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Tactile Sensor Without Wire and Sensing Element in the Tactile Region using New Rubber Material

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1. Introduction

Recently the idea of covering a robot's surface with a 'skin' of soft tactile sensors has attracted the attention of researchers, and some human-interactive robots covered with such sensors have actually been made (Tajima et al., 2002; Kanda et al., 2002). However, most conventional tactile sensors need a large number of sensing elements and wires because every detection point needs one sensing element and wiring to an A/D converter. There are some studies aiming to overcome this wiring problem by using 2D surface communication or wireless communication (Shinoda & Oasa, 2000; Ohmura et al., 2006), but these are very complicated and expensive solutions.

We have developed a soft areal tactile sensor made of pressure-sensitive conductive rubber without any wire or sensing element in the tactile region. The distribution of applied pressure, relating to the resistivity change of the pressure-sensitive rubber, can be estimated by using inverse problem theory. We employed electrical impedance tomography (EIT) to reconstruct the resistivity distribution from information obtained by electrodes placed around the region.

EIT is an established method in medical and industrial applications (Holder, 2005), but it has not been applied to tactile sensors until recently. Nagakubo and Alirezaei proposed a tactile sensor using an EIT algorithm operating with commonly used EIT software and commercially available pressure-sensitive rubber (Nagakubo & Kuniyoshi, 2006; Alirezaei et al., 2006). Their method is based on the same principle as ours, but their pressure-sensitive conductive rubber is not suitable for this method. We have newly developed special pressure-sensitive conductive rubber for this sensor, and adopted a new computation technique suitable for this rubber. We have also developed a prototype sensor system that can measure pressure distribution in real-time.

In this paper, we describe basic structure and computation technique of our sensor system, as well as experimental results obtained using our prototype sensor system.

2. Device design

2.1 Basic structure

We have developed, in collaboration with Tokai rubber industries, Ltd., a new type of pressure-sensitive conductive rubber, the resistivity of which increases when pressure is

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applied, unlike ordinary conductive rubber. This new rubber is suitable for a tactile sensor using EIT, because its initial resistivity can be set low, which leads to the accurate reconstruction of pressure distribution from voltage measurements with relatively low noise. Fig. 1 shows the dimensions of the pressure-sensitive conductive rubber that we used in experiments. We formed the rubber into a 1-mm-thick, 195-mm-diameter disc and put 16 electrodes around the disc by vulcanization gluing at regular intervals.

This rubber also has the important feature that its resistivity increases in either case where compressive or tensile strain is applied to it. Fig. 2 shows the relationship between the distortion factor and the resistivity of the rubber. The filled circles are for the compressive case, and the open triangles are for the tensile case. We confirmed that the resistivity increases regardless of the type of strain (i.e. any type of stress).

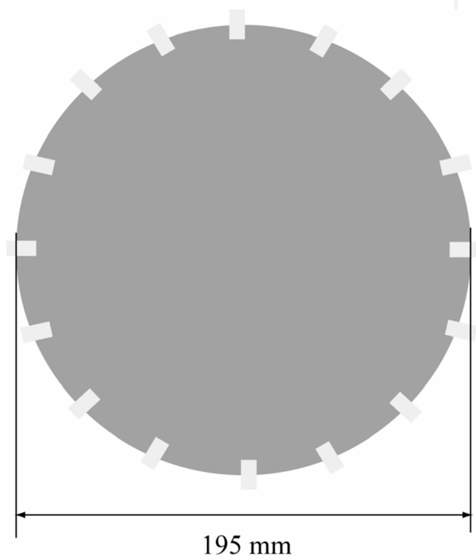

Fig. 1. Pressure-sensitive conductive rubber sheet with 16 electrodes

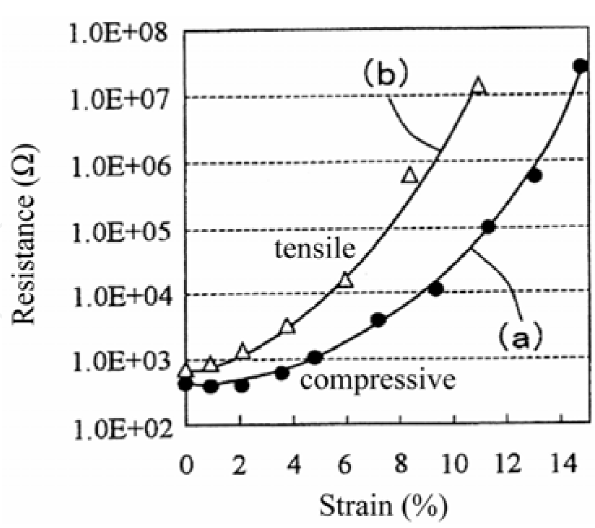

Fig. 2. Resistance changes depends on a) compressive, and b) tensile strains

2.2 Measurement system

The processing of our tactile sensor consists of two steps. The first step is the measurement of conductivities using the 16 electrodes placed around the rubber sheet at even intervals.

An AC voltage is applied, and resistance is calculated using the four-electrode method from the differential voltage between neighboring electrodes, for every possible combination (Fig. 3). In the figure, alternating voltage is supplied between the first and second electrodes and the differential voltage is measured between the 10th and 11th electrodes. The number of possible combinations is 208. However, the number of the independent measured data is actually 104, because the measurements when the supply and the measuring electrode pairs are symmetrically positioned are not independent.
This basic measurement procedure of EIT was developed at Sheffield University (In the original method, current source is used, but we use voltage source instead, for circuit simplicity). The main advantages of this procedure are that it is relatively precise and easy. We can measure at quite a high rate by switching measurement electrodes with a higher frequency AC voltage. In the experiment, we used a 3.685kHz, 4.5 V_{pp} AC voltage. This frequency was determined from the conversion speed of an A/D converter in our sensor controller, dsPIC board, described below.

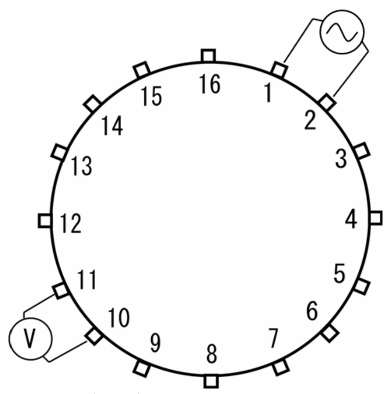

Fig. 3. Conductivity measurement method

2.3 Reconstruction algorithm

In the second step, the distribution of resistivity change is reconstructed from the measurements. This distribution also indicates the pressure distribution because the resistivity change is caused by the change of the pressure applied to the sheet. To get a reconstruction image, we use a sensitivity matrix (Kotre, 1989) that is the Jacobian matrix between δV and $\delta\rho$.

$$\delta V(m,n) = S_{m,n,x,y}\, \delta\rho\,(x,y) \tag{1}$$

Here, m and n indicate the position of the applying electrode pair and the measuring electrode pair, respectively, and x and y indicate the position coordinates of the discrete domain in the rubber plate.
The sensitivity matrix can be obtained by numerically solving a forward problem. Then solving (1) by using a least squares (Lawson & Hanson, 1974) or generalized inverse matrix method, the distribution of resistivity change $\delta\rho\,(x,y)$ is obtained. However this is inverse problem. The inverse solution is apt to become instable and, in our case, the ordinary least squares method does not work because of this instability. To overcome this problem, inverse problem theory suggests various normalization methods. We employed the positive value constraint, because we can assume that the resistivity change is always positive thanks to our new pressure-sensitive conductive rubber, unlike ordinary EIT method that uses the regularization technique.

Equation (2) shows the least squares method with a non-negative constraint. In the next section, we show that the constraint successfully stabilizes the solution. In the case of EIT, *A, x, b* are corresponding to *S*, $\delta\rho$, δV.

$$\min_x \|Ax - b\|^2 \quad (x \geq 0) \tag{2}$$

This method needs the sensitivity matrix in advance; we calculate the matrix using (3).

$$S_{m,n,x,y} = \int_a \nabla\phi_m \cdot \nabla\phi_n \, da \tag{3}$$

Here, $\nabla\phi_m$ and $\nabla\phi_n$ are the electric potential gradient, which is derived from the electric supply from the electrode pair of m or n, respectively. In other words, we can calculate each component of the sensitivity matrix by integrating the inner products of the potential gradients that are caused by the electric current from m and n electrode pairs in the area indicated by x and y. This equation can be derived from electromagnetic theory.
Fig. 4 shows the example calculation results of the inner products. These solutions are obtained by using the Partial Differential Equation Toolbox on MATLAB (The MathWorks Inc.).

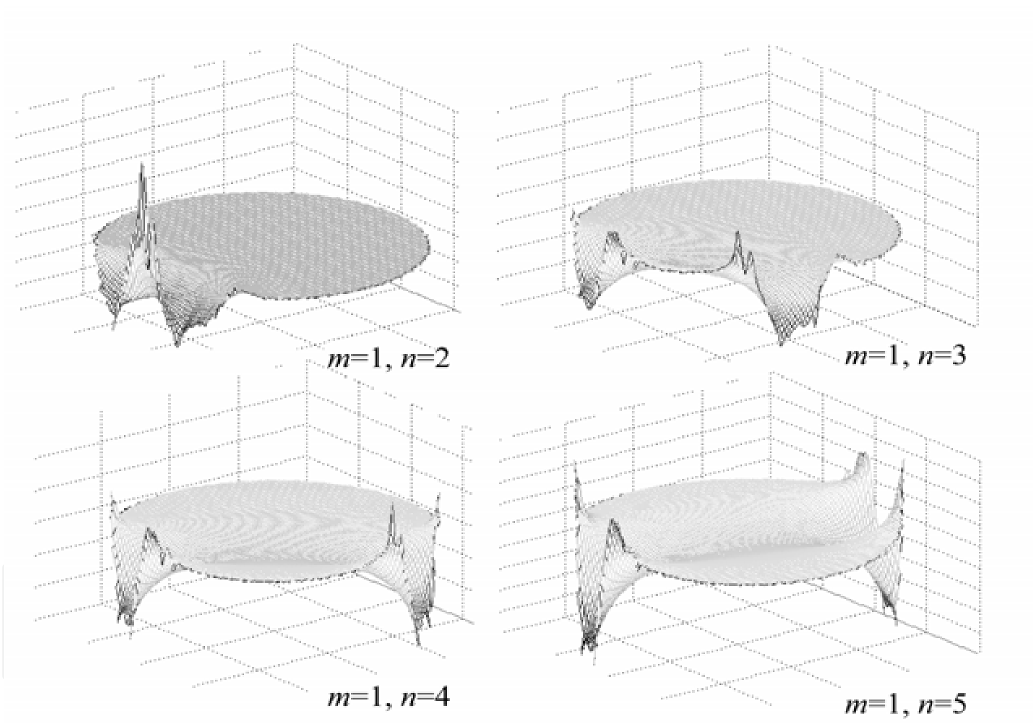

Fig. 4. Example calculation results of the inner product of the potential gradients that caused by *m* and *n* electrode pairs

3. Reconstruction experiments

We conducted experiments to determine the performance of our tactile sensor. The measurement conditions were as follows (Kato et al., 2008).
We measured the potential of all electrodes by using sensor controller and driver board (Fig. 5). The main controller is dsPIC board that is a general-purpose 35x50 mm²

sensing/controlling board we developed, having a dsPIC (Microchip technology 30F6012A) as the CPU and a USB interface IC (FTDI FT232RL) for 1 Mbps communication.
It has many connectors through which most pins are accessed. It also has a stacking connector for an extension board. A tactile sensor controller we developed based on the dsPIC board uses a 12 bit A/D converter and digital I/Os in the 30F6012A. Its program is written in C and downloaded in flash memory of the 30F6012A, as firmware.
Within dsPIC board, all measurement is done using Lock-in amp method. Lock-in amp method is very durable to noise and can be effectively treated by DSP module in dsPIC. The collected data are sending to PC via USB. The reconstruction algorithm is treated by PC.

Fig. 5. Sensor controller and driver consisting of dsPIC board and extension board

The reconstruction algorithm produced the intensity distribution image of the change in resistivity from 208 measured values (Redundant pairs were measured for noise tolerance). The relation between the change in resistivity and pressure distribution is not perfectly clear, but we can conjecture it from Fig. 2. To display the reconstruction image in gray scale, we smoothed the image by inserting interpolation pixels among the pixels that represented actual data. We found that this interpolation successfully displayed a natural distribution image through the anti-aliasing effect when the pressure point was spread over more than one reconstruction domain.

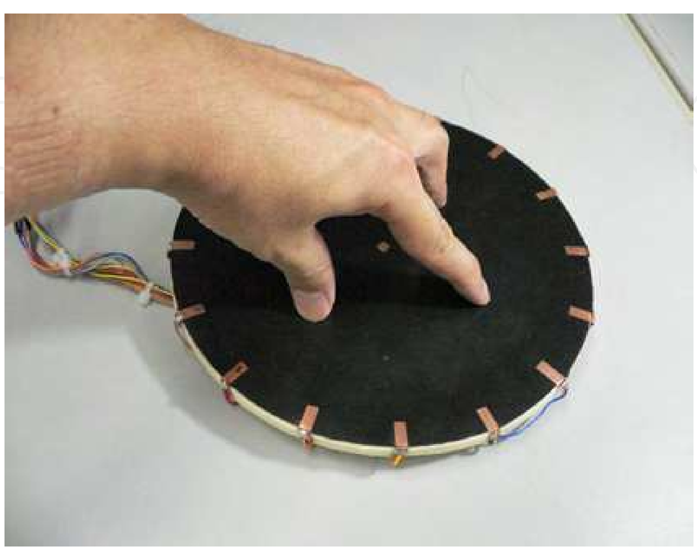

Fig. 6. Point pressures are applying by fingers

First, we tested the stabilization ability of our non-negative least squares algorithm. We applied point pressures by finger as shown in Fig. 6. We compared the reconstruction images generated using a generalized inverse matrix method and those generated using the non-negative least squares method from the same data. The non-negative constraint successfully stabilized the solution, as shown in Fig. 7, while the generalized inverse matrix method failed. The image obtained by non-negative least squares was very stable, and we found that areal tactile sensor functioned well enough for practical usage.

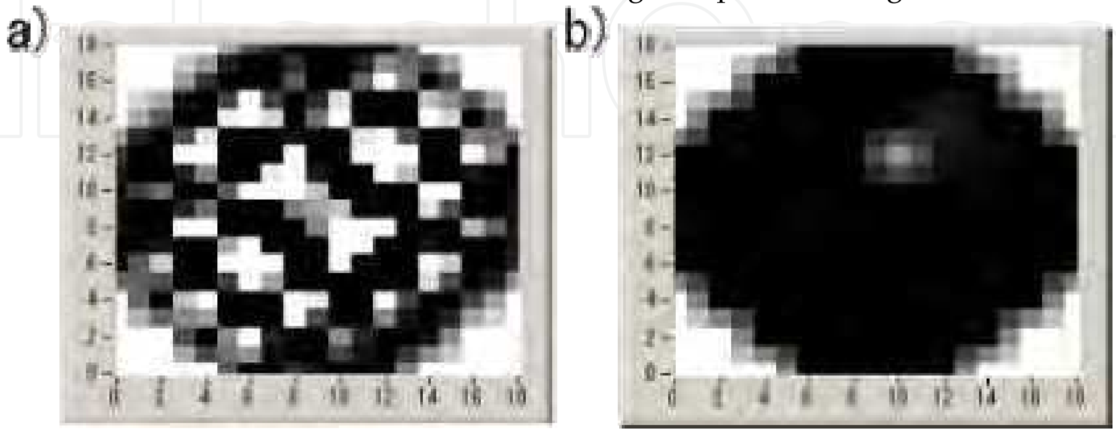

Fig. 7. Comparison between ordinal least square solution and non-negative least square solution from the same input data a) ordinal least square solution, b) non-negative least square solution

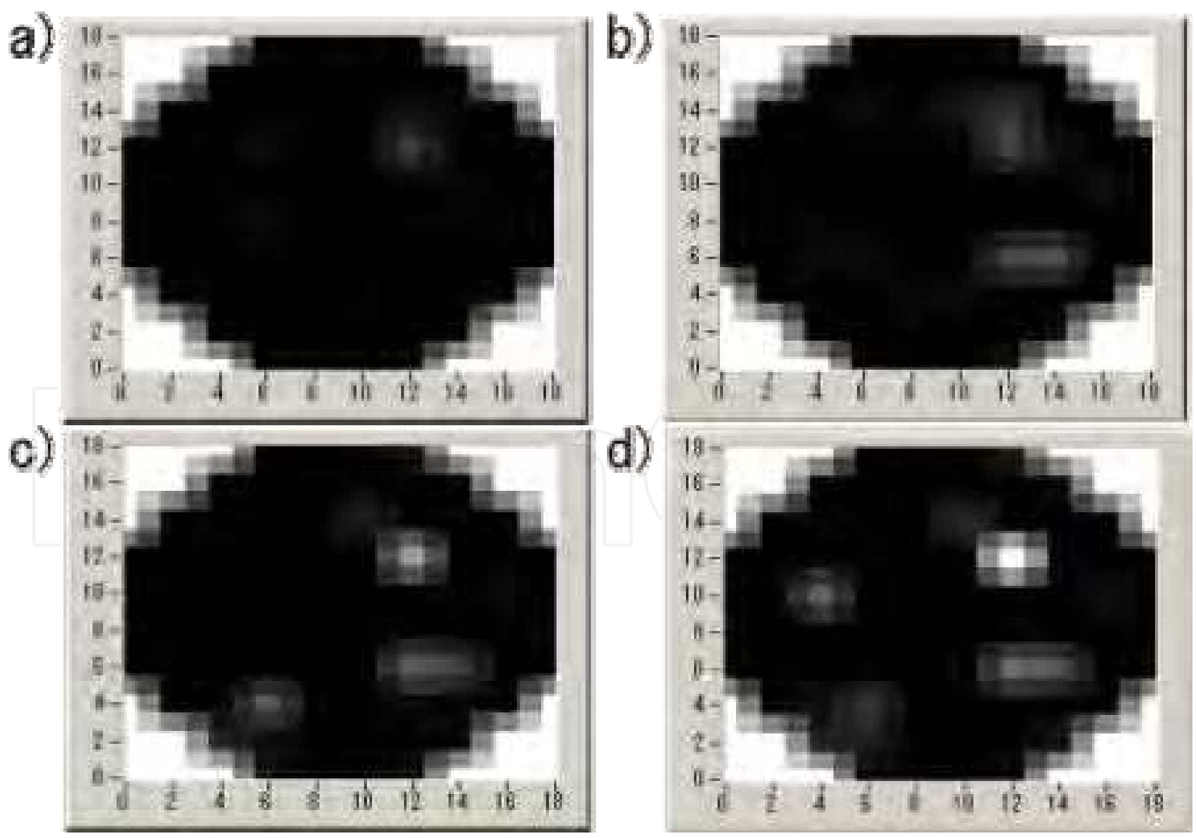

Fig. 8. Reconstructed pressure distribution when three or four point pressures are applied at a time a) a pressure point, b) two pressure points, c) three pressure points and d) four pressure points

Next, we tested multiple pressure points. Fig. 8 shows reconstructed images when applying multiple pressure points by fingers. The images, from the upper left to the lower right, show the reconstruction results when pressure applied to one, two, three or four points. We found that the non-negative least squares algorithm makes it possible to recognize individual pressure points.
Lastly, we measured the update time including the measurement time and reconstruction time. The update time was about 360ms. This is relatively slow; however, we can improve the time by optimizing measurement process.

4. Confirmation of basic performance

To examine basic tactile sensor performance, we compared experiments using a digital force gauge (Shimpo FGC-2B) as shown in Fig. 9 under the same conditions as in previous sections. A disk-like tip of 25mm in diameter was attached to the digital force gauge to apply force to conductive rubber. Data was collected in parallel by tactile sensors.

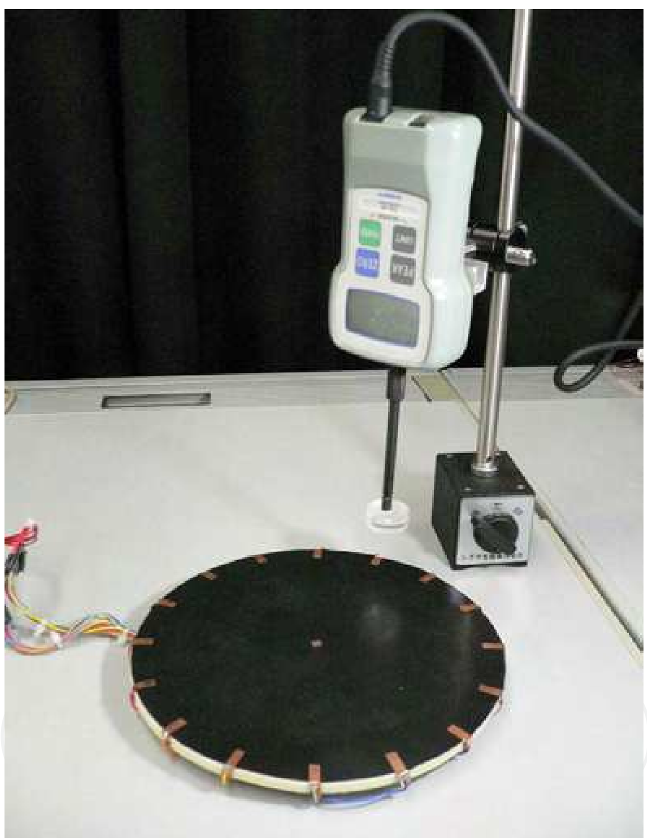

Fig. 9. Experimental setup using digital force gauge

Fig. 10 shows time-averaged reconstructed values by adding time-changing pressures by the force gauge at one point near the center. Since the tip of the force gauge is almost same size as the integration area -- 20mm in diameter -- corresponding to an element of the sensitivity matrix, responses were expected to appear on only one or a few adjacent elements, which was confirmed by results. When the location for adding force was changed, the area expressing the peak also changed. When peaks appeared in multiple areas, they were in areas adjacent to each other.

We extracted time profile of the value in the area showing the peak (Fig. 10) and compared it with measurement from the digital force gauge (Fig. 11). We found good tracking of pressure changes at an early stage, but output is reduced with repeated pressure changes, possibly due to the present characteristic of the material in which deformation tends to remain longer than the force recovery to the original state when large force is applied. We plan to improve response by increasing restoration force and speed by optimizing characteristics such as Young's modulus.

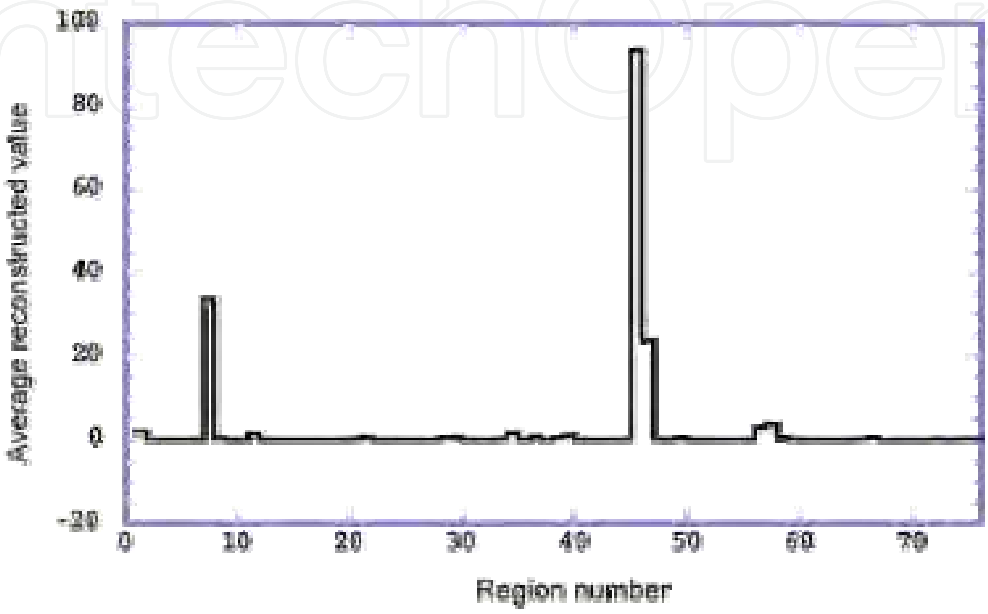

Fig. 10. Average of reconstructed value of each region when pressure changing over time was applied to 1 point

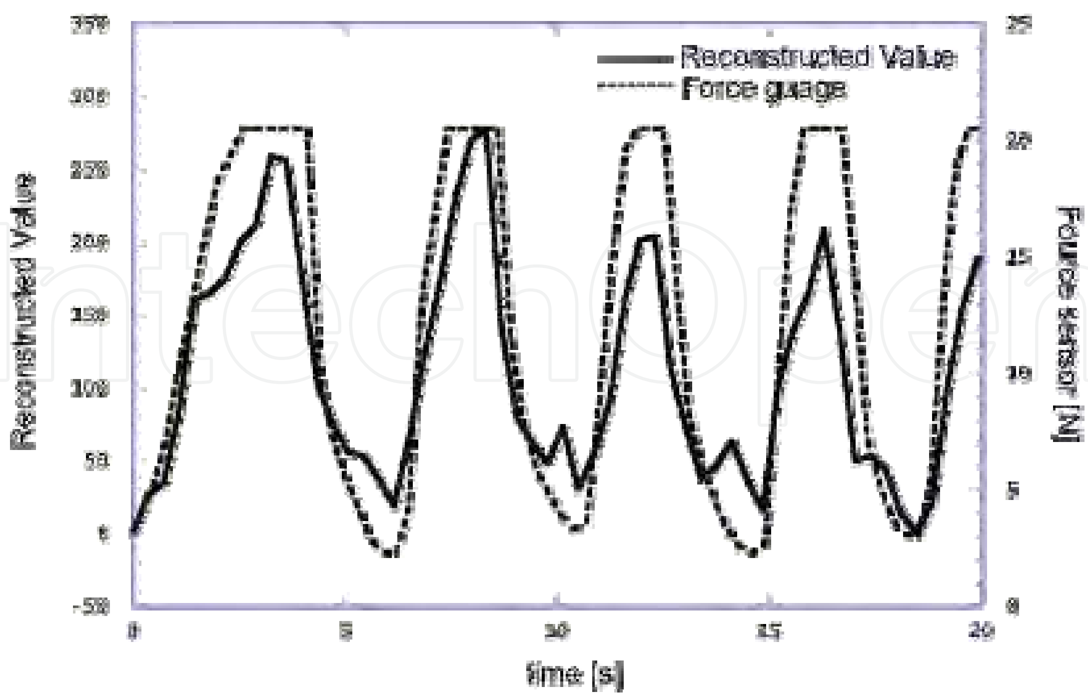

Fig. 11. Comparison of time traces between reconstructed value of the tactile sensor and force measurement of the digital force gauge when changing force is applied

To estimate noise, we measured signal to noise ratio, assuming 2-norm of the voltage measurement vector in the unloaded condition as noise and 2-norm of the voltage vector approximated by the least squares method with a force of 25N applied to one point as a signal. The ratio was found to be 27dB.

5. Conclusion

We developed a tactile sensor system based on the EIT method that has no wire or sensing elements in the tactile region. We believe that the sensor system is extremely durable to shocks and large transformations, and is low cost because there is no wire or sensing elements. We obtained good results from the experiments investigating the basic performance of our sensor system. The ordinary EIT algorithm assumes not only positive reconstructed values but also negative values, which leads to instability in reconstruction with noisy data. We restrict the reconstructed values to positive, which is justified by using a new kind of rubber whose electrical resistivity always increases in response to applied deformation.

In the future, we will improve the accuracy of the sensor and shorten the measurement time. We will also mount sensors as artificial sensitive skin on various objects (e.g. robots, seats and bumpers of automobile).

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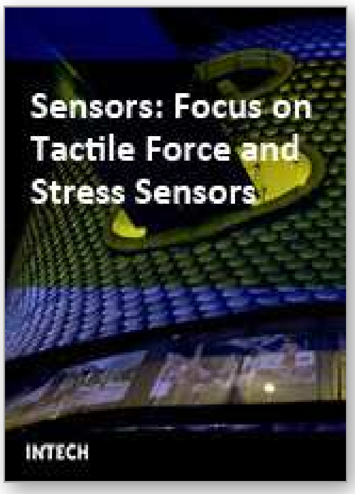

Sensors: Focus on Tactile Force and Stress Sensors

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This book describes some devices that are commonly identified as tactile or force sensors. This is achieved with different degrees of detail, in a unique and actual resource, through the description of different approaches to this type of sensors. Understanding the design and the working principles of the sensors described here requires a multidisciplinary background of electrical engineering, mechanical engineering, physics, biology, etc. An attempt has been made to place side by side the most pertinent information in order to reach a more productive reading not only for professionals dedicated to the design of tactile sensors, but also for all other sensor users, as for example, in the field of robotics. The latest technologies presented in this book are more focused on information readout and processing: as new materials, micro and sub-micro sensors are available, wireless transmission and processing of the sensorial information, as well as some innovative methodologies for obtaining and interpreting tactile information are also strongly evolving.