatrix}_{A1}, \ldots\ldots \begin{vmatrix} e_{s1}, e_{s2} \\ e_{s3}, e_{s4} \end{vmatrix}_{A8} \\ \ldots\ldots \\ \begin{vmatrix} e_{s1}, e_{s2} \\ e_{s3}, e_{s4} \end{vmatrix}_{G0}, \begin{vmatrix} e_{s1}, e_{s2} \\ e_{s3}, e_{s4} \end{vmatrix}_{G1}, \ldots\ldots \begin{vmatrix} e_{s1}, e_{s2} \\ e_{s3}, e_{s4} \end{vmatrix}_{G8} \end{Vmatrix} = \begin{vmatrix} e_{1,1}, e_{1,2}, e_{1,3}, e_{1,4} \ldots\ldots e_{1,15}, e_{1,16} \\ e_{2,1}, e_{2,2}, e_{2,3}, e_{2,4} \ldots\ldots e_{2,15}, e_{2,16} \\ \ldots\ldots \\ e_{14,1}, e_{14,2}, e_{14,3}, e_{14,4} \ldots\ldots e_{14,15}, e_{14,16} \end{vmatrix}$$

The seventh line of matrix E for example corresponds with the following line segments in Fig. 9 from left to right, the other line of E have the similar corresponds. Element at row 2i-1 and 2i and column 2j-1 and 2j corresponds to the node (i, j).

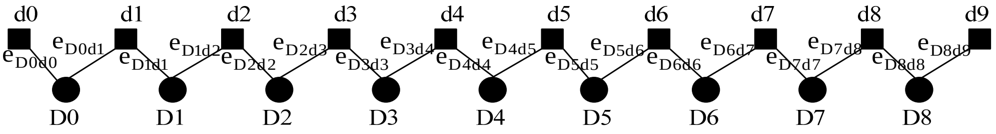
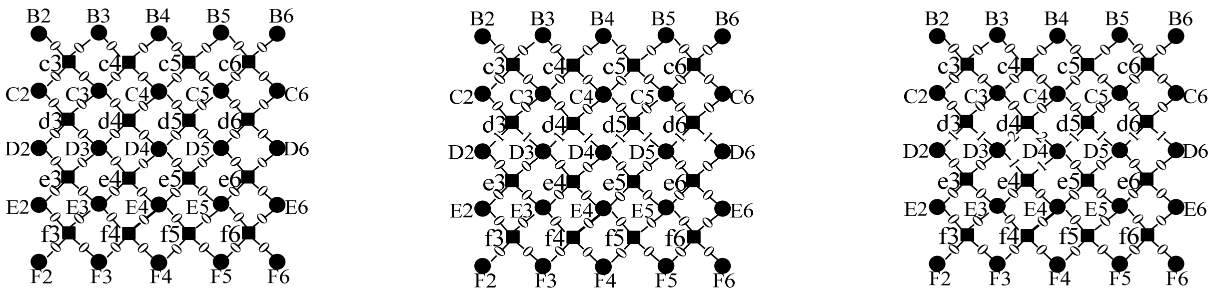


Fig. 9. First line of matrix E corresponds with the line segments of nodes.

The steps of solving the location of force-bearing point with the resistance matrixes are as follows:

- **Step 1:** E=0 when the sensor is kept free of the action of force and the map indicates as Fig. 10 (a);
- **Step 2:** If R1 (i,j)<R10(i,j) (j<=i), that means s1,s2 of all nodes of row(i) may be possible less than s0, then all elements of row(2i-1) of E should be added by 1, while if R1(i,j) <R10(i,j) (j>i), that means s3, s4 of all nodes of row(i) may be possible less than s0, and all elements of row(2i) of E should be added by 1;
- **Step 3:** If R2(i,j)<R20(i,j), that means s1, s3 of node(i,j) or s2, s3 of node(i,j-1) may be possible smaller than s0, then E(2i-1,2j-1), E(2i,2j-1), E(2i-2,2j-2), E(2i-2,2j-2) should be added by;
- **Step 4:** If R3<R30(i,j) (i,j)(j<=i), that means s1, s3 of all nodes of column (i) may be possible less than s0, then all elements of column (2i-1) of E should be added by 1. While if R3 (i,j) <R30(i,j)(j>i), column (2i) of E should be added by 1;
- **Step 5:** If R4(i,j)<R40(i,j), that means the s1, s2 of node(i,j) or s3, s4 of node(i-1,j) may be possible smaller than s0, the E(2i-1,2j-1), E(2i-1,2j), E(2i-2,2j-1), E(2i-2,2j) should be added by 1;
- **Step 6:** The largest element of matrix E corresponds to the shortest distance between line segments of nodes.

Assume that the sensor is single-point forced and the force-bearing point is D4, the line segments of D4 is s1<s0, s2>s0, s3>s0, s4>s0, the resistance matrixes changes. Then the matrix E changes according to above steps and is shown as Fig. 10(b) ~ 10(e):



(a) Map of E when no force. (b) Map of E according R1. (c) Map of E according R2.

(d) Map of E according R3. (e) Map of E according R4

Fig. 10. Map of matirx E according to the resistance matrix.

$$E=\begin{vmatrix} 0\ldots0,1,0,1,0,0\ldots0 \\ \ldots\ldots \\ 0\ldots0,1,0,2,1,0\ldots0 \\ 1\ldots1,1,2,4,2,1\ldots1 \\ 0\ldots0,0,1,2,0,0\ldots0 \\ \ldots\ldots \\ 0\ldots0,0,0,1,0,0,\ldots0 \end{vmatrix}$$

From the above analysis D4 can be easily found as force-bearing point of sensor, and line |D4d4| is the shortest line segment between all nodes. With above step we can solve the point-bearing of the sensor correctly.

4.3. The Magnitude of Force

If node D4(0,0,0) move to D4'(x, y, z) when sensor is acted by force F, the resistance between row |D4'D5| and row |d4d5| becomes smaller than resistance between row |D4D5| and row |d4d5|. Then, |D4'd4| <|D4d4| according to equation (1), the distance is shown in Figs. 11-12.

$$\begin{aligned} \left|D4'd3\right| &= \sqrt{(D4'O')^2+(O'P')^2+(P'd4+d4c4)^2} \\ &= \sqrt{(D4'O')^2+(O'P')^2+(P'd4)^2+2\times(P'd4)(d4c4)+(d4c4)^2} \\ &= \sqrt{(D4'd4)^2+2\times(P'd4)(d4c4)+(d4c4)^2} \end{aligned}$$

As |D4'd4|<|D4d4|, |P'd4|<|Pd4|, then we can find |D4'c4|<|D4c4|. Similarly, we conclude |D4'd3|<|D4d3|.

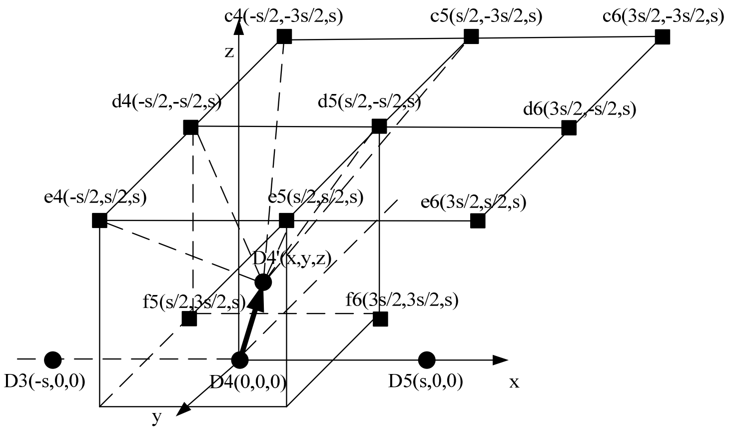


Fig. 11. Distance between nodes of sensor.

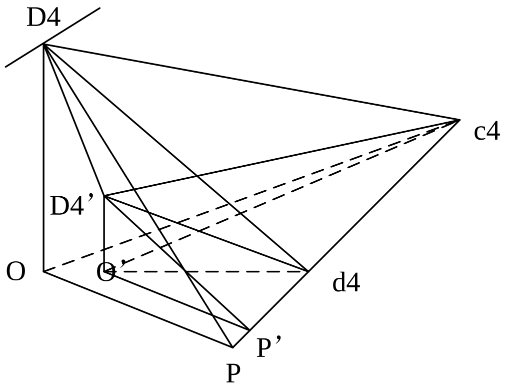


Fig. 12. Distance between nodes.

Thus if resistances between row/column of upper layer and row/column of lower layer become smaller, then the resistance between the row/column of upper layer and other row/column of lower layer of same direction shall become smaller according to conclusion (1). We can find the resistance R1(4,4)=g*|D4’d4=g*s1|, R1(4,3)=g*|D4’c4|=g*s6 and R2(4,3)=g*|D4’d3|=g*s5. For s5, s6 and s1 can be obtained by R1, R2, R3, R4 according to conclusion (1), x, y, z can be obtained by the following function groups:

$$\begin{cases} s1=\sqrt{(x+s/2)^2+(y+s/2)^2+(z+s)^2} \\ s6=\sqrt{(x+3s/2)^2+(y+s/2)^2+(z+s)^2} \\ s5=\sqrt{(x+s/2)^2+(y+3s/2)^2+(z+s)^2} \end{cases}$$

If node D4 (0,0,0) move to D4’ (x, y, z) acted by force F, the direction of F consistent with the direction of line segment $\overrightarrow{D_4D_4{}'}$ according to conclusion (3).

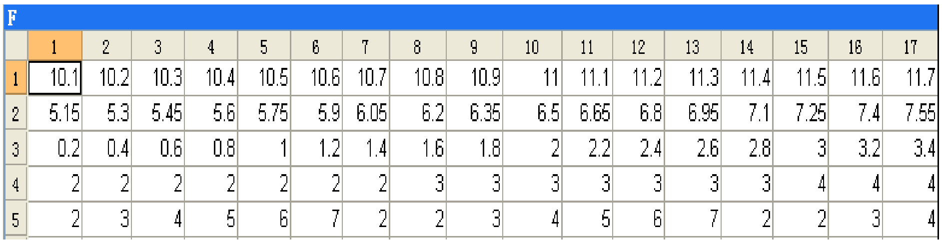
$$\begin{cases} Fx=k*x \\ Fy=k*y \\ Fz=k*z. \end{cases} \quad \Longrightarrow \quad \text{Fx, Fy, Fz can be obtained.}$$

5. Simulation

Using the ideal model of a conductive rubber sensor array, the algorithm mentioned was simulated for the cases that a force with different magnitude was extorted at a number of points. The real applied force, given by Fx, Fy and Fz, and their locations, given by x and y coordinate, are listed in Table 1, from the top to the bottom rows, respectively.

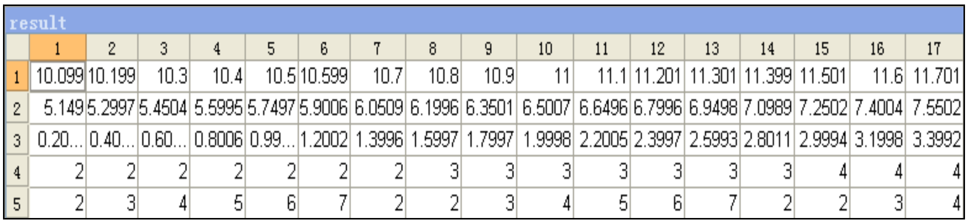
Table 2 shows the simulation results. Following table from top to bottom rows, respectively, expresses Fx, Fy, Fz, x and y coordinate of force-bearing point which is obtained by analyzing the resistance matrix.

Table 1. The force applied to the sensor.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	10.1	10.2	10.3	10.4	10.5	10.6	10.7	10.8	10.9	11	11.1	11.2	11.3	11.4	11.5	11.6	11.7
2	5.15	5.3	5.45	5.6	5.75	5.9	6.05	6.2	6.35	6.5	6.65	6.8	6.95	7.1	7.25	7.4	7.55
3	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8	3	3.2	3.4
4	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4	4	4
5	2	3	4	5	6	7	2	2	3	4	5	6	7	2	2	3	4

Table 2. The force obtained by decoupling algorithm.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	10.099	10.199	10.3	10.4	10.5	10.599	10.7	10.8	10.9	11	11.1	11.201	11.301	11.399	11.501	11.6	11.701
2	5.149	5.2997	5.4504	5.5995	5.7497	5.9006	6.0509	6.1996	6.3501	6.5007	6.6496	6.7996	6.9498	7.0989	7.2502	7.4004	7.5502
3	0.20...	0.40...	0.60...	0.8006	0.99...	1.2002	1.3996	1.5997	1.7997	1.9998	2.2005	2.3997	2.5993	2.8011	2.9994	3.1998	3.3992
4	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4	4	4
5	2	3	4	5	6	7	2	2	3	4	5	6	7	2	2	3	4

We can find the simulation result corresponds to the force acted on the sensor very well under the ideal condition. The simulation of the sensor is based on the assumption that the characteristic of conductive rubber sensor is ideal, while the real characteristic of conductive rubber is not ideal linear, the repeatability and stability of materials is not very well, the noise introduced by the acquisition circuit and so on, the measurement results exist a lot of error, how to eliminate these disturbances are also a problem for us to deal with.

The measurement exist blind spots in this sensor, that is to say, if the force is acted on the most lateral nodes of the rows/columns of upper nodes, the magnitude of force on these nodes may unable to solve. Node A0 for example, if s1 (A0) <s0, s2 (A0)>s0, s3 (A0)>s0, and s4 (A0)>s0, then we can find that the s5, s6 of A0 can't be obtained by the existing arrayed structure, so we can't solve the magnitude of the force of these nodes.

6. Conclusion

The paper presents a conceptual design of three-dimensional flexible arrayed tactile sensor based on conductive rubber. We can include from the simulation that the sensor can be applied for tactile detection. It is three-dimensional and flexible and can be used to simultaneously solve the problem of flexibility and three-dimensional acquisition. The measurement of this sensor is based on the overall flexible tactile arrayed matrix varies with the current so-called arrayed tactile sensor. The sensor will meet the urgent need of the intelligent operation of current humanoid robot which has broad application prospects.

As we didn't consider the nonlinearity and the hysteresis characteristic of the conductive rubber in this paper, we should correct these errors with advanced intelligent algorithm when the real character is taken into account. The three-dimensional flexible arrayed tactile sensor based on conductive rubber can correctly detect the force acted on the sensor with the intelligent information processing model. Moreover the resistance matrix is proportional to the nodes scale, the improvement of the resolution and increasing the scale of the sensor will cause the increase in the ranks of the rows and column. We can improve the processing technology to increase the distinguish radio and reduce the volume of the sensor.

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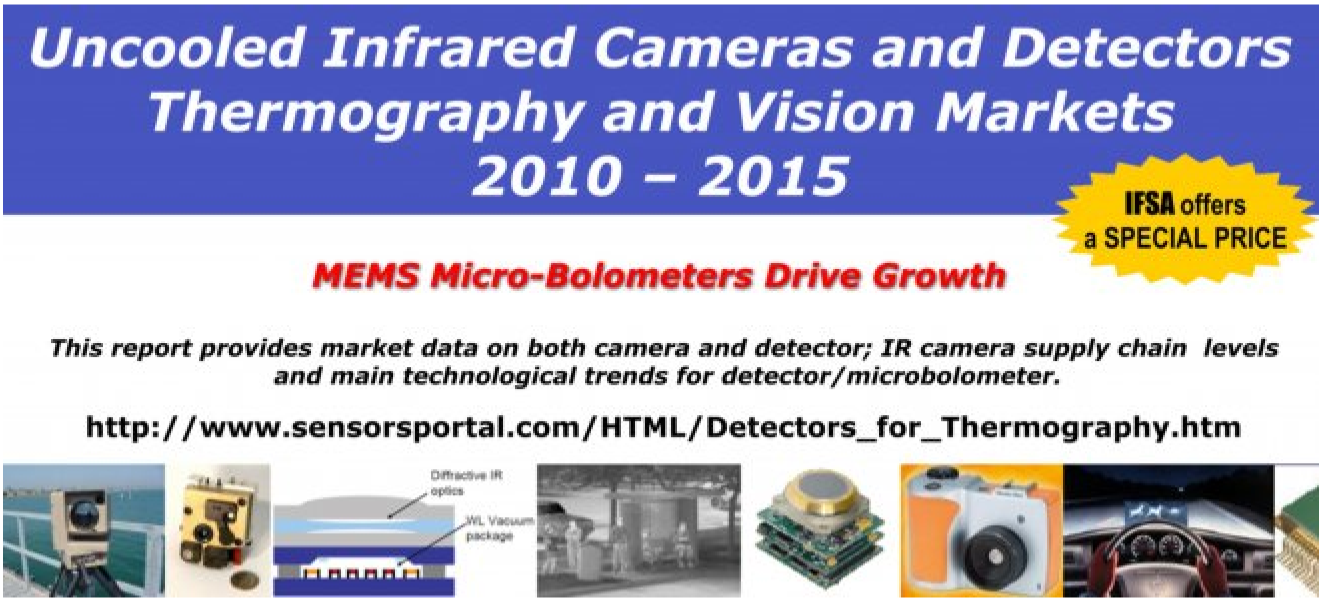

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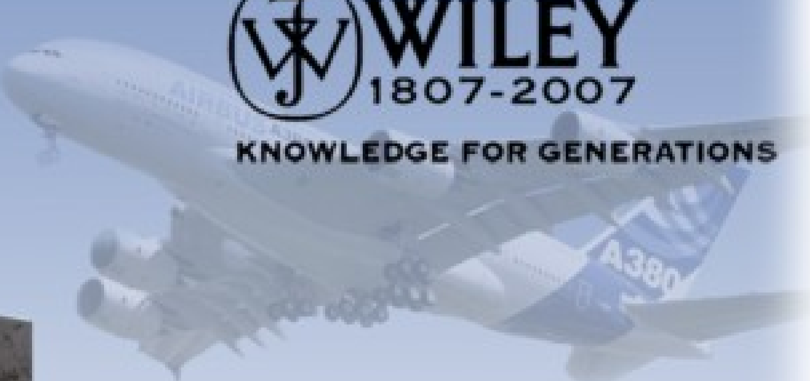
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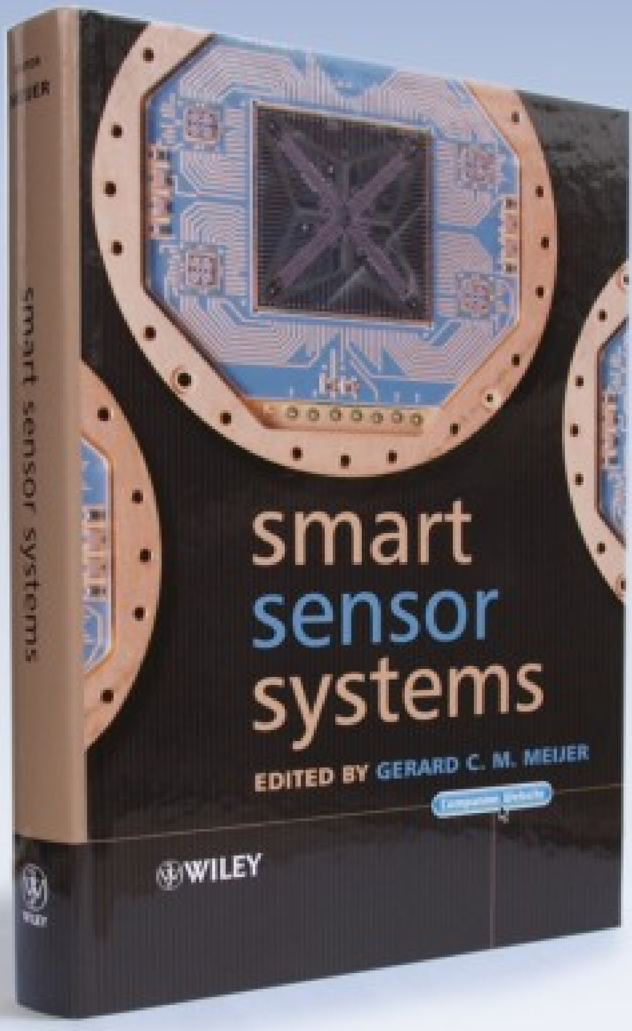
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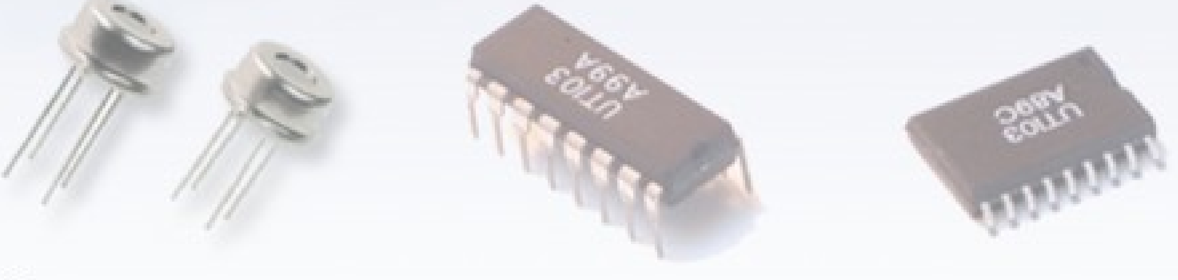
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