Development of Flexible Contact Sensor for Normal Load and Normal Load Position Measurement using Hemispherical Elastic Body

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Abstract

To prevent objects from dropping due to ineffective grasping, robotic hands need to be covered with flexible sensors to determine the magnitude, position, and direction of the applied load. In the present study, a novel sensor was developed, that consists of a hemispherical elastic body and a load measurement layer; the latter is composed of a pressure-sensitive electrically conductive material sandwiched between an upper and a lower electrode. Changing the load on the pressure-sensitive material causes its internal resistance to vary. This gives rise to a change in the voltage measured between the upper and lower electrodes, and allows the load on the sensor to be determined. This study focused on the application of a normal load to different positions on the sensor. The dependence of the voltage change on the magnitude and position of the load was investigated.

Key words
Sensor, Flexible Structure, Robotic Hand, Elasticity, Measurement

1. Introduction

The shrinking birthrate and aging Japanese society has led to a decrease in the number of individuals working in the medical and healthcare industries. Therefore, there is a growing interest in humanoid robots that can care for the aged and for young children. In these situations, humanoid robots must be more cautious about their surroundings because they interact with humans directly, and there are obstacles and unpredictable events around them. To ensure safety, humanoid robots need to be built with softer covers and more effective tactile sensors that are capable of determining the contact load, load position, and load direction[1]. Furthermore, technology developed for robots can lead to the realization of prosthetic limbs and robotic hands that can assist with nursing care and welfare[2]. A robotic hand must be able to adaptively grip objects with different shapes, sizes and levels of hardness. To avoid damaging an object, the applied load must not be too large. In addition, to prevent dropping an object, the magnitude, position and direction of the applied load must be known. Ideally, this information should be determined by sensors installed in flexible, deformable fingertips with contact regions that are close to being hemispherical in shape[3].

Using standard pressure sensing technology, an optical waveguide-type tactile sensor capable of measuring normal and shear forces was developed[4]. However, this type of sensor was difficult to integrate into a small region because it requires a CCD camera. Later, a sensor using pressure-sensitive conductive rubber[5] and a composite sensor containing electrically conductive carbon black powder mixed with a polymer[6] were developed, but these sensors could only measure normal loads and were unable to detect the load direction.

Thus, a flexible contact sensor for three-axis load measurement using an elastic body and a pressure-sensitive conductive material has been developed in a previous study[7, 8]. The sensor has a load detection layer composed of multiple zones. It is possible to separately measure the shear component and components of the load based on the relationship among the voltage changes in each zone. However, the sensor cannot measure the load applied to any position. So, it cannot be used in robot hand that grips the object of various shapes. And, the relationship between the voltage change and the load position is not known for this sensor. Further, measurement of the magnitude of the load is required to prevent falling grasping objects.

In the present study, a novel sensor using a hemispherical elastic body and a load measurement layer was developed for use in the fingertips of a robotic hand. The sensor is capable of determining the magnitude, position and direction of the applied load. To investigate the effectiveness of this sensor, normal loads were applied and the dependence of the voltage change on the magnitude and position of the load was investigated.

2. Structure of the Sensor

Figure 1 shows a schematic of the proposed sensor structure. It contains a flexible hemispherical elastic body and a load measurement layer[7, 8]. The hemispherical elastic body is made from silicon rubber, and has a radius of 30 mm. The load measurement layer has a stacked structure consisting of a lower electrode, a fixing film, a pressure-sensitive conductive material, and an upper electrode. The pressure-sensitive layer is a mixture of 20 wt% vapor grown carbon fiber and polycarbonate (PC/VGCF), and has dimensions of $65 \times 65 \times 0.1$ mm. Further, VGCF is dispersed in the material[9, 10]. The upper electrode and the lower electrode are made from thin layer of copper alloy. In addition, the upper electrode is formed on a flexible polyimide, and the lower electrode is formed on a glass epoxy sheet. The upper electrode is divided into four zones as shown in Fig. 1 (Zones 1-4, travelling counter-clockwise).

Figure 2 shows the equivalent circuit diagram for the sensor. Fixed resistances with $R = 100 \ \Omega$ are connected in parallel to each of the electrode zones. The power supply voltage $V_s$ is 9 V. Since the resistance of the PC/VGCF layer changes with applied pressure, the load can be determined by measuring the voltage $V_m (m = 1, 2, 3, 4)$.
across the upper and lower electrodes, and evaluating the voltage change $dV_m (m = 1, 2, 3, 4)$ due to the presence of the load.

3. Experimental Methodology

The experiments were carried out using Compact Table-Top Universal Tester (EZ-L-500N, Shimadzu corporation). A normal load $P_n$ was applied to different positions on the sensor, and the dependence of the voltage change in each zone on the magnitude and position of the load was investigated. A normal load $P_n$ is perpendicular to the x-y plane of the sensor. As shown in Fig. 3, the load position was defined using polar coordinates. The angle $\phi$ is measured counter-clockwise from Zone 1 and $\Delta r$ is the distance from the central axis of the sensor. The angle $\phi$ was set to 0, 15, 30 or 45° and $\Delta r$ was set to 0, 5, 10 or 15 mm. A hemispherical indenter with a diameter of 5.0 mm was used to compress the sensor. The cross head speed was 3.0 mm/min, and the total displacement was 15 mm. Figure 4 shows the flowchart of experimental.

4. Experimental Results and Discussion

4.1 Calibration of the voltage of the sensor

Figure 5 shows the dependence of the voltage $V_m$ on the applied load $P_n$ in each zone for $\phi = 0^\circ$ and $\Delta r = 0$ mm. It can be seen that $V_m$ decreases with increasing $P_n$. The curves overlap because the load is being applied to the center of the sensor.

Figures 6(a) and 6(b) shows the dependence of the voltage change $dV_m$ on $P_n$ in each zone for $\phi = 0^\circ$ and $\Delta r = 0$ and $\Delta r = 15$ mm, respectively, and $\phi = 0^\circ$. In Fig. 6(a), the curves overlap because the load is being applied to the center of the sensor. However, Fig. 6(b) corresponds to the case where the load is being applied within Zone 1, and $dV_m$ is largest for Zone 1 and smallest for the opposing Zone 3, with Zones 2 and 4 being intermediate. Further, the dependence of voltage change $dV_m$ on load $P_n$ in each zone is non-linear from Fig. 6(a) and 6(b). Therefore,
substituting the voltage change of each zone in Eq. (1), (2), (3), (4) is respectively the voltage change of each zone $\Delta V'_m$ ($m = 1, 2, 3, 4$).

Figure 7 shows the relationship between $\Delta V'_m$ and $dV_m$ for $\Delta r = 0$ mm. This relationship can be used to create master curves allowing the applied load in each zone to be determined from the measured voltage change. The data in Fig. 7 can be approximated by the following cubic functions, based on least squares fitting.

$$\Delta V'_1 = 0.0744dV^3 - 0.1986dV^2 + 0.3400dV'_1$$  \hspace{1cm} (1)

$$\Delta V'_2 = 0.0627dV^3 - 0.1315dV^2 + 0.3108dV'_2$$  \hspace{1cm} (2)

$$\Delta V'_3 = 0.0707dV^3 - 0.1790dV^2 + 0.3288dV'_3$$  \hspace{1cm} (3)

$$\Delta V'_4 = 0.0849dV^3 - 0.2128dV^2 + 0.3448dV'_4$$  \hspace{1cm} (4)

Figure 8 shows the dependence of the voltage change $\Delta V'_m$ on $P_n$ in each zone for $\phi = 0^\circ$ and $\Delta r = 0$ mm. In Fig. 8, dependence of the voltage change on applied load is in the linear.

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Fig. 5 Dependence of measured voltage $V_m$ ($m = 1, 2, 3, 4$) on applied load $P_n$ for $\Delta r = 0$ mm

Fig. 6 Dependence of voltage change $dV_m$ ($m = 1, 2, 3, 4$) on load $P_n$ in each zone for (a) $\Delta r = 0$ mm and (b) $15$ mm

Fig. 7 Relationship between voltage change $\Delta V'_m$ ($m = 1, 2, 3, 4$) and voltage change $dV_m$ ($m = 1, 2, 3, 4$) for $\phi = 0^\circ$ and $\Delta r = 0$ mm

Fig. 8 Dependence of voltage change $\Delta V'_m$ ($m = 1, 2, 3, 4$) on load $P_n$ in each zone for $\Delta r = 0$ mm
4.2 Determining the distance from the sensor center

To determine the distance of the load application point from the sensor center, the overall voltage change $V$ is first determined using Eq. (5). The $x$ and $y$ components of $V$ are then described by Eq. (6). The amount voltage change $\Delta V$, which depends on $\Delta r$, can then be expressed as shown in Eq. (7).

\[ V = dV_1 + dV_2 + dV_3 + dV_4 \]  
\[ V_x = dV_1 - dV_2 \quad , \quad V_y = dV_2 - dV_4 \]  
\[ \Delta V = \sqrt{V_x^2 + V_y^2} \]

Figure 9 shows the dependence of $\Delta V$ on $V$ for $\Delta r = 0, 5, 10$ and $15$ mm, and $\phi = 0^\circ$. In Fig. 9, dependence of voltage change $\Delta V$ on total voltage change $V$ is changing the boundary when $5V$ value of the total voltage change. The slope of the straight lines in the graph is defined as the sensor coefficient $k_1$ and $k_2$, and is given by the following equation.

\[ k_1 = \frac{\Delta V}{V} (0 \leq V \leq 5) \]  
\[ k_2 = \frac{\Delta V - a}{V} (5 \leq V) \]

Figure 10 shows the relationship between $k_1$ and $\Delta r$ in the case of total voltage change is less than $5V$. It is seen to be linear, and can be approximately expressed as

\[ \Delta r = 39.4k_1 \]  

Figure 11 shows the relationship between $k_2$ and $\Delta r$ in the case of total voltage change is more than $5V$. It can be approximately expressed as

\[ \Delta r = -375k_2^2 + 151k_2 \]

This means that if $k_1$ and $k_2$ are determined for each zone, Eq. (9) and (10) can be used to calculate the distance of the load position from the center of the sensor. Figure 12 shows the relationship between the calculated value of $\Delta r$ and total voltage change $V$ for $\phi = 0^\circ$, which was applied at arbitrary positions on the sensor, with true $\Delta r$ values of 0, 5, 10 and 15 mm. In Fig. 12, this sensor can be seen that the distance $\Delta r$ from the center of the sensor can be measured. Figure 13 shows the relationship between the calculated value of $\Delta r$ and total voltage change $V$ for $\phi = 15^\circ$. In Fig. 13, this sensor can be seen that the distance from the center of the sensor $\Delta r$ can be measured in case of changing the angle $\phi$.

4.3 Determining the angle $\phi$

To determine the angle $\phi$, the $x$ and $y$ components of $V_x'$ and $V_y'$ are determined using Eq. (12). And the overall voltage change $V'$ is determined using Eq. (13).

\[ V_x' = \Delta V_1' - \Delta V_3' \quad , \quad V_y' = \Delta V_2' - \Delta V_4' \]  
\[ V' = \Delta V_1' + \Delta V_2' + \Delta V_3' + \Delta V_4' \]
Therefore, angle $\phi$ is the difference between the angle $\phi_0$ and error of the angle $e$. It can be approximately expressed as

$$\phi = \phi_0 - e$$

Figure 16 shows the relationship between the calculated value of $\phi$ and total voltage change $V$ for $\Delta r = 15$ mm, which was applied at arbitrary positions on the sensor, with true $\phi$ values of 0, 15, 30 and 45°. In Fig. 15, error occurs in the measured value. The reason is considered to the error of the angle $e$ is not constant in the range of low load. Therefore, it is necessary to control the measurement area by preload.

Figure 14 shows the relationship between $V_y'$ and $V_x'$ for $\phi_0 = 0, 15, 30$ and 45° ($\Delta r = 15$ mm)

![Fig. 12 Relationship between the calculated value of $\Delta r$ and total voltage change $V$ ($\phi = 0^\circ$)](image1)

![Fig. 13 Relationship between the calculated value of $\Delta r$ and total voltage change $V$ ($\phi = 15^\circ$)](image2)

![Fig. 14 Relationship between $V_y'$ and $V_x'$ for $\phi = 0, 15, 30$ and 45° ($\Delta r = 15$ mm)](image3)

![Fig. 15 Relationship between error of the angle $e$ and angle $\phi_0$](image4)

$$\phi_0 = \tan^{-1} \frac{V_y'}{V_x'} = \tan^{-1} \frac{\Delta V_y' - \Delta V_x'}{\Delta V_y' - \Delta V_x'}$$

$$e = 0.0116\phi_0^2 - 0.517\phi_0$$
4.4 Determining the load magnitude

Figure 17 shows the dependence of the total voltage change $V'$ and the applied load $P_n$ for different values of $\Delta r$. It is seen to be linear in the range of load is less than 30N, and can be approximately expressed as

$$P_n = 2.54V'$$

(17)

This means that if $P_n$ is determined for each zone, Eq. (17) can be used to calculate the applied load. However, total voltage change is decreasing the distance of the load position from the center of the sensor with an increase in the range of load is more than 30N. The reason is considered to the height of the elastic body is changed by increasing the distance of the load position from the center of the sensor.

5. Conclusions

The goal of the present study was the development of a sensor that can measure the magnitude, position and direction of an applied load. A sensor using a hemispherical elastic body and a load measurement layer was developed and its performance was evaluated. The sensor was divided into four separately measurable zones. By applying a normal load to different positions on the sensor and measuring the voltage change in the four zones, the following results were obtained:

1. The magnitude of the applied load could be determined by measuring voltage change in each zone in the range of load is less than 30N.
2. The polar coordinates of the load position could be determined from the load applied to each zone in the range of total voltage change is more than 2V.

By measuring the voltage change associated with the load, it is possible to determine the location and magnitude of the normal load in the case of certain conditions. Figure 18 shows the flowchart of measurement.

The present study was carried out using a relatively large sensor, and miniaturization will be required in order to use such sensors in the fingertips of robotic hands. This will be a subject for future work.
Nomenclature

- $e$: error of the angle
- $k_1$: sensor coefficient in the case of total voltage change is less than 5V
- $k_2$: sensor coefficient in the case of total voltage change is more than 5V
- $P_n$: applied load
- $\Delta r$: distance from the center of the sensor
- $dV_m$: voltage change
- $\Delta V_m'$: voltage change was calibrated to linear
- $V_x$: $x$ components of voltage change
- $V_y$: $y$ components of voltage change
- $\Delta V$: amount voltage change
- $V_x'$: $x$ components of voltage change was calibrated to linear
- $V_y'$: $y$ components of voltage change was calibrated to linear
- $V'$: total voltage change was calibrated to linear
- $\phi$: the angle

References


