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# Research of a Novel Three-dimensional Force Flexible Tactile Sensor Based on Conductive Rubber

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**Abstract:** A novel three-dimensional force flexible tactile sensor using conductive rubber with "overall injection molding" technique is presented. The sensor is based on conductive rubber's force-sensitive property. The sensor is flexible and can measure 3-D force. The rubber's characteristics, the sensor's structure and its principle are described. The results of simulation will be also presented. *Copyright © 2010 IFSA.*

**Keywords:** Tactile sensor, Three-dimensional force, Conductive rubber, Force-sensitive property.

## 1. Introduction

Tactile sensor is defined as a device or system can acquire the external information via interaction. Being an important sensing capability of ideal robots, tactile sensor can help robots to complete a variety of complex tasks with accurate perception. Especially, the tactile sensor used as a robot's skin should be able to measure 3-D force and also need to be so flexible that it can be mounted on curved robot's surface.

With the development of robot technology, much attention has been attracted to the research on tactile sensor, and different types of techniques have been explored in realizing the tactile sensors, they are MEMS [1, 2], capacitive [3], piezoelectric [4, 5], optical [6], pressure-conductive rubber [7, 8] and so on.

The authors propose a new tactile sensor utilizing piezoelectric vibration [4]. This tactile sensor comprises two piezoelectric materials, one is used for the vibration of the sensor element and the other is used for the measurement of the change in mechanical impedance induced by an external force. Although this tactile sensor has a high sensitivity, wide measurement range and goo flexibility, the force it measured is limited to pressure. In [1], a tactile sensor which can measure three components forces is designed. The authors have fabricated the tactile sensor using flexible MEMS technology based on polymer material. Because the tactile sensor is composed of 100 micro force sensors, its fabrication is complex.

We discuss a new three-dimensional force flexible tactile sensor made via "overall injection molding" technique in this paper. A type of conductive rubber is adopted as sensitive material. This sensor is flexible and it can also measure 3-D force. The other advantage of the sensor is that we can fix its structure first, and then fill the model with conductive rubber, so we can produce three-dimensional force flexible tactile sensors in batches.

## 2. Characteristics of Conductive Rubber

Conductive rubber has many excellent features, such as flexibility and workability, and especially, its electricity-conducting is required. Especially, in state of force applied, conductive rubber's resistance will change.

Based on quantum tunnel effect theory [9-11], we suppose the statistic average value of the conductive particle space is $\omega$, and relationship between the macro current density $J(\varepsilon)$ and $\omega$ is:

$$J(\omega) = J_0 \exp\left[-(\pi\chi\omega/2)(\varepsilon/\varepsilon_0 - 1)^2\right], \tag{1}$$

where, $\varepsilon_0$ is the field between spaces without external forces, $\varepsilon$ is the field between spaces in state of external force applied, $\chi = \left(2m\phi/\hbar^2\right)^{1/2}$ is the tunneling constant, $m$ is the electronic mass, $\hbar$ is the reduced Planck constant, and $\varphi$ is the barrier height.

When there is no external force applied, the rubber's length is $l_0$, and its initial resistance is $R_0$. In ideal condition, in state of force $F$ applied, the relationship of $F$ and rubber's deformation $\Delta l$ meets the Hook's Law within the elastic deformation,

$$F = k_1(l - l_0) = k_1\Delta l\,, \tag{2}$$

where $k_1$ is the Hook constant.

Secondly, we assume $\omega = k_2 l$, so

$$\varepsilon/\varepsilon_0 = \omega/\omega_0 = l/l_0 \tag{3}$$

In fact, according to Ohm's law, the resistance of rubber has the form

$$R = \rho l/S\,, \tag{4}$$

where, $l$ is the length, $S$ is the cross-sectional area, $\rho$ is the resistivity.

We bring (1)-(3) to (4), then the relationship of resistance value change along with external forces is as follows:

$$\begin{aligned} R(F) &= l/S\sigma = Jl/ES \\ &= \left[(l_0k_1+F)/(\sigma_0 Sk_1)\right]\times\exp\left[k_2F^2\pi\chi/(2k_1(k_1l_0+F))\right] \\ &\approx \left[(l_0k_1+F)/(\sigma_0 Sk_1)\right]\times\left[1+k_2F^2\pi\chi/(2k_1(k_1l_0+F))+\cdots\right] \\ &= R_0+\left[R_0/(k_1l_0)\right]F+\left[k_2R_0\pi\chi/(2k_1^2l_0)\right]F^2+\left[\pi^2\chi^2k_2^2R_0/(8k_1^3l_0(k_1l_0-F))\right]F^4+\cdots \end{aligned} \tag{5}$$

In actual use, we adopt the quadratic term,

$$R(F) = R_0 + AF + BF^2 \tag{6}$$

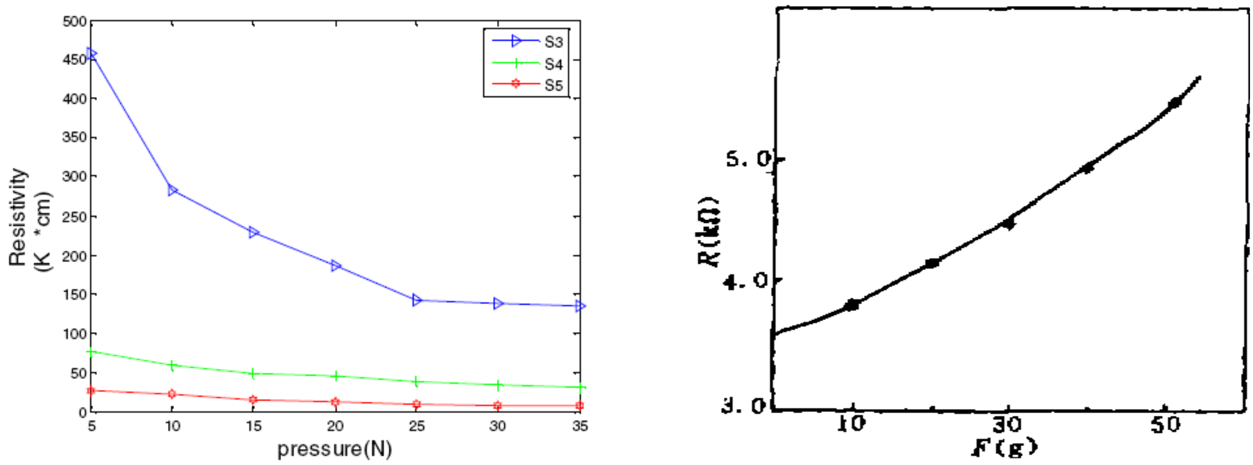
Among this $A = R_0/(k_1l_0)$ , $B = k_2R_0\pi\chi/(2k_1^2l_0)$ . According to (2), if the external force is pressure, $F$ is negative, and $F$ is positive in state of pull applied.

In this paper, the sensor's design is just based on the conductive rubber's property as expressed in (6). Recently, there are many existing study on conductive rubber's force-sensitive property. In Fig. 2(a), piezoresistive effect experiment was discussed to test the relationship between pressure and resistance using some different samples [12], and the relationship of resistance value change along with external pull is shown in Fig. 2(b) [13]. According to the previous research, we can describe the relationship between rubber's resistance and external force with quadratic polynomial.

**Fig. 1.** The conductive rubber.

## 3. Structure of the Sensor

Most of the conventional types of sensor structure are armor-type arrangement, and their flexibility can not meet actual need of the humanoid robot. In [7], Makoto Shimojo used pressure-conductive rubber as sensitive material to discuss a new tactile sensor. It is primarily based on the fact that the rubber's resistance value would reduce when there is pressure force applied. The sensor is thin and flexible, but detected tactile information is generally limited to pressure force.




(a) Pressure (b) Pull

**Fig. 2.** The relationship between conductive rubber's resistance and external force.

We present a novel structure of the sensor, and its sensitive element is an integral mold. In order to achieve the integrity of sensitive element, we have designed a special mold to make the sensitive element, as shown in Fig. 3. We first fix electrodes and wires as the sensitive element's structural frame, and then fill the mold with liquid conductive rubber.

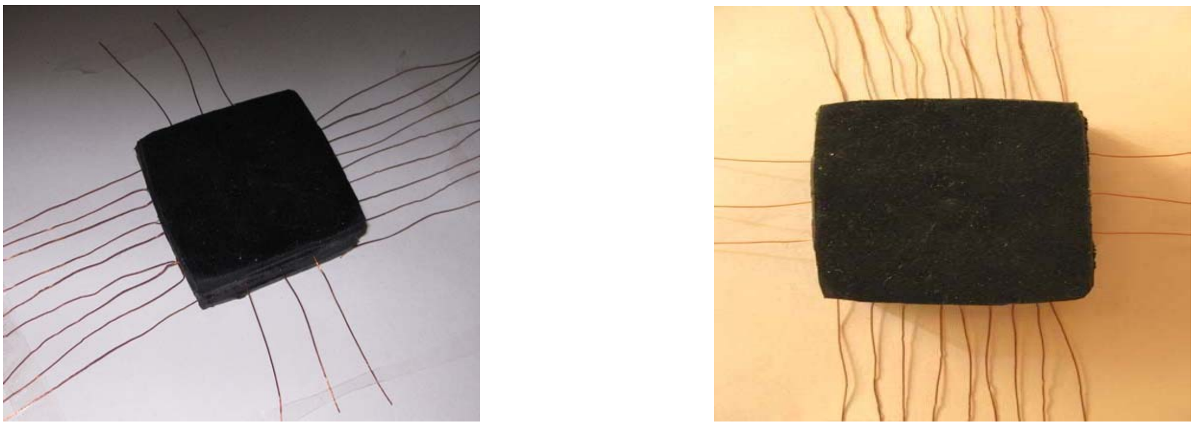
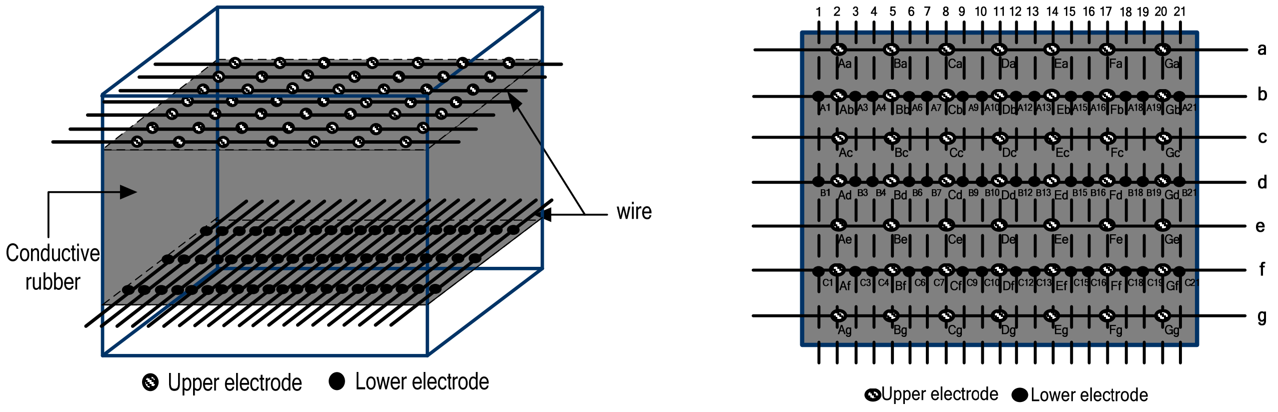


**Fig. 3.** The sensor's sensitive element.

As shown in Fig. 4, the sensor's sensitive element is a special integral model. Electrodes and wires are disposed as two layers in the interior of the conductive rubber. We can adjust the quantity of electrodes and wires according to the actual size of the sensor which is adapted to the object. The upper electrodes are connected by wires in the horizontal direction and the lower electrodes are connected by wires in the vertical direction. In this paper, we call upper row-wire and lower column-wire as "row" and "column" respectively, and the resistance of the rubber between each upper row-wire and each lower column-wire is called as "row-column resistance".




(a) The schematic diagram of sensitive element (b) Top view of the sensor's sensitive element

**Fig. 4.** The structure of sensitive element.

The structure breaks through the armor-type arrangement of those previous tactile sensors. This sensor is more facile to fabricate, and the complexity of its external circuit is also reduced.

Fig. 5 shows the sensitive element's size in detail.

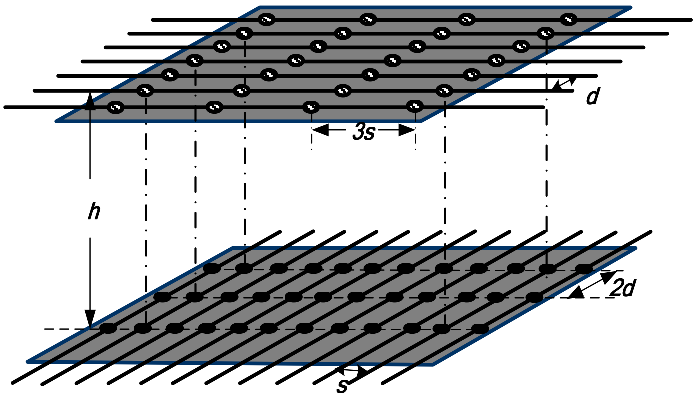



**Fig. 5.** Size of the sensor's sensitive element.

## 4. Principle of 3-D Force Sensing

### 4.1. Scanning Method

Because the rubber is conductive, there is a resistance between two electrodes on different layers. In this paper, we call electrode as "node" for convenience, so this resistance is called as "node resistance". As shown in Fig.6, the resistance between node $C_c$ and node $B_6$ is denoted as $r_{C_c B_6}$.

The scanning method used in this paper is based on the zero potential scanning method which is presented in [14], as shown in Fig. 7. Voltage is applied to the row $c$ to be selected, and other rows are brought to zero voltage. As for column direction, operational amplifiers were connected to all of the columns, and all of the columns are brought to zero voltage. By doing this, the error in measurement due to leak resistance between electrodes can be excluded.

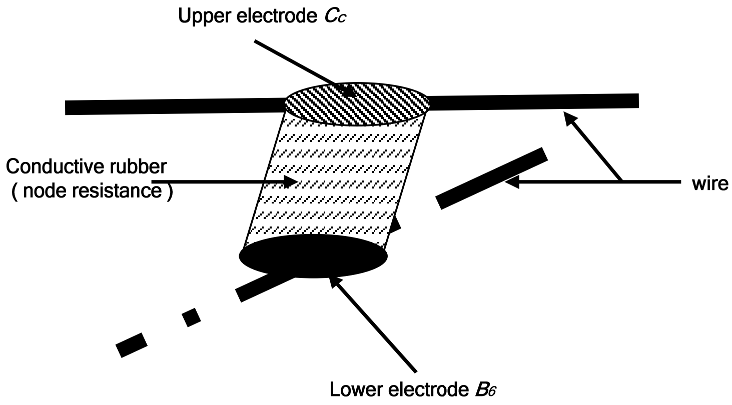
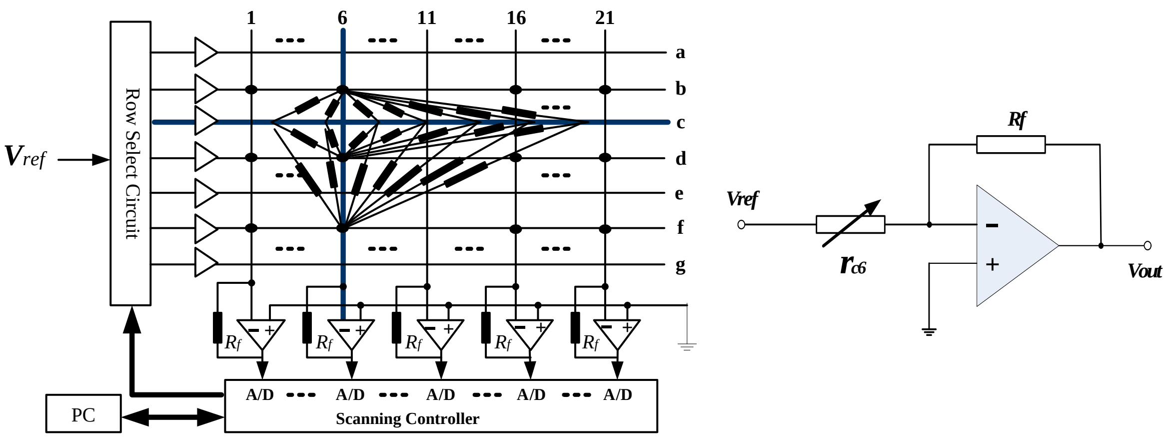



**Fig. 6.** Resistance between node $C_c$ and node $B_6$ (node resistance $r_{C_c B_6}$).




(a) (b)

**Fig. 7.** Resistance between row-wire c and column-wire 6.

Through this scanning method, we can see that the row-column resistance is in fact a parallel resistance of a number of node resistances. In Fig. 7 (a), the row-column resistance $r_{c6}$ denoted as:

$$r_{c6} = r_{A_c A_6} \parallel r_{A_c B_6} \parallel r_{A_c C_6} \parallel \cdots\cdots \parallel r_{G_c A_6} \parallel r_{G_c B_6} \parallel r_{G_c C_6} \tag{7}$$

According the theory of parallel resistance, the row-column resistance $r_{c6}$ can be expressed as,

$$r_{c6} = 1 \Big/ \left( \sum_{\alpha = A_c}^{G_c} \sum_{\beta = A_6}^{C_6} \frac{1}{r_{\alpha\beta}} \right) \tag{8}$$

Fig. 7 (b) is the equivalent circuit for row c, and the voltage $V_{out}$ is expressed in (9).

$$V_{out} = -\frac{R_f}{r_{c6}} V_{ref} \tag{9}$$

### 4.2. Principle of the Sensor

When there is no force applied on the sensor,

$$r^0_{C_cB_6} = \rho l^0 / S = Hl^0 , \tag{10}$$

where, $l^0 = |C_cB_6|$ is the length of the rubber between node $C_c$ and node $B_6$, $H = \rho / S$ .

In state of $F = [Fx_c, Fy_c, Fz_c]^T$ applied on $C_c$ , there is component of the force $F$ along $\overrightarrow{C_cB_6}$ , as shown in Fig. 8, the three components are $f_1, f_2, f_3$, we have

$$\begin{aligned} f_1 &= Fx_c \cos\theta_{xc} \\ f_2 &= Fy_c \cos\theta_{yc} , \\ f_3 &= Fz_c \cos\theta_{zc} \end{aligned} \tag{11}$$

where, $\theta_{xc} = \arctan(\sqrt{d^2 + h^2} / 2s)$ , $\theta_{yc} = \arctan(\sqrt{(2s)^2 + h^2} / d)$ , $\theta_{zc} = \arctan(\sqrt{d^2 + (2s)^2} / h)$ , $f_1$ and $f_2$ are both positive, and $f_3$ is negative.

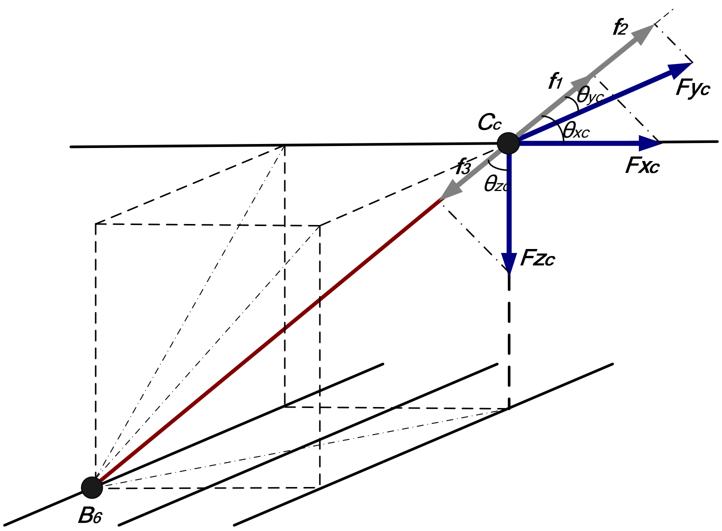



**Fig. 8.** Component of the force F.

According to (6), in state of $F$ applied on $C_c$ , the node resistance $r_{C_cB_6}$ will be

$$\begin{aligned} r_{C_cB_6} &= r^0_{C_cB_6} + A\sum_{i=1}^{3} f_i + B(\sum_{i=1}^{3} f_i)^2 \\ &= r^0_{C_cB_6} + A \sum_{\Delta=xc,yc,zc} F_\Delta \cos\theta_\Delta + B( \sum_{\Delta=xc,yc,zc} F_\Delta \cos\theta_\Delta)^2 \end{aligned} \tag{12}$$

Analogously, other node resistances between node $C_c$ and other nodes on low column 6 have the form

$$\begin{cases} r_{C_cA_6} = r^0_{C_cA_6} + A\sum\limits_{\Delta=xc,yc,zc} F_\Delta \cos\omega_\Delta + B(\sum\limits_{\Delta=xc,yc,zc} F_\Delta \cos\omega_\Delta)^2 \\ r_{C_cG_6} = r^0_{C_cG_6} + A\sum\limits_{\Delta=xc,yc,zc} F_\Delta \cos\varphi_\Delta + B(\sum\limits_{\Delta=xc,yc,zc} F_\Delta \cos\varphi_\Delta)^2 \end{cases} \tag{13}$$

Because of the rubber's elasticity, there are also 3-D forces applied on other upper nodes around node $C_c$, and these forces are defined as $Fx_\nabla, Fy_\nabla, Fz_\nabla$ ($\nabla = A_c, B_c, D_c, E_c, F_c, G_c$) , we have

$$\begin{cases} r_{A_cA_6} = t_1(Fx_{A_c}, Fy_{A_c}, Fz_{A_c}) \\ r_{A_cB_6} = t_2(Fx_{A_c}, Fy_{A_c}, Fz_{A_c}) \\ r_{A_cC_6} = t_3(Fx_{A_c}, Fy_{A_c}, Fz_{A_c}) \\ \vdots \\ r_{G_cA_6} = t_{19}(Fx_{G_c}, Fy_{G_c}, Fz_{G_c}) \\ r_{G_cB_6} = t_{20}(Fx_{G_c}, Fy_{G_c}, Fz_{G_c}) \\ r_{G_cC_6} = t_{21}(Fx_{G_c}, Fy_{G_c}, Fz_{G_c}) \end{cases} \tag{14}$$

According to (12) and (14), $r_{c6}$ can be expressed as a function of variables $Fx_\nabla, Fy_\nabla, Fz_\nabla$ ($\nabla = A_c, B_c, C_c, D_c, E_c, F_c, G_c$)

$$r_{c6} = f_6(Fx_{A_c}, Fy_{A_c}, Fz_{A_c}, \cdots\cdots, Fx_{G_c}, Fy_{G_c}, Fz_{G_c}) \tag{15}$$

Similarly, other row-column resistances can be expressed as,

$$r_{ci} = f_i(Fx_{A_c}, Fy_{A_c}, Fz_{A_c}, \cdots\cdots, Fx_{G_c}, Fy_{G_c}, Fz_{G_c})\ (i = 1, 2, \cdots, 20, 21) \tag{16}$$

We can obtain three displacements of all nodes on row $c$ by solving above equation (16).
In actual use, the sensor measure 3-D force as follows:

***Step 1:*** When there is no force applied on the sensor, we can obtain the row-column resistance matrix

$$R^0 = \begin{bmatrix} r^0_{a1} & r^0_{a2} & \cdots & \cdots & r^0_{a20} & r^0_{a21} \\ r^0_{b1} & r^0_{b2} & \cdots & \cdots & r^0_{b20} & r^0_{b21} \\ r^0_{c1} & r^0_{c2} & \cdots & \cdots & r^0_{c20} & r^0_{c21} \\ r^0_{d1} & r^0_{d2} & \cdots & \cdots & r^0_{d20} & r^0_{d21} \\ r^0_{e1} & r^0_{e2} & \cdots & \cdots & r^0_{e20} & r^0_{e21} \\ r^0_{f1} & r^0_{f2} & \cdots & \cdots & r^0_{f20} & r^0_{f21} \\ r^0_{g1} & r^0_{g2} & \cdots & \cdots & r^0_{g20} & r^0_{g21} \end{bmatrix};$$

***Step 2:*** Similarly, in state of force applied on the sensor, we also can obtain the other row-column resistance matrix

$$R = \begin{bmatrix} r_{a1} & r_{a2} & \cdots & \cdots & r_{a20} & r_{a21} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ r_{g1} & r_{g2} & \cdots & \cdots & r_{g20} & r_{g21} \end{bmatrix};$$

***Step 3:*** Making a compare of $R^0$ and $R$, if $R^0 = R$, then there is no force applied on the sensor, else if $R^0 \neq R$, then there is force applied, and we can analyze the force by step 4;

***Step 4:*** According to step 2, we have $r_{ci}(i = 1, 2, \cdots\cdots, 20, 21)$, then by solving (15), the 3-D force applied on the node $A_c, B_c, C_c, D_c, E_c, F_c, G_c$ can be obtained. Analogously, the information of 3-D force applied on every node will be obtained with analysing all row-column resistances $r_{\lambda i}{}'(\lambda = a, b, d, e, f, g; i = 1, 2, \cdots\cdots, 20, 21)$.

Fig. 9 illustrates the program simply.

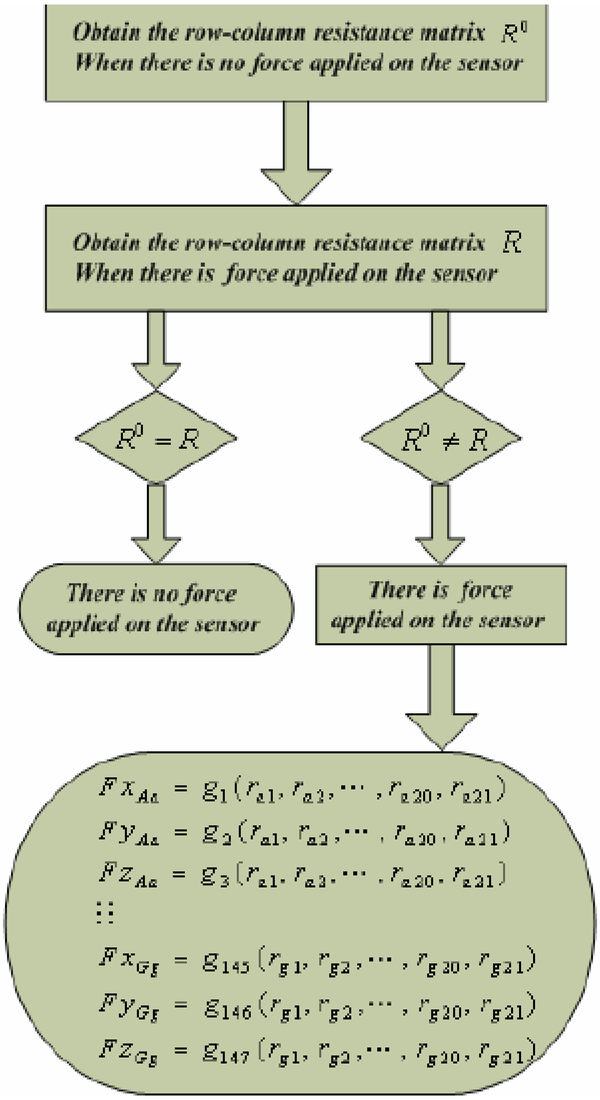
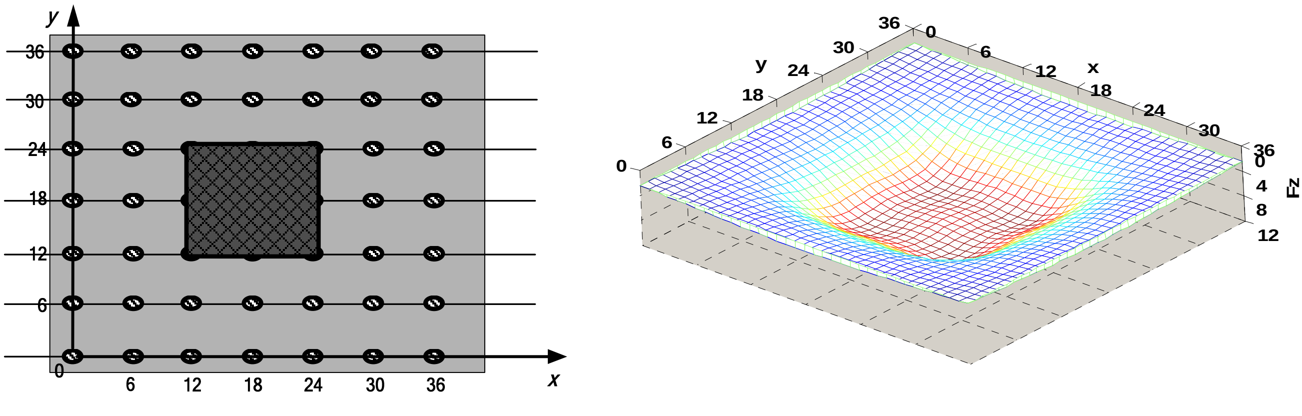



**Fig. 9.** Program of 3-D force sensing.

## 5. Simulation Results and Discussion

We also have two simulations for the sensor's principle mentioned. Firstly, we put a square block on the sensor's surface (Fig. 10(a)), and the block's quality $m = 1kg$ , so its gravity $G = 9.8N$ . Because the block's gravity, there is a pressure $Fz = 9.8N$ applied on the sensor. The simulation result is shown in Fig. 10(b).




(a) (b)

**Fig. 10.** There is pressure *Fz* applied on the sensor.

Secondly, several forces with different magnitude were applied on node $D_c$ (Fig. 11 (a), 11 (c), 11 (e)) , and Fig. 11 (b), 11 (d), 11 (f) show the simulation results.

From above simulation results, we can find the simulation results correspond to the actual forces very well. But the simulation is based on an ideal model, i.e., the characteristic of conductive rubber is ideal. However, in actual condition, the characteristic of conductive rubber is not as ideal as our assumptions, for example, the repeatability and stability of rubber is not very good, and the rubber's resistance and its volume may not make a linear relationship very well, these problems are our next work to deal with.

## 5. Conclusions

In this paper, we presented a novel three-dimensional force flexible tactile sensor based on conductive rubber. Instead of a conventional array structure, an "overall injection molding" structure was adopted. As a result, we were able to incorporate the advantages of a thin, flexible property, as well as the ability of measuring 3-D force.

This paper provides a new idea for the study of 3-D tactile sensor, and this idea has a broad prospect for application. Because of the especial character of conductive rubber and the complexity of the sensor's structure, there is still a lot of work to do to improve the performance of the sensor. The improvement of structural design, a large number of complex information processing and so on will all be our next work.

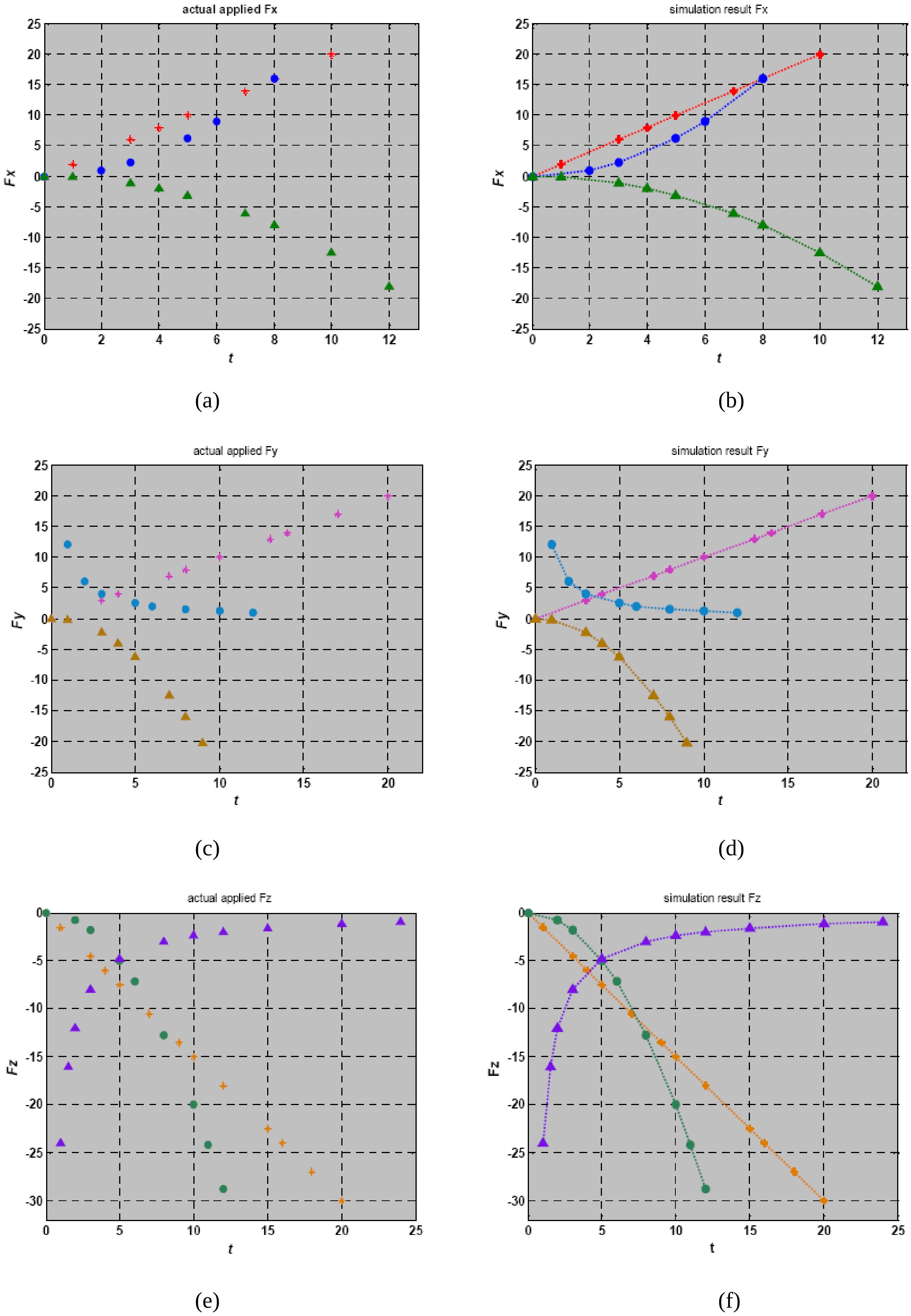



**Fig. 11.** There are several forces with different magnitude applied on node $C_c$ .

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The Second International Conference on Sensor Device Technologies and Applications

# SENSORDEVICES 2011

August 21-27, 2011 - French Riviera, France

www.sensorsportal.com

**Important deadlines:**

| | |
|---|---|
| Submission deadline | March 23, 2011 |
| Notification | April 30, 2011 |
| Registration | May 15, 2011 |
| Camera ready | May 22, 2011 |

**Tracks:**
- Sensor devices
- Photonics
- Infrared
- Ultrasonic and Piezosensors
- Sensor device technologies
- Sensors signal conditioning and interfacing circuits
- Medical devices and sensors applications
- Sensors domain-oriented devices, technologies, and applications
- Sensor-based localization and tracking technologies

**http://www.iaria.org/conferences2011/SENSORDEVICES11.html**

The Fifth International Conference on Sensor Technologies and Applications

# SENSORCOMM 2011

August 21-27, 2011 - French Riviera, France

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**Important deadlines:**

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|---|---|
| Submission deadline | March 23, 2011 |
| Notification | April 30, 2011 |
| Registration | May 15, 2011 |
| Camera ready | May 22, 2011 |

**Tracks:**
- APASN: Architectures, protocols and algorithms of sensor networks
- MECSN: Energy, management and control of sensor networks
- RASQOFT: Resource allocation, services, QoS and fault tolerance in sensor networks
- PESMOSN: Performance, simulation and modelling of sensor networks
- SEMOSN: Security and monitoring of sensor networks
- SECSED: Sensor circuits and sensor devices
- RIWISN: Radio issues in wireless sensor networks
- SAPSN: Software, applications and programming of sensor networks
- DAIPSN: Data allocation and information in sensor networks
- DISN: Deployments and implementations of sensor networks
- UNWAT: Under water sensors and systems
- ENOPT: Energy optimization in wireless sensor networks

**http://www.iaria.org/conferences2011/SENSORCOMM11.html**

The Fourth International Conference on Advances in Circuits, Electronics and Micro-electronics

# CENICS 2011

August 21-27, 2011 - French Riviera, France

www.sensorsportal.com

**Important deadlines:**

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|---|---|
| Submission deadline | March 23, 2011 |
| Notification | April 30, 2011 |
| Registration | May 15, 2011 |
| Camera ready | May 22, 2011 |

**Tracks:**
- Semiconductors and applications
- Design, models and languages
- Signal processing circuits
- Arithmetic computational circuits
- Microelectronics
- Electronics technologies
- Special circuits
- Consumer electronics
- Application-oriented electronics

**http://www.iaria.org/conferences2011/CENICS11.html**

# Guide for Contributors

## Aims and Scope

*Sensors & Transducers Journal (ISSN 1726-5479)* provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

## Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

## Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

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