Development of an Arrayed Tactile Sensor Having Four Stories and Recognition of Contact State Using Neural Networks

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Keywords: tactile sensor having four stories, arrayed sensor, recognition of contact state, neural networks

In the human skin, four kinds of tactile receptors are distributed three dimensionally, i.e., not only on the skin surface but also in the four corresponding depths of the skin. The final goal of this study is achieving a flexible tactile sensor having four stories imitating the human skin, for recognizing contact state skillfully.

A tactile sensor composed of many force sensing elements distributed on four stories is assumed (Fig. 1). By changing the shape of a contact object, the stress distribution in the sensor sheet is simulated by FEM (Fig. 2). The shape of contact object is recognized by applying neural networks to the FEM simulated data of force sensing elements (Fig. 3). The recognition results for the unknown test data are shown in Tables 1 and 2, in which the objects are intentionally shifted from the learned position by over 10% of the side of their circumscribed square. The results exhibit the effectiveness of using four stories.

The MEMS fabrication method of an arrayed capacitive tactile sensor made of PDMS is proposed (Fig. 4), in which Parylene is used as an anti-stiction layer against PDMS for the purpose of peeling off the PDMS sheet easily from the substrate in the pattern transfer process. By stacking this sensor one by one, the fabrication of a sensor having four stories is possible.

An arrayed sensor with one story was preliminarily fabricated (Fig. 5). A distributed load was detected by the sensor composed of 3×3 sensing elements (Figs. 6 and 7), which implies the potential of the proposed sensor for tactile sensing.

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Development of an Arrayed Tactile Sensor Having Four Stories and Recognition of Contact State Using Neural Networks

Daisuke Ono* Non-member
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In the human skin, four kinds of tactile receptors are distributed three dimensionally, i.e., not only on the skin surface but also in the four corresponding depths of the skin. Imitating this, a tactile sensor having four stories is proposed, inside each story of which capacitive force sensing elements are distributed in an array. The recognition method of contact state using neural networks is proposed. The stress distribution of a sensor sheet is obtained, and the outputs of the sensing elements are simulated by FEM. By applying the outputs to neural networks, it is confirmed that the contact shape recognition is possible, and the sensor having four stories achieves higher recognition rate compared with that having one story. The MEMS fabrication method of an arrayed capacitive tactile sensor made of PDMS is proposed, in which Parylene is used as an anti-stiction layer for the purpose of peeling off the PDMS sheet easily from the substrate. By stacking this sensor one by one, fabrication of a sensor having four stories is possible. A sensor having one story is preliminarily fabricated. The basic performance of one force sensing element and that of an arrayed sensor composed of 3×3 elements are characterized, which shows the potential of the proposed sensor for tactile sensing.

Keywords: tactile sensor having four stories, arrayed sensor, recognition of contact state, neural networks

1. Introduction

An advanced tactile sensor, the performance of which is the human equivalent, is desired in robot hand applications. The human skin contains numerous force-sensing receptors distributed in approximately 1 mm intervals(1)-(3). By using MEMS technology, numerous arrayed miniature force sensing elements with uniform performance can be fabricated on a silicon wafer with fine resolution of several microns, which may make it possible to fabricate a practical tactile sensor. In the reported micromachined tactile sensors(4)-(8), the force sensing elements are distributed two dimensionally on a surface. However, in the human skin, four kinds of tactile receptors (Meissner corpuscle, Merkel cell, Ruffini ending, and Pacinian corpuscle) are distributed three dimensionally, i.e., not only on the skin surface but also in the four corresponding depths of the skin(1) (Fig. 1).

In the human tactile sensing, the brain synthesizes nerve signals from many receptors and obtains cutaneous stress distribution to finally recognize the contact state. This human information processing mechanism has not been cleared yet: therefore, many artificial intelligence methods are proposed and evaluated. As one of the methods of processing information from many sensing elements, neural networks (referred to herein as NN) are well known(9). As for the pattern recognition by vision sensors, there are many researches applying NN for processing image pixel data. However, there are few reports applying NN for tactile sensors(10), since a practical tactile sensor composed of many sensing elements has not been established mainly because of fabrication difficulties.

In the present paper, a tactile sensor having four stories is proposed, and the information processing method for this sensor using NN is investigated. First, in case of contact shape recognition, the effectiveness of the sensor having four stories compared with that having one story is investigated by FEM simulation. Second, the MEMS fabrication method of an arrayed capacitive tactile sensor made of four PDMS sheets, which is a kind of silicone rubber, is proposed. Finally, an arrayed sensor of one layer is practically fabricated. The performance of one capacitive force sensing element and that of an arrayed sensor composed of 3×3 elements are characterized.

2. FEM Simulation on Data Processing of Arrayed Tactile Sensor Having Four Stories

2.1 Acquisition of Contact Data by FEM

Assuming a tactile sensor composed of many force sensing elements distributed on four stories, FEM simulation is employed to simulate the data from these sensing elements(10). As a tactile sensor, an elastic sheet is assumed of which side is 15.0 mm and thickness is 5.0 mm, as shown in Fig. 2. Sensing elements are horizontally distributed in 1.25 mm pitch, and vertically...
The stress distribution of a tactile sensor is simulated. The stress magnitude is 10 gf. Figure 3(b) shows a simulated example of the stress distribution against the assumed tactile sensor, being applied force of which bottom shapes are employed. Each object is pressed vertically at each node on FEM nodes within this area are interpolated, being assigned to the corresponding sensing element as its output.

In case of recognizing the shape of a contact object using NN, the stress distribution in the sensor sheet is simulated under the condition shown in Fig. 3(a). The contact objects having various shapes are employed, in order that the number of sensing elements be the same among these two type sensors for achieving fair comparison.

It is necessary to assign $\sigma_{\text{sensor}}$ at each node on FEM meshed element to each sensing element of the tactile sensor (Fig. 2). A sampling area is assumed, center of which is the position of a sensing element, and radius of which is the half of the pitch of elements. The $\sigma_{\text{sensor}}$ data of FEM nodes within this area are averaged, being assigned to the corresponding sensing element as its output.

2.2 Recognition Method of Object Shape Using Neural Networks

The shape of contact object is recognized by applying NN to the FEM simulated data of force sensing elements. It is assumed that only approximate contact position is known by some recognition method. Then, the important point is to recognize the shape with robustness to unwanted shift of the object from the reference position, where the template for the recognition was constructed. The method using NN for object shape recognition is schematically shown in Fig. 4.

As the object shape, seven kinds of circle, doughnut, ellipse, octagon, square, star, and triangle are employed, which are circumscribed for a 10 mm square. As the training data, the stress distributions when the objects are shifted from the center of the sensor surface by 1.25 mm are recognized.

Unknown objects shifted from the center of sensor by 1.25 mm are recognized.

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Unknown objects shifted from the center of sensor by 1.25 mm are recognized.

2.3 Results of Object Shape Recognition

The number of neurons of each layer of the NN (Fig. 4) in both cases of the one story sensor and the four stories sensor is as follows: 676 for the input layer, 676 for the first hidden layer, 20 for the second hidden layer, and 7 for the output layer. The employment of two hidden layers, and the definition of the number of neurons of them are based on the adjustment by trial and error. Note that the adjustment in case of the four stories sensor was much easier than that in case of the one story sensor, implying the good interpolating ability of using four stories.

The results of object shape recognition for unknown objects in case of the one story sensor are shown in Table 1. Those in case of

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Unknown objects shifted from the center of sensor by 1.25 mm are recognized.
the four stories sensor are shown in Table 2. The shaded values in these tables are the maximum NN’s output value among the seven candidates. Seeing Table 1, in case of the one story sensor, the circle is mistaken for the octagon, and vice versa. By contrast, seeing Table 2, all objects are finely recognized as the correct shapes in case of the four stories sensor.

The stress distributions on each surface of the four stories are shown in Fig. 5. Seeing this figure, the contour edge of stress distribution becomes obscure as the depth becomes large, which means the influence of the object shift on the stress distribution change becomes smaller. If four stories are employed, the stress information of deeper stories, which is robust to the object shift, is available, which would be one of the reason of higher recognition ability of using four stories compared to that of using only one story.

3. Preliminary Experiment on PDMS Fabrication

3.1 Peeling-Off Method  The fabrication of an arrayed tactile sensor having four stories is described hereinafter. In this sensor, polydimethylsiloxane (PDMS, Dow Corning Toray Co., Ltd. SILPOT 184 W/C) is used as the structural material. Preliminary experiments concerning PDMS fabrication were carried out in advance of fabricating the tactile sensor, which is documented in the following of this section.

PDMS is highly adherent to silicon material, which makes it difficult to peel it off from the surface of a silicon wafer. Thus, photoresist was adopted as a sacrificial layer, on which PDMS is spun at 3,000 rpm, followed by defoaming under vacuum in 30 min, and baking at 180°C in 45 min. These defoaming and baking are common processes annexed to the spin-coating of PDMS in the following of this article. After that, the photoresist was wet-etched away using acetone. As the result, it was possible to peel off the PDMS: however, the PDMS swelled, since it has not high resistivity to organic solvents.

Considering this circumstance, Parylene was tested as an anti-stiction layer for PDMS peeling. It was experimentally proven that Parylene is successfully non-adherent to PDMS, which makes it possible to peel a PDMS layer easily from the Parylene surface.

3.2 Pattern Transfer  Photoresist was spun on a silicon wafer, and patterned by photolithography. Then, Parylene was conformally deposited on it. After that, PDMS was spun and peeled off. The experimental method is schematically shown in Fig. 6. A SEM image of PDMS after peeling off is shown in Fig. 7, which exhibits that the pattern of the photoresist is successfully transferred to the PDMS sheet.

3.3 Electrode Fabrication  Two methods for patterning aluminum for electrodes were tested. One is as follows: aluminum was deposited on PDMS by vacuum evaporation. Then, photoresist was spun on it and patterned by photolithography, which was used as the mask for the wet-etching of aluminum. Another is a lift-off process, in which patterned photoresist is prepared on PDMS, then aluminum is deposited on it, followed by etching of the photoresist for lifting and removing the aluminum on it.

The photographs of results using the former and the latter methods are shown in Figs. 8 and 9, respectively. Looking at these figures, the aluminum could not be patterned successfully in both methods. Moreover, the electrical connection on the electrode could not be confirmed.

To address this problem, a shadow mask method was employed, as shown in Fig. 10. A silicon wafer of 500 µm in thickness was prepared as the mask, the correspondent positions to electrodes of which were etched vertically by using DRIE. Deposition of aluminum by sputtering was first applied: however, the resultant edge of aluminum was blurred owing to the conformal deposition characteristic of sputtering method. Thus, deposition of aluminum by vacuum evaporation was used in this study instead of sputtering. The photograph of evaporated aluminum on PDMS is shown in Fig. 11, which exhibits a fairly sharp resultant edge of aluminum due to the vertical deposition characteristics of vacuum evaporation method. On the resultant electrode, the electrical connection was surely confirmed.

4. Microfabrication of Arrayed Tactile Sensor Having Four Stories

4.1 Fabrication Process  Based on the preliminary
experiments on PDMS fabrication mentioned in the previous chapter, a fabrication process of arrayed tactile sensor is described in this section. The fabrication process of the sensor having one story proposed in this study is schematically shown in Fig. 12.

The process is as follows: Parylene (1 µm) for anti-stiction layer is conformally deposited on a silicon wafer, the only function of which is to support the PDMS layer. Then, PDMS (300 µm) is spin-coated at 500 rpm (Fig. 12(a)). Aluminum (1.5 µm) is deposited for electrodes using the shadow mask method (Fig. 12(b)). Then, PDMS (10 µm) is spin-coated for covering up the electrodes (Fig. 12(c)). PDMS is etched by O₂ plasma using DRIE for revealing the bonding pads of lower electrodes (Fig. 12(d)). At this step, the lower structure is completed. The upper structure is also fabricated by the same process.

Next, the spacer structure, which bears a number of concave space serving as the gap between two electrodes of a capacitor, is fabricated. For this purpose, Parylene (1 µm) is deposited on patterned photoresist (3 µm), then, PDMS (10 µm) is spun on it (Fig. 12(e)). The upper structure and the spacer structure are bonded with each other by applying heat and pressure. Each sealed concave space has lower and upper electrodes, forming a capacitor (Fig. 12(h)). The upper silicon wafer is taken away from the upper structure (Fig. 12(i)). The PDMS of the upper structure is etched by O₂ plasma using DRIE for revealing the bonding pads of upper electrodes (Fig. 12(j)). The capacitance of each sealed concave space changes as the distance between electrodes changes when the structure is deformed based on applied force, i.e., a capacitive force sensing element is realized.

The obtained structure having many sensing elements forms one story, four of which are stacked one by one and bonded to each other, finally forming an arrayed tactile sensor having four stories, as shown in Fig. 13.

4.2 Fabrication Result A sensor having one story has been fabricated at the moment. An optical microscope image of this sensor is shown in Fig. 14(a), of which layout of capacitive sensing elements is shown in Fig. 14(b). Including a 5×5 array,
many types of array are designed on trial. Wiring in one direction, and that in its perpendicular direction are formed, on the crossing areas of which, capacitive sensing elements exist. By selecting corresponding two bonding pads for these two directions, detecting the capacitance of a target sensing element is possible.

5. Preliminary Characterization

5.1 Characterization of One Sensing Element

A weight was set on the surface of the fabricated sensor having one story. Then, the capacitance change of one sensing element (1 mm square, 3 µm gap) was detected with the aid of a CV converter IC (MicroSensors Inc., MS3110), the programmable gain of which was set to 0.1 pF/V. Four weights of 5, 10, 20, and 50 gf were employed, of which radii are 5.5, 6.5, 7.5, and 10 mm, respectively. Namely, whole area of one sensing element was covered by each weight and was applied pressure of 516, 738, 1,109, and 1,560 Pa, respectively.

Experimental results of output voltage of the IC for several applied force, which are observed by an oscilloscope, are shown in Fig. 15. It is confirmed that the capacitance surely changes by applying force. The results are arranged in Fig. 16, which shows the relationship between applied pressure and capacitance change of one sensing element. It is proven that the capacitance increases as the pressure increases. In this figure, the theoretical value is based on the FEM multiphysics simulation, which analyzes the capacitance under the boundary condition defined by the mechanical deformation of the sensor structure. Measured and theoretical curves have similar trends, although the error is rather large at the pressure of 1,560 Pa.

5.2 Characterization of Arrayed Sensor

A distributed load was preliminarily detected using the developed arrayed sensor having one story. A weight of 5 gf was set, i.e., the pressure of 516 Pa was applied, under two conditions: one is that the weight completely covers the surface area of an arrayed sensor consisting of 3×3 sensing elements (see Fig. 17(a)), and another is that the weight partially covers the arrayed sensor, leaving some uncovered elements near the corner of the sensor (see Fig. 17(b)). Then the capacitance change of each sensing element was detected one by one. The results for these cases are shown in Figs. 18(a) and (b), respectively. Looking at these figures, in the former case, almost the constant capacitance changes for all the sensing elements were observed. In the latter case, the capacitance changes were different for each sensing element, depending on the extent of the pressure applied and the position of the sensing element.
elements are obtained: while in the latter case, the comparatively lower capacitance changes are obtained at the sensing elements near the corner of the fabricated sensor, where the sensing elements are not covered completely by the weight. These results imply the possibility of this sensor to detect a distributed load.

6. Conclusions

Imitating the human skin structure, a tactile sensor having four stories is proposed. To briefly summarize: 1) the information processing method for this sensor using neural networks is investigated. The FEM simulation results exhibit the effectiveness of using four stories for contact shape recognition. 2) A MEMS fabrication process of this sensor is proposed. 3) A preliminary characterization of the fabricated device was carried out, which implies the basic potential of the proposed sensor for tactile sensing.

A complete fabrication of a sensor having four stories is the projected work. Further characterization of contact state recognition by applying many sensing elements to neural networks is also the projected work. For processing the data from many capacitive sensing elements, a detecting circuitry using active matrix method(15) is under consideration.

Acknowledgments

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(15) For example, http://www.sharp.co.jp/products/ld/tech/s2_4_3.html

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