Tactile Sensing Using Nonlinear Elasticity

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Abstract: We propose a new sensor element for a tactile sensor skin which covers a large area such as a whole surface of a robot. The element acquires not only contact force but also contact area by using the nonlinear elasticity of skin materials. This paper provides the structure and theory of our tactile sensor element, and presents experimental results.

Keywords: Tactile sensor, Artificial skin, Robot skin, Contact area, Nonlinear elasticity

1. Introduction

The tactile sensor skin which covers a large area such as a whole surface of a robot is hoped in robotics[1]. Tactile sensor skins are generally realized as arrays of sensor elements which detect some kinds of parameters related to pressure or deformation. Some tactile sensor skin have been reported[2][3][4], but they don't have enough ability to detect minute shape features of an object as the human skin do.

One strategy to improve ability of a tactile sensor is to make sensor elements very small and to array them in high density. On the contrary, we propose another strategy; the side length of a sensor element is several centimeters and the element acquires not only contact force but also contact area. The tactile sensor skin composed of the elements is soft, stretchable, and capable to cover a large area easily (Fig.1). Our strategy is based on the fact that a Two Point Discrimination Threshold (TPDT) of the human is several centimeters except on a face and hands, while the human can discriminate sharpness of objects sensitively in spite of such a large TPDT at any part of the skin. We think that sharpness is one of the key components for human touch feelings[5].

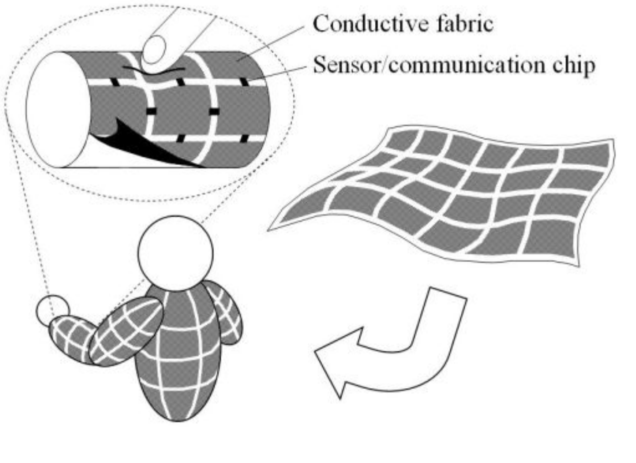

Fig.1: Tactile sensor skin composed of proposed sensor elements. It is soft, stretchable, and capable to cover a large area easily.

The sensor element proposed in this paper is consist of insulator layers and conductive fabric. The pieces of conductive fabric work not only as sensor elements but also as communication paths when IC sensor/communication chips are placed at the boundary of the pieces, thus any wiring to each element is no longer needed[6] (Fig.1 and 2). In order to acquire contact force and contact area, we make use of the nonlinear elasticity of insulators.

In this paper, we describe the structure and the theory of the sensor element, and show experimental results.

2. Structure of sensor element

The structure of our sensor element is very simple. In Fig.3, we show schematically a cross-section of the sensor element prototype. The element consists of two layers; the upper layer is made of soft urethane foam (15 [kg/m^3]) and the lower hard (60 [kg/m^3]), and each layer is 2 [mm] in thickness. There are three pieces of conductive fabric over the soft urethane foam, between the soft and hard, and under the hard. Each piece has an area of 30×30 [mm^2]. The side length of the pieces is comparable to the TPDT of human forearm. The

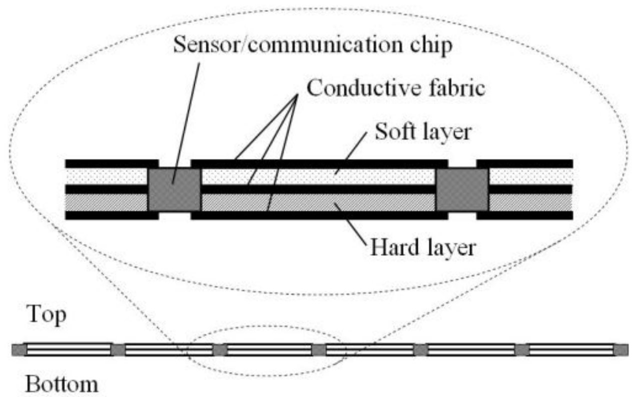

Fig.2: Cross-section of tactile sensor skin. A set of soft and hard layers and three pieces of conductive fabric form one tactile sensor element.

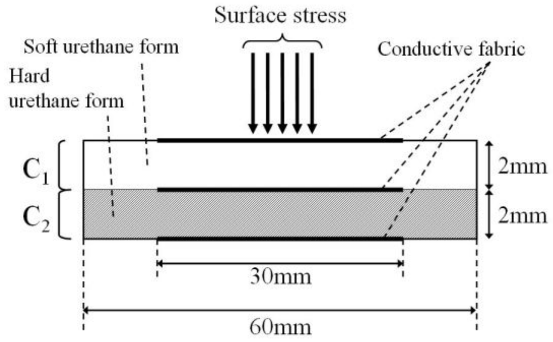

Fig.3: Cross-section of prototype.

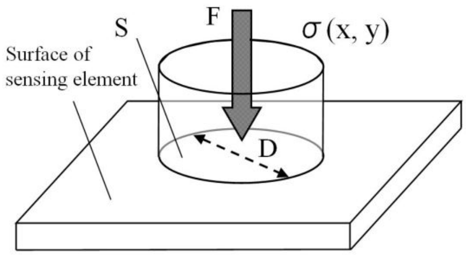

Fig.4: Supposed surface stress $\sigma(x, y)$.

urethane foam and conductive fabric are adhered each other by soft double-faced tape. Then two capacitors are formed in the layers. We call the capacitor in the upper soft layer C_1, and the lower hard layer C_2. Supposing a surface of a robot body hard, we adhered the bottom of the sensor element prototype to an acrylic base.

3. Sensing theory

We suppose a surface stress illustrated in Fig.4; A constant surface stress $\sigma(x, y)$ [Pa] is vertically loaded to the surface of the sensor element in the contact field S, that is

$$\sigma(x,y) = \begin{cases} F/S & \text{if } (x,y) \in \mathrm{S} \\ 0 & \text{if } (x,y) \notin \mathrm{S} \end{cases} \quad (1)$$

where F [N] is the contact force and S [m^2] is the area of S. We assume that S is circular and take the diameter D [m] of S as a parameter which represents S. (Eq.(2) represents the entropy elasticity[7].)

The nonlinear elasticity of urethane foam is typically formulated as

$$\sigma = \frac{E_n}{3}\left(\frac{1}{\lambda_n} - \lambda_n^2\right) \ (n = 1, 2) \quad (2)$$

$$\lambda_n = 1 - \frac{\Delta d_n}{d_n} \quad (3)$$

where E_n [Pa] is the elasticity modulus, λ_n the extension ratio, and d_n [m] the initial thickness of the layer

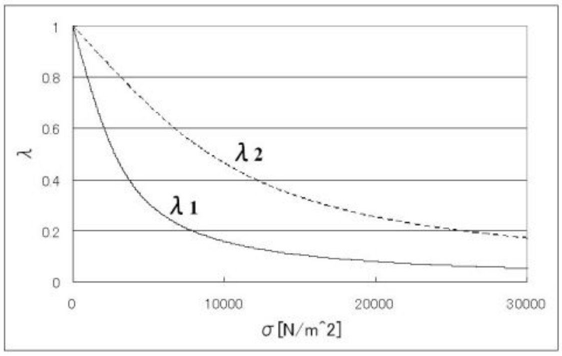

Fig.5: Relationship between surface stress σ and extension ratio λ_n.

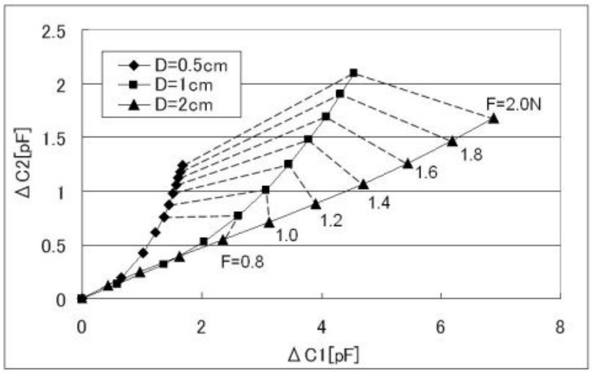

Fig.6: Simulation results. Calculated (ΔC_1, ΔC_2) for various (F, D)s.

n. E_1 is about 4,750 [Pa] and E_2 is 15,400 [Pa]. The suffix n means the layer identification; 1 means the upper soft layer and 2 the lower hard layer. The following expression of λ_n (Fig.5) is obtained by solving Eq.(2),

$$\lambda_n = \sqrt[3]{\frac{1}{2} + \sqrt{\frac{1}{4} + \left(\frac{\sigma}{E_n}\right)^3}} + \sqrt[3]{\frac{1}{2} - \sqrt{\frac{1}{4} + \left(\frac{\sigma}{E_n}\right)^3}}. \quad (4)$$

Assuming that the conductive fabric have no tension and that the Poisson's ratio of urethane foam is zero, we consider that $\Delta d_n(x, y)$ is determined simply by $\sigma(x, y)$ locally. Due to the difference between E_1 and E_2, there are different displacement distributions $\Delta d_n(x, y)$ in the soft and hard layers for a (F, D).

We measure the electric capacitance between the pieces of conductive fabric to detect $\Delta d_n(x, y)$. The capacitance is formulated as

$$C_n = \int \frac{\varepsilon_n}{d_n - \Delta d_n} \mathrm{d}s \ (n = 1, 2). \quad (5)$$

By mapping from (ΔC_1, ΔC_2) to (F, D) in advance, we can acquire F and D simultaneously.

Figure 6 shows the results of simulation. The curved lines of constant D are away from each other and it indicates mapping (ΔC_1, ΔC_2) to (F, D) is possible.

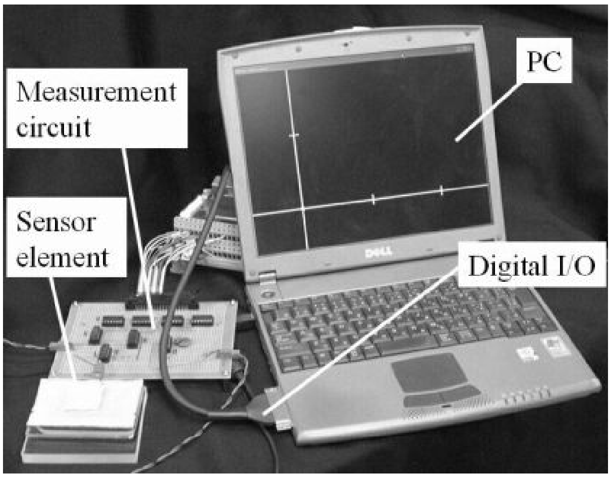

Fig.7: Experimental setup.

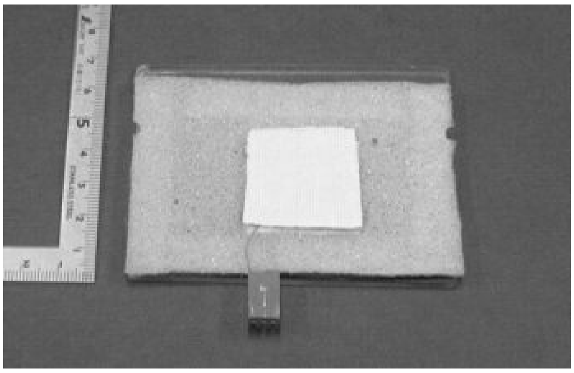

Fig.8: Photograph of prototype.

4. Experiment

We measured ΔC_n by an oscillation method; we generated a RC oscillation using the sensor element as C, and counted pulses par 2 [ms] by a 16-bit counter. PC imported the data via a digital I/O, and achieved around 80 [Hz] sampling rate (Fig.7).

We conducted primary experiments that examined whether the sensor element prototype (Fig.8) could discriminate four different stimulators; A: D = 0.5 [mm] (as impulse), B: D = 1 [cm], C: D = 2 [cm], and D: whole area. The stimulators were vertically pressed to the element by hand with force up to around 10 [N] .

4.1 Flat base

At first, we conducted an experiment of the sensor element adhered on a flat base. Figure 9 shows the results of experiment. It is confirmed possible to discriminate the four stimulators.

4.2 Curved base

Next, we conducted an experiment of the sensor element adhered on a curved base. The reason why this

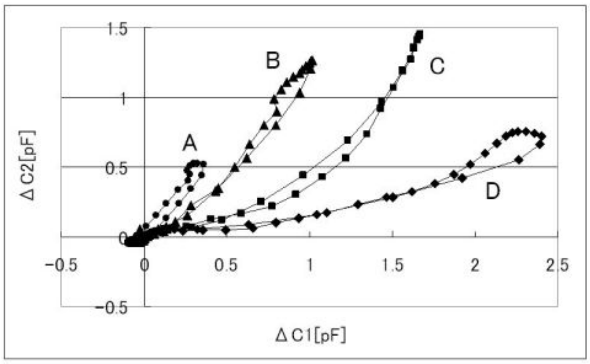

Fig.9: Experimental results with flat base. Measured (C_1, C_2)s for object A with the diameter D of 0.5 [mm] (as impulse), B with D of 1 [cm], C with D of 2 [cm], and D with a large plane surface.

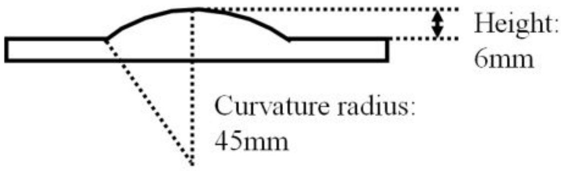

Fig.10: Cross-section of curved base.

experiment was conducted is that a surface of a robot body is not always flat. The cross-section of the curved base is illustrated in Fig.10. Figure 11 shows the results of experiment. Although the curved lines of constant D are closer to each other than those of in Fig.9, it is confirmed possible to discriminate A (D = 0.5 [mm]), B (D = 1 [cm]), and C (D = 2 [cm]).

5. Discussion

The experimental results (Fig.9) indicates that the sensitivity of the prototype to the diameter D is low especially when D is smaller than 1 [cm]. The prime factor is, we consider, the conductive fabric used as electrodes. Although we assumed the ideal conductive fabric which had no tension in the sensing theory, the real conductive fabric has tension when it is stretched. Due to the tension, the displacement distribution may expand than the contact area and also the tension may resist the surface stress to reduce the value of the displacement. These problems are improved with the conductive fabric more elastic.

The sensor element described in this paper outputs the same value wherever an object contacts within the surface of the element and the localization accuracy of the sensor skin composed of the elements may seems very low (ie. several-centimeter error). But we can estimate the center position of the surface stress distri-

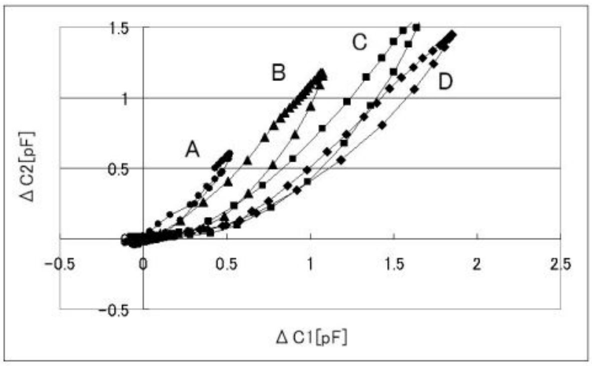

Fig.11: Experimental results with curved base. Measured (C_1, C_2)s for object A with the diameter D of 0.5 [mm] (as impulse), B with D of 1 [cm], C with D of 2 [cm], and D with a large plane surface.

bution from proportions of the outputs of the adjacent elements. So, the localization accuracy for the center of the force distribution of the sensor skin can be higher than the resolution of the elements.

6. Conclusion

In this paper, we proposed our new tactile sensor element. By using the sensor elements, we can compose a tactile sensor skin which covers a large area such as a whole surface of a robot. The sensing theory and experimental results of the element are presented. It is confirmed possible to discriminate the diameters of the tested four stimulators.

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