1. Introduction

Many studies on humanoid robots, which imitate human figures, are being conducted\(^1\). The essential elements for a humanoid robot include appearance, brain capable of thinking in the same manner as humans do, limbs capable of moving dexterously, and sensors controlling five senses. The sensors hold the key to allow these robots to further imitate humans. Among the sensory organs, a visual sensor and a tactile sensor are particularly important. For the visual sensor, with an advance in semiconductor technology, inexpensive high-resolution miniature cameras and high-speed cameras are being developed.

In contrast, compared with the visual sensor, the tactile sensor has made slow progress. The typical tactile sensors include a touch panel sensor and an industrial pressure sensor. The former, the touch panel sensor, is capable of making measurement on a wide surface; however, no practical sensor has not been developed, which has the ability to detect exclusively not only whether the sensor has come into contact with an object but also the strength of the contact force. The latter, the industrial pressure sensor, for measuring precise values according to its applications, is made of strong and hard solid materials. The solid sensor attached to the robot hand, when grasping objects, may damage a grasped object in the hand due to its hardness. To avoid such accidents, the tactile sensor made of soft materials need to be attached to the robot hand and fingertips, which grasp objects. The future robots will be requested to perform works using tools. For the robots to manipulate the tools skillfully, three-dimensional force information: i.e. contact position, direction of force, and force strength, must be provided to the robot hand and fingertips. Thus, the tactile sensors for robot hands need to have the soft detection face and the ability of three-dimensional force information.

The sensor type, which may serve as the tactile sensor, with a soft detection face, capable of detecting three-dimensional force information, includes an optical tactile sensor composed of a flexible elastomer and a camera. The optical tactile sensor has two advantages of: 1) low occurrence of failure because of less electronic connections; and 2) being capable of dealing easily with different sizes of two-dimensional target surfaces for detection because of two-dimensional images being provided. The studies on the optical tactile sensors include, for example, those, of which objective is to detect
the force strength and contact position on the images of the behavior of a dye embedded in the elastomer, which has been acquired by a camera. It should be noted that the design of this sensor type involves the step of embedding a dye within the elastomer, requesting the expertise of manufacturing elastomers. The study on another type of tactile sensors is also being conducted, in which a layered light (slit light) is irradiated to acquire the images of deformation of the elastomer as a contour by a camera, and based on the acquired image information, the force strength and direction, and contact position are detected. Additionally, the other study have been conducted, in which the tactile sensor using the layered light was miniaturized to the size attachable to the fingertip of the robot hand.

The aforementioned tactile sensor using the layered light approximates the deformation of the elastomer by cubic polynomials according to the relationship in Young's modulus between the elastomer and its deformation. To find the parameters of the cubic polynomials, information on four points are required. The information on two points, the vertex of the elastomer and the fixing point of the elastomer, may be easily obtained. To find the information on the remaining two point, two-layer slit lights. A slit is used between two-layer slit lights to avoid interference with each other, imposing a restriction on miniaturization of the tactile sensors.

On the other hand, to attach the tactile sensor to the finger pulp of the robot hand, the tactile sensor need to be shaped into a small size, as well as into a convex tailored to the finger pulp.

To meet this requirement, this study first uses two layers of thin, soft elastomer membranes, between which a mushroom-shaped connector is inserted, so that the detection face of the tactile sensor is forced to be shaped into a flat form and the sensor has the capability of detecting three-dimensional information on the aforementioned images drawing a contour with the convex-shaped detection face. Based on that, an attempt to miniaturize the tactile sensor was made in the present study to reduce the number of the slit light layers.

2. System Configuration

2.1 Hardware

The tactile sensor proposed in this study is capable of detecting information using an algorism involving the steps described below. First, applying a force on an elastomer membrane causes it to be deformed. Next, a slit light is irradiated on the deformed elastomer membrane to acquire its image by a camera as a coarse contour line. Then, from the acquired image, the intersection of the slit light and the long axis or short axis of the contour line is found. Finally, based on the correlation between positional coordinates, which have previously learned the image information, and force information, three-dimensional information on the force applied on the elastomer membrane is evaluated.

Fig. 1 shows a proposed tactile sensor composed of a soft elastomer membrane and a mushroom-shaped connector. Fig. 2 shows the cross-sectional view of the tactile sensor. The tactile sensor is made of three main components: a cylindrical housing containing a slit light member, an ultra-miniature camera, and a convex-shaped detection face formed by the soft elastomer membrane and the mushroom-shaped connector. In this study, the cylindrical housing containing the slit light member, which had been used in our previous study, was reused. The ultra-miniature CMOS camera (ACB-U04v2, Asahi Electronics Laboratory) used in the study is a compact camera commonly incorporated in mobile terminals, for example, cell-phones.

Fig. 3 shows the appearance and schematic view of the force detection face. The force detection face has been shaped into a convex to imitate the finger pulp of the human hand. This enables the force detection face to
make detection on a wider range of plane than a flat plane and prevents the tactile sensor housing from hitting against the target object. To shape the force detection face into a convex, the mushroom-shaped connector made of ABS resin is used. Moreover, the mushroom-shaped connector is inserted between two layers, each made of three soft elastomer membranes as shown in Fig. 3-(b). The first layer, which comes into contact with a body, is made of soft urethane resin (Hitohada gel®), which is ultra-soft urethane resin like human skin. The first layer has been fixed to the mushroom-shaped connector with an instant adhesive. The second and third layers are made of thin rubber films. The force applied onto the first layer is transmitted to the third layer through the connector. To detect the force, information on the deformation of the third layer is used. Moreover, the second layer with a through hole formed is retained by means of an elastic force of the rubber film to prevent the connector from being out of alignment.

The proposed sensor irradiates the slit light on the deformed portion of the rubber film of the third layer. The slit light enables the deformation of the elastomer membrane to be acquired by the camera as the contour line information. Then, three-dimensional force information is evaluated based on the acquired image. When a force is applied onto the detection face, the slit light is irradiated onto the elastomer membrane as shown in Fig. 4. The connector tilts toward the direction, in which the force is applied. Fig. 5 shows the movement of the tilting connector. As known from Fig. 5, when the connector moves, the force applied onto the first layer is transmitted to the third layer.

2.2 Fitting of an approximate curve to the deformation of the elastomer membrane

In our previous studies, cubic polynomials were used to approximate the deformation of the elastomer membrane. In this case, the cubic polynomials are derived from the correlation between Young’s modulus and distortion. Two points, one being the vertex of the deformation of the elastomer membrane and the other being the fixed point, can be easily found. To estimate the cubic polynomials, information on other two points is necessary. To acquire the information, in our previous studies, two layers of slit lights were used as shown in Fig. 4-(a). However, to use two layers of slit lights, it was required that a slit be installed in order to prevent the
slit lights from interfering each other. This has imposed limitation on the miniaturization of the tactile sensor.

On the other hand, when the deformation of the elastomer membrane is visually observed, it is considered that quadratic polynomials are sufficient to approximate the deformation of the elastomer membrane. When the deformation of the elastomer membrane is approximated using quadratic polynomials, information on three points to find the parameters. As described before, information on two points, the vertex and end point, may be easily obtained, obtaining information only on other one point is sufficient. Accordingly, as shown in Fig. 4-(b), only one layer of slit light may be used. Note that trade-off exists between the order of the approximate curve and estimation accuracy. If the deformation of the elastomer membrane is approximated suing quadratic polynomials rather than cubic polynomials, the accuracy in force detection may be deteriorated due to a reduction in approximation accuracy.

Then, a comparison was made between the accuracy when cubic polynomials were used and the accuracy when quadratic polynomials were used in approximating the deformation of the elastomer membrane. It was assumed that the deformation of the elastomer membrane formed, when a force was applied on the force detection face, be divided into the right and left halves as shown in Fig. 6. Five coordinate values for each half of the deformation were obtained and based on the coordinate information, approximation was made using either of the cubic polynomials and quadratic polynomials.

The results were shown in Fig. 7. Figs. 7-(a) and 7-(b) show the results of the approximation of the deformation of the elastomer membrane using the cubic polynomials. Figs. 7-(c) and 7-(d) show the results the approximation of the deformation of the elastomer membrane using the quadratic polynomials. As known from Fig. 7-(a), almost no error is observed between the approximate curve and the input point. However, in other cases, errors are observed between the approximate curve and the input point. The observed errors take almost the same levels of values. For this reason, it may be determined that even if the deformation of the elastomer membrane is approximated using the quadratic polynomials, the accuracy of force detection may be less affected.

2.3 Estimating the correlation in image processing between the images and the force

According to the previous section 2.2, in this study,
the deformation of the elastomer membrane was approximated using the quadratic polynomials. However, the deformation of the elastomer membrane is insufficiently approximated using the quadratic polynomials only to detect the force. This means that the step of converting the result of the approximation using the quadratic polynomials to force information is required. Two-dimensional information is obtained from the approximate curve. The use of the two-dimensional information with no modification leads to a large amount of calculation. To address this problem, the proposed tactile sensor uses the direct distance between the vertex of the deformation of the elastomer membrane and the obtained point to reduce the amount of calculation.

When a force is applied onto the detection face, the image as shown in Fig. 8-(a) can be obtained from the camera, which acquires the deformation of the elastomer membrane. When the image obtained from the camera is labelled for each of regions, the image as shown in Fig. 8-(b) can be obtained. To calculate the actually applied force, the image-processed information shown in Fig. 8-(b) is used. The processed image is divided into three layers: the layer of the shadow of the mushroom-shaped connector (namely, the vertex of the deformation of the elastomer membrane), the blue layer, and other peripheral layer. The information necessary for the divided image to detect the applied force can be represented as shown in Fig. 9. The information necessary to detect the applied force is estimated according to the process as described below. First, with no force applied, the center point \( C_0 \) of the elastomer membrane is found. When the force is applied, the layer of the shadow of the connector appears. The center point of gravity \( C_1 \) in the layer is obtained. Then, the straight line \( M_1 \) passing through \( C_0 \) and \( C_1 \) and the straight line \( M_2 \) intersecting \( M_1 \) are obtained. The points where the each of regions intersects with the straight lines \( M_1 \) and \( M_2 \) are obtained. The straight lines \( M_1 \) and \( M_2 \) extend in four directions from \( C_1 \); therefore, three intersection points in each direction, namely 12 intersection points in total, can be obtained. Then, the distance \( L_i \) \((i = 1 \text{ to } 12)\) between each of 12 intersection points and \( C_1 \) is obtained. The correlation between the distance \( L_i \) and the force \( F \) can be expressed as in the formula (1):

\[
\begin{align*}
F_x &= A + \sum_{i=1}^{12} a_i L_i \\
F_y &= B + \sum_{i=1}^{12} b_i L_i \\
F_z &= C + \sum_{i=1}^{12} c_i L_i
\end{align*}
\]

where, \( A, B, C, a_i, b_i, c_i \) are coefficients.

For the tactile sensor to detect the force, the values for these coefficients need to have been evaluated in advance. In this study, multi-regression analysis is used to calculate the values for the coefficients. In this case, the input values were measured using another sensor and a large amount of data sets corresponding to the distances \( L_i \) between 12 intersection points and \( C_1 \) were used to calculate the appropriate coefficients. The accuracy of the input values for the force \( F \) depends on the accuracy of output from the tactile sensor. For this reason, the use of another high-curacy sensor enables the accuracy of the proposed tactile sensor to be improved. The used another sensor will be described in detail in the next section.
2.4 Obtaining the parameters for deformation

When a strong force is radially applied on the tactile sensor at an angle, the layer of the shadow of the connector may overlap the blue layer in some cases. In such a case, the image is acquired by the camera as shown in Fig. 10-(a). Since this image have no blue layer, the method for detecting the force described in the section 2.2 cannot be used. To address this problem, the interpolation of the blue layer, which is lost from image due to being overlapped by the layer of the shadow of the connector, should be made. Fig. 10-(b) shows the image, on which the outline of the lost blue layer have been restored by interpolation using the method described below:

(1) Obtain the center point of gravity $G_1$.
(2) Obtain the straight line $M_1$ passing through the center point of gravity $G_1$ of the layer of the shadow and the center point $C_0$ of the elastomer membrane with no force applied.
(3) Obtain the straight line $M_2$ passing through the center point of gravity of the layer of the shadow and intersecting the straight line $M_1$. Each of lines can be obtained as shown in Fig. 11.
(4) Obtain the intersection $X_1$ between the straight line $M_1$ and the blue layer.
(5) Obtain two intersections $X_2$ and $X_3$ between the straight line $M_2$ and the blue layer.
(6) Obtain a circle $R_1$ passing through the three obtained intersections, $X_1$, $X_2$, and $X_3$. This circle may be assumed to be the outline of the lost blue layer.
(7) Obtain the intersection between the circle $R_1$ and the straight line $M_1$ assuming that the intersection other than $X_1$ is $X_4$.
(8) The others may be obtained from the intersections between the straight lines $M_1$ and $M_2$, and each of layers.

Assuming that this type of interpolation may be used to obtain 12 intersections, the force can be detected based on the information on deformation of the elastomer membrane as described in section 2.3.

3. Evaluation Experiment

The image-processing correlation between two-dimensional images obtained by the proposed tactile sensor and estimated three-dimensional information must have been learned in advance. In this study, to obtain force data for learning, a six-axis force sensor (XFS-PS P1, Nitta Corp.) was used. 350 force data for learning were used to obtain the values for coefficients necessary for calculating force information by multi-regression analysis. The coefficients obtained through learning were used to compare between the output from the tactile sensor and the output from the six-axis force sensor with the force entered other than the force data for learning. Two kinds of forces were entered as shown schematically in Fig. 12. It was assumed that the input pattern 1 be the force applied at the angle of 10 [deg] toward the center of the force detection face from the vertical direction. The input pattern 2 was assumed to be the force applied at the angle of 10 [deg] toward the middle point between the center and end of the force detection face from the vertical direction.

Fig. 13 shows the output results of $F_x$ and $F_z$ with the
input pattern 1 given. Moreover, Table 1 shows the error between the output from the tactile sensor and the output from the six-axis force sensor and the standard deviation of the error with respect to $F_z$, which has the largest force component. As known from Fig. 13, the proposed tactile sensor may output high-accuracy force information with a minor error 0.043[N].

The output results of $F_x$ and $F_z$ with the input pattern 2 give are as shown in Fig. 14. With respect to $F_z$, which has the largest force component, the error between the output from the tactile sensor and the output from the six-axis force sensor and the standard deviation of the error are as shown in Table 1. Although the error between 0.0921[N] and the input pattern 1 increased, force information could be output with a small error.

On the other hand, a delay in output was observed between the tactile sensor and the six-axis force sensor in some cases. This type of delay might occur due to a time lag in transferring the acquired camera images to the PC. Solving the problem of the delay may improve the error or the standard deviation of the error listed in Table 1, increasing the detection accuracy of the tactile sensor.

In the previous study $^4$, which used two-layer slit lights and a neural network for learning, with respect to $F_z$, the error between the output from the tactile sensor

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<th>at central point</th>
<th>at middle point</th>
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<tr>
<td>averaged error [N]</td>
<td>0.043</td>
<td>-0.019</td>
</tr>
<tr>
<td>standard deviation of error</td>
<td>0.0921</td>
<td>0.1077</td>
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Table 1 Results of estimated force $F_z$. 

4. Conclusion

Fig. 12 Pushing of tactile sensor.

Fig. 13 Results of force estimation.

Fig. 14 Results of force estimation.
and the six-axis force sensor was $2.0 \times 10^{-7} \pm 0.171[N]$. In terms of the standard deviation of the error, in this study using a one-layer slit light, a smaller value for the error may be given. Once the problem of delay has been solved, it is estimated the error becomes smaller; therefore, with only one-layer slit light, high-accuracy output may be obtained compared with the tactile sensor using two-layer slit lights.

4. Conclusion

In this paper, the authors propose an algorithm for miniaturizing an optical tactile sensor using a thin, flexible elastomer membrane. Formed into the size of a human finger pulp, the tactile sensors may also be used as the sensors attached to the fingertips of a robot hand.

With regard to hardware, this tactile sensor is composed mainly of three components; a flexible elastomer membrane, a layered light, and an ultra-miniature camera. Irradiating a sheet-like light (namely, slit light) onto a deformed elastomer enables the deformation of the elastomer to be represented as a contour. Acquiring the images of this contour using the camera makes it possible to reflect stereoscopically the deformation of the elastomer. The two-dimensional images acquired from the camera are used to detect three-dimensional force information.

With respect to software, this optical tactile sensor approximates the deformation of the elastomer by polynomials to detect the force information. The prior studies conducted by the authors approximated the deformation of the elastomer by cubic polynomials. A two-layered light was used because four points need to be found to estimate the parameters for the cubic polynomials. In this study, the quadratic polynomials were used to approximate the deformation of the elastomer. For this reason, three points composed of two points, the fixed point and vertex of the elastomer, and one point acquired by one layer of the slit light, are sufficient to estimate the parameters, leading to the miniaturization of the sensor.

The force detection was shaped into a convex to imitate the finger pulp of the human hand. This enabled the force detection face to make detection on a wider range of plane than a flat plane and prevents the tactile sensor housing from hitting against the target object. To shape the force detection face into a convex, the mushroom-shaped connector made of ABS resin was used. Moreover, the mushroom-shaped connector is inserted between two layers, each made of soft elastomer membranes.

As a preliminary experiment, an experiment, where the images of the deformation of the elastomer membrane were acquired by the camera and approximate the deformation by the cubic and quadratic polynomials, was conducted. Based on this finding, we assumed that even though the quadratic polynomials were used to approximate the deformation of the elastomer membrane, the detection accuracy might be less affected because of small error between the cubic and quadratic polynomials. The method, where two-layered sheet-like light is used as in prior studies, requires the precise formation of slits to avoid interference between the two slit lights. In contrast, with the method for detecting force information, where one layer of sheet-like light is used to make approximation by the quadratic polynomials, no interference occurs, making it possible to miniaturize the sensor dramatically compared with the prior studies by the authors and the general light section method.

As an evaluation experiment, comparison of output was made between a 6-axis force sensor and the proposed tactile sensor. When a force was exerted at an angle of $10[^\circ]$ from the vertical direction toward the center of the elastomer, the error of vertical force $F_z$ was $0.043[N]$. This may be converted to the mass $5[g]$ or lower. Moreover, a force was exerted at an angle of $10[^\circ]$ from the vertical direction (as with the method above described) toward the middle point (namely, point equal to $1/4$ of the whole size of the elastomer) between the center and end of the elastomer, the error $F_z$ was $0.0921[N]$. This may be converted to the mass $10[g]$ or lower. It is suggested that the detection error $5[g]$ or lower at the center with higher detection frequency is sufficient to use with the tactile sensors of the fingertips of the robot hand.

A series of findings demonstrated that the algorithm for detecting force, which is proposed in this report, is effective. In addition, compared with the prior studies conducted by the authors, the proposed method has successfully achieved $5[mm]$ or more reduction of the height (thickness) of the tactile sensor.

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