Large Area Tactile Sensor based on Proximity Connection of Tactile Sensing Elements

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In this paper, we propose a stable proximity connector RPC (Resonant Proximity Connector) to TDC (Two-Dimensional Communication) sheet for integration of tactile sensor chips in a large area robot skin. RPC is an electrode whose length is a quarter of the electromagnetic wavelength. The induced resonance around the electrode reduces the impedance between the connector and TDC sheet, which allows sensor chips to connect with TDC sheet stably. Simulation results on straight, ring, spiral RPCs show that the concept is effective. We also confirmed experimentally that power can be supplied to the sensor element in TDC sheet successfully.

Keywords : Two-Dimensional Communication, sensor network, proximity connection, resonance, impedance matching

1. Introduction

Future robots having contact with people will require robot skins on the surfaces. Signal transmission from the tactile sensor elements is an important problem in realizing a large area of soft sensor skin.

In currently available technologies, we have two typical physical forms of signal transmission. First one is to connect sensors with line-form media such as optical fiber, electric wire, cable, etc. In this method, the sensor can transmit signals with the minimal energy. However, as the number of sensors increases, the effort of wiring increases and wiring often becomes virtually impossible. The physical flexibility of the device is lost by wiring, which is crucial in artificial skin. There are some works to overcome this problem [5,6]. However, they still have hurdles to clear for practical use.

The other one is to construct sensor network with electromagnetic wave which propagates in the air. In this method, sensors communicate with each other without wiring. However, power supply to the sensor element that is required to transmit high bit rate tactile signal is difficult.

We proposed Two-Dimensional Communication (TDC) method to realize wireless sensor networks in two-dimension [1,4]. Figure 1 shows the illustration of TDC sheet. TDC sheet is composed of two conductive layers and a dielectric layer. In this system, each sensor chip communicates with omni directional microwave traveling in the sheet. Using TDC method, we can connect a large number of sensors without complicated wires. TDC sheet can be realized with flexible materials as rubber or fabrics for fabricating artificial skins for robots.

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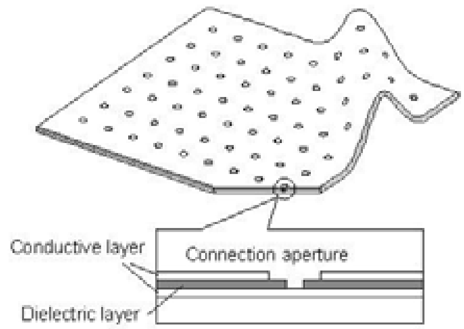

Figure 1. Illustration of two-dimensional communication sheet [4].

When we put sensor chips into TDC sheet, we should realize a stable connection between sensor chips and a TDC sheet. If we make the connection by mechanical and electrical contact to the TDC sheet, the production process is complex and causes stress concentration around the connection that made the device fragile. In this paper, we propose a method of stable non-contact connection between sensor chips and a TDC sheet to solve the problems related to mechanical connection.

The idea of communication using two dimensional medium was originally proposed by us [1] and some other groups [2,3] at the early 2000s. In the researches [2] and [3], however, high speed communication through the medium was out of consideration. Mechanical and electrical connections of elements to the conductive layers were also necessary. Our method provides high-speed connection using microwaves with no electrical contact at each sensor.

2. Resonant Proximity Connector

A primitive method to connect sensor chips and TDC sheet without electrical contact is to utilize the capacitive coupling existing between them. Let the radiation impedance of TDC sheet Z_o. In this case, the impedance seen from the terminal of sensor chips is a total of the impedance Z_o and the reactance $1/j\omega C$ where C is the capacitance between the connector and the TDC 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 TDC sheet as shown in Figure 2. The reactance X from C is written as

$$X = \frac{1}{\omega C} = \frac{d}{2\pi f \varepsilon_0 \varepsilon_r S} \quad \cdots(1)$$

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 = 2.5×2.5×π mm^2, d = 0.5 mm, and ε_r = 4.9, the reactance X is 38.9 Ω. Since Re[Z_0] for a TDC 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

$$\omega L = \frac{1}{\omega C} \quad \cdots(2)$$

that follows the capacitance change by the gap d, which makes the circuit design of the sensor chip complex. (Figure 2).

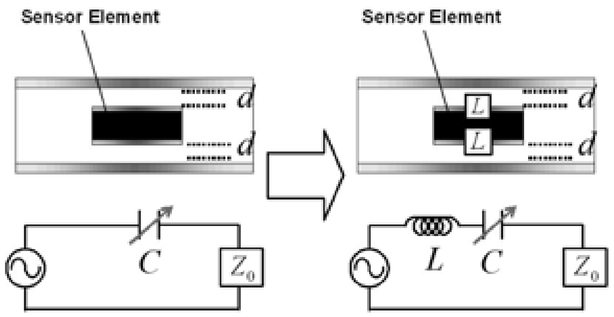

Figure 2. Illustration of the proximity connection.

Figure 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 λ/4 electrode. Then the impedance Z_1 between A and B

$$Z_1 = V / I \quad \cdots(3)$$

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 use various shapes of electrodes with their length of λ/4 that are parallel to the TDC sheet. We conducted simulation analysis to examine our theory. In next section, we describe the simulation model and the results.

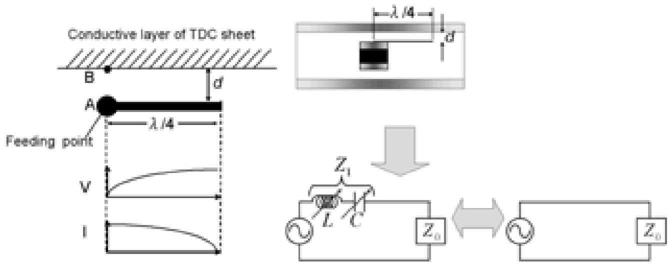

Figure 3. Schematic explanation of RPC

3. Numerical Simulation

We conducted simulation analysis using the software MW-Studio (AET Japan, Inc) considering metallic resistance. Figure 4 shows the illustration of the simulation model. The simulation model consists of a SMA connector, TDC sheet, and the electrode we propose. In this simulation, we set copper foil whose thickness is 35μm 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.

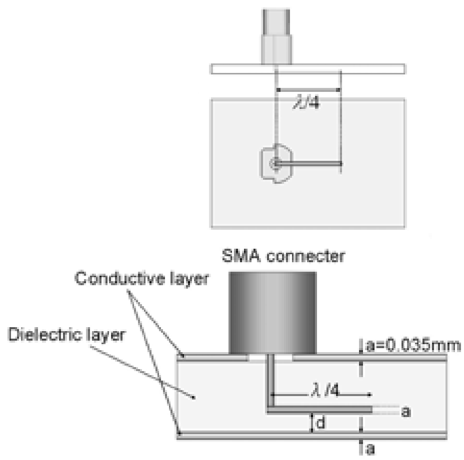

Figure 4. RPC model for simulation analysis

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

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}} \quad \cdots(4)$$

where c is the velocity of the electromagnetic wave. For f = 2.4GHz, λ is equal to 56.5 mm. Although the exact length of λ/4 is 14.1 mm, we set the electrode length 15.3 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 0.8mm.

The software gives the impedance Z at the SMA connector that is the sum of the radiation impedance Z_0 of the TDC 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

$$Z_1 = Z - Z_0 \quad \cdots\cdots (5)$$

Table 1 shows Z_1 for various gaps d. The reactance is less than 2 Ω for $0.1 \le d \le 0.5$, which shows our theory is effective for stable connection irrespective of the distance between the electrode and TDC sheet. The reason why the real parts of Z_1 are negative is that they were calculated mechanically by equation (5). We show the results at other frequencies for comparisons in Table 1 and Figure 5.

Table 1. The impedance Z_1 for various gaps d

d [mm]	Impedance Z_1 [Ω]		
	2.4GHz	1.0GHz	3.0GHz
0.1	-2.14+j1.96	-1.30-j20.92	50.0+j50.9
0.2	-3.60+j0.82	-2.64-j29.57	120.0+j86.7
0.3	-6.67-j0.17	-2.23-j36.56	159.0+j124.3
0.4	-8.89-j0.97	-2.15-j40.59	191.8+j155.9
0.5	-11.0-j1.95	-2.21-j42.94	211.4+j186.2

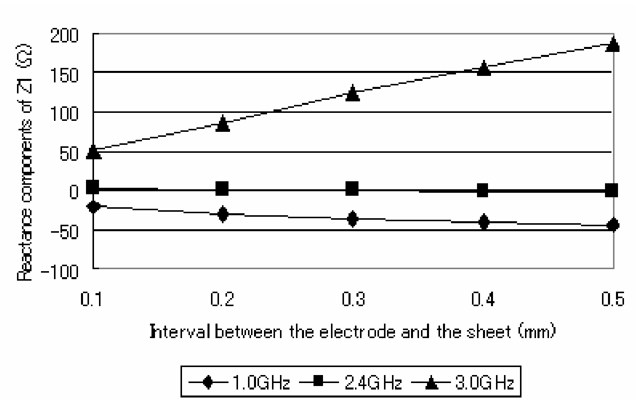

Figure 5. Reactance components of Z_1 for various d of the straight electrode

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

We show the simulation model of a circular electrode in Figure 6. The size of TDC sheet is infinite, and the diameter of the electrode is 5.6 mm. As shown in Table 2 and Figure 7, the reactance of Z_1 is less than 5Ω at 2.4GHz.

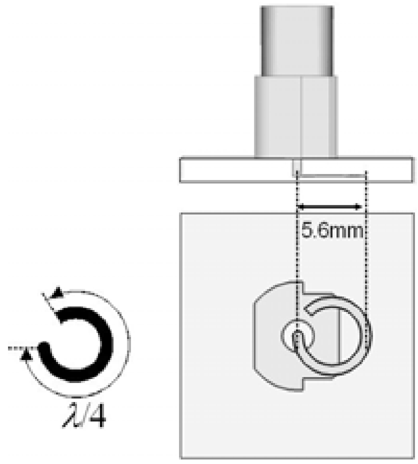

Figure 6. Circular model of the RPC connector

Table 2. The calculated impedance Z_1 of the circular electrode for various gaps d

d [mm]	Impedance Z_1 [Ω]		
	2.4GHz	1.0GHz	3.0GHz
0.1	-5.07+j1.69	0.81-j17.88	34.6+j54.2
0.2	-5.64+j4.67	6.45+j32.03	76.2+j97.4
0.3	-6.89+j2.16	-2.64-j32.87	117.2+j123.5
0.4	-9.56-j2.07	-0.47-j36.92	123.6+j128.9
0.5	-11.66-j4.54	-1.07-j40.76	17.4+j149.7

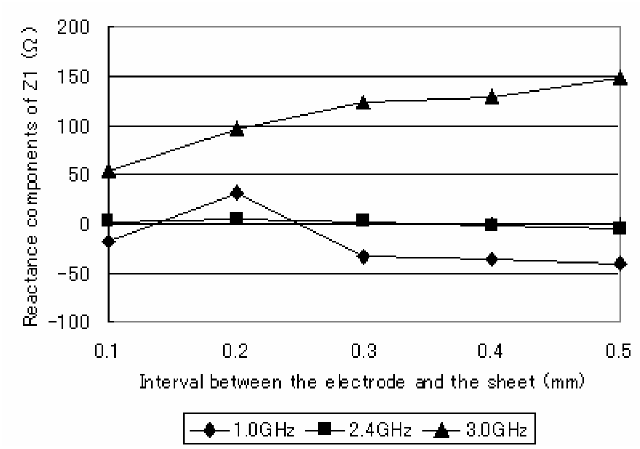

Figure 7. Reactance components of Z_1 for various d of the circular electrode

Figure 8 shows the spiral electrode model. The diameter of the electrode is 2.8 mm. Table 3 and Figure 9 show the impedance Z_1 of the spiral model for various gaps d. The reactance is less than 5 Ω, hence we can say that our theory is effective also for such a very small spiral electrode.

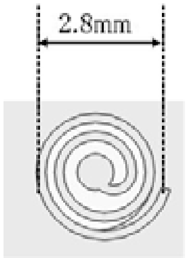

Figure 8. Spiral electrode model of RPC.

Table 3. 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

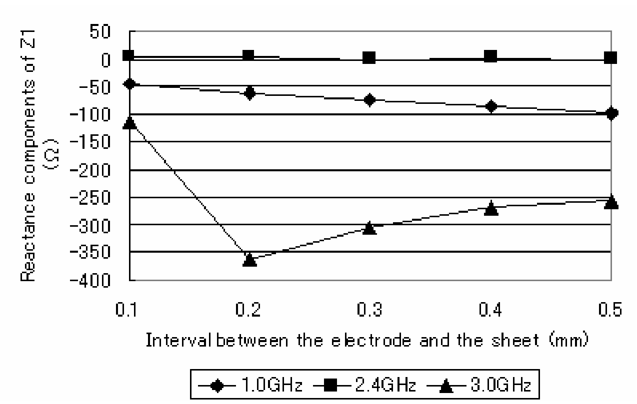

Figure 9. Reactance components of Z_1 for various d of the spiral electrode

4. Discussion on Power Supply

We supply each sensor chip with power from the edge of a TDC sheet. In this section, we discuss the effective frequency of power supply. First, consider the power is supplied by a low frequency signal source whose wavelength is much longer than the size of the TDC sheet. Then we can deal with TDC sheet as a large area of a condenser.

The efficiency of supplying power is deteriorated when sensors are put in low density. To consider this problem, we cut out a unit area including a single sensor from the TDC sheet as shown in Figure 10 (left). We also show the equivalent circuit in Figure 10 (right). In Figure 10, C_1 is the capacitance between a sensor and the TDC sheet, and C_0 is the capacitance between two layers of the unit TDC sheet for one sensor, excluding the contribution of the sensor area.

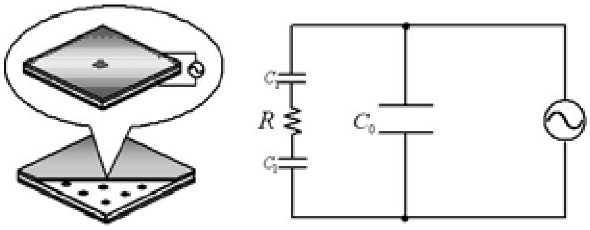

Figure 10. A unit area where a sensor is put (left) and the equivalent circuit (right).

We compare the power W_R consumed at R with the power W_C consumed at C_0. In order to maximize W_R, we should attach L_1 to cancel C_1 as Figure 11 shows. On the other hand, the current into C_0 supplied by the power source is minimized by the inductance L_0. If we can realize the lossless resonance, the influences of both capacitances can be canceled. However, the quality factors of the resonances are finite, which are denoted by residual resistances R_0 and R_1 as shown in Figure 12.

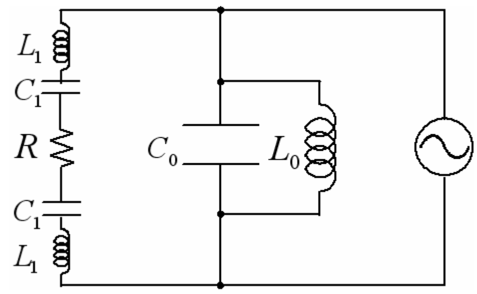

Figure 11. Illustration of circuit canceling C_0 and C_1

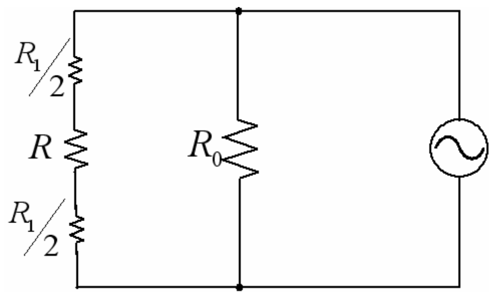

Figure 12. Equivalent circuit of residual resistances at the resonances.

These resistances are written as

$$R_0 = Q_0 \frac{1}{\omega C_0} \quad \text{(6)}$$

$$R_1 = \frac{2}{Q_1 \omega C_1} \quad \text{(7)}$$

where Q_0 and Q_1 are quality factors of the resonances.

Then the ratio of W_C to W_R is given as

$$\frac{W_C}{W_R} > \frac{R_1 + R}{R_0} = \frac{C_0}{C_1}\frac{2}{Q_0 Q_1} + \frac{\omega C_0 R}{Q_0} > \frac{d_1 S_0}{d_0 S_1}\frac{2}{Q_0 Q_1} \quad \text{(8)}$$

where d_0 and d_1 are the thickness of the TDC sheet and the distance between the sensor and the TDC sheet, respectively, and S_1 and S_0 are the area of the sensor and the area of the unit TDC sheet for one sensor, respectively.

If we assume that d_0 = 2 mm, d_1 = 0.5 mm, and $Q_0 = Q_1$ =30, the inequality can be written as

$$\frac{W_C}{W_R} > \frac{1}{1800}\frac{S_0}{S_1} \quad \text{(9)}$$

This equation means that the power W_C wasted at C_0 exceeds W_R for a large value of S_0/S_1. For example, if we put a sensor whose area is 1×1 mm^2 in a TDC sheet whose area is 4×4 cm^2, more than half of supplied current is wasted. Therefore, non-contact power supply by capacitive coupling at a low frequency becomes inefficient for a low density of sensor implantation.

On humans back, two-point discrimination threshold is about 5 cm [7]. So when we consider applying TDC technology and RPC connector to whole body artificial skin, use of a low frequency signal source whose wavelength is much longer than sensor chip spacing is inefficient. In such cases, use of microwaves whose wavelength is comparable to or less than sensor chip intervals will be preferable. Therefore, we design a sensor chip that obtains operation power by microwave.

5. Experiment on Power Supply

We conducted experiment on microwave power supply in TDC 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 TDC sheet in Figure 13.

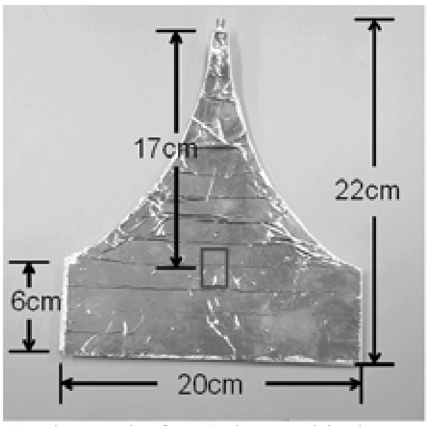

Figure 13. Photograph of TDC sheet used in the experiment. The square 17cm from feeding point indicates the location where a rectification circuit was put.

We measured the supplied power through a rectification circuit put on the λ/4 electrode. We show the photograph of circuit with the electrode in Figure 14.

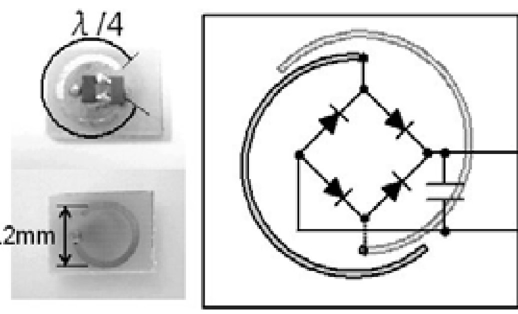

Figure 14. Photograph of the electrode (left) and diagram of the rectification circuit connected with the electrode (right).

We supplied power from the edge of TDC sheet with a 2W-2.4GHz power amplifier, and put the electrode with the rectification circuit into the TDC sheet. The location of the circuit is 17 cm from feeding point (Figure 13).

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 Figure 15.

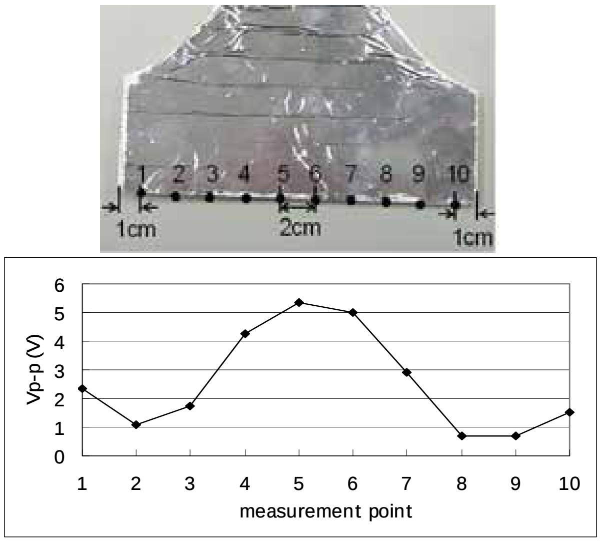

Figure 15. Measurement point of Vp-p (top) and the result of the measurement (bottom). The numbers of the horizontal axis in the bottom graph denote the points of the top figure.

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. The data of Figure 15 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,

$$P = EH \cdot S = E^2\sqrt{\frac{\varepsilon_0\varepsilon_r}{\mu}} \cdot S \quad \text{(10)}$$

we obtain the equivalent power passing through the bottom side of the sheet, where S and μ is the cross section area of the TDC sheet, and magnetic permeability, respectively. For ε_0 = 8.854×10^{-12} (m^{-3}kg^{-1}s^{4}A^2), ε_r=2.3, μ= 4π×10^{-7}(kg m s^{-2} A^{-2}), S = 1.2×10^{-3} (m^2), and d_0 = 6 mm, the value of P written in the equation (10) is 110 (mW).

Next we measured the output voltage at resistance R in Figure 14. We show the results for various Rs (47, 100, 470, 1000, 5600 Ω) in Figure 16. A sufficient voltage for circuit operation was obtained. Figure 17 shows the power supplied to R that were calculated from the data of Figure 16. The maximal power consumed at R was 20 mW for R = 470 Ω.

Finally, we measured the effect of gap distance change between the electrode and the TDC 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.

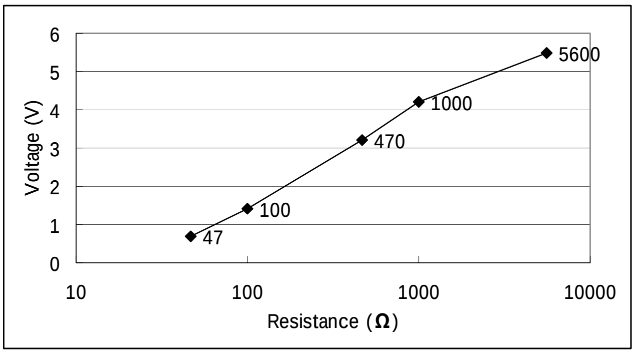

Figure 16. Output voltage at resistance R for various vaules of R.

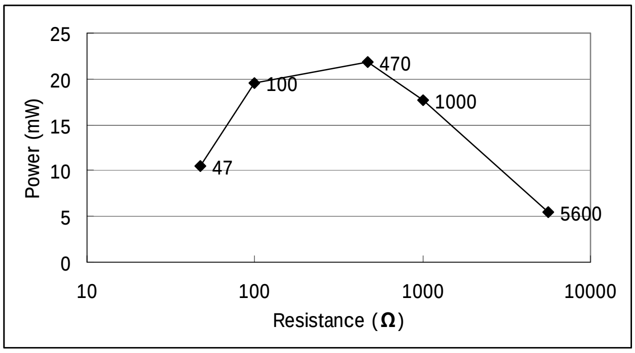

Figure 17. Power consumed at resistance R for various vaules of R.

6. Conclusion

In this paper, we proposed a stable proximity connector RPC (Resonant Proximity Connector) to TDC (Two-Dimensional Communication) sheet for integration of tactile sensor chips in a large area robot skin. RPC is an electrode whose length is a quarter of the electromagnetic wavelength. The induced resonance around the electrode reduces the impedance between the connector and TDC sheet, which allows sensor chips to connect with TDC sheet stably. Simulation results on straight, ring, spiral RPCs showed that the concept is effective.

We also discussed the power supply for distributed sensors. When sensor's density is low, microwave power supply becomes effective. By the experiment in power supply with a RPC and a rectification circuit, we confirmed that power can be supplied to the sensor element in TDC sheet successfully.

Fabricating a sensor chip equipped with a sensor, RPC, and communication functions, is a future work.

References

[1] H.Shinoda, N.Asamura, M.Hakozaki and X.Wang, "Two-Dimensional Signal Transmission Technology for Robotics" *Proc. 2003 IEEE Int. Conf. on Robotics & Automation*, pp. 3207-3212, 2003.

[2] 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.

[3] 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.

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

[5] 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.

[6] 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.12321-12325, 2005.

[7] S.Weinstein, "Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Part, Sex, and Laterality" The Skin Senses, C.C. Thomas, pp.195-222, 1968.