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Digital Tactile Sensing Elements Communicating through Conductive Skin Layers

Mitsuhiro HAKOZAKI and Hiroyuki SHINODA

Graduate School of Information Physics and Computing
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 Japan
hako@cc.tuat.ac.jp (M. Hakozaki) shino@alab.t.u-tokyo.ac.jp (H. Shinoda)

Abstract

In this paper, we propose a tactile sensing element that communicates through two dimensional conductive skin layers without individual wires. Each tactile element has sensors and signal processors, and it broadcasts coded tactile signals through a couple of conductive layers. Since the conductive layers can be used for both the electrical power supply and the communication, simply sandwiching the chips between the layers completes electrical connection of tactile sensing chips. Since no metal wires exist, the skin is elastic and tough. High-resolution sensor skins can be easily fabricated in various shapes. In addition, because the tactile elements transmit the locally detected stress data with coded signals, we can obtain high-SN-ratio data from a very small sensing element put at a remote location. This paper describes the skin structure, the communication architecture, the structure of the sensing chip, and the results of basic experiments.

Keywords; tactile sensor, sensitive skin, robot skin, conductive rubber

1. Introduction

Recently we proposed an idea of a wireless sensing chip for realizing elastic robot sensor skin [1,2]. Wireless data communication using electromagnetic coupling between each tactile sensing chip and a ground coil makes the skin fabrication process easy and endows the elasticity and toughness to the skin, which resolves the difficulties that the former tactile sensors suffered from [3,4].

One problem of the proposed method, however, is that it is difficult to increase the efficiency of wireless energy transmission to and from small tactile elements, which results in large power loss in sensing. In addition, the wireless transmission can be a noise source for other sensors and communications.

In this paper we propose a new tactile sensing element that communicates through common conductive skin layers. The sensing chips need electrical contact to a couple of conductive layers, but the two layers can be shared by multiple chips, and the sensing chips need no individual metal wires. The chip has a couple of electrical contact points on the top and the bottom of it to be used for both signal transmission and energy supply to the chip.

Since no metal wires exist, the skin is elastic and tough. The fabrication of the skins in various shapes is almost as simple as that with the former wireless sensing chips, while we can avoid the large energy loss and scattering noises.

In addition, since the tactile elements transmit the locally detected stress data with coded signals, we can obtain high-SN-ratio data from a very small sensing element put at a remote location. The fast operation of the sensing chip communication enables us to realize a high resolution and large area sensor skin with a large number of sensing elements.

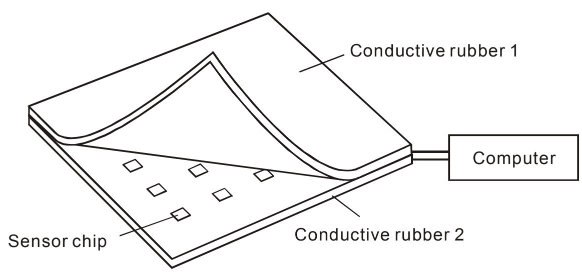


Fig. 1: Schematic diagram of the conductive-skin-layer communication in a robot skin. Every sensing chip uses two common conductive layers for both data communication and energy supply.

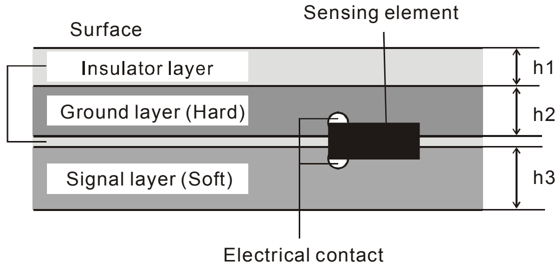


Fig. 2: Cross section of the proposed robot skin.

2. The Sensor Skin Structure and Its Operation

The structure of the proposed sensor skin is shown in **Fig. 1** and **Fig. 2**. Each chip electrically contacts with two layers of conductive rubber. The superficial conductive layer is the electrical ground and made of harder material than the deep layer. It is similar to the human skin structure that the sensing element is located at the boundary between a superficial hard layer and a deep soft layer [5].

Each sensing chip has a 16 bit ID number. A computer connected to the skin reads out the stress data from a sensing chip that the computer designates. The timing chart of the skin operation is shown in **Fig. 3**. When the computer starts the powering, the impedance between the two contact points on every sensing chip is low. After the powering term, the chip waits the ID signal from the computer with the terminal impedance high.

In our first version, each chip operates with a 10 MHz clock on the chip, and signals are sent at 1 MHz between the computer and each chip. Because the computer's clock and the sensing chip's clock are not synchronized, each chip once measures the ratio r_f between the two clock frequencies when we turn on the skin. Since the length of the data packet in this system is 32 bit, the chip calculates r_f by counting its 10 MHz clock for 32 continuous pulses from the computer.

After storing the r_f, each chip reads the ID data from the computer, setting the time origin at the first fall of the computer signal after powering. If the detected number coincides with the chip's ID number, it sends back the stress data stored on the chip. If it does not coincide, it keeps the impedance of the terminal high.

The time to transmit 32 bit data from each sensing chip including chip identification and powering is 60 μs in this system. Each chip keeps measuring stress data regardless of the communication operation. The measurement time to obtain one sample of stress data by a chip is 1 ms.

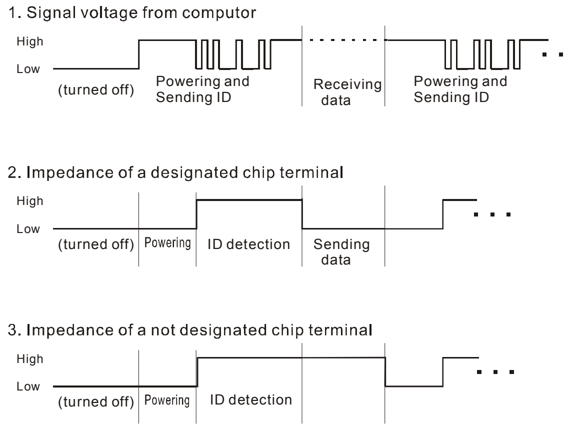


Fig. 3: Timing chart of the communication between a sensing element and a computer.

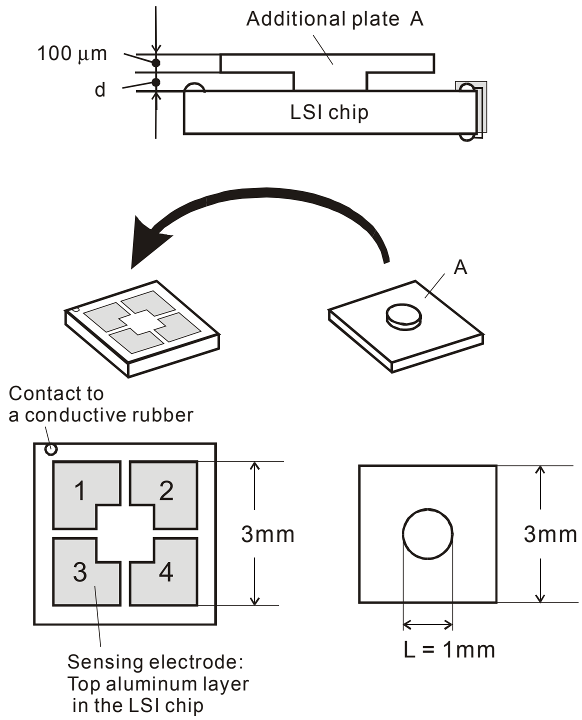


Fig. 4: The structure of the digital tactile sensing chip. The surface of the additional plate A is conductive.

3. Stress Detection

One sensing element detects 3 components of the stress with a hybrid structure as is shown in **Fig. 4** based on a capacitive method [6,7,8,9].

The sensing operation is illustrated in **Fig. 5**. In the top aluminum layer of the LSI chip, four electrodes, 1 to 4, are formed. We call these "sensing electrodes."

In the LSI chip, a local circuit as is shown in **Fig. 5** is formed. Here suppose the capacitance between the plate A and the ith sensing electrode is written as C_i. If we connect the ith sensing electrode to the electrical ground, the self-oscillation circuit oscillates at a frequency $f_j = \alpha / C_i R$.

The f_i is rewritten as

$$f_i = \frac{\alpha}{R} \cdot \frac{1}{\varepsilon_0 S} d_i \qquad (1)$$

where d_i is the average distance between the additional part A and the ith electrode, and ε_0, S, and α are the vacuum dielectric constant, the area of the each electrode, and a constant ≈ 0.5, respectively. The main circuit in the LSI chip measures this frequency by counting the oscillation for a constant time.

If we express normal stress distribution on the plate A as $p(x,y)$ using the coordinate system in **Fig. 5**, the average normal stress and its derivatives are given as

$$p = -\beta(\Delta f_{12} + \Delta f_{34}) \qquad (2)$$

$$p_x \equiv \frac{\partial}{\partial x} p = -\gamma(\Delta f_{24} - \Delta f_{13}) \qquad (3)$$

$$p_y \equiv \frac{\partial}{\partial y} p = -\gamma(\Delta f_{12} - \Delta f_{34}) \qquad (4)$$

where

$$f_{ij} \equiv f_i + f_j \qquad (5)$$

and Δf_{ij} is the frequency difference form the initial frequency at p(x,y) = 0. The resistance R is 100 kΩ and the initial oscillation frequency is about 10 MHz when $d_i \sim 0.1$ mm.

If a sensing chip has a not negligible height H compared with the width, the p_x and p_y are proportional to shearing stress τ_{xz} and τ_{yz}, respectively.

The sensitivity $1/\gamma$ in Eq. (3) and (4) can be increased by decreasing the diameter L in **Fig. 4**, keeping the β in Eq. (2) nearly constant.

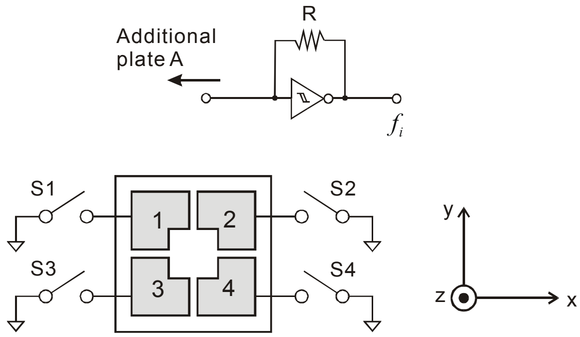


Fig. 5: Sensing of the capacitance. The main circuit in the LSI chip measures the oscillation frequency f_i (i = 1, 2, 3, and 4) when the i th switch is on.

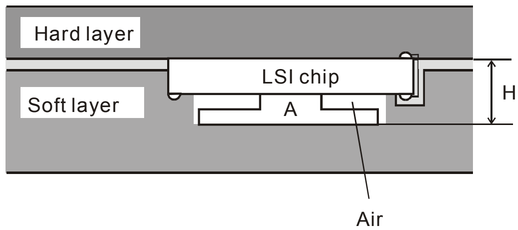


Fig. 6: Locating the sensing chip at the boundary between a hard layer and a soft layer. If the height of the sensing chip H is not negligible, the p_x and p_y are proportional to shearing stress τ_{xz} and τ_{yz}, respectively.

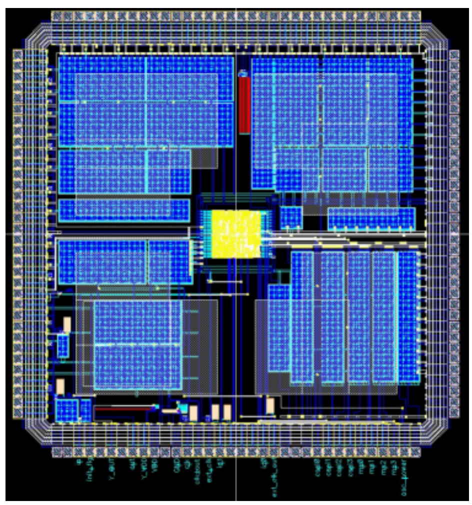


Fig. 7: The mask pattern of the preliminary version of the LSI chip for basic evaluations. (5 mm square)

4. Fabrication of a Prototype Sensor

We have already fabricated a preliminary version of the LSI chip to evaluate the basic operation. The design was supported by VDEC (VLSI Design and Education Center) at the University of Tokyo. A custom LSI based on a CMOS 0.35 μm rule was fabricated by Rohm Ltd., Japan. The photograph of the mask pattern is shown in **Fig. 7**. An 8000 gate digital circuit for sensing and communication occupies a 0.5 mm square area on the chip. The estimated power consumption at 10 MHz operations is 1 mW in average.

Before experiments using the LSI chip, we examined the sensing ability using electrodes formed on a circuit board as is shown in **Fig. 8**. The electrodes with a plate A are connected to a test circuit simulating the LSI chip, and we observed the oscillation.

We show a waveform of the oscillation in **Fig. 10**. The oscillation frequency under no pressure on the plate A was 9.8 MHz. The fluctuation of the oscillation frequency for 1 ms measurement time was about 1 kHz, which means we can obtain 0.01% resolution of the capacitance detection. Though the capacitance C_i is smaller than 1 pF, the circuit oscillated stably because the size of the circuit was small.

(a)
(b)

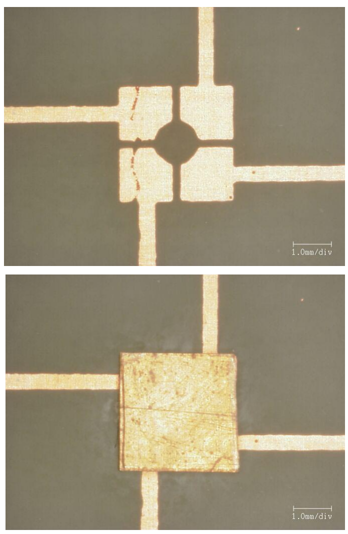


Fig. 8: (a) Electrodes 1 to 4 formed on a circuit board. The length of the outer side is faithful to **Fig. 4**. (b) A top view of a plate A attached to the board over the four electrodes.

5. Experiments

The experimental setup is shown in **Fig. 9**. We put a soft layer (Young's modulus E = 4.4 x 10^5, thickness h = 3mm) on the plate A with the circuit board fixed on a rigid XYZ stage. We observed the frequencies f_{13} and f_{24} while we moved the XYZ stage keeping the upper surface of the soft layer fixed to a rigid plate. In **Fig. 11** (a), we plotted the oscillation frequencies as a function of the z displacement of the XYZ stage. Since the gap between the plate A and the sensing electrodes decrease, the oscillation frequencies decrease. On the other hand, **Fig. 11** (b) shows the frequencies f_{13} and f_{24} while we moved the stage in x direction. In this case f_{13} increases while f_{24} decreases.

Since the capacitance can be measured with 0.01% resolution, we can detect 1μm surface displacement from the oscillation frequency. Then the range-ability (the ratio of the maximum displacement to the minimum detectable displacement-change) of this sensing element is evaluated at 10 bit, for the maximum displacement 1 mm with 1 ms measurement time.

Fig. 12 shows the plots of $\Delta f_{13} + \Delta f_{24}$ and $\Delta f_{13} - \Delta f_{24}$ of the measured frequencies. When we move the stage vertically in z direction, $\Delta f_{13} + \Delta f_{24}$ changed selectively. On the other hand, the $\Delta f_{13} - \Delta f_{24}$ selectively changed for the horizontal movement. These results show the $\Delta f_{13} + \Delta f_{24}$ and $\Delta f_{13} - \Delta f_{24}$ are selectively sensitive to the normal strain and the shearing strain of the soft layer, respectively.

The plots in **Fig. 11** and **Fig. 12** showed non-linearity. We think it is caused by non-linearity of the elasticity property of the soft layer. Therefore the sensor cannot estimate the surface displacement very precisely, but it can still detect both very small displacement ≈ 1 μm and a large displacement more than 1 mm.

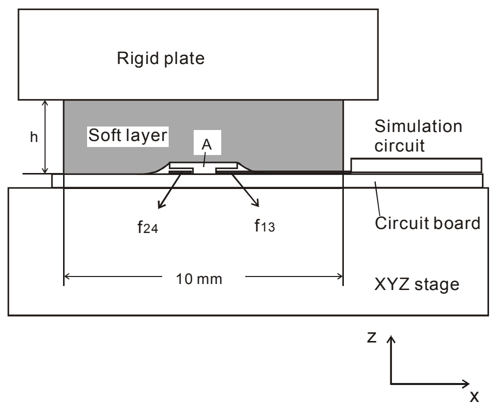


Fig. 9: Experimental setup.

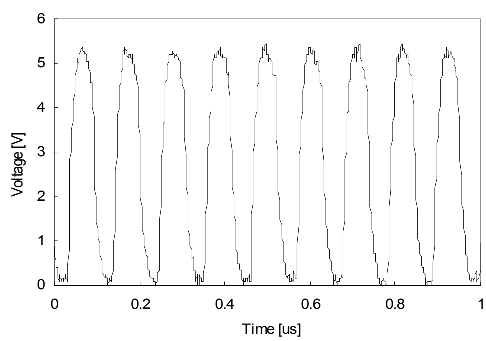
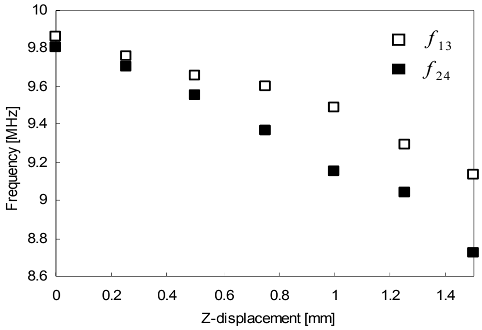
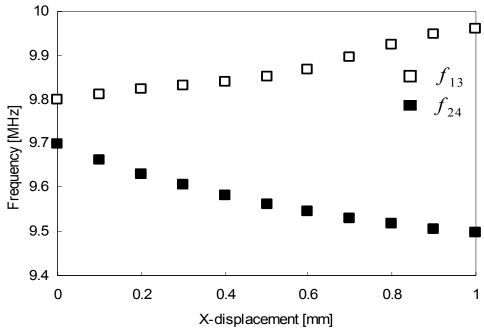


Fig. 10: An oscillation waveform.

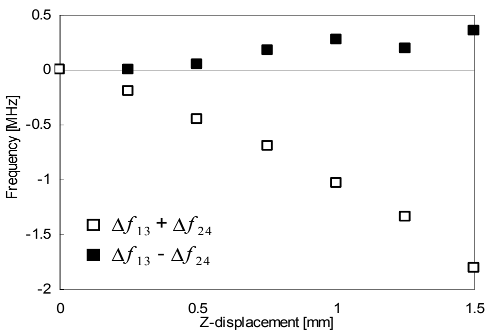


(a)

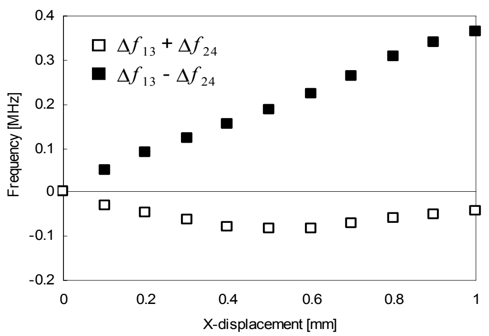


(b)

Fig. 11: Experimental results. (a): The oscillation frequencies f_{13} and f_{24} while we moved the XYZ stage in z direction. (b): The case of movement in x direction.



(a)



(b)

Fig. 12: Plots of $\Delta f_{13} + \Delta f_{24}$ and $\Delta f_{13} - \Delta f_{24}$ while we moved the XYZ stage in z direction. (b): The case of movement in x direction.

6. Summary

We proposed a tactile sensing element that communicates through two dimensional conductive skin layers without individual wires.

1. We showed architecture of the tactile element communication. The tactile element operates at 10 MHz and sends 32 bit data packets at 1 MHz through the conductive layer.
2. We showed a structure of the sensing chip that can measure both normal and shearing stress.
3. We fabricated a LSI chip including communication circuit (0.5 mm square) and sensing oscillators.
4. Experimental results showed that a sensing chip located at the bottom of a 3-mm-thick elastomer could detect a uniform displacement of the elastomer-surface from 1 μm to 1 mm.

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