Two-Dimensional Sensor Integration Using Resonant Proximity Connector

-Basic Technology and Application to Elastic Interface Device-

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Abstract— **Two-dimensional communication (TDC) is a new physical layer of communication proposed last year. The sensors attached on the TDC sheet communicate with omnidirectional microwave traveling in two-dimensional sheets. In this paper, we propose "Resonant Proximity Connector (RPC)" that enables non-contact (proximity) connection of the sensor elements to the TDC sheet. A small device of 5 mm in diameter for 2.4 GHz signal in the present design enables the stable proximity connection to the TDC sheet using resonance. Simulation analyses show that the change of the reactance seen from the sensor element to the TDC sheet is less than 7 Ω when the distance between the RPC and the TDC sheet changes from 0.2 to 0.5 mm. RPC enables us to easily attach sensor elements with no electrical contact on various materials of TDC sheets. As a useful application of RPC, we propose a new man-machine interface which measures two-dimensional patterns of myoelectric potentials from a surface of a forearm. High density 2D patterns of the myoelectric signals can even predict the movements of one's fingers and forearm before the real motion. In the latter part of this paper, we show the results of the basic feasibility studies of 2D myoelectric signal measurements. This system is considered to be useful for inputting users' intention to a machine as well as conventional electromyography.**

Keywords- Two-Dimensional Communication, Networked Sensing, Man-Machine Interface, Electromyography (EMG).

I. INTRODUCTION

One important problem of networked sensing is how to physically connect a large number of sensor elements to the network in rooms, cars, or on clothes. Wiring efforts are serious in many cases, and in some cases, the wires physically impair the functions of the system. Wireless connection is free from wiring. However, the difficulty of power supply to sensor elements, and the poor communication capacity are problematic.

As one solution to this problem, we proposed a new physical layer of communication "Two-dimensional communication (TDC)" last year [1]. In the system, each sensor chip communicates with omnidirectional microwave traveling in two-dimensional sheets. The TDC sheet can be fabricated with various low-cost materials including stretchable sheets like conductive fabrics. Once the communication sheets are equipped on the surfaces of desks and rooms, the sensors can communicate being provided with electrical power by microwave without individual wires.

In this paper, we propose "Resonant Proximity Connector (RPC)" that enables non-contact (proximity) connection of the sensor elements to the TDC sheet. A small device of 5 mm in diameter for 2.4 GHz signal in the present design enables the stable proximity connection to the TDC sheet using resonance. The change of the reactance between a RPC and a TDC sheet is less than 7 Ω when the distance between the RPC and the TDC sheet changes from 0.2 to 0.5 mm in our simulation. This connector enables us to easily attach sensor elements with no electrical contact on various materials of TDC sheets.

In the latter part of the paper, we introduce an application of this basic technology. If we can connect a large number of sensing elements on a stretchable material, various useful man-machine interfaces can be realized. Especially we propose a wristband-shaped interface measuring 2D myoelectric signal on the human arm. We explain the usefulness and the basic experiments in the following sections.

II. RESONANT PROXIMITY CONNECTOR

A. Preceding Study of Two Dimensional Communication

Fig. 1 shows the configuration of a TDC sheet. The sheet consists of three layers. Two conductive layers are set to sandwich the dielectric layer. The sheet has the connection apertures on the surface of it for inputting and receiving signals. When an alternate current along the conductive layers are impressed through the aperture, there exists a propagation mode of the electromagnetic wave signal within the dielectric layer. This electromagnetic wave is used for signal transmission between each communication node attached on the aperture. Since arbitrary frequencies are available within the TDC sheet for communication, one can use not only conventional communication protocols such as IEEE 802.11a/b/g, Bluetooth and etc. but also original one.

Any materials with high conductivity are available as the conductive layers like conductive fabrics and conductive rubbers. In the previous paper, the TDC sheet composed of stretchable conductive fabrics were fabricated. Two PCs were connected to the TDC sheet, and it was confirmed that stable communications through the sheet using the IEEE 802.11b protocol was possible. An achieved throughput between two PCs was 11 Mbps which is a limit of the protocol. The theoretical and experimental details of signal transmission are described in [1].

Power transmission to the each sensor node by microwave is also possible in TDC system. Since the signal energy is restricted within a 2D medium, wasted power is smaller than that of the wireless communication. The efficiency is inversely proportional to the first power of the distance from the source while it is second power in the three dimensional propagation. Moreover, since the signal energy does not leak to an atmosphere, we can use high power microwave without harmful effects to a human body. We already confirmed that a sensor node attached on 40 cm by 50 cm TDC sheet could absorb 60 mW on average under 2 W microwave (2.4 GHz) input that produced standing waves in the sheet.
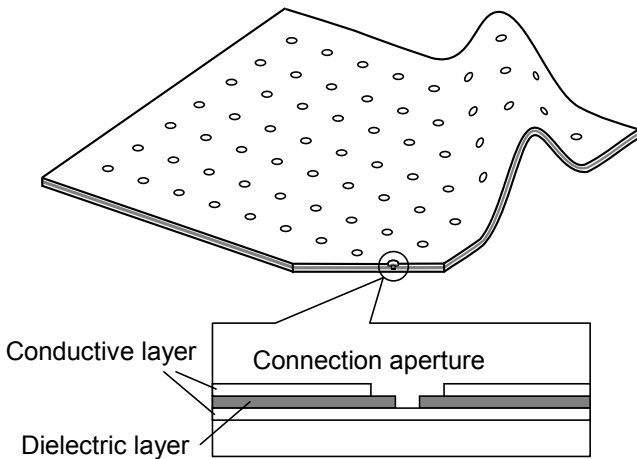

Figure 1. Schematic illustration of Two Dimensional Communication [1].

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B. Principle of Resonant Proximity Connector

In attachment of sensor elements to a TDC sheet, it is desirable that no electrical contact is required. Proximity connection makes the production process easy, and endows the elasticity and the durability of the device composed of deformable TDC sheet.

Fig. 2 shows the schematic illustration of the capacitive connection at a connection aperture. Let the capacitance between the electrode and the conductive layer C. In this case, input impedance seen from the sensor chip is described as a series connection of the TDC sheet impedance Z_0 and the capacitance C. In order to emit a microwave into the TDC sheet, we cancel the reactance of C by adding an inductance L that satisfy

$$\omega L = 1/\omega C . \qquad (1)$$

where ω is the angular frequency of the carrier wave.

One problem of this simple proximity connection is that the reactance of C becomes larger than the impedance Z_0 in many cases. For example, for a 5 mm-diameter electrode apart from the conductive layer by $d = 0.4$ mm, the reactance of C is as large as 30 Ω when the relative permittivity of the dielectric layer is 5 and the frequency is 2.4 GHz. On the other hand, the radiation impedance Z_0 of the TDC sheet is given as

$$Z_0 = 7.7 + 20j \quad \Omega \qquad (2)$$

for 0.4 mm-diameter wire to drive the TDC sheet [1] at 2.4 GHz when the dielectric-layer-thickness is 1.6 mm. Since the reactance of C is larger than Z_0, the connection is strongly affected by the distance d. The distance d could be changed according to the deformation of the elastic TDC sheet.

Fig. 3 shows the basic principle of the connector we propose named "Resonant Proximity Connector (RPC)" for improving the connection stability. The difference between the former connector and the RPC is the length of the electrode. The RPC is a rectangular electrode here whose length is designed so as to be a quarter of the wave length ($\lambda/4$) of the signal carrier.

The rectangular electrode and the conductive layer form a microstrip line as shown in Fig. 3 When we apply voltage between the points A and B in Fig. 3 (b), the produced electric field is vertical to the layer. The electric field and the current are the minimum and the maximum, respectively, at the left end of the electrode, which means the impedance Z_1 between A and B becomes zero ideally (when the radiation from the ends and the ohmic loss on the metal surface are negligible).

It is important that the resonant condition only depends on the length of the electrode. If the connection impedance Z_1 remains small regardless of the gap d between the electrode and the conductive layer, we can keep stable connection to the TDC sheet in deformations of the TDC sheet. This is the basic principle of RPC.
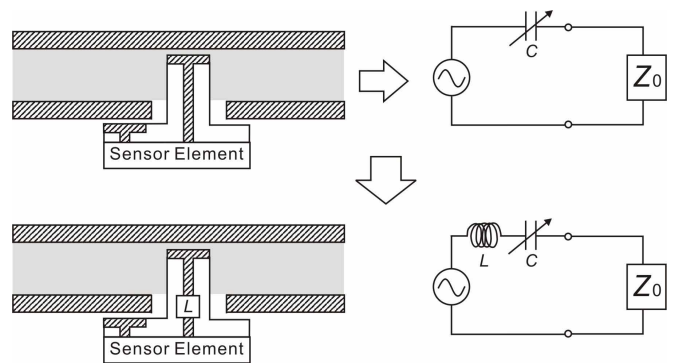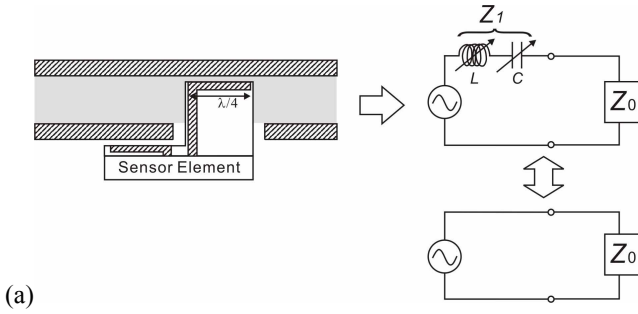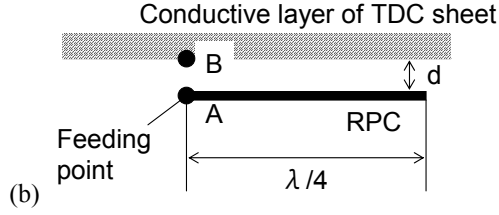

Figure 2. Illustration of proximity connection between the sensor chip and the TDC sheet. The capacitance C changes by the deformation of the sheet.

(a)

(b)

Figure 3. Schematic illustration of the Resonant Proximity Connector (RPC). The equivalent circuit between A and B is a series resonant circuit. The resonant frequency weakly depend on the distance between the electrode and the TDC sheet. The length of the electrode is designed to be $\lambda/4$ of the carrier signal.

C. Simulation Model

So as to confirm the theory of the RPC, we conducted simulation analyses using the software MW-STUDIO (AET Japan, Inc.) Fig. 4 shows the simulation model. The model is composed of three parts. Those are the TDC sheet, the RPC and the SMA connector. In order to compare the results with future experimental results, the setting is faithful to that of the future basic experiment. The TDC sheet is made of the two copper layers which sandwiches the glass epoxy substrate. The thickness of the copper layers (as the conductive layers in Fig. 1) are 35 μm each, and the resistivity is faithful to the real one, 2×10^{-8} Ωm. The thickness of the glass epoxy layer (as the dielectric layer whose relative permittivity $\varepsilon_r = 4.9$) is 2.1 mm. The interval d between the electrode and the sheet is a variable in the simulations. At the boundary of the sheet, all electric energies passed through to the outside. Therefore the infinitely spreading TDC sheet was modeled. The RPC is modeled using the copper whose length is 14.1 mm so as to correspond to the $\lambda/4$ within the dielectric medium at 2.4 GHz. The thickness of the RPC is also 35 μm. The SMA connector has the same dimensions as those of the actual one.

In the simulation, the input impedance seen from the SMA connector can be monitored. That means the observable input impedance of the RPC model is $Z_0 + Z_1$ shown in Fig. 3 (a). So as to know the characteristic impedance of the TDC sheet Z_0, at first, we simulated as $d = 0$. The electrode of the RPC was touching on the conductive layer. In this case, Z_1 was equal to 0 and we could observe Z_0 alone. Then the interval d was varied among 0.2, 0.3, 0.4 and 0.5 mm so as to simulate the effect of the change of the distance between the sheet and the electrode.
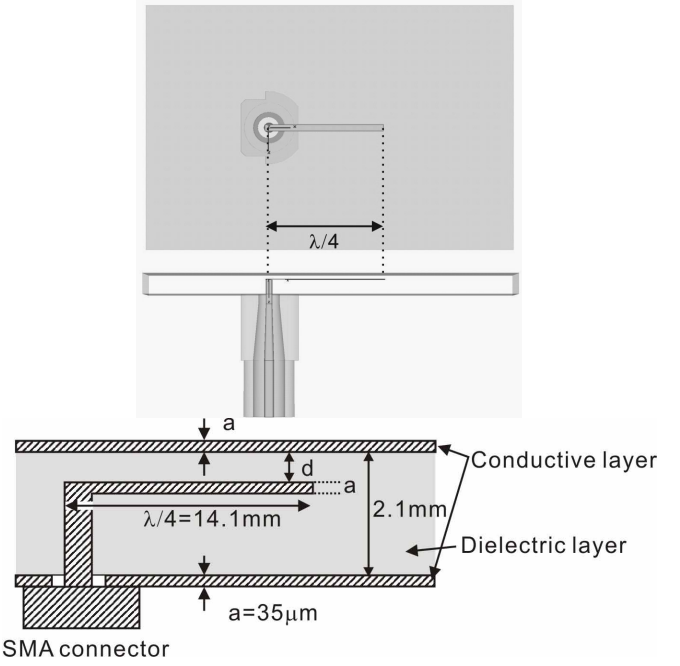

Figure 4. RPC model for simulation analyses

D. Simulation Results

Table 1 shows simulation results of the impedances $Z_0 + Z_1$ (the impedance at SMA connector in the simulation model). When the gap $d = 0$, the situation represents the short between the electrode and the conductive layer. In this case, the input impedance is equal to the characteristic impedance of the TDC sheet Z_0. Therefore, the impedance Z_1 is calculated by subtracting Z_0 from the observable input impedance $Z_0 + Z_1$.

Fig. 5 shows the reactance components of the Z_1. At the resonant frequency 2.4 GHz, it is clear that the reactance change is small for any intervals between the electrode and the conductive layer. This result indicates that the resonance occurs at the designed frequency (2.4 GHz) and the impedance of the RPC is small. The range of the variation of the reactance components are within 12 Ω from $d = 0.2$ to 0.5 mm. The variation is about 50 % of that of the simple capacitance connection of the 5 mm-diameter electrode. These results show that the RPC is effective as the theory expected.

TABLE I. IMPEDANCES $Z_0 + Z_1$ FOR THE VARIOUS GAPS d.

d (mm)	Impedance (Ω)		
	1GHz	2.4GHz	3GHz
0 (short)	4.44 + 30.07 j	28.32 + 94.83 j	74.34 + 137.9 j
0.2	2.03 + 5.37 j	26.21 + 99.03 j	139.1 + 150.4 j
0.3	2.43 - 2.09 j	22.39 + 95.34 j	143.0 + 167.1 j
0.4	1.17 - 7.62 j	19.28 + 90.61 j	143.2 + 178.9 j
0.5	1.10 - 11.94 j	16.32 + 86.65 j	136.2 + 189.0 j

Figure 5. The reactance components of the impedance Z_1 for various d.
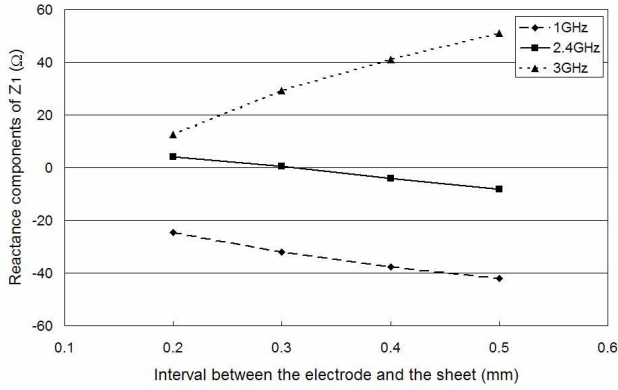

Figure 7. The reactance components of the impedance Z_1 for various d using the circular-RPC.

E. Circular shape of the RPC

A remarkable point of the RPC is that the resonant condition only depends on the length of the electrode. Therefore, a smaller size of RPC is also possible by curving the electrode keeping the total length equal to $\lambda/4$. The circular type of the electrode (circular-RPC) with the diameter of 5.6 mm as shown in Fig. 6 (a) was also simulated.

Fig. 7 shows the simulation results of the reactance components of the Z_1 for various d using the circular-RPC. At 2.4 GHz, it is clear that the reactance is small for any intervals as the former RPC model (straight electrode) demonstrated. The variation of the reactance components is about 7 Ω from d = 0.2 to 0.5 mm. The variation is about 30 % of that of the simple capacitance connection of the 5 mm-diameter electrode.

A smaller size of RPC is also expected by the spiral design of the electrode (spiral-RPC shown in Fig. 6 (b)). From the simulation results of the spiral-RPC, we confirmed that the size of the connector could be lessened down to 3 mm ideally. Performance evaluation of the circular-RPC and the spiral-RPC is our future work. Both types of the RPC is also expected to be robust against the inclination of it.
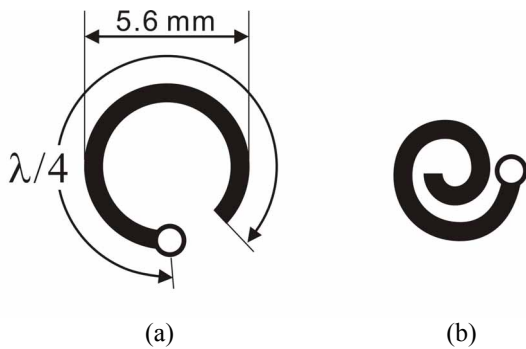

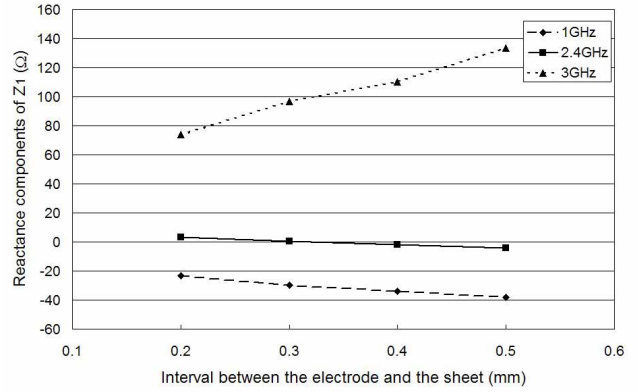Figure 6. Circular and spiral design of RPC electrode.

III. WRISTBAND-SHAPED ELECTROMYOGRAPHY SYSTEM

One application of TDC proposed here is a multi-electrodes electromyography (EMG) system. By distributing many electrodes with detector circuits on a skin surface, one can obtain 2D myoelectric signals. The myoelectric signal is an electrical impulse that produces contraction of muscle fibers in the body. One of a remarkable point of the EMG is that a detected area on the skin is strongly related to an operated distal part. That means, if one could observe the 2D myoelectric signal patterns on the forearm precisely, it is easy to determine which finger moves. Another important advantage of the myoelectric signal is that the signal can be detected before a limb moves. These advantages are useful for realizing a new man-machine interface which inputs data of body movements with a rapid response time.

There are several previous studies which deal with usages of the EMG as interfaces. Kawamoto et al. [2] use the myoelectric signals as an input for a power assist system. In that system, the signals are used for detecting an onset of the movement of legs. Other papers such as [3] and [4] are also discussing the possibility for using EMG as the interface. In these researches, the myoelectric signals are obtained from several measurement points which are upon major muscles instead of obtaining 2D patterns. Researches which deal with a pattern matching for estimating the motion using such a small number of data points are also conducted [5]. A data acquisition through a 2D electrode array is also studied. In [6], a high density electrode array on a rigid plate is developed which contains 130 channels of electrodes within 45 mm x 60 mm area. In [7], an electrode array on a flexible substrate was applied to face muscles with electrode paste for rehabilitation purpose.

However, EMG measurement systems can not be used for general-purpose man-machine interface due to a wiring problem. The problem is that it requires a huge number of the wires for communication. Even when one fabricates the system using a bendable substrate as a substitution for the wiring, its low stretchability makes it hard to keep a steady

contact between all the electrodes and the skin surface. The instability results in a low performance of the measurement. Therefore TDC technology is effective to realize such an elastic sensing device.

Fig. 8 shows the schematic illustration of the multi-electrode EMG system using a TDC sheet for finger movement estimation. The electrodes with electric circuits are arranged on the inner surface of the wrist-band. The wireless module assembles the myoelectric data through the TDC sheet and sends them to a host processing machine using conventional wireless communication. The device can be worn easily and it enables one to move one's arm freely. Since we can use stretchable materials for the communication sheet, the system can produce a firm contact force between the electrodes and the skin surface. It makes the measurement robust. Elasticity is also important from the aspect of user's comfortableness.

Fig. 9 shows the cross section of one unit for the myoelectric signal measurement. The unit consists of three electrodes, an amplifier, an A/D converter and a communication LSI chip. A subtraction of the voltages between A-G and B-G are amplified. The amplified signals are digitized by A/D converter just upon the electrodes. Then the digital data are transmitted in the TDC sheet to the wireless module. Consequently the system is stable to external noises.

Here, let us estimate possible number of measurement points when the communication throughput is at 10 Mbps. Myoelectric signals have frequencies ranging from a few hertz to a several kilohertz. Therefore a sampling frequency is desired to be about 10 kHz. Assuming that the signals are converted into 10 bit digital signals by the A/D converter, data can be serially obtained from 100 points. Based on a theoretical discussion in the TDC, over-100-Mbps communication is possible using 2.4 GHz carrier signal. The performance is sufficient for covering the whole forearm.

Based on the above mentioned advantages, following applications are expected.

- An input interface for small devices such as mobile phones or PDAs.

- Operating artificial limbs.

- Inputting commands by one's behaviors for video games and etc.

- Recording behaviors of athletes by the myoelectric signals. The stored data are useful to know the motions and to teach the motions.

- Reducing response delays for remote operating systems since the myoelectric signals are obtained just before the actual motions.

In the following sections, we show the results of basic feasible studies on myoelectric measuring.
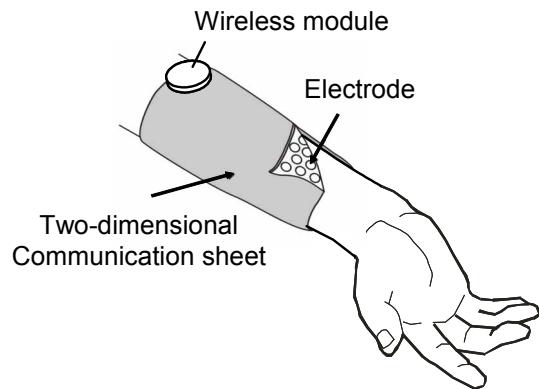

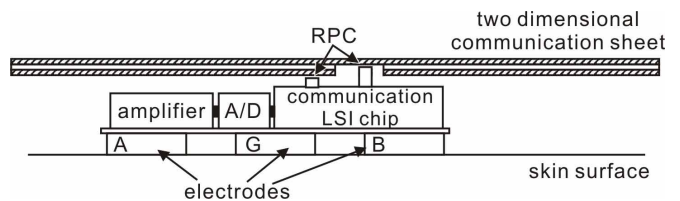Figure 8.   Schematic diagram of the wristband-shaped electrode array for EMG.

Figure 9.   A cross section of a measurement unit. The measurement unit consists of three electrodes, an amplifier, an A/D converter and a communication LSI chip.

IV.   ESTIMATION OF FINGER MOVEMENT

A.   Experiment using traditional EMG system

In this section we show our fundamental feasibility study whether an estimation of fingers movement is possible or not by observing 2D myoelectric signal patterns. In the experiment, we obtained 2D patterns using commercially available electrodes with the paste.

Fig. 10 shows the experimental settings. Four electrodes were attached along with the forearm which forms one column. For the ground electrode, we put one electrode at elbow where there was a small amount of muscle. The electrical potential at elbow was independent of any motions of the finger. The difference in potentials between neighboring electrodes within the column was measured. Three signals were obtained from one column. Totally 6 columns were applied for covering whole forearm, i.e. data were obtained from 18 positions.

One subject was asked to push a button with one finger and relevant myoelectric signals were measured. The measurement duration was 2 seconds. He was directed to push the button after about 1 second of the measurement started. Varying the pushing finger, we observed how the 2D patterns changed according to the moving finger. Myoelectric signals were amplified 10,000 times by the differential amplifiers. Each signal was filtered by a high pass filter circuit whose cut off frequency was 100 Hz for reducing noises and the effect of the polarization potential. The data were digitized to 12 bit digital signals and sampled at 10 kHz to the PC. Due to the

limitation of the device, only two columns were measured simultaneously. For covering whole forearm, the measurements were conducted three times for each finger by changing the columns.
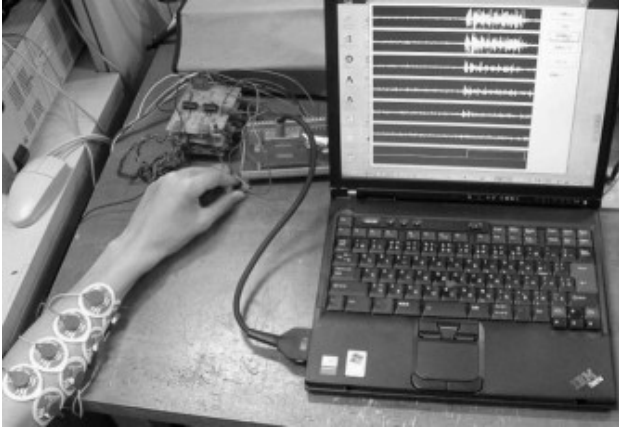

Figure 10. Experimental settings using electrodes with paste.

B. Results

Fig. 11 shows the 2D distributions of the myoelectric signal intensities 0.05 second before the button was pushed. The data represents the intensity of high frequency components of the signals whose cut-off frequency is 400 Hz. More than 400 Hz components were better for observing the differences since they were not influenced by the external noises such as a hum noise. Eighteen data were synchronized based on the onset of the button pushing. The upper figure represents the results of the push with the thumb and the lower one represents the results with the index finger. In the results, the second and the third columns from the right represent the data from the inner forearm as shown in the upper left figure. The first and the fourth columns show the data from the side of the forearm. The leftmost two columns are the data from the outer forearm. The differences of the signal power are presented by gray scale variations as shown in the chart. The thresholds of the gray scale were linearly determined so that we could see the differences well. Comparing the data between the thumb and the index finger, the distributions at the outer electrodes are apparently different. As this way, we also observed the differences of the 2D patterns comparing with the rest of three fingers each other. We confirmed that the distribution was roughly matched to the anatomical muscle distribution. The finger behavior is expected to be estimated by the 2D myoelectric intensity distribution without detailed information of the wave forms.

In our prototype EMG system (Fig. 12), we confirmed that a dry electrode (without paste) is achieved if the input impedance of the amplifier is high enough. Moreover, we also confirmed that a conductive fabric can be used for the electrodes. It enables us to fabricate a light and well stretchable wristband shaped EMG system. Performance evaluation of the electrode is our future work.
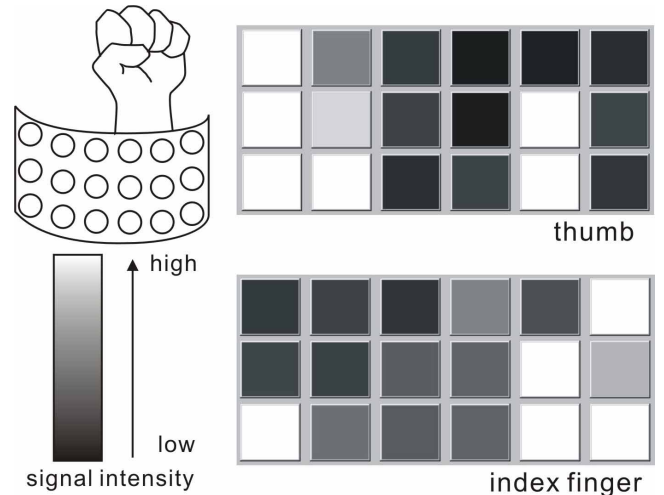

Figure 11. Two dimensional distributions of the myoelectric signal intensities. The picture shows the results 0.05 second before the button was pushed.
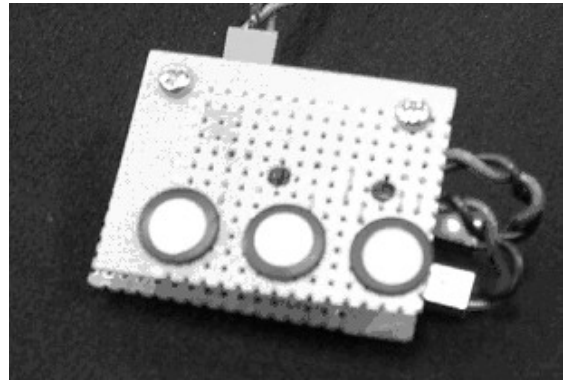

Figure 12. A prototype system using the dry electrodes.

V. CONCLUSIONS

In this paper, we proposed a method of non-contact connection of the sensor elements to the TDC sheet. A small device (Resonant Proximity Connector, RPC) of 5 mm in diameter for 2.4 GHz signal in the present design enables the stable proximity connection to the TDC sheet using resonance. Simulation analyses showed that the reactance change seen from the sensor element to the TDC sheet was about 7 Ω when the distance between the RPC and the TDC sheet changed from 0.2 to 0.5 mm.

RPC enables us to easily attach sensor elements with no electrical contact on various materials of TDC sheets. As a useful application of RPC, we proposed a new man-machine interface which measures two-dimensional patterns of myoelectric potentials from a surface of a forearm. High density 2D patterns of the myoelectric signals can even predict the movements of one's fingers before the real motion.

So as to examine the feasibility of obtaining 2D myoelectric signals, we conducted experiments using commercially available electrodes. As a result, we confirmed that observing the 2D signal intensity patterns helped us to

estimate the movement of the fingers. We also confirmed that a conductive fabric could be used as the electrode for measurement.

Based on these experimental results, now we are developing the wristband-shaped interface. This system is considered to be useful for inputting users' intention to machines as well as conventional electromyography. In addition, new usages are expected such as recording the human's action by the myoelectric signals or reducing a delay in a remote operating system.

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