Tough, Bendable and Stretchable Tactile Sensors Array for Covering Robot Surfaces

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***Abstract*— This study proposes a bendable and stretchable tactile sensors array and its data acquisition circuit with the aim of realizing a tough tactile skin for robotic surface. Its pressure sensitive part consists of conductive fabrics and pressure-conductive rubber sheets arranged in a matrix form. The entire pressure sensitive part is covered with silicone rubber, which makes up for not only the weakness to mechanical damage and water wetness but also the lack of restoring force. The data acquisition circuit consists of a small number of electronic components. The experimental result shows that each tactile cell of the sensor can detect normal force of 0.7N $\sim$ 3N with small hysteresis and high repeatability, the sensor can detect force distribution without inaccurate sensing due to a wraparound current, and the mechanical properties of the sensor are suitable for practical use in tough conditions.**

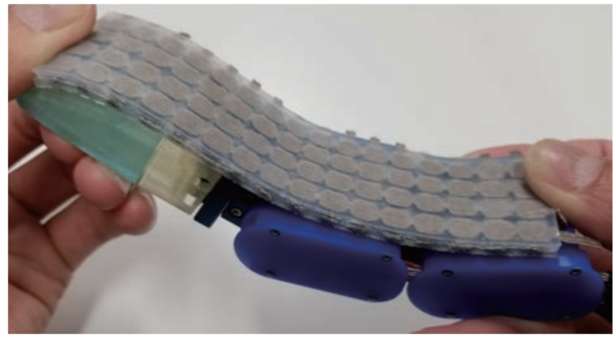

Fig. 1. The proposed bendable and stretchable tactile sensors array with a 16×4 matrix configuration using conductive fabrics and pressure-conductive rubber sheets

I. INTRODUCTION

Contact state estimation is a common problem many robots confront in executing their tasks. Interaction of force between a robot and its environment through contact plays an important role in various performances of robots such as locomotive of mobile robots and dexterity of manipulators. If a complete model of the environment is available, the problem could be analytically solved and an optimal motion plan would be derived. However, uncertainty necessarily exists in real environments, and so a methodology which enables a robot to plan and generate its motion in the unmodeled environment is required. The requirement is recently becoming higher in production automation of complicated tasks, which need delicate and stable contact and have to be done by human hands, for example, manipulation of deformable or fragile objects.

Softness of surfaces brings various benefits to robots in real tasks: It absorbs model errors of the robots, suppresses impacts and vibrations at contact, and enlarges frictional force with the objects by forming surface contact. Thus, these effects are widely exploited in tires and crawlers of mobile robots, soles of legged robots, and fingertips of robotic hands. These material features are useful for efficiently transmitting the driving force of the mobile robots and for stably grasping with weak force by the robotic hands, but on the other hand, when large force acts, deformation due to the softness cannot be ignored. In order to solve this problem, it is required to sense the contact position and force and incorporate this information appropriately into the control of the robots.

Here, a tactile sensors array, which has distributed detection elements on its surface, is advantageous as compared with a force/torque sensor embedded at one point inside the structure. It is because a tactile sensors array is able to recognize a contact region, not a single point, planarly formed on the surface, and measure the magnitude of the force acting at each part in the contact region. This can be also available for estimating the shape of the deformed soft material.

A variety of tactile sensors aiming to cover surfaces of robots (such sensors are also called "artificial skins") have been proposed in various detection principles, sensor structures, and data acquisition methods [1], [2], [3]. Detection principles mainly applied in existing tactile sensors are resistive type and capacitive type, and there are some methods of constituting only with thin and bendable parts, that is, sheet-shaped conductors, resistors and insulators. Therefore, different kinds of bendable tactile sensors have been proposed [4], [5], [6], [7]. For example, Shimojo et al. presented a thin and bendable tactile sensor composed of a pressure-conductive rubber sheet and stitched electrical wires [4], and Lee et al. proposed a very thin and flexible capacitive tactile sensor using polymethylsiloxane (PDMS) elastomer as a structural material fabricated by MEMS process [5]. However, it is difficult to construct tactile sensors that are not only bendable but also stretchable. For realizing a stretchable tactile sensor, it is required to devise shape or material of electrical wires connecting between detection elements to be expandable [8], or to make the detection element itself stretchable [9], [10]. An example of the former method is

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a stretchable tactile sensors array proposed by Jentoft et al., whose wires are made of wavy-shaped flexible printed circuit [8]. Such a method can utilize various existing detection elements, but there are demerits in principle; complexity of fabrication process and wideness of the insensitive area between the elements. In the latter method, some studies use conductive fabrics. Hoshi et al. developed a capacitive type of tactile sensors array composed of conductive fabrics sandwiching soft urethane foams [9], and Yoshikai et al. used conductive knitting structure for whole-body tactile sensing of humanoids [10]. These structures can be easily fabricated and widely expanded, but the weakness of their elastic restoring force may become a demerit in terms of mechanical elements. Such a fabric is also weak in wear-resistance and waterproofness and so it cannot be used in tough environments. Another method to construct a stretchable tactile sensor is to form a soft strain gauge by filling a narrow flow path formed inside flexible silicone rubber material with conductive liquid metal [11], [12], [13]. It is easy to make small-sized, complicated and three-dimensional structure.

On the other hand, an electronic circuit for data acquisition is an important design factor as well as the pressure sensitive part. Since it is difficult to configure the circuit to be deformable, it has to be miniaturized and embedded in a space other than the soft surface of the robot. Especially, in the case of a tactile sensors array, a circuit for switching a large number of detection channels is required, which is generally constructed as a two-dimensional scanning circuit [1], [2], [4], [14], [15]. Therefore, it is also important to implement such a data acquisition circuit compactly without affecting the structural design of the robot.

In this paper, we propose a bendable and stretchable tactile sensors array as shown in Fig. 1 and its compact data acquisition circuit with the aim of realizing a tough tactile skin for robotic surfaces. Its pressure sensitive part is composed of conductive fabrics, pressure-conductive rubber sheets and silicone rubber. The pressure-conductive rubber sheets construct a matrix of resistive detection elements, which are sandwiched by the conductive fabrics used as stretchable conductive sheets. These electrical components are embedded in layer-structured silicone rubber. This structure brings wear-resistance and waterproofness while maintaining bendability and stretchability. In addition, a simple scanning method consisting of a multiplexer and a demultiplexer is proposed for the data acquisition circuit. This method prevents detection error due to a wraparound current.

The contributions of this paper are as follows:

- A novel bendable and stretchable pressure sensitive part is constructed with conductive fabrics and pressure-conductive rubber sheets. The entire pressure sensitive part is covered with silicone rubber. It makes up for not only the weakness to mechanical damage and water wetness but also the lack of restoring force, which are defect of the conductive fabrics.
- A simple configuration of a data acquisition circuit for scanning tactile sensors arrays is proposed. Generally, in a resistive tactile sensors array, it is necessary to avoid inaccurate sensing due to a wraparound current caused by reaction at points other than the scan target point. The scanning circuit implemented in this paper consists of a small number of electronic components by devising the way of inputting the reference voltage of the multiplexer and demultiplexer.

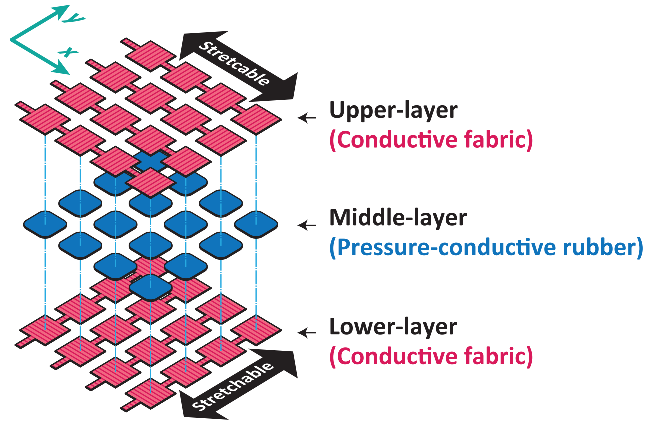

Fig. 2. Structure of the pressure sensitive part (Pressure-conductive rubber in the middle layer is sandwiched by conductive fabrics in the upper and lower layers. The conductive fabrics in the upper layer are connected in the *x* direction and separated in the *y* direction, and oppositely in the lower layer, connected in the *y* direction and separated in the *x* direction.)

II. SENSOR DESIGN

A. Pressure Sensitive Part

The structure of the pressure sensitive part of the proposed tactile sensors array is shown in Fig. 2. It consists of three layers of electrical parts: Pressure-conductive rubber (Velostat, thickness of about 0.1mm) at the middle-layer, and knit conductive fabrics (plated with Silver) at upper and lower layers. Small fragments of the pressure-conductive rubber are arranged in a two-dimensional matrix. The conductive fabrics in the upper layer are connected in the *x* direction and separated in the *y* direction, and oppositely in the lower layer, connected in the *y* direction and separated in the *x* direction. When the pressure-conductive rubber is pressurized at a certain point and the resistance value decreases, a current path is formed from the upper layer to the lower layer passing through the row and the column including the point occurs, depending on the magnitude of the pressure. Thus, we can measure the magnitude of the pressure at each position by switching the row connected to the high electric potential in the upper layer and the column connected to the low electric potential in the lower layer. Note that the knit conductive fabric has anisotropy in stretchability depending on the weaving direction, and it is easily stretched in a certain direction but hardly stretched in the perpendicular direction. Therefore, in both of the upper and lower layers, the conductive fabrics are oriented so as to be stretchable in the direction in which the fabrics are connected.

This pressure sensitive part is, as shown in Fig. 3, covered with silicone rubber for accurately positioning the com-

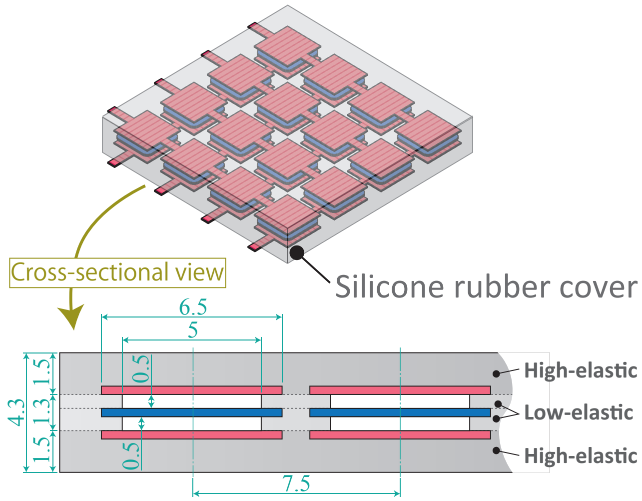

Fig. 3. Structure of the silicone rubber covering the pressure sensitive part (Four layers of silicone rubber sheets with different elasticities are utilized for positioning and upgrading the pressure sensitive part.)

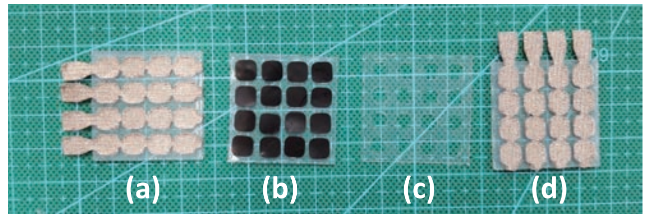

Fig. 4. Fabricated component parts of the pressure sensitive part ((a) 1st silicone layer and the conductive fabric in the lower layer, (b) 2nd silicone layer and the fragments of the pressure-conductive rubber, (c) 3rd silicone layer, and (d) 4th silicone layer and the conductive fabric in the upper layer)

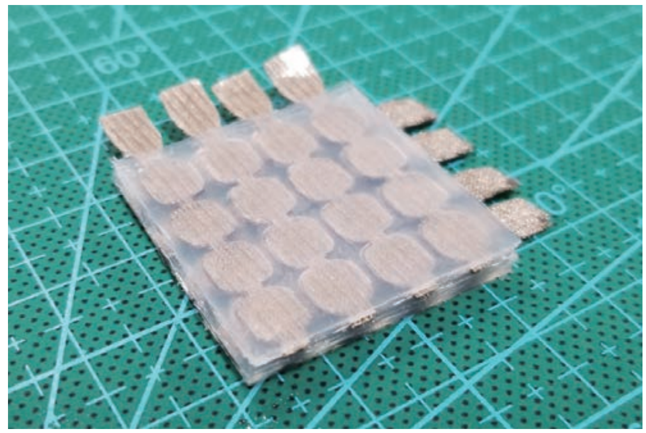

Fig. 5. Constructed 4×4 matrix configuration of the tactile sensors array

ponents and improving wear-resistance and waterproofness. As seen in the sectional view, there is a void between the conductive fabric and the pressure-conductive rubber so that these components do not contact with each other in an unloaded state. It prevents erroneous reaction to bending or stretching of the sensor structure which causes compression strain in the thickness direction. The silicone cover is constructed by dividing it into four layers and attaching them to constrain the inner components. Here, two kinds of silicone rubber having different elasticities are used: high elasticity (Dragon Skin 20) on both surface sides and low elasticity (Ecoflex 00-20) inside. This is to make the surface tough against physical damage such as tearing and wearing while to improve the stretchability and the sensitivity. For the prototype of the sensor, we decided the dimensions as follows; the pitch of the detection elements is 7.5mm, the width of each element is 6.5mm, the thickness and the width of the void are 0.5mm and 5mm, and the total thickness of the sensor is 4.3mm. The size of the element is able to be changed. It is possible to make it larger or smaller, although the fabrication becomes more difficult as the size is smaller.

Figs. 4 and 5 show the fabricated component parts and the constructed tactile sensors array, respectively. Here a small-sized (4×4) matrix configuration was adopted with aiming to verify the basic characteristics of tactile sensing. Note that the size of the matrix is arbitrary, and the numbers of the rows and the columns can be different. However, it affects the difficulty level of configuration of the data acquisition circuit described in the next section and its sampling time.

B. Data Acquisition Circuit

Fig. 6 shows an equivalent circuit diagram for data acquisition. This circuit consists of two ICs (multiplexer and demultiplexer) and one reference resistor. Connected to the matrix of the pressure sensitive part, electrical paths in the upper layer are formed from the voltage source to the conductive fabrics of each row through the demultiplexer, and those in the lower layer are from the conductive fabrics of each row to the ground through the multiplexer and the reference resistor. By setting the channel-select inputs of the demultiplexer and the multiplexer, it is possible to measure the reaction current at the point in arbitrary row and column from the sensor-output voltage. After setting the channel-select and performing the AD conversion of the voltage of one point, set the next channel and do the same. By repeating this process, the sensor measures the voltage of all points. The sensor detect normal force from the voltage value and the pressed position from the order of data acquisition.

When scanning such a matrix of resistive-type tactile sensors array, it is demanded to prevent erroneous detection due to a wraparound current generated by pressurization at points other than the target point. One of general methods is to input the same electric potential as that of the output voltage at the moment for all rows excepting the selected row, which is only connected to the voltage source, as shown in Fig. 6. We realized this method in a simple way by connecting the sensor-output terminal to the GND terminal of the demultiplexer. In this cace, although the potential difference between the VDD and GND terminals of the demultiplexer dynamically changes, the circuit operates stably as long as this potential difference keeps larger than the threshold voltage for driving the IC. The requirement can be satisfied by adjusting the reference resistance so

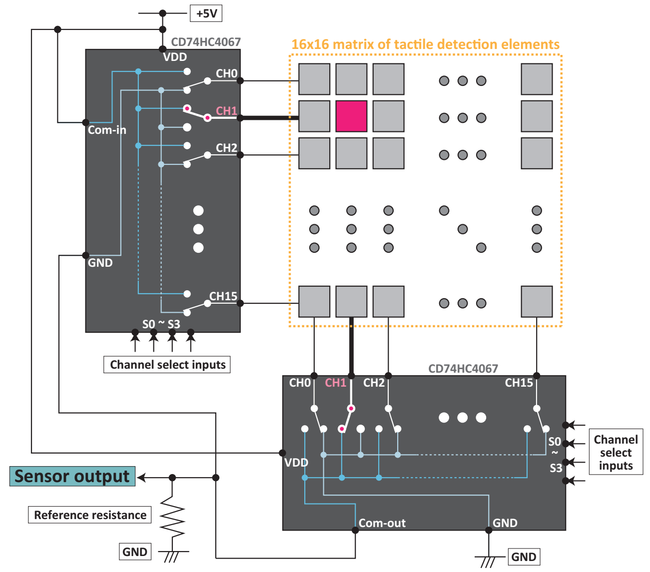

Fig. 6. Equivalent circuit diagram for data acquisition (The circuit is composed of two ICs (multiplexer and demultiplexer) and one reference resister. The common output (sensor signal output) of the multiplexer is connected to the Gnd terminal of the demultiplexer for avoiding wraparound current.)

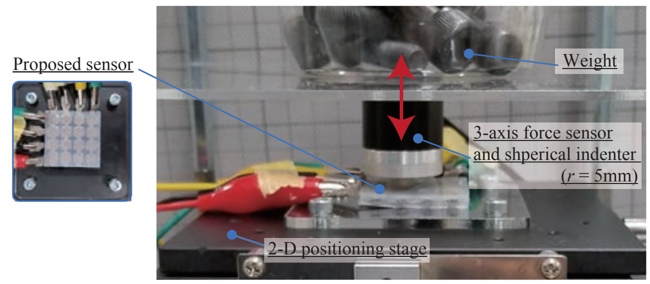

Fig. 7. Experimental setup for performance evaluation (Normal force loaded on the proposed sensor is presicely measured by 3-axis force sensor, the compression point is adjusted by 2-D positioning stage, and the load is controlled by the mass of the weight.)

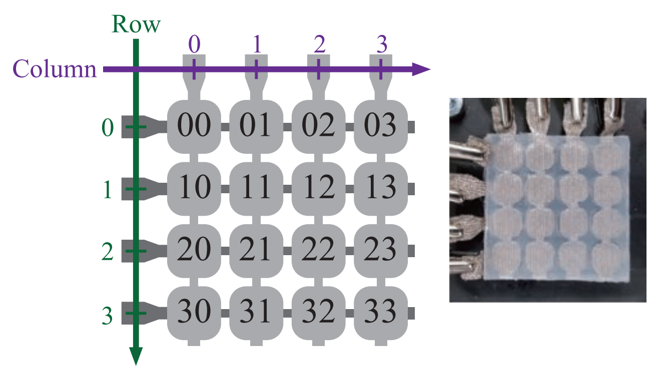

Fig. 8. Definition of the numbering of the taxels of the proposed sensor (For example, the taxel at i-th row and j-th column is called as “taxel ij” or “taxel (i, j)” in this paper.)

that the output voltage does not exceed the threshold. If an unexpected pressurization makes the output voltage exceed the threshold, the operation of the demultiplexer stops at that moment and the output voltage decreases, which brings saturation of the output voltage but causes no fatal trouble in the circuit.

We adopted 16 channel analog multiplexer/demultiplexer 74HC4067 for both the multiplexer and the demultiplexer. By setting the four channel-select inputs in each of the ICs, it is possible to scan up to $256 (= 16 \times 16)$ detection elements. A PSoC 5 CY8C58LP family processor module was adopted for switching the channel-select inputs and AD conversion of the output voltage.

III. PERFORMANCE EVALUATION

This section describes experiments to examine the following characteristics of the sensor. Hereinafter, we call the tactile detection elements as “taxels.”

- Sensitivity to normal force
- Variance of sensitivity among all taxels
- Response to distributed load

A. Experiment Method

The overview of the experimental setup is shown in Fig. 7. The proposed sensor is fixed on a 2-D positioning stage. A spherical indenter ($r = 5$mm) is fixed on a 3-axis force sensor (USLG25, measuring range XY: $\pm$5N and Z: $+$10N, Tec Gihan Co., Ltd.). The 3-axis force sensor is attached to a flat plate that slides vertically. The compression point can be arbitrary adjusted by moving the 2-D positioning stage, and the force is changed by the mass of the weight on the flat plate. Fig. 8 shows a definition of numbering of the taxels. Comparing the output of the proposed sensor with the accurate value obtained by the 3-axis force sensor, we examine the characteristics in each loading condition. To suppress the influence of creep property caused by viscoelasticity of the soft materials, we measure the data at the time 10s after each compression.

B. Sensitivity

To investigate sensitivity to the normal force of the sensor and the influence of hysteresis, we loaded and unloaded normal force of 0.1N $\sim$ 5N at the center of a single taxel (1, 1). Fig. 9 shows the amount of the sensor output current corresponding to the compressed normal force. It can be seen that, the current linearly increases when the force is 0.7N $\sim$ 1.5N, the gradient gets smaller in 1.5N $\sim$ 3N, and the current becomes almost constant at more than 3N. Thus, each taxel of the sensor can detect normal force of 0.7N $\sim$ 3N. When unloading force, the relationship between the current and the normal force is almost the same as that of loading process. However, the current corresponding to the same force is slightly larger in unloading process. This is considered to be the influence of hysteresis caused by using elastic materials (pressure-conductive rubber and silicone rubber).

C. Variance of sensitivity

To investigate variation in the sensitivity among all of the taxels, we loaded constant normal force about 2N one-by-

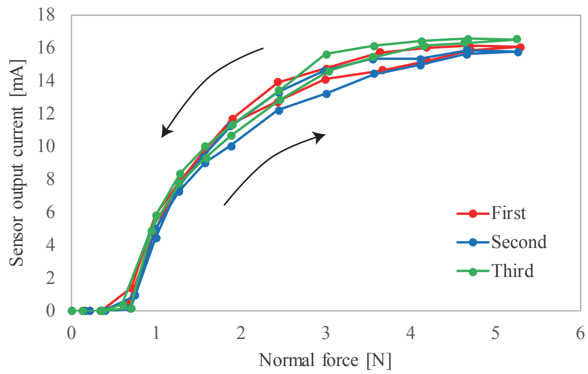

Fig. 9. Experimental result of sensitivity to the normal force (Relationship between the current of taxel (1, 1) and the normal force)

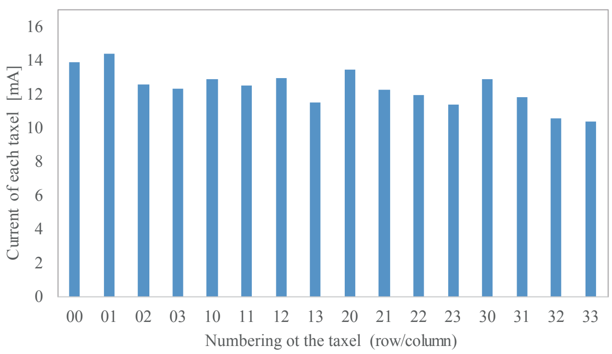

Fig. 10. Experimental result of variance of sensitivity of all taxels (Sensor output current of taxels (0, 0) $\sim$ (3, 3) when constant normal force (2N) is load at the center of each element one-by-one)

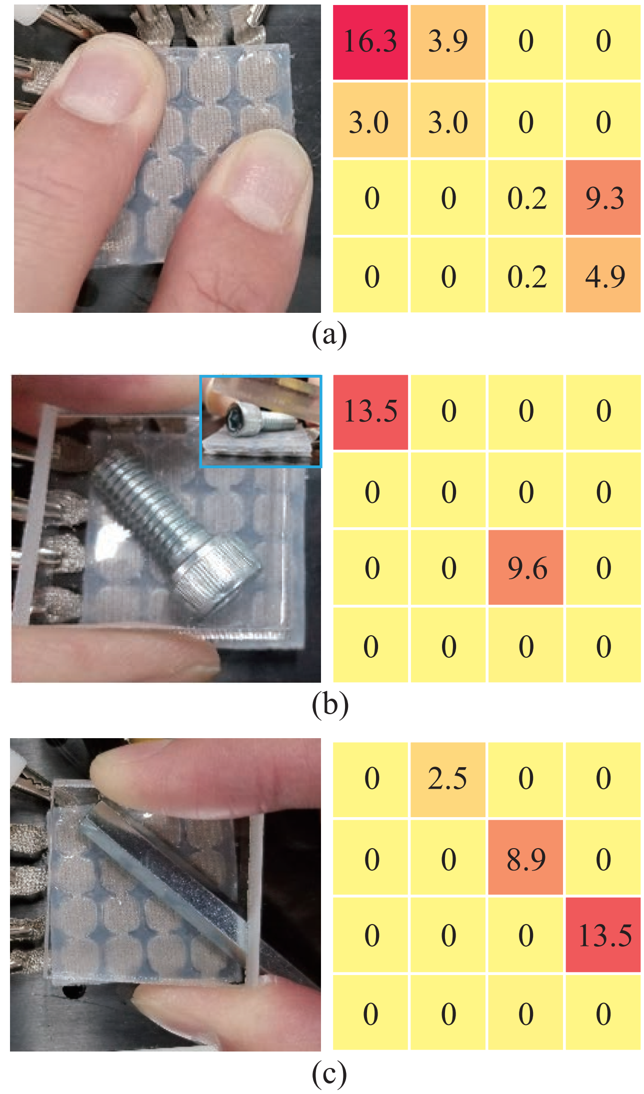

Fig. 11. Experimental result of response to distributed load (Sensor output current of taxels (0, 0) $\sim$ (3, 3) when distributed load is added by (a) a finger, (b) a bolt and (c) a metal rod, respectively. The color of the 4×4 cells at the right side indicates the magnitude of the current, and the number of each cell means the actual amount of the current (mA). The sensor output currents of all 16 elements are measured every 13ms.)

one at each taxel. Fig. 10 shows the sensor output current which occurred when each of the taxels (0, 0) $\sim$ (3, 3) is pressed. It can be seen that, the current is 14.4mA at the maximum, 10.4mA at the minimum, and 12.4mA on average. The variation of the current is within the range of $+16\%$ $\sim$ -19% compared to the average. Thus, the variance of sensitivity among the element is not so large, but it should be minimized by calibration for precise force measurement. The cause of the variance and its improvement method are discussed in section 4.

D. Response to distributed load

To investigate the response of the sensor to distributed load, we pressed multiple taxels of the sensor simultaneously by using fingers, a screw bolt and a metal rod. Fig. 11 shows current distribution of the taxels with color maps and numbers which mean the amount of the sensor output current of the corresponding 4×4 cells. When two separate areas were compressed with two fingers as in Fig. 11 (a), multiple taxels contacting with the fingers reacted. The magnitude of the reaction spread with two peak points which were strongly pressed. In Fig. 11 (b), two separate points were compressed with the head and the tip of the screw bolt. Only two taxels (0, 0) and (2, 2) corresponding the two points reacted and the surrounding taxels did not reacted at all. In Fig. 11 (c), a linear area was compressed with the metal rod. Three taxels in the same orientation as the rod reacted, and the gradual change in the magnitude reflected inclination of the rod to the sensor surface. The cycle time for sampling all taxels was about 13ms. It can be seen that, the current is flowing at the position corresponding to the shape of the object. In addition, no wrapcurrent was generated even if two separated areas were pressed at the same time. Therefore, it is said that the sensor can detect the distributed load.

IV. DISCUSSION

The experimental results of the sensitivity of the sensor showed that the sensor was able to detect normal force of 0.7N $\sim$ 3N with one taxel. The hysteresis was small and

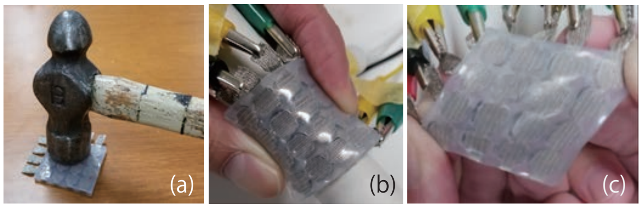

Fig. 12. Durability test of the proposed sensor (The sensor was (a) applied with strong impact force with a hammer, (b) bent around cylinders with different diameters and (c) stretched with pinched at the both ends.)

the repeatability was high. We investigated whether these characteristics are maintained even in tough conditions as shown in Fig. 12. Even after strong impact force was applied with a hammer, the sensor was not broken and normally worked. In addition, erroneous reaction was not seen even in bending with a radius of 10mm or stretching by 25%. Therefore, it is confirmed that the proposed sensor is tough, bendable and stretchable.

The sensitivity among the taxels has non-negligible variance. The cause is considered to be the internal resistance of the conductive fabric from the fact that the taxel (3, 3) is the worst response. That is, the conductive fabric has unignorable resistance in the longitudinal direction, which slightly prevents current flow from the taxel to the current detecting circuit. Thus, the variance can be corrected by calibration after constructing the sensor because the cause of the variance is not a noise but a structural factor. Furthermore, the variance can be decreased by improvement of the configuration, for example, change of the cutting shape of the conductive fabric, or use of the conductive fabric with smaller resistance.

The void for avoiding erroneous reaction is an important design parameter to adjust the sensitivity of the sensor. Applied force on the sensor is at first supported by the parts other than the void parts until the void is crushed and the inner conductive components contact each other. Thus, the larger and thicker the supporting parts are, the less sensitive the sensor becomes against weak force. We actually found that the structure without void had high sensitivity to normal force. Therefore, the sensitivity of the sensor can be adjusted to its usage by changing the width and the thickness of the void or changing the modulus of elasticity of the supporting parts.

V. CONCLUSIONS

This paper proposed a novel configuration of a tough, bendable and stretchable tactile sensors array for covering a robot surface. These mechanical properties are brought about by constructing the sensor with conductive fabrics, pressure-conductive rubber sheets, and silicone rubber covering the entire pressure sensitive part. This paper also proposed a compact data acquisition circuit for scanning the tactile sensors array. Each tactile element can detect normal force of 0.7N $\sim$ 3N with less hysteresis and high repeatability. Distributed load is accurately detected without a wraparound current. The toughness of the sensor enables its operation even if it is subjected to impact force, bending load, or tensile stress. Owing to these characteristics, the sensor is expected to be used in various scenes where strong force acts on robot surfaces. Our future work is to implement the sensor to a robotic hand which has soft surfaces at the gripping parts. We measure the output of the sensor and investigate what information can be obtained while the hand is grasping various objects or contacting with environments.

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