Large Area Sensor Skin based on Two-Dimensional Signal Transmission Technology

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Abstract

In this paper, we propose a stretchable large area sensor skin based on Two-Dimensional Signal Transmission (2DST) technology. A small tactile sensor chip with stable non-contact connectors (Resonant Proximity Connector: RPC) to a 2DST sheet is developed. The sensor nodes communicate by microwave that propagates in a two-dimensional sheet. Sensor nodes connect to the 2DST sheet via RPCs without electrical contact anywhere on the sheet and also receive the power for operation from the microwave in the sheet. RPC is a spiral electrode whose total length is a quarter of the electromagnetic wavelength. The induced resonance around the electrode reduces the impedance between the connector and 2DST sheet, which allows sensor chips to connect to the 2DST sheet stably. Simulation results on spiral RPCs show that the concept is effective. We produce an on-off type tactile sensor element which consists of a RFID-tag and RPC, and experimentally confirm that the sensor element works in a stretchable 2DST sheet.

1. Introduction

Realizing an elastic and practical senor skin that covers a large area of robot surface has been an impeding demand in robotics ever since the end of 1990s [1,2]. Such a skin is not only a device for the autonomous motion of a robot but also a new form of interface between humans and the information world. A wearable thin elastic sensor skin is also an important target of haptics. In the development of stretchable sensor skin, wiring to the tactile elements had been a simple but hard-to-solve problem. The existing devices [3],[7], and [8] suffer from the fragility that ascribes to the stress concentration to the wires. Cell-bridge system proposed by us [9] intended to remove long wires from a robot skin. But the short bonding between the bridge chip (sensing/communicating LSI) and the cell (conductive site in the skin) was still fragile.

In this paper, we propose a stretchable and tough skin based on Two-Dimensional Signal Transmission (2DST) technology. In communication of 2DST [10], the sensor nodes communicate by microwave that propagates in a two-dimensional sheet. Sensor nodes connect to the 2DST sheet without electrical contact anywhere on the sheet and also receive the power for operation from the microwave through the sheet. The sheet structure is simple as shown in Fig. 1. An insulator sheet is sandwiched by two conductive sheets. The conductive sheets can be realized by stretchable conductive fabrics. Since the relative position of the sensor chips to the conductive fabrics is movable, the device is tough keeping the elasticity. In addition, the production process for integrating a large number of sensor elements is simple.

The idea of communication using two dimensional medium was originally proposed by us [11] and some other groups [12], [13] at the early 2000s. In the researches [12] and [13], however, high speed communication through the medium was out of consideration. In addition, mechanical and electrical contacts of elements to the conductive layers were necessary. Our method provides high-speed connection using microwaves with no electrical contact at each sensor.

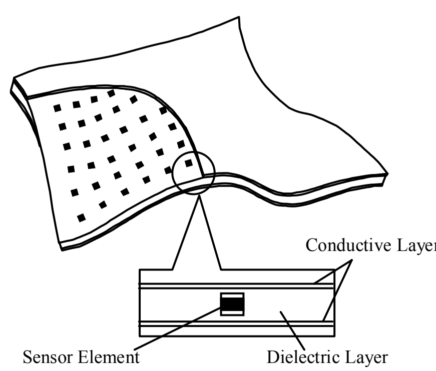

Fig. 1. Illustration of sensor skin based on Two-Dimensional Signal Transmission (2DST) sheet.

In the following sections, we show a small and stable non-contact connector (Resonant Proximity Connector: RPC) to 2DST sheet. We propose a tactile sensor chip with a RPC and fabricate the prototype of on-off type sensor chip using a commercial RFID tag. We finally confirm the operation of the sensor skin experimentally. RPC and the idea of the sensor skin based on 2DST were partly published in a domestic conference held in Japan [14]. But the details of the design and experiments as a sensor skin are reported first in this paper.

2. Resonant Proximity Connector

In 2DST, we supply energy to the sensor elements and communicate with the sensor elements through a couple of conductive layers as shown in Fig. 1. A traveling electromagnetic wave mode inside the sheet is used for 2DST. The electromagnetic wavelength in 2DST sheet is much larger than the sheet thickness, while it is smaller than the width and length. The detail of the electromagnetic wave and theoretical limit of energy absorption are described in [10]. The unsolved problem is to obtain stable non-contact connection between the sensor chip and 2DST conductive layer.

A primitive method to connect sensor chips to 2DST sheet without electrical contact is to utilize the capacitive coupling existing between them. Let the radiation impedance of 2DST sheet Z_0. In this case, the impedance seen from the terminal of sensor chips is the total of the impedance Z_0 and the reactance $1/j\omega C$ where C is the capacitance between the connector and the 2DST sheet.

One problem in using capacitive coupling C is that it highly depends on the variation of the gap d between the connector and the 2DST sheet as shown in Fig. 2. The reactance X from C is written as

$$X = \frac{1}{\omega C} = \frac{d}{2\pi f \varepsilon_0 \varepsilon_r S} \tag{1}$$

where S, ε_0 and ε_r denote respectively the area of the connector, the dielectric constant in the air, and the relative permittivity of the dielectric layer. For f = 2.4GHz, $S = 2.5\times2.5\times\pi$ mm^2, d = 0.5 mm, and ε_r = 4.9, the reactance X is 38.9 Ω. Since Re[Z_0] for a 2DST sheet with 1 mm thickness is as small as 5 Ω at 2.4 GHz, the reactance X causes serious loss of connection. Therefore we have to prepare variable inductance L to satisfy

$$\omega L = \frac{1}{\omega C} \tag{2}$$

in order to cancel the reactance (impedance matching). It makes the circuit design of the sensor chip complex since L should be variable according to C (Fig. 2).

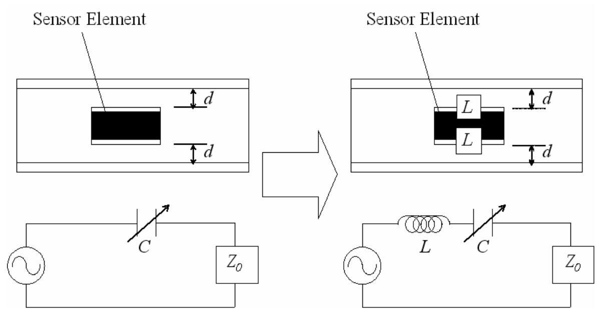

Fig. 2. Illustration of the proximity connection.

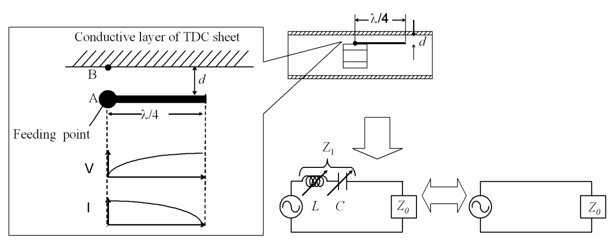

Fig. 3. Schematic explanation of RPC. "*V*" is the vertically measured voltage between A and B, while "*I*" is the horizontal current in the electrode.

Fig. 3 shows the illustration of the proximity connector we propose here. The connector is an electrode whose length is a quarter of the wavelength λ. When we apply voltage between A and B, the voltage V and the current I are respectively the minimum and the maximum at feeding point A on the $\lambda/4$ electrode. Then the impedance Z_1 between A and B

$$Z_1 = V/I \tag{3}$$

becomes the minimum.

The condition of the resonance depends on the length of the electrode and hardly depends on the gap distance d. We can design various shapes of electrodes keeping their total length equal to $\lambda/4$ in the plane parallel to the 2DST sheet. We conducted simulation analysis to examine our theory. In next section, we describe the simulation model and the results.

3. Numerical Simulation

We conducted simulation analysis using the software MW-Studio (AET Japan, Inc) considering metallic resistance. Fig. 4 shows the illustration of the simulation model. The simulation model consists of a SMA connector, 2DST sheet, and the electrode we propose. In the simulation, we set copper foil whose thickness is 35 μm as the conductive layer, and a glass epoxy board whose thickness and relative permittivity are 2.1 mm and 4.9, respectively. Although we will not use SMA connectors and a glass epoxy board for sensor implantation, we assume them for experimental confirmation.

Since the resonance only depends on the length of the electrode, the form of the electrode can be circular or spiral to make the connector smaller. We conducted simulation analysis here on a spiral electrode.

The wavelength λ of electromagnetic wave which travels in 2DST sheet is written as

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}} \tag{4}$$

where c is the velocity of the electromagnetic wave. For f = 2.4 GHz, λ is equal to 56.5 mm. Although the exact length of $\lambda/4$ is 14.1 mm, we set the electrode length 14.7 mm to obtain the best result considering the open-end correction and the effect of the feeding point size. The width of the electrode is 0.2 mm.

The software gives the impedance Z at the SMA connector that is the sum of the radiation impedance Z_0 of the 2DST sheet and the connection impedance Z_1. In order to obtain Z_1, we first obtain the value of Z_0 for d = 0 mm (electrically shorted). Then we calculate Z for various gaps d. We show final results of Z_1, obtained by

$$Z_1 = Z - Z_0 \, . \tag{5}$$

Table 1 shows Z_1 for various gaps d. The reactance of Z_1 is less than 5 Ω for 0.1 mm ≤ d ≤ 0.5 mm, which shows our theory is effective for stable connection irrespective of the distance between the electrode and 2DST sheet. The reason why the real parts of Z_1 are negative is that they were calculated mechanically by equation (5). We also show the results at other frequencies for comparisons in Table 1 and Fig. 5. As shown in these results, the impedance Z_1 is low enough especially at 2.4GHz.

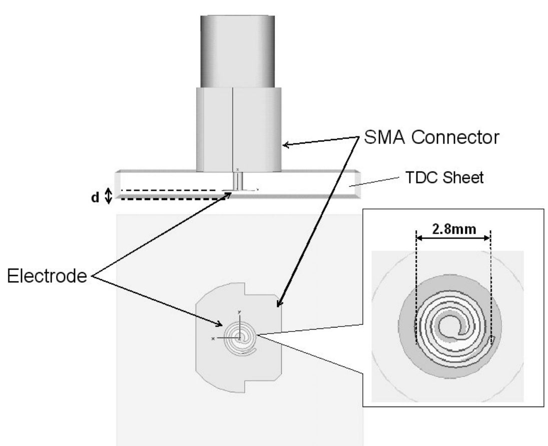

Fig. 4. Spiral RPC model for simulation analysis

Table 1. The calculated impedance Z_1 of the spiral electrode for various gaps d

d [mm]	Impedance Z_1 [Ω]		
	2.4GHz	1.0GHz	3.0GHz
0.1	-2.44+j4.75	1.286-j45.29	449.2-j114.1
0.2	-1.68+j4.18	-0.844-j61.78	29.4-j360.9
0.3	-3.1-j0.77	-1.804-j74.84	-22.3-j306.0
0.4	-3.5+j1.35	-1.278-j85.10	-47.8-j268.7
0.5	-5.75-j1.62	-1.732-j98.71	-53.3-j257.7

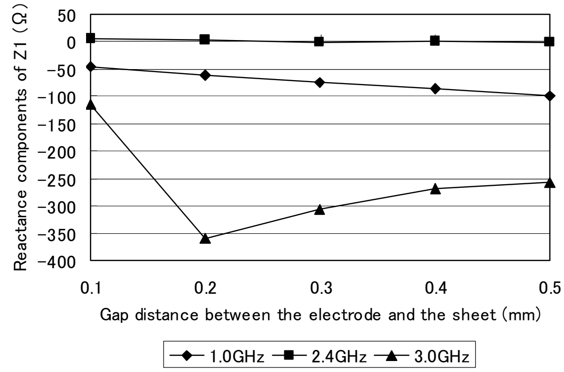

Fig. 5. Reactance components of Z_1 for various d of the spiral electrode

4. Experiment of power supply

We conducted experiment on microwave power supply in 2DST sheet. The sheet consists of aluminum foil as the conductive layer and a flexible poly olefin sheet as the dielectric layer. The thickness d_0 of the sheet is 6 mm. We show the photograph of the 2DST sheet in Fig. 6.

We measured the supplied power through a rectification circuit put on the $\lambda/4$ electrode. We show the photograph of circuit with the electrode in Fig. 7.

We supplied power from the edge of 2DST sheet with a 2W-2.4GHz power amplifier, and put the electrode with the rectification circuit into the 2DST sheet. The power receiving unit is located at 17 cm from feeding point (Fig. 6).

First, we evaluated the power propagating in the sheet. We measured the peak-to-peak voltage of the signal at 10 points on the edge of the sheet. The measurement points and the result are shown in Fig. 8.

Although a standing wave is produced in the sheet, we estimate equivalent traveling wave power that has the same amplitude of electric field as the measured one (for evaluation of the connector). The data of Fig. 8 show that the average of Vp-p at the edge is 2.56 (V). Substituting Vp-p / $(2\sqrt{2}\, d_0)$ for the following variable E, the power reaching the edge of 2DST sheet is

$$P = EH \cdot S = E^2 \sqrt{\frac{\varepsilon_0 \varepsilon_r}{\mu}} \cdot S \tag{6}$$

where S and μ is the cross section area of the 2DST sheet, and magnetic permeability, respectively. We obtain the equivalent power passing through the bottom side of the sheet. For $\varepsilon_0 = 8.854\times10^{-12}$ ($m^{-3}kg^{-1}s^4A^2$), ε_r=2.3, μ= $4\pi\times10^{-7}$(kg m s^{-2} A^{-2}), $S = 1.2\times10^{-3}$ (m^2), and d_0 = 6 mm, the value of P written in equation (6) is 110 (mW).

Next we measured the output voltage at resistance R in Fig.7. We show the results for various Rs (47, 100, 470, 1000, 5600 Ω) in Fig. 9. A sufficient voltage for circuit operation was obtained. Fig. 10 shows the power supplied to R that were calculated from the data of Fig. 9. The maximal power consumed at R was 20 mW for R = 470 Ω that is close to the theoretical limit calculated from equation (6) [10].

Finally, we measured the effect of gap distance change between the electrode and the 2DST sheet. We measured the output voltage at R for various gap distance d_1 from 0.1 mm to 0.5 mm. Then the observed output was almost constant and the fluctuation was within 50 mV for R = 470 Ω.

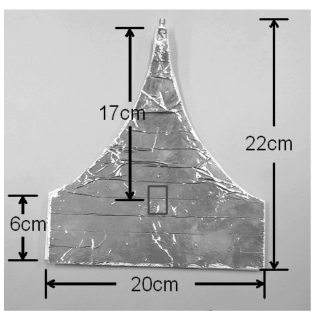

Fig. 6. Photograph of 2DST sheet used in the experiment. The square marked at 17 cm from feeding point indicates the location where a rectification circuit was put.

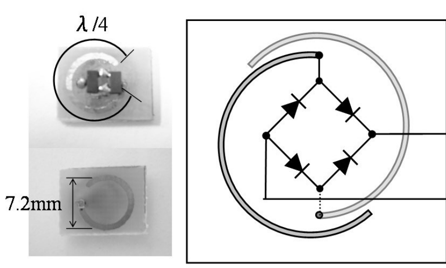

Fig. 7. Illustration of power receiving unit. Photograph of the electrode (left) and diagram of the rectification circuit connected to the electrode (right).

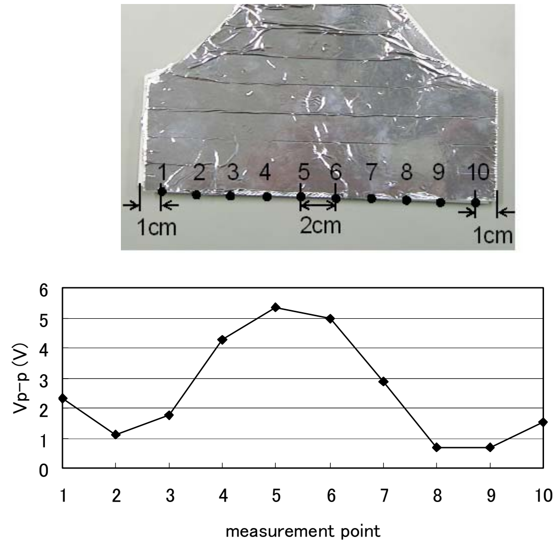

Fig. 8. Measurement point of *V*p-p (top) and the result of the measurement (bottom). The numbers of the horizontal axis in the bottom graph identify the points of the top figure.

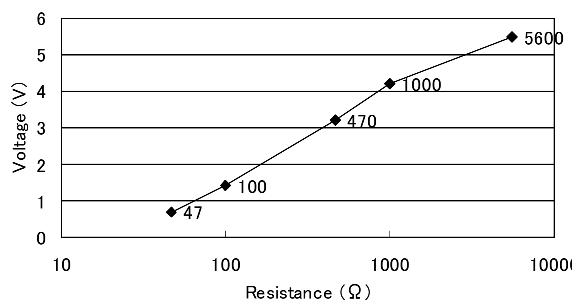

Fig. 9. Output voltage at resistance *R* for various values of *R*.

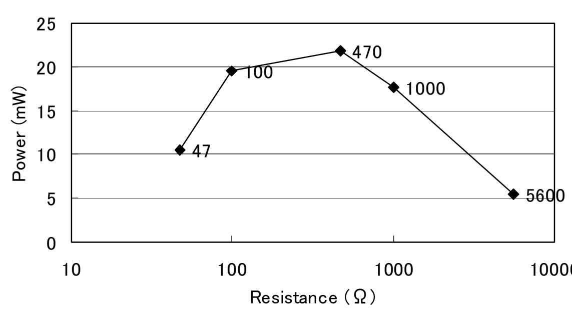

Fig. 10. Power consumed at resistance *R* for various values of *R*.

5. A tactile element composed of RFID tag

We designed a simple structure of tactile sensor element to confirm the principle. A sensor element is composed of two spiral RPCs and a passive RFID tag. The tag we used (Japan information system, DL-1000) has its own ID, and it responds to the tag reader. The signal frequency for energy supply from the tag reader and response from the tag is 2.4 GHz. We show the tactile sensor element in Fig. 11.

Two RPCs sandwich urethane foam. One of the RFID tag's electrodes is electrically connected to one of the RPCs. In the initial state, there is a gap between the other electrode of RFID tag and the other one of the RPCs. That forms a mechanical ON-OFF switch between the RFID tag and the RPC. The simple sensor element responds its ID when vertical force is applied that turns on the sensor element. By preparing the table between the element IDs and their locations, we can realize a two-dimensional on-off switch array without individual wires to the sensing elements. The dimension of sensor element is 6mm × 6mm × 3mm.

We also fabricated a stretchable 2DST sheet using knitted conductive fabrics. The insulator layer is made of urethane foam. The sheet can be stretched in any direction. The size of the prototype sheet is 200 mm × 200 mm × 4.74 mm. The tag reader is connected at the corner of the 2DST sheet as Fig. 12 shows. Then we put the sensor chip into the 2DST sheet and confirmed that the sensor chip responds when the sheet is pressed. We show the experimental view in Fig. 13.

We show a characteristic of the sensor chip in Fig.14. The figure shows the detection probability of the tag by the tag reader versus the applied force on the sensor chip. The probability was estimated by 25 trials for each value of applied force. As shown in Fig. 14, when this sensor is pressed by 0.5 N, the probability of the sensor response reaches 90 %. The result shows the detection threshold of this tactile sensor is around 0.4 N.

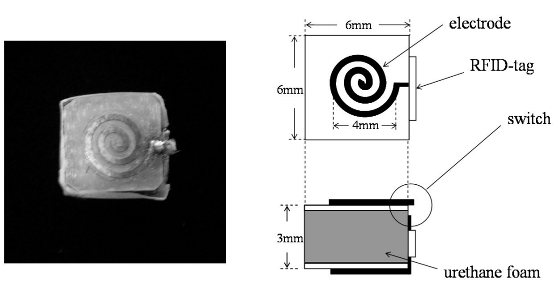

Fig.11. The photograph (left) and the illustration (right) of the tactile sensor chip.

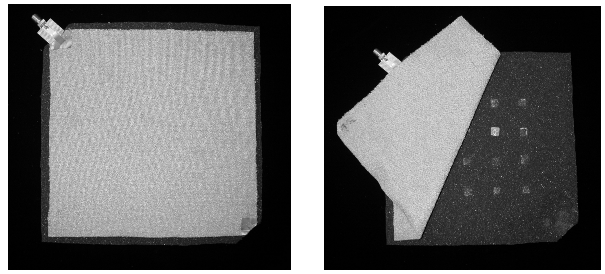

Fig. 12. The prototype of 2DST sheet (left) and the sensor element put into the sheet (right).

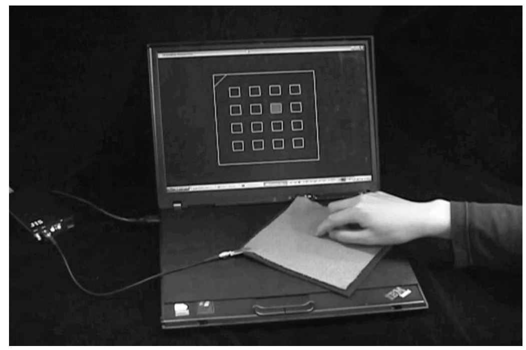

Fig. 13. The sensor element reacts when the sheet is pressed.

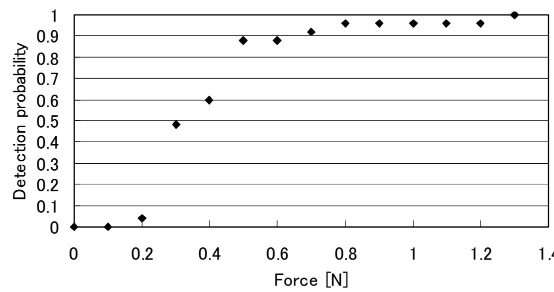

Fig. 14. Relationship between detection probability of the sensor ID and applied force to the sensor.

6. Conclusion

In this paper, we proposed a large area artificial skin based on Two-Dimensional Signal Transmission (2DST) technology. In order to obtain stable non-contact connection between a sensor chip and a 2DST sheet, we showed a spiral design of Resonant Proximity Connector (RPC). RPC is an electrode whose total length is a quarter of the electromagnetic wavelength. The induced resonance around the electrode reduces the impedance between the connector and 2DST sheet, which allows sensor chips to connect with the 2DST sheet stably. Simulation results on spiral RPC showed that the concept is effective.

Next, we confirmed that DC power can be supplied to the sensor element in the 2DST sheet successfully in experiments. Through RPC and a rectification circuit, 20 mW power was obtained.

Finally we fabricated a prototype of on-off type tactile sensor chip with spiral RPCs and a RFID tag. The size of the sensor is within 6 mm square. We confirmed the successful operation of the sensor chip in a stretchable 2DST sensor sheet realized with knitted conductive fabrics.

One unsolved problem in the research is to remove the standing wave in 2DST sheet that causes dead zones in the skin. It is crucial to solve the problem for high-density sensor location.

A great future challenge is to develop new tactile sensor chips which can measure applied stress as continuous quantity.

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References

[1] H.R.Nicholls, M.H.Lee, “A Survey of Robot Tactile Sensing Technology,” The International Journal of Robotics Research, Vol. 8, No.3, pp.3-30, 1989.

[2] M.H.Lee, H.R.Nicholls, “Tactile sensing for mechatronics – a state of the art survey,” Mechatronics, Vol.9, pp.1-31, 1999.

[3] T.Someya, Y.Kato, T.Sekitani, et al., “Conformable, flexible, large-area networks of pressure and thermal sensors with organic transistor active matrixes,” PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, Vol.102, No.35, pp.12321-12324, 2005.

[4] Y. Hoshino, M. Inaba, and H. Inoue, “Model and Processing of Whole-body Tactile Sensor Suit for Human-Robot Contact Interaction,” Proc. of the 1998 IEEE International Conference on Robotics & Automation (ICRA '98), pp. 2281-2286, 1998.

[5] R. Kageyama, S. Kagami, M. Inaba, and H. Inoue, “Development of Soft and Distributed Tactile Sensors and the Application to a Humanoid Robot,” Proc. of the IEEE International Conference on Systems, Man, and Cybernetics, 2: pp. 981-986, 1999.

[6] O. Kerpa, K. Weiss, and H. Worn, “Development of a Flexible Tactile Sensor System for a Humanoid Robot. Proc. of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003),” Vol1. pp. 1-6, 2003.

[7] J.Engel, J.Chen, Z.Fan, C.Liu, “Polymer micromachined multimodal tactile sensors,” SENSORS AND ACTUATORS A-PHYSICAL 117 (1), pp.50-61, 2005.

[8] M.Sergio and N.Manaresi, M.Tartagni, et al., “A Tactile Based Capacitive Pressure Sensor,” Sensors, 2002. Proceedings of IEEE, Vol.2, pp.1625-1630, 2002.

[9] T. Hoshi, A. Okada, Y. Makino, and H. Shinoda, “A Whole Body Artificial Skin Based on Cell-Bridge Networking System,” Proc. 3rd International Conference on Networked Sensing Systems (INSS 2006), pp.55-60, 2006.

[10] Y.Makino, K.Minamizawa and H.Shinoda, “Two Dimensional Communication Technology for Networked Sensing System” *Proc. INSS 2005,* pp.168-173, 2005.

[11] M. Hakozaki and H. Shinoda, “Digital Tactile Sensing Elements Communicating through Conductive Skin Layers,” Proc. 2002 IEEE Int. Conf. on Robotics & Automation, pp.3813-3817, 2002.

[12] K. V. Laerhoven, N. Villar, A. Schmidt, and H.W. Gellersen, “Pin & Play: The Surface as Network Medium,” IEEE Communication Magazine, pp. 90-95, 2003.

[13] J. Lifton and J. Paradiso, “Pushpin Computing System Overview: A Platform for Distributed, Embedded, Ubiquitous Sensor Networks,” Proc. Perv. Comp., LNCS 2414, pp. 139-151, 2002.

[14] H. Chigusa, Y. Makino, and H. Shinoda, “Large Area Tactile Sensor based on Proximity Connection of Tactile Sensing Elements,” Proc. IEEJ 23rd Sensor Symposium, pp. 437-442, 2006.