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A Large Area Robot Skin Based on Cell-Bridge System

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***Abstract*—In this paper, we introduce a soft and stretchable robot skin. There are two novel technologies. One is the "cell-bridge system"; a communication system that consists of two dimensional areas called "cells" and signal transmission devices called "bridges". The other is the "nonlinear tactile element"; a sensor element that has a several-centimeter-square sensing area and acquires a contact area in addition to a contact force. The two parameters are obtained from two capacitances in the sensor structure. The elements are also utilized as the cells, and the bridges measure the capacitances. Using soft materials, we can develop a large-area, soft, and stretchable robot skin without long wires. In the array structure, a contact position can be estimated with finer resolution than the size of the sensor element by calculating a spatial centroid from the measured contact forces.**

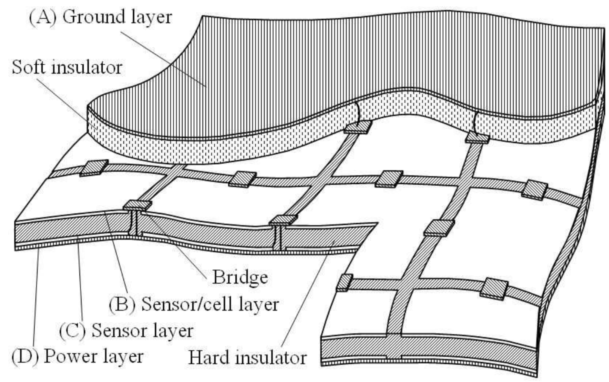

Figure 1. Illustration of proposed robot skin.

I. INTRODUCTION

Recently, there is a growing interest in home robots [1]-[4] that can care for the aged and young children and that can be alternatives to companion animals. Such robots have need of tactile sensor skins [5] which (i) cover their whole surfaces, (ii) sense rich tactile information, and (iii) are soft and stretchable to interact with humans safely and to be mounted on free-form surfaces. To realize such a robot skin, various arrays of pressure-sensitive tactile sensor elements have been tried [6]-[11]. One approach to enhance ability of the sensors for practical uses is arraying tactile elements in high density. However, we have no practical techniques available now with which we can mount a million of tactile elements with 1 mm spacing in a stretchable sensor skin.

To solve this problem, we proposed a novel signal transmission system in which the network is constructed by "cells" and "bridges" [12]. The bridge is a communication chip that can transmit and receive electric signals. The cell is a two dimensional medium through which the bridges exchange signals each other. Many kinds of such materials as conductive rubber or fabric are available for it. By connecting sensor elements to the cells, we can realize a high-density sensor network. Furthermore, the cell-bridge system is more effective when the cells are given some additional function of sensor or actuator. For example, the cells are given a function of electrostatic speaker in [13].

In this paper, we apply this system to a robot skin (Fig. 1). The cells are also components of our tactile sensor elements proposed in [14]. The sensor element has a several-centimeter-square large sensing area and acquires not only a contact force but also a contact area using nonlinear elasticity. Owing to the additional sensing parameter, i.e. the contact area, a robot skin which detects minute shape features is easily realized by arraying the elements in low density. In consequence, we can cover a whole surface of a robot with a small number of the elements. This proposition is inspired by the characteristics of the human tactile sensation. While Two Point Discrimination Thresholds (TPDT) of humans are as large as several centimeters except on especially sensitive parts, faces and hands [15], sharpness of objects can be discriminated sensitively even on such large TPDT parts. From these facts, we suppose that sharpness is one of the key components to produce general human tactile sensation [16], and that sensitivity to sharpness is a high priority for human-like sensor skins. Besides, the resulting robot skin can estimate a contact position with finer resolution than the size of the sensor element owing to the array structure.

The rest of this paper is organized as follows. Firstly, Section II describes the proposed tactile sensor skin. After that, we demonstrate how to estimate the contact position in Section III.

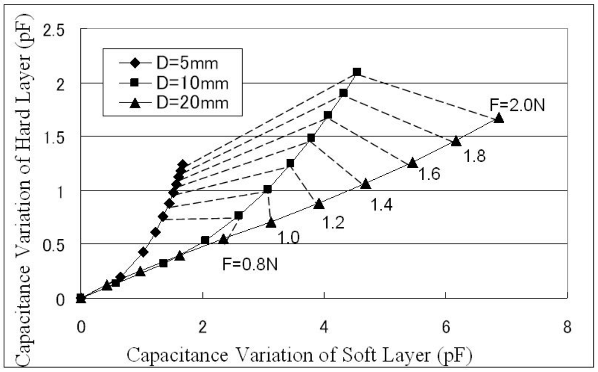

Figure 2. Simulation results. Calculated (ΔC_1, ΔC_2)s for various (F, S)s. D is a parameter defined as $D \equiv 2\sqrt{S/\pi}$ to represent a diameter of S for a circular object. [14]

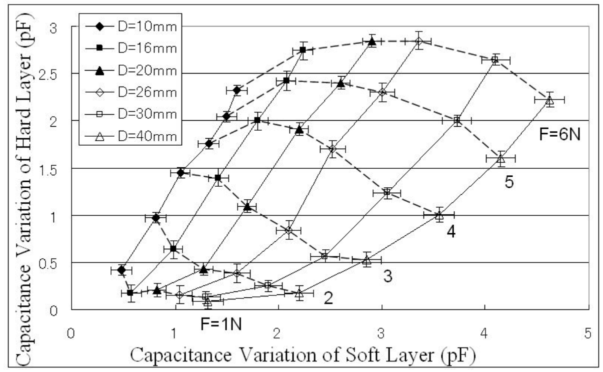

Figure 3. Experimental results of five trials. Averaged trajectories of (ΔC_1, ΔC_2)s for various (F, S)s with error bars representing maximal deviations. [14]

II. CELL-BRIDGE BASED ROBOT SKIN

A. Structure

Fig. 1 shows the structure of the proposed robot skin. There are two compressible insulator layers which have different stiffness. Besides, there are four stretchable conductive layers; the conductive layers A, B, C, and D are the ground layer, the sensor/cell layer, the other sensor layer, and the power layer, respectively. The conductive layers A and B sandwich the soft insulator layer forming the capacitor named C_1, and B and C sandwich the hard insulator layer forming C_2. This pair of the capacitors is one tactile sensor element. The conductive layers C and D are isolated by a thin stretchable insulator layer. The bridge is mounted in the structure and connected to the conductive layers locally by short wires. It is supplied power from the layers A and D (the ground and power layers). These two layers also function as electrostatic shields. It measures the capacitances C_n [F] (n = 1, 2) and sends measured data to the host computer through the conductive layer B (the cell layer) by multi-hoping method. The structure described here can maintain softness of the robot skin because it contains no long wires.

B. Nonlinear tactile element [14]

In this section, we explain the sensing theory of the tactile element. Here, we suppose a uniform pressure distribution $\sigma(x, y)$ [Pa] is vertically loaded to the surface of one of the sensor elements in a contact field S; that is

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

where F [N] is the total intensity of the contact force and S [m^2] is the area of S. Now we take note of the area of S, not the shape, so we suppose that S is circular for simplicity. We also assume as follows. First, the nonlinear elasticity of the insulator layers is the entropy elasticity [17] expressed as

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

where n is the layer identification; n=1 means the upper soft layer and 2 the lower hard layer. $\lambda_n \equiv 1 - \Delta d_n/(d_n - d_{n0})$ is the extension ratio of the layer n. E_n [Pa], d_n [m], and d_{n0} [m] are the elasticity modulus, the initial thickness, and the saturated thickness, respectively. E_1 is 4.8 kPa and E_2 is 15 kPa by actual measurement. Second, the conductive layers have negligible tension and the Poisson's ratios of the insulator layers are zero, which means that a displacement distribution $\Delta d_n(x, y)$ [m] is simply determined by a local value of $\sigma(x, y)$.

We measure the electric capacitances C_n [F] between the conductive layers to detect $\Delta d_n(x, y)$. Ignoring fringing fields, the capacitance is formulated as

$$C_n = \iint_{\text{Element}} \frac{\varepsilon_n}{d_n - \Delta d_n(x, y)} \mathrm{d}x\mathrm{d}y \tag{3}$$

where ε_n [F/m] is the dielectric constant of the layer n. If we can make the second assumption mentioned above, (C_1, C_2) is uniquely determined by (F, S). Then the key question is whether the inverse mapping from (C_1, C_2) to (F, S) is possible or not for the layers 1 and 2 having different hardness.

Fig. 2 shows the results of a numerical simulation for the elasticity moduli E_1 = 4.8 kPa and E_2 = 15 kPa. It shows that the plot of (ΔC_1, ΔC_2)s for various (F, S)s spans a two dimensional space, where (ΔC_1, ΔC_2) are the capacitance differences by the applied force, and $D \equiv 2\sqrt{S/\pi}$ is a parameter to represent the diameter of S for a circular object. It implies that we can determine (F, S) uniquely from (ΔC_1, ΔC_2) when F is larger than a threshold, now around 1.0 N.

We conducted an experiment to examine the feasibility of the proposed sensing method. We measured C_n of the sensor element prototype by a self oscillation method; we generated an RC oscillation including the sensor element as

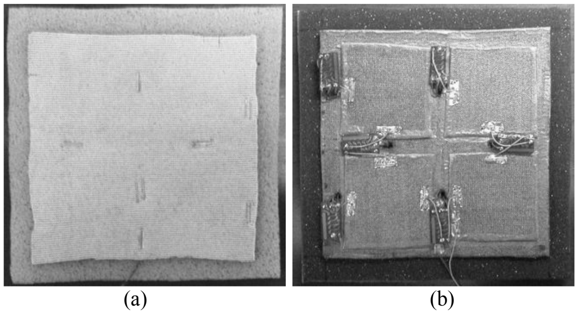

Figure 4. Developed 2×2 tactile sensor array. Each sensor element is 40×40×9 mm^3. (a) and (b) are top and bottom views of the test model.

the capacitor, and counted pulses per 2 ms by a 16-bit counter. A PC imported data via a digital I/O, and achieved about 40 Hz effective sampling rate. We used six acrylic stimulators with diameters D = 10, 16, 20, 26, 30, and 40 mm. Each stimulator was vertically pressed at the center of the sensor element. It was operated quasi-statically by a mechanical z-stage, with measuring the pressing force F by a weighting machine. Fig. 3 shows how (F, S)s are represented in the (ΔC_1, ΔC_2) space. It is confirmed that the plot of (ΔC_1, ΔC_2)s spans a two dimensional space sufficiently. The reason of the quantitative difference from the simulation result (Fig. 2) is considered to be the tension of the actual conductive fabric.

C. Bridge chip

The first prototype of CMOS LSI for the bridge is based on 0.35 µm rules. While the size of the LSI is 5×5 mm^2, the total area of the analog-digital mixed circuits is within 1.5 mm^2. The operating frequency of the LSI is 50 MHz. Each bridge measures C_n by an 8-bit A/D converter and it has a function to transmit signals to the neighboring chip. We packaged the LSI in 9×16×2 mm^3 using a flexible substrate.

D. Prototype

We have developed a test model of the robot skin (Fig. 4) using the first prototype of the LSI. The test model is a 2×2 array and the size of each element is 40×40 mm^2 and 9 mm thick. It is verified that the bridges measure the capacitances of the sensor elements and the measured data are transmitted to the host computer successfully.

For simplicity of the protocol, there are additional layers for signal transmission (i.e. the layer B in Fig. 1 is only used as the sensor layer) in this version. Meanwhile, we have completed fabrication of the next version of the LSI, which utilizes the layer B for signal transmission, and we are checking its performance now.

III. Estimating Contact Position

A. Basic theory

The proposed sensor element has no sensitivity to a contact position within its sensing area because C_n is a spatial integrated value (see (3)). In consequence, the localization ability of the robot skin seems to be limited by the size of the sensor element.

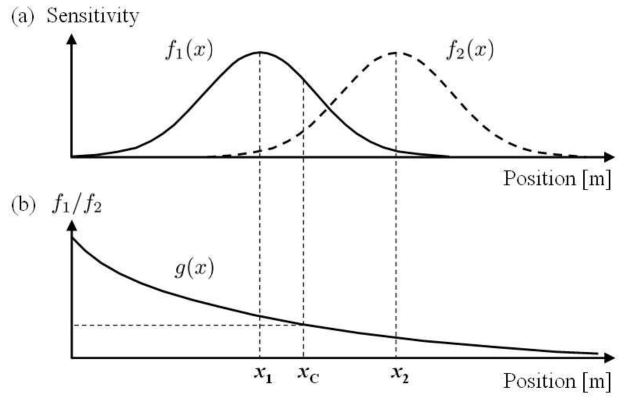

Figure 5. (a) Supposed Gaussian sensitivity distribution, f_1 and f_2. (b) Ratio of f_1 to f_2. The contact position x_C can be estimated from the ratio of the measured data.

Generally, in fact, it is possible to estimate a contact position from output data of discrete sensor elements if their receptive areas overlap each other. For example, we suppose two adjacent sensors of which the sensitivity distributions f_i (i = 1, 2) are the Gaussian distributions (Fig. 5 a) expressed as

$$f_i(x) = \exp\left\{-(x - x_i)^2 / s^2\right\} \tag{4}$$

where i is the element identification. x_i [m] and s [m] are the means and the standard variation, respectively. When a force F is applied to the elements at x_C [m], their outputs are expressed as $F \times f_i(x_C)$. So the ratio of the outputs are calculated as

$$g(x_C) \equiv \frac{F \times f_1(x_C)}{F \times f_2(x_C)} = \alpha \exp(-\beta\, x_C) \tag{5}$$

where $\alpha \equiv \exp\left\{(x_2{}^2 - x_1{}^2)/s^2\right\}$ and $\beta \equiv 2(x_2 - x_1)/s^2$. From (5), we can derive the contact position x_C (Fig. 5 b) as

$$x_C = g^{-1}(f_1/f_2)\,. \tag{6}$$

While the theory explained here is based on the Gaussian sensitivity distribution, its basics also hold true with other types of sensitivity distributions.

B. Experiments and results

We conducted experiments to examine the possibility of the estimation of the contact position. Fig. 6 shows ΔC_1 and ΔC_2 of the two adjacent elements A and B when the pressing position moves along their center line. It turns out that both sensor elements respond at the same time when the stimulator contacts both of them. This fact indicates that it is

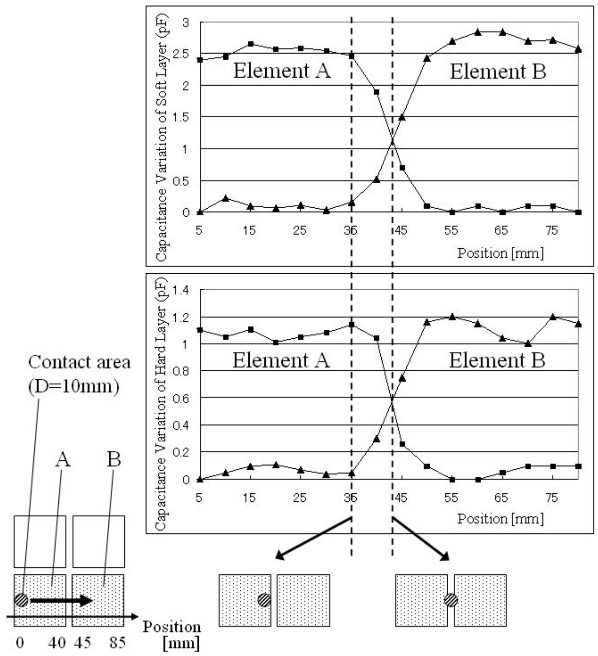

Figure 6. Experimental results. ΔC_1 and ΔC_2 of the two adjacent sensor elements. The stimulator (D = 10 mm) was vertically pressed at F = 3 N. A and B respond together when both of them are pressed.

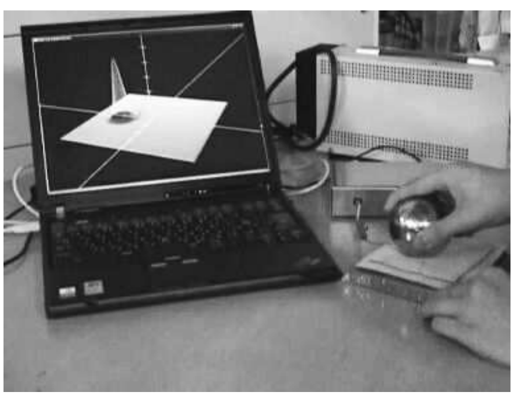

Figure 7. Demonstration. The two adjacent sensor elements are pressed by the spherical stimulator. The height and the standard variation of the Gaussian means F and D/4, respectively. In addition to the two parameters, the contact position is also estimated.

possible to estimate the contact position in our robot skin when the stimulator moves beyond the boundaries between the sensor elements, although it is still impossible to estimate the contact position when the stimulator moves within one sensor element.

The estimation of the contact position is demonstrated in Fig. 7. In this demo, we calculate simply a spatial centroid from the measured contact forces and consider it as the contact position.

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