A Flexible and Stretchable Tactile Sensor utilizing Static Electricity

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Abstract—The tactile sensor is required for various robots. In humanoid robots, flexibility of the sensor is an important feature for preventing physical damage and for interacting with the human. Moreover, stretchability of the sensor has advantages that the sensor is nonbreakable and that the sensor can be easily mounted on curved surfaces or deformable parts such as joints. This paper proposes a novel tactile sensor made of flexible and stretchable silicone rubber. A structure of the sensor is similar to the capacitive tactile sensors. However, the proposed sensor utilizes a different principle from existing sensors. The sensor utilizes static electricity and electrostatic induction phenomenon, and can detect some touch conditions. This paper reports the principle and characteristics of the proposed sensor. Experiments show that the sensor output depends on touch area, touch velocity, and material of touch objects. However, the sensor does not depend on touch weight. Moreover, the experiment shows that even if the proposed sensor is stretched, it performs as the tactile sensor.

I. INTRODUCTION

The tactile sensor is required for various robots such as robot hands and humanoid robots. In some humanoid robots, the tactile sensor is utilized to interact with the human. For example, when many humans interact with the humanoid robot such as Robovie shown in Fig.1, they often try to stroke a robot’s head, to hug the robot, or to shake hands. To recognize such communications, some humanoid robots have the tactile sensor over the robot’s whole body.

Flexibility and stretchability of the tactile sensor are important features for the humanoid robots. If a surface of the humanoid robot is soft, uncomfortable feeling when they hug the humanoid robot may be reduced. Moreover, the flexibility is expected to improve safeness. The stretchability of the sensor has advantages that the sensor is nonbreakable and that the sensor can be easily mounted on curved surfaces or deformable parts such as joints. However, many existing tactile sensors [1]–[5] have flexibility, but do not have stretchability. Hoshi and Shinoda [6] proposed flexible and stretchable robot skin made of conductive fabric and urethane foam. However, they do not discuss the sensor output when the skin is stretched.

Some tactile sensors are implemented to the body of the humanoid robot. Tajima et al. [7] proposed a distributed tactile sensor made of conductive fabric and gel. Ohmura et al. [8] proposed a tactile sensor that the sensor elements were mounted on a flexible printed circuit board. Miyashita et al. [9] proposed a robot skin that piezoelectric films were embedded in silicone rubber. These tactile sensors have flexibility, but do not have stretchability.

This paper proposes a flexible and stretchable tactile sensor which is expected to be suited for humanoid robots. The sensor can detect touch and release by using static electricity and electrostatic induction. The static electricity and the electrostatic induction are well-known phenomena from old times. However, authors do not know an example that these phenomena were utilized as the tactile sensor. By using the static electricity, the sensor consists of only charged bodies and conductive material, and has very simple structure. In this paper, the sensor is made of soft silicone rubber because the sensor is expected flexible and stretchable. Characteristics of the sensor are investigated by some experiments.

A remainder of this paper is organized as follows. First, the principle of the sensor is introduced. The principle is based on the static electricity and the electrostatic induction phenomenon. Then, several experimental results are shown.
to demonstrate characteristics of the sensor. Moreover, the experiment shows that even if the sensor is stretched, it performs as the tactile sensor.

II. PRINCIPLE OF THE SENSOR

A principle of the proposed tactile sensor is shown in Fig. 2. Fig. 2a shows the structure of the sensor system. The sensor consists of a base sheet at the bottom of the sensor, a conductive wire on the base sheet, and a charged body on the conductive wire. The conductive wire is connected to the ground through a resistor R. A voltmeter V measures voltage between the wire and the ground. The structure of the sensor is similar to capacitive tactile sensors. However, the principle of the proposed sensor is different from the existing tactile sensors. The existing capacitive tactile sensors measure the change of the capacitance whereas the proposed sensor measures the static electricity. In the proposed sensor, when an object touches the charged body of the sensor, the static electricity occurs in the object and the sensor. Moreover, at this time, the static electricity generates the electrostatic induction in the wire. Therefore, the charged body and the conductive wire are performed as the tactile sensor by measuring the voltage of the electrostatic induction.

Each step of the principle is described in the following. All objects are discharged on initial condition shown in Fig. 2a. At a first step shown in Fig. 2b, the static electricity occurs in the sensor and the object when the object touches the sensor. However, the electrostatic induction does not occur, and the voltmeter indicates 0 V because the quantities of the positive and negative electric charge are the same. In the figure, the object and the sensor are charged to the positive and the negative, respectively. Fig. 2c shows a second step. When the object is released from the charged body, the electrostatic induction occurs in the wire because of effect of the negative charge in the charged body. In other words, the positive charges are collected under the charged body, and the negative charges are collected at near the resistor. Therefore, the voltmeter indicates negative value. At a third step shown in Fig. 2d, the charges move to the ground because the wire is connected to the ground through the resistor, and the voltmeter indicates 0 V. At a fourth step shown in Fig. 2e, when the positive charged object approximates to the sensor, the electrostatic induction occurs in the wire again. At this step, the positive charges are collected at near the resistor, and the voltmeter indicates the positive value. A reason that both the charged body and the wire are charged to the negative is the difference of the quantity of charge between the object and the sensor. At a final step shown in Fig. 2f, the charges move to the ground, and the voltmeter indicates 0 V. Therefore, the proposed sensor can detect touch and release by the principle.

We discuss a characteristic of the static electricity. The work functions of each object are the important factor to decide whether the object is charged to positive or negative. The electrons in an object which has the low work function move to another object easily. In other words, the electrons in the object which has the low work function reduce, and the object is charged to positive. If there are objects which have the higher or lower work function than the proposed sensor, the sensor output when the objects touch the sensor is not constant; the positive or negative value is observed when the objects touch the sensor. Therefore, the material of
the charged body of the sensor should have the very low or high work function for stable sensor output.

III. EXPERIMENT

A. Experimental Setup

A structure of the developed tactile sensor is shown in Fig.3. Fig.3a shows a top view of the sensor. A square sensor element and a wire for connecting the element to an amplifier are printed on a insulated silicone rubber sheet. The shape of the sensor element is arbitrary. A cross sectional view of the sensor is shown in Fig.3b. The sensor element is sealed in the insulated silicone rubber. In addition, the sensor element can be made of arbitrary materials as is clear from the principle of the sensor. For example, if the aluminum foil is sealed in the insulated silicone rubber, it performs as the tactile sensor. In this study, we use the conductive silicone rubber (Fujikurakasei XA-819A) as the sensor element and the conductive wire which can be stretched nominal 180% [10].

A developed tactile sensor is shown in Fig.4. The size of the sensor element is square 10 mm on a side. The output of the sensor element is connected to an amplifier shown in Fig.5. The amplifier is a noninverted amplifier and is connected to an A/D converter. The resistors Rs and Rf equal 10k Ω. Therefore, the amplifier doubles the sensor output. A resistor Ri is the input impedance and equals 1M Ω.

B. Characteristics

The sensor output when a human finger touches the sensor is shown in Fig.6. From this figure, the positive value is observed when the finger touches the sensor. The sensor output returns to 0 V shortly after the touch. In contrast, the negative value is observed when the finger releases from the sensor. This output characteristic is observed at some objects which are made of different materials. Additionally, the characteristic may change as is pointed out in the section II if the sensor is made of different materials. The silicone rubber used in this study is charged to negative very strongly. Therefore, the positive sensor output is observed when almost all the objects touch the sensor.

We perform four experiments to investigate the output characteristics of the developed sensor: 1) a response to some weights, 2) a response to some areas of the sensor element, 3) a response to some touch velocities, and 4) a response to some materials of the touching object. In 1) to 3) experiments, we use an object R for touching the sensor. It is a cylinder made of acrylic resin (diameter = 20 mm, height = 40 mm), and a natural rubber sheet is pasted on the bottom surface. In addition, the experiments 2) to 4) are iterated 50 times for each experimental condition.

The first experiment shows a response to some weights. The object R is put on the sensor element on initial condition, and the weight is changed by a compression testing machine. Time courses of the weight and the sensor output are shown in Fig.7. The weight varies 0 N to 12 N continuously, but the sensor output continues to indicate 0 V. The static electricity occurs when the object touches or rubs the sensor. However, in the experiment, the object is only put on the sensor. Therefore, the static electricity does not occur, and the sensor does not respond to the weight. In addition, the vibration is observed in the time course of the weight. A reason is that the noise from a motor in the compression testing machine affects a load transducer.

The second experiment shows a response to some areas
The sensor output when the human touches the sensor

The upper and lower figure show the time courses of the weight and the sensor output, respectively.

The relationship between the sensor output and the area of the sensor element

The relationship between the sensor output and the height of fall

of the sensor element. The areas of the sensor element are 25, 50, 100, 150, and 225 mm². The object R is dropped from 30 mm height and the sensor output is measured. Because of bounce of the object, the sensor output is vibratile signal. Thus, we consider a first peak of the sensor output in each trial as a trial result. Fig.8 shows averages and standard deviations of peaks of all trials. The figure shows that amplitude of the sensor output is varied by the area of the sensor element. A reason that the sensor output is related to the area of the sensor element is as follows. If the area of the sensor element is large, the quantity of the electric charge by the electrostatic induction is also many. Moreover, much time is required for that the many charges flow to the ground through the resistor R. Therefore, the voltage at the sensor element is held a high level for a long time. In contrast, if the quantity of the electric charge is few, the charges flow to the ground immediately, and the voltage of the sensor element is not held a high level.

The third experiment shows a response to some touch velocities. The touch velocity is changed by modifying the drop height to 10, 30, 50, 70, and 90 mm. In addition, the area of the sensor element is 100 mm². Fig.9 shows averages and standard deviations of peaks of all trials. The result shows that the sensor output is varied by the drop height. In other words, the sensor output is varied by the touch velocity. A reason that the sensor output is related to the touch velocity is similar to the reason described in the previous paragraph. If the touch velocity is slow, the electric charges by the electrostatic induction flow to the ground before observing the sensor output, and the sensor output is low. In contrast, if the touch velocity is fast, much time is required for that the charges flow to the ground, and the sensor output is high.

Finally, the fourth experiment shows a response to some materials of the touching object. In this experiment, the area of the sensor element and the drop height is 100 mm² and 30 mm, respectively. The dropped objects are an aluminum cylinder (diameter = 20mm, height = 30mm), an acrylic resin cylinder (diameter = 20 mm, height = 40mm), a polyethylene sheet, a copier paper, and a natural rubber sheet. To make
Fig. 10. The sensor output for each material

Fig. 11. Two photographs show the same tactile sensor element. The element shown in an upper photograph is unstretched. A lower photograph shows the same element which is stretched triple length to the lateral direction.

C. Stretchable Tactile Sensor

In this study, the stretchable conductive silicone rubber is utilized as the tactile sensor element. Therefore, even if the element is stretched by external force, the sensor is expected to perform as the tactile sensor. The sensor output when the sensor is stretched is investigated by the experiment. Fig.11 shows a tactile sensor utilized in the experiment. An upper photograph shows an unstretched tactile sensor that the size is 5×5 mm. The sensor shown in a lower photograph is the same sensor but is stretched to triple length. As a result, the size of the sensor element is changed to 15×3.5 mm.

In the experiment, two sensors are tested as the stretchable sensor. The size of a tactile sensor element A is 5×5 mm. The elongation percentages of the element A are 100% and 200%. The size of another sensor element B is 10×10 mm. The elongation percentages of the element B are 25% and 50%. At before and after the stretch, the sizes and the areas of the sensor elements are shown in Table I. After stretching the sensor, the sensor output when the object R used in the previous section is dropped from 30 mm height is measured. An example of the sensor output is shown in Fig.12. The figure shows that the sensor performs as the tactile sensor even if the sensor is stretched. Moreover, the experiment is iterated 50 times for each elongation percentage. Averages and standard deviations of peaks of all trials are calculated and compared with Fig.8. A result is shown in Fig.13. The figure shows that the sensor output depends on the area of the sensor element.

Table I: The Sizes and Areas of the Sensor Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Unstretched</th>
<th>100% Stretched</th>
<th>200% Stretched</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5×5 mm</td>
<td>10×4 mm</td>
<td>15×3.5 mm</td>
</tr>
<tr>
<td></td>
<td>25 mm²</td>
<td>40 mm²</td>
<td>52.5 mm²</td>
</tr>
<tr>
<td>B</td>
<td>10×10 mm</td>
<td>12.5×9.25 mm</td>
<td>15×8 mm</td>
</tr>
<tr>
<td></td>
<td>100 mm²</td>
<td>118.75 mm²</td>
<td>120 mm²</td>
</tr>
</tbody>
</table>

IV. CONCLUSION AND FUTURE WORK

This paper proposed the novel tactile sensor utilized the static electricity and the electrostatic induction phenomenon. The sensor consisted of the charged body and the conductive sensor element only. Additionally, the structure of the sensor was very simple. The arbitrary materials were utilized as the sensor. In this paper, the conductive and the insulation silicone rubber were utilized as the sensor element and the charged body, respectively. Therefore, the developed sensor was flexible and stretchable. The experiments showed that the sensor output depends on the area of the touch, the velocity of the touch, and the material of the object. However, the sensor did not respond to the weight. Moreover, the sensor output when the sensor was stretched was investigated. The result showed that even if the sensor had been stretched, the sensor could detect touch and release. Additionally, the stretched sensor output also depended on the area of the sensor element.

The proposed sensor does not to respond to the weight as described above. In general, the characteristic is seemed as
Fig. 12. This figure shows an example of the sensor output after stretching the sensor element A to triple length. Even if the sensor is stretched, the sensor detects touch and release of the object.

Fig. 13. The results in the section III-C are superimposed on Fig. 8. The sensor output depends on the area of the sensor element even if the sensor is stretched.

In the future work, we investigate the other characteristics of the sensor: rubbing, rolling, and vibration. Additionally, to avoid the depending on the condition of the sensor surface, the other structure of the sensor is proposed. Moreover, we apply the sensor to a humanoid robot for demonstrating advantages of the sensor. We expect that the sensor is suited to detect stroking.

REFERENCES


