Paper:

Flexible Tactile Sensor Skin Using Wireless Sensor Elements Coupled with 2D Microwaves

Hiroyuki Shinoda*, **Hiromasa Chigusa****, **and Yasutoshi Makino*****

*The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
E-mail: shino@alab.t.u-tokyo.ac.jp
**Future Architect, Inc.
***Keio University

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The stretchable sensor skin we propose uses microwaves propagating in a two-Dimensional Signal Transmission (2DST) sheet. A small tactile sensor chip with a pair of Resonant Proximity Connectors (RPCs) couples with 2D microwaves carrying signals. Chip operating power is also supplied by 2D microwaves. The RPC is a spiral electrode whose arc length is a quarter of the electromagnetic wavelength. Chip operating power is supplied by 2D microwaves. Sensor chips are connected to the 2DST sheet by RPCs without electrical contacts anywhere on the sheet. Resonance induced at the electrode reduces impedance between the connector and the conductive layer of the 2DST sheet, enabling sensor chips to be connected stably to the sheet. Experimental results on the RPC show the concept to be effective. We fabricated a 1-bit (touch detection) tactile sensor element consisting of a RFID-tag and RPCs, and confirmed in experiments that the sensor element operates in a stretchable 2DST sheet.

Keywords: tactile sensor, haptics, flexible robot skin, wireless sensor chip, 2D microwaves

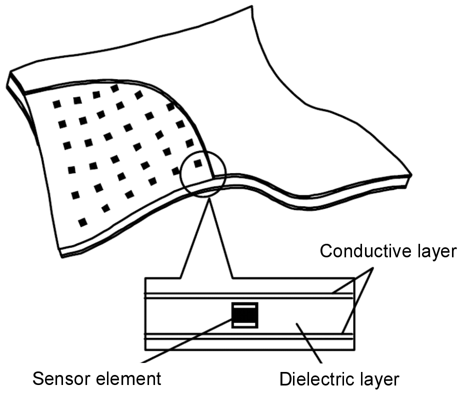


Fig. 1. Sensor skin based on 2DST sheet.

1. Introduction

Realizing an elastic and practical senor skin that covers a large area robot surface has been a pending problem in robotics since 1980s [1, 2]. In the development of stretchable sensor skin, wiring to the tactile elements had been a simple but challenging problem. Many of the existing devices suffer from the fragility due to the stress concentration around the wires. One category of the current solutions to the problem is to use optical methods. Gelforce [3] uses optical markers monitored by a camera placed in a finger. Optical wave guides used in KINOTEX produced by Nitta Corp. realize a stretchable and thin skin. In the research of [4], the sensor skin was successfully mounted on a humanoid robot by dividing electronic circuits from elastic skin using an optical method. The second category is based on tomographic reconstruction. In the researches of [5] and [6], the resistivity pattern by the skin deformation is measured using a tomographic technique without wires in the skin. The last category is to develop elastic circuits with elastic materials [7, 8]. This category also includes a net structure that realizes a stretchable surface using nonstretch strings [9]. Although the above mentioned methods have realized the flexibility in each scene, a skin easily attached to any part of a robot and having sufficient spatial and intensive resolution remains to be realized.

In this paper, we propose the forth category to realize robust and stretchable skin using microwaves propagating in a two-Dimensional Signal Transmission (2DST) sheet. Small tactile sensor chips with Resonant Proximity Connectors (RPCs) are coupled with 2D microwaves carrying signals. The power for sensor operation is also supplied by the microwaves. Sensor chips connect to the 2DST sheet by the RPCs without electrical contact at any location on 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 no electrical contact is necessary between conductive fabrics and sensor chips, the device can be robust without stress concentrations. The tactile sensing ability of the skin is enhanced by improving the sensor chips.

The idea of wireless tactile sensing chip was first introduced in [10]. However the work did not show the method to integrate them in a skin-like device. In this paper we show a connection method between the sensor chips and the 2D electromagnetic wave sandwiched by two conduc-

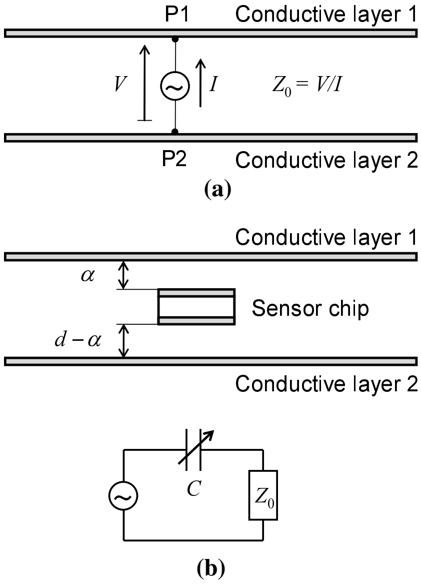


Fig. 2. Definition of (a) radiation impedance Z_0 and (b) capacitive connection.

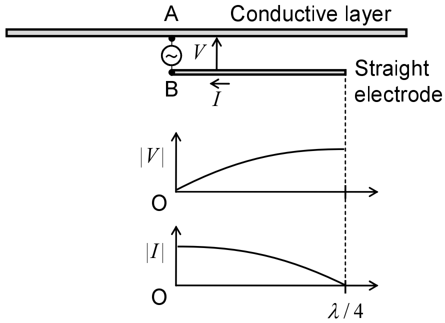


Fig. 3. RPC. V: vertically measured voltage between electrode and TDC sheet. I: horizontal current in electrode.

tive layers. The concept of signal transmission using two dimensional medium was originally proposed by some groups including us [11–13] mainly in the computer network society in the early 2000s. In those researches, however, mechanical and electrical contacts of elements to conductive layers were necessary. Our method provides flexible connection using microwaves with no electrical contacts at sensors.

We present an example of an RPC [14] and a 1-bit (touch detection) sensor chip consisting of two RPCs and a commercial radio frequency identification (RFID) tag, and confirm operation feasibility of the sensor skin in experiments.

2. Resonant Proximity Connector (RPC)

The 2DST uses a traveling electromagnetic wave mode inside the sheet. The electromagnetic wavelength λ of $\sim$ 10 cm is much larger than the sheet thickness d and the sensor chip size w but shorter than the characteristic length L of the 2DST sheet. The relationship $\lambda > w, d$ prevents the scattering by asurrounding sensor chips and sheet defects. The condition $\lambda < L$ increases the transfer efficiency of signal energy from a small sensor chip to the signal detector of the skin, under a typical condition. The details of the electromagnetic wave and theoretical limit of energy transmission are described in [15]. The problem remaining to be solved is to obtain stable noncontact connection between sensor chips and the conductive 2DST 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 the 2DST sheet be Z_o. Radiation impedance at P1 and P2 as shown in **Fig. 2(a)** is defined as the ratio of voltage between P1 and P2 to current flowing from P2 to P1. Impedance seen from sensor chip terminals is the total of impedance Z_o and reactance $jX = 1/j\omega C$ of the gap where C is capacitance between the sensor chip electrode and the 2DST sheet, as shown in **Fig. 2(b)**.

One problem with capacitive coupling C is that it depends greatly on variations in gap d between the sensor chip electrode and sheet. Reactance X of C is written as follows:

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

S is the area of the electrode, ε_0 the dielectric constant of the vacuum, and ε_r relative permittivity of the dielectric layer. For $f = 2.4$ GHz, $S = 2.5 \times 2.5 \times \pi$ mm^2, $d = 0.5$ mm, and $\varepsilon_r = 2.0$, reactance X is 95 Ω. Since Re[Z_0] for a 2DST sheet 1 mm thick is 5 Ω at 2.4 GHz, reactance X causes significant connection loss. X is sensitive to gap distance d, thus the received/transmitted signal amplitude at the sensor chip also is, destabilizing signal transmission. We propose minimizing gap reactance X to makes the signal amplitude insensitive to gap distance change.

The proximity connector we propose, shown in **Fig. 3**, is an electrode one quarter the length of wavelength λ. When we apply an alternating voltage between A and B, the amplitude of current I is the maximum at feeding point B for the electrode length equal to $\lambda/4$. In this condition, impedance Z_{AB} between A and B, as follows,

$$Z_{AB} = V_{AB}/I_{AB} \quad \dots \dots \dots \dots (2)$$

is minimized in its absolute value. We call this noncontact connector a Resonant Proximity Connector (RPC).

The resonance condition depends on the electrode length, and dependence on gap distance d is weak. We can design various electrodes shapes keeping the length to be $\lambda/4$ in the plane parallel to the 2DST sheet. A spiral shape makes the electrode compact.

3. Experiments on RPC

In fabrication of the spiral RPC shown in **Fig. 4**, which is shaped the same as that in **Fig. 5**, we formed a copper strip into a spiral on a 6 mm square circuit substrate. The substrate's relative dielectric constant is 2.0. The RPC

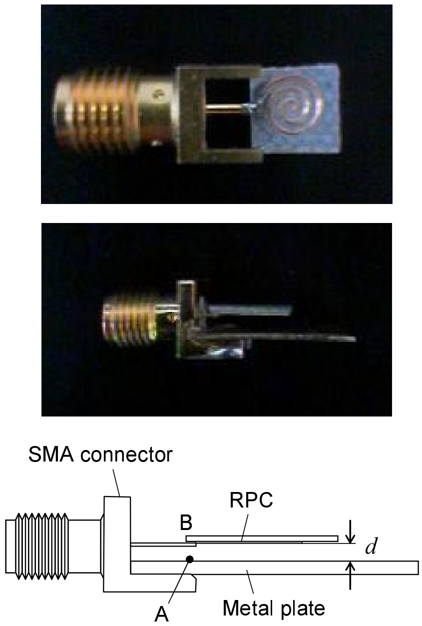
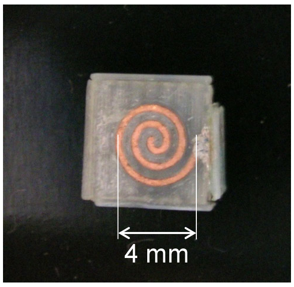
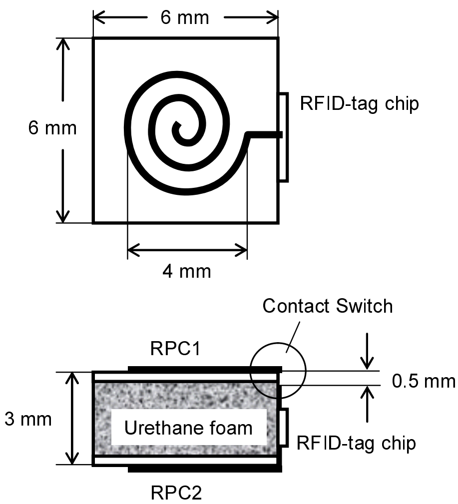


Fig. 4. RPC experiment setup. Impedance at the top of the SMA connector was measured with a network analyzer for different distances d.



(a)

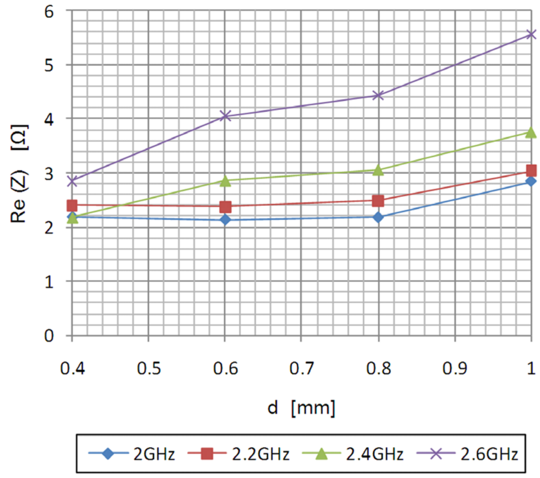


(b)

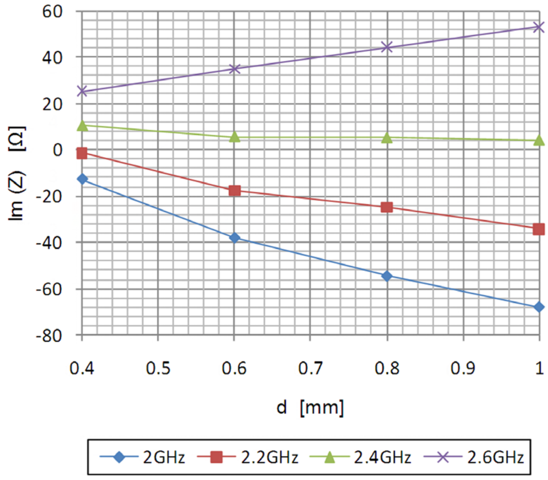
Fig. 5. Tactile sensor chip (a) photograph and (b) structure.

electrode is 4 mm in diameter and the electrode length adjusted to obtain preferable properties.

The impedance at the top of the SMA connector was measured with a network analyzer. The metal plate in



(a) Real part



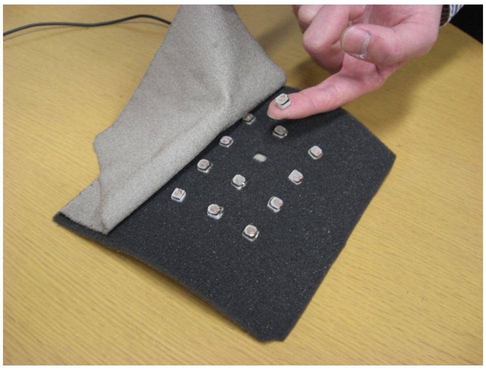
(b) Imaginary part

Fig. 6. Results of experiments.

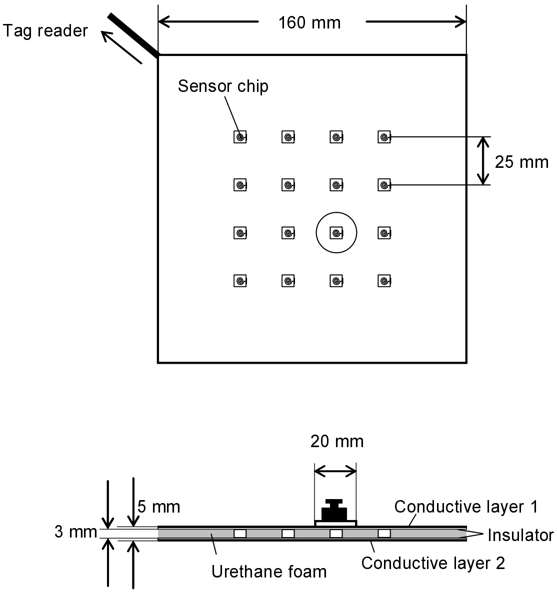
Fig. 4 simulates the metal layer of the 2DST sheet. The foot of the spiral – point B in **Fig. 4** – is connected to the sensor circuit input/output port when the RPC is on the sensor chip. The RPC reduces impedance between A and B as shown in **Fig. 3**. We measured real and imaginary parts of impedance for gap distances d from 0.4 mm to 1 mm, as shown in **Fig. 6**. **Fig. 6(b)** shows that reactance (the imaginary part) of impedance changes significantly for 2.0, 2.2, and 2.6 GHz. For 2.4 GHz, however, reactance remains relatively small within 10 Ω, comparable to the radiation impedance of a sheet 1 mm thick. This is because the resonant frequency minimizing the reactance component depends mainly on the electrode length, not on gap distance d. Real parts for 2.4 GHz are 4 Ω at most. These results show that the RPC is effective in stable non-contact connection.

4. Tactile Element Using RFID Tag

We designed a simple tactile sensor element that detects 1 bit contact information. A sensor element of $6 \times 6 \times 3$ mm^3 consists of two spiral RPCs and a passive RFID tag



(a)



(b)

Fig. 7. Sensor skin.

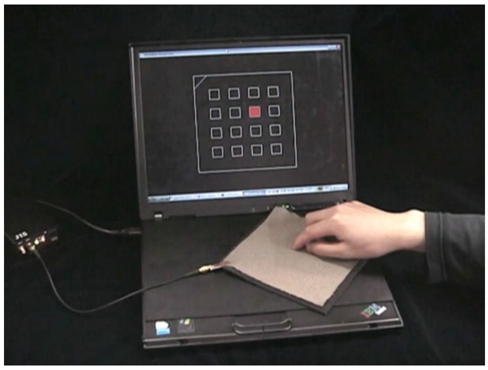


Fig. 8. Experiment.

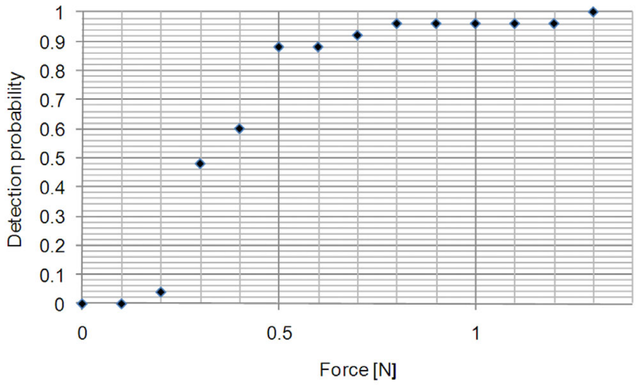


Fig. 9. Sensor ID detection probability vs. force applied to sensor.

as shown in **Fig. 5**. The tag (Japan Information System, DL-1000) has its own ID responding to the tag reader. The signal frequency is 2.4 GHz.

Two RPCs sandwich a layer of elastic material, urethane foam in this prototype. One RFID tag electrode is electrically connected to one RPC. The other open terminal of the RFID tag keeps a 0.5 mm gap from the other RPC in the initial state to form a mechanical switch between the RFID tag and RPC. The simple sensor element responds with its ID when vertical force applied exceeds the threshold, turning the switch on. If the force is lower than the threshold, the RFID tag returns no signal. Preparing a correspondence table between element IDs and their locations, we realize a 2D switch array without individual wires to sensing elements.

We fabricated a stretchable $160 \times 160 \times 5$ mm^3 2DST sheet using knitted conductive fabrics. The insulator layer is urethane foam. The tag reader is connected at the corner of the 2DST sheet. We put the sensor chip inside the 2DST sheet as shown in **Fig. 7** and confirmed that the chip responds when vertical force is applied, as shown in **Fig. 8**.

We evaluated the sensor threshold. **Fig. 9** shows tag detection probability versus force applied to the sensor chip. As shown in **Fig. 7**, we pressed the sensor surface above a sensor chip with a rigid board 20 mm in diameter. Probability was estimated in 25 trials for each force applied. As shown in **Fig. 9**, sensor response probability reaches 90% when the sensor is pressed at 0.5 N. The detection threshold, which is 0.4 N in this prototype, is controlled by sensor chip design independent of signal connection between the sensor electrode and the skin sheet.

5. Summary and Discussion

The flexible artificial skin we have proposed uses microwaves to propagate two-dimensionally. To obtain stable noncontact connection between the sensor chip and 2DST sheet, we designed a spiral RPC whose electrode length is one quarter that of the electromagnetic wavelength. Resonance induced at the electrode reduces impedance between the connector and the conductive layer of the 2DST sheet, enabling sensor chips to be connected stably with the 2DST sheet. Experimental results using a spiral RPC showed the concept to be feasible.

We fabricated a prototype tactile sensor chip with two spiral RPCs and an RFID tag. The sensor was $6 \times 6 \times 3$ mm^3, confirming the success of sensor chip operation in a stretchable 2DST sensor sheet realized using knitted conductive fabric.

One problem remaining is removing the standing wave in the 2DST sheet causing dead zones in the skin. Another is realizing a standard LSI for tactile sensing and 2DST communication.

The major factor to be considered in the design of a thinner sensor skin with higher tactile element density is 2D microwave attenuation. Since attenuation length is proportional to skin thickness [15], thickness is minimized while ensuring the required signal transmission length. Secondly, the requirement that the arc length of RPC spiral should be one quarter that of the wavelength limits sensor chip miniaturization. Significantly smaller sensor chips will be connected to the 2DST sheet by simple capacitive coupling, requiring an impedance matching circuit on each sensor to cancel capacitive reactance adapting to gap distance changes.

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Name:
Hiroyuki Shinoda

Affiliation:
Associate Professor, Department of Information Physics and Computing, Graduate School of Information Science and Technology, The University of Tokyo

Address:
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Brief Biographical History:

1995- Lecturer, Tokyo University of Agriculture and Technology
1997- Associate Professor, Tokyo University of Agriculture and Technology
1999- Visiting Researcher, UC Berkeley
2000- Associate Professor, The University of Tokyo

Main Works:

- Information physics, tactile/haptic interfaces, sensor systems and devices, sensor networks, two-dimensional communication, human interfaces, and optical/acoustic measurement.

Membership in Academic Societies:

- The Society of Instrument and Control Engineers (SICE)
- The Japan Society of Mechanical Engineers (JSME)
- The Institute of Electrical Engineers of Japan (IEEJ)
- The Robotics Society of Japan (RSJ)
- The Virtual Reality Society of Japan
- The Institute of Electrical and Electronics Engineers (IEEE)

Name:
Hiromasa Chigusa

Affiliation:
System Engineer, Future Architect, Inc. Japan

Address:
1-2-2 Osaki, Shinagawa-ku, Tokyo 141-0032, Japan

Brief Biographical History:

2003- Department of Mathematical Engineering and Information Physics, School of Engineering, The University of Tokyo
2005- Graduate School of Information Science and Technology, The University of Tokyo
2007- Future Architect, Inc. Japan

Main Works:

- "Large Area Sensor Skin Based on Two-Dimensional Signal Transmission Technology," Proc. World Haptics 2007, Tsukuba, Japan, pp. 151-156, Mar. 2007.

Name:
Yasutoshi Makino

Affiliation:
Keio University

Address:
4-1-1 Hiyoshi, Kohoku-ku, Yokohama-shi, Kanagawa 223-8526, Japan

Brief Biographical History:
2007- Received Ph.D. degree of Information Science and Technology from The University of Tokyo
2008- Researcher in The University of Tokyo
2009- Assistant Professor in Keio University

Main Works:
• Y. Makino and H. Shinoda, "Myoelectric Pattern Measurement Based on Two-Dimensional Communication Technology," Proc. SICE Annual Conf. 2007, pp. 2145-2149, 2007.

Membership in Academic Societies:
• The Society of Instrument and Control Engineers (SICE)