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Real-time curvature estimation of printable soft gripper using electro-conductive yarn

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***Abstract*— Automatic handling of many types of food materials are required to realize the automation of production of commercially prepared box lunches. A printable soft gripper was developed for food handling which is simple to produce with a 3D printer. However, the sensing ability of the printable soft gripper was not discussed in previous research. In this paper, a novel method for estimating the curvature of a printable soft gripper using electro-conductive yarn is presented. Electro-conductive yarn is a conductive material, and the resistance of strings is changed by stretching. It is less expensive than other sensors that can be used for curvature measurement. Additionally, it is easy to assemble and disassemble by hand. Electro-conductive yarn is applied to a prototype printable soft gripper, and the proposed estimation method is verified experimentally. From the experimental results, the estimated curvature from the resistance of the electro-conductive yarn coincide with the actual curvature of the gripper. Our proposed method of using electro-conductive yarn was successful for estimating the curvature of a printable soft gripper.**

I. INTRODUCTION

Currently, several millions commercially prepared box lunches per day are consumed in Japan [1]. Therefore, automation of the production of the box lunches is required. To produce box lunches, the handling of food using a robot hand must be realized [2][3]. Hence, a printable soft gripper was developed for food handling which can grasp foods that are soft and easily deformed [4]. It is possible to use a 3D printer to easily produce the soft gripper. However, the sensing ability of the printable soft gripper to sensing is not discussed sufficiently in previous research. Bending of the printable soft gripper was successfully measured using a strain gage [5][6]. However, when using strain gages for measuring the bending of the printable soft gripper, the finger size of the gripper is limited by strain gage's size and the production cost of gripper increases.

In this research, we propose a novel method to estimate the curvature of the printable soft gripper using electro-conductive yarn [7][8]. Electro-conductive yarn is a very low cost conductive material, and the resistance of the strings is changed by stretching. Additionally, the sensor size can be determined by users.

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In this paper, a concept regarding the estimation of curvature using electro-conductive yarn is proposed. Then, the calibration method is presented. Finally, the proposed estimation method is applied to prototype printable soft gripper, and estimation result is verified by experiment.

The remainder of this paper is organized as follows: Section 2 presents estimation method for the curvature of a printable soft gripper. Section 3 shows calibration method for estimation setup. In Section 4, the electro-conductive yarn is applied to the prototype printable soft gripper, and proposed estimation method is experimentally verified. Section 5 concludes this paper.

II. ESTIMATION METHOD FOR THE CURVATURE OF A PRINTABLE SOFT GRIPPER

A. Concept of a printable soft gripper using electro-conductive yarn

Our proposed printable soft gripper using electro-conductive yarn and supplementary positioning of electro-conductive yarn is shown in Fig. 1. An electro-conductive yarn is attached to a surface of a finger. When a finger bends, the yarn extends accordingly. Fig. 2 shows a cross-section view of the electro-conductive yarn. When the air pressure is applied to the printable soft gripper, each chamber expands and the finger is bent. Then, the electro-conductive yarn is extended, and the cross area is decreased by Poisson's effect. The resistance of the electro-conductive yarn then decreases as each electro-conductive material is contacted, as shown in Fig. 2. The curvature of the printable soft gripper can be estimated using this change in resistance.

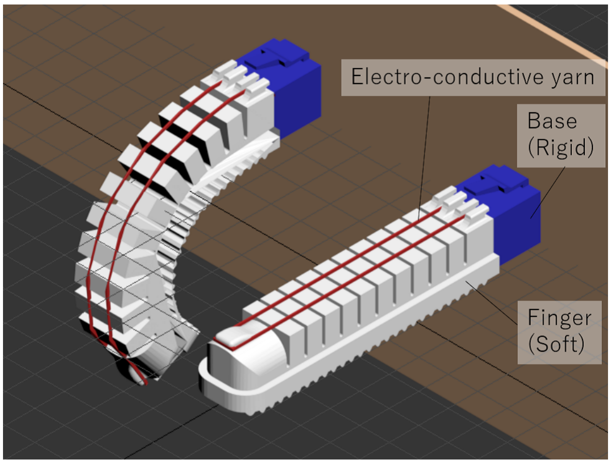

Fig. 1. Soft Gripper using electro-conductive yarn.

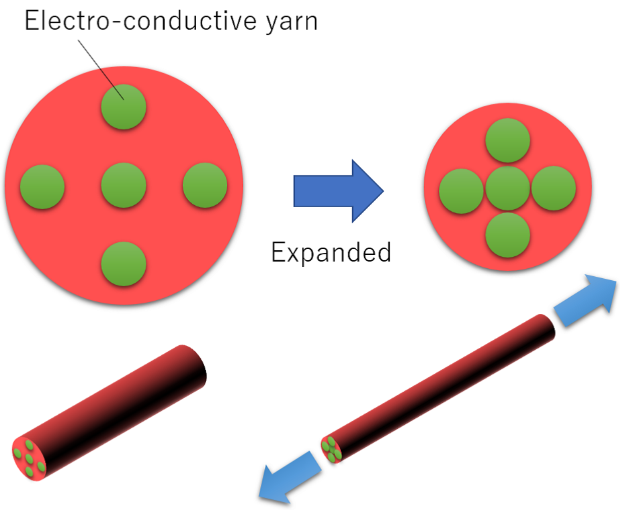

Fig. 2. Cross-section view of electro-conductive yarn.

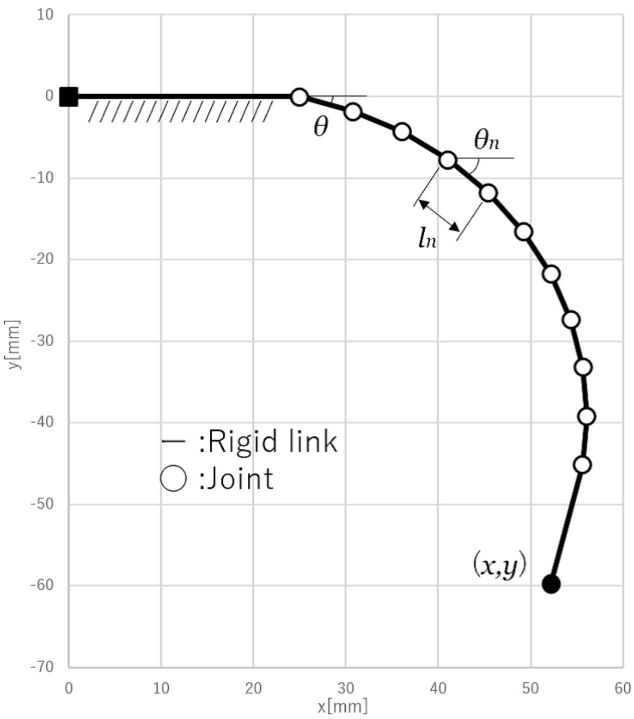

Fig. 3. Approximated model of soft gripper.

B. Approximated model of the printable soft gripper for estimation

In this subsection, the geometry of the printable soft gripper is presented. The fingers of soft gripper are approximated as a discrete model as shown in Fig. 3. The chamber section of the soft gripper is approximated as a set of active joints, which are represented by white circles. There are few curves that occur in the other section of the soft gripper. Therefore, the gripper can be approximated as a rigid body, which are represented by black bars. The tip position of the finger (x, y) is calculated by:

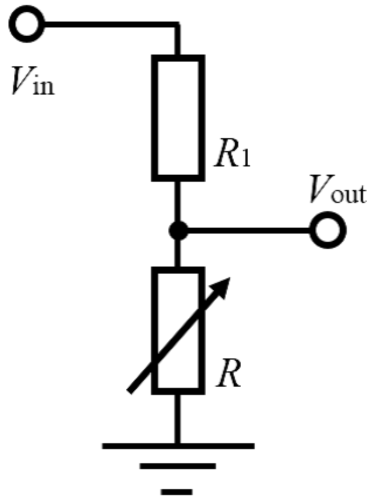

Fig. 4. Circuit for measuring.

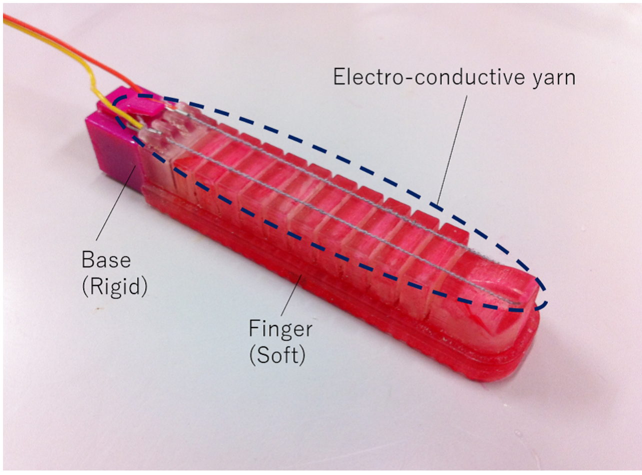

Fig. 5. Prototype of soft gripper using electro-conductive yarn.

$$x = \sum l_n \cos \theta_n, \tag{1}$$

$$y = \sum l_n \sin \theta_n, \tag{2}$$

where l_n and θ_n denote the length of the n-th link and the angle of the n-th joint, respectively. For the case of a printable soft gripper, air pressure is applied to individual chambers uniformly. Therefore, each angle bends equally, if there are no other forces applied to the finger. In this paper, n-th joint angle θ_n is assumed as:

$$\theta_n = n\theta, \tag{3}$$

where θ represents the first joint angle. When using the function of the relationship between the resistances of the electro-conductive yarn and the joint angle, the tip position of the finger (x, y) is calculated by:

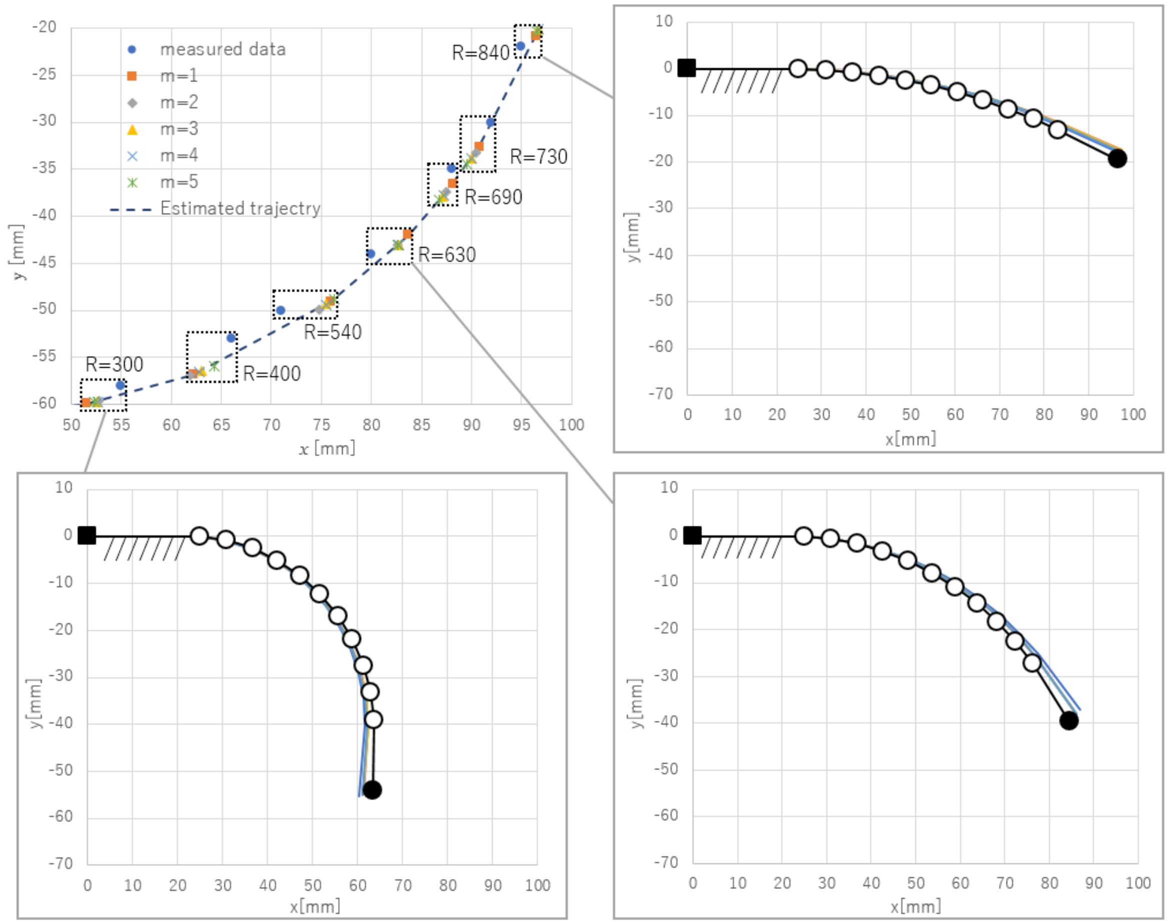

Fig. 6. Measured tip position of soft gripper for calibration.

$$x = \sum l_n \cos(nf(R)), \tag{4}$$

$$y = \sum l_n \sin(nf(R)), \tag{5}$$

where R and $\theta = f(R)$ show the resistance of the electro-conductive yarn and the function of the relationship between the resistance of the electro-conductive yarn and the joint angle, respectively. The resistance of the electro-conductive yarn R is measured in 10 Hz using the circuit which shown in Fig. 4. The output voltage is measured by an AD converter, then the resistance of the electro-conductive yarn is calculated as:

$$R = \frac{R_1 V_{out}}{V_{in} - V_{out}}, \tag{6}$$

where V_{in} and R_1 represent the constant input voltage and constant resistance, respectively. The function describing the relationship between the resistance of the electro-conductive yarn and joint angle is calibrated using this method, as discussed in the next section.

III. Calibration Method for Estimation Setup

A. Calibration method

In this section, the function of the relationship between the resistance of the electro-conductive yarn and the joint angle is measured experimentally. First, the function of the relationship between the resistance of the electro-conductive yarn and the joint angle is defined by the m-th order polynomial function:

$$\theta = k_m R^m + \ldots + k_1 R + k_0, \tag{7}$$

where k_m denotes the coefficients of the polynomial. For the calibration of Eq. (7), several experimental data sets are established. We perform S trials with different pressure values applied to the printable soft gripper, then the resistance of the electro-conductive yarn at s-time experiment R_s and the tip position of the finger at s-time experiment (x_s, y_s) are measured for each trial. The tip position of the finger from the resistance is estimated by:

$$x_{es} = \sum l_n \cos(k_m R_s^m + \ldots + k_1 R_s + k_0), \tag{8}$$

$$y_{es} = \sum l_n \sin(k_m R_s^m + \ldots + k_1 R_s + k_0), \tag{9}$$

where (x_{es}, y_{es}) represents the estimated tip position of finger as estimated by the resistance at the s-th time experiment. The coefficients of the polynomial k_m are determined by minimizing the least squares of error about (x_s, y_s) and (x_{es}, y_{es}) as:

$$\min \sum ((x_s - x_{es})^2 + (y_s - y_{es})^2). \tag{10}$$

Using this method, the function describing the relationship between the resistance of electro-conductive yarn and joint angle can be calibrated.

B. Selection of polynomial's order

In this subsection, the order of the polynomial function for Eq. (7) is selected. If the order of polynomial function is high, Eq. (7) shows a high degree of accuracy, while the time required to estimate the tip position will be longer. Therefore, the order of Eq. (7) should be select a low value to realize a real-time estimation. In this study, the tip position of the finger is estimated using several different polynomial orders. Then the error of the estimated values are compared.

The finger of the printable soft gripper using electro-conductive yarn, shown in Fig. 6, was used for the verification of the polynomial order. The electro-conductive yarn is connected to the AD converter of the MCU (STM32F401 Nucleo-64, ST microelectronics, Switzerland) based on the circuit shown in Fig. 4. The resistances of the electro-conductive yarn are calculated by Eq. (6).

First, the resistances of the electro-conductive yarn and the tip positions of finger are measured for calibration. In this study, each data point is measured seven times. The measured tip positions of finger are shown in Fig. 6 as blue dots, and the resistances of the electro-conductive yarn in each trial are shown by R in Fig. 6. Then, the order values of 1 through 5 are calculated to estimate the tip position. The estimated positions with each polynomial function is shown by the other dots in Fig. 6. Additionally, the average error of the estimated values are shown in Fig. 7. The trajectory of the fingertip is shown in bar line in Fig. 6. The trajectory of fingertip is not affected by the value of polynomial's order because of the model shown in Eq. (3).

From results of Fig. 7, the error of the estimated tip position is not sufficiently decreased, when the order of the polynomial function is increases. Therefore, this paper selected m = 1 for Eq. (6). The time required for estimation will be decreased and real-time estimation can be realized.

IV. EXPERIMENTAL VERIFICATION

In this section, the electro-conductive yarn is applied to the prototype printable soft gripper. Then, our proposed estimation method is experimentally verified. The prototype of the printable soft gripper using electro-conductive yarn is shown in Fig. 8. The base and fingers of the gripper are printed by a 3D printer (Objet350 Conex3, Stratasys, USA) which can print soft material. The gripper has three fingers (finger(R)(G)(B)), and each finger is fixed to the base at even intervals.

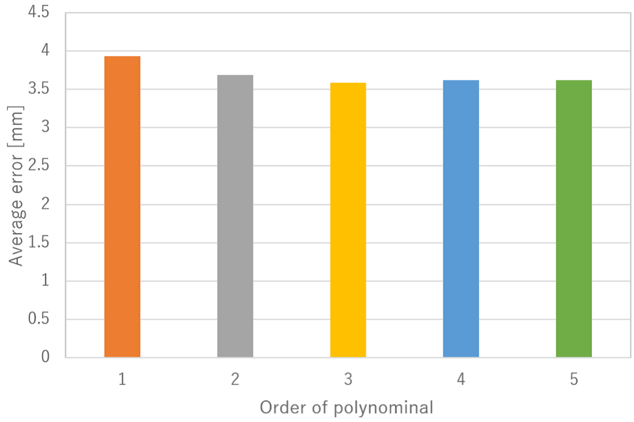

Fig. 7. Average error of tip position which are estimated by each order polynomial.

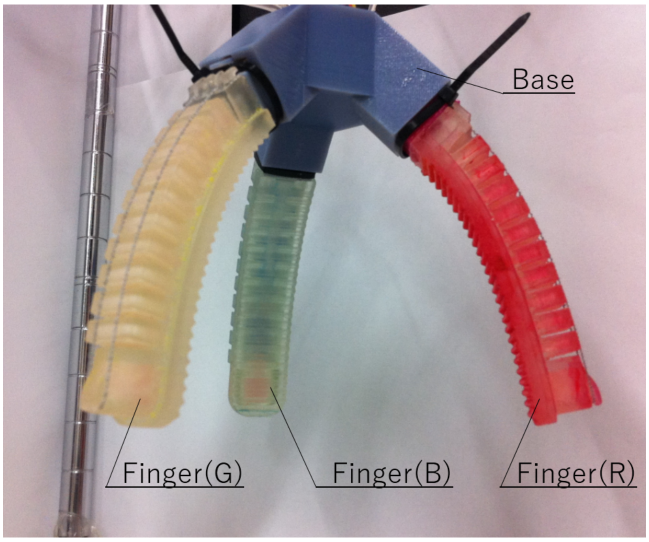

Fig. 8. Prototype of soft gripper using electro-conductive yarn (Three fingers).

Each finger has electro-conductive yarn and each resistance is measured by the AD converter of MCU as discussed in Section 3. Additionally, these values are sent to PC where the functions of the relationship between the resistance of each electro-conductive yarn and joint angle are calibrated according to the method discussed in Section 3.1. The PC estimates the curvature and tip position of fingers using Eqs. (4)-(5), then the estimated shape of fingers is displayed in real time. The measuring sampling time of the resistance is 0.1 s, and estimated curvature and tip position of fingers are uploaded in 0.1 s.

The experiment results of printable soft gripper are shown in Fig. 9. Fig. 9 (a) and Fig. 9 (b) show the estimated result of the finger's curvature. The red line shows the estimated result of finger (R), and green line and blue line show the estimated result for fingers (G) and (B), respectively. Fig. 9 (c) and Fig. 9 (d) show the actual curvature of the printable

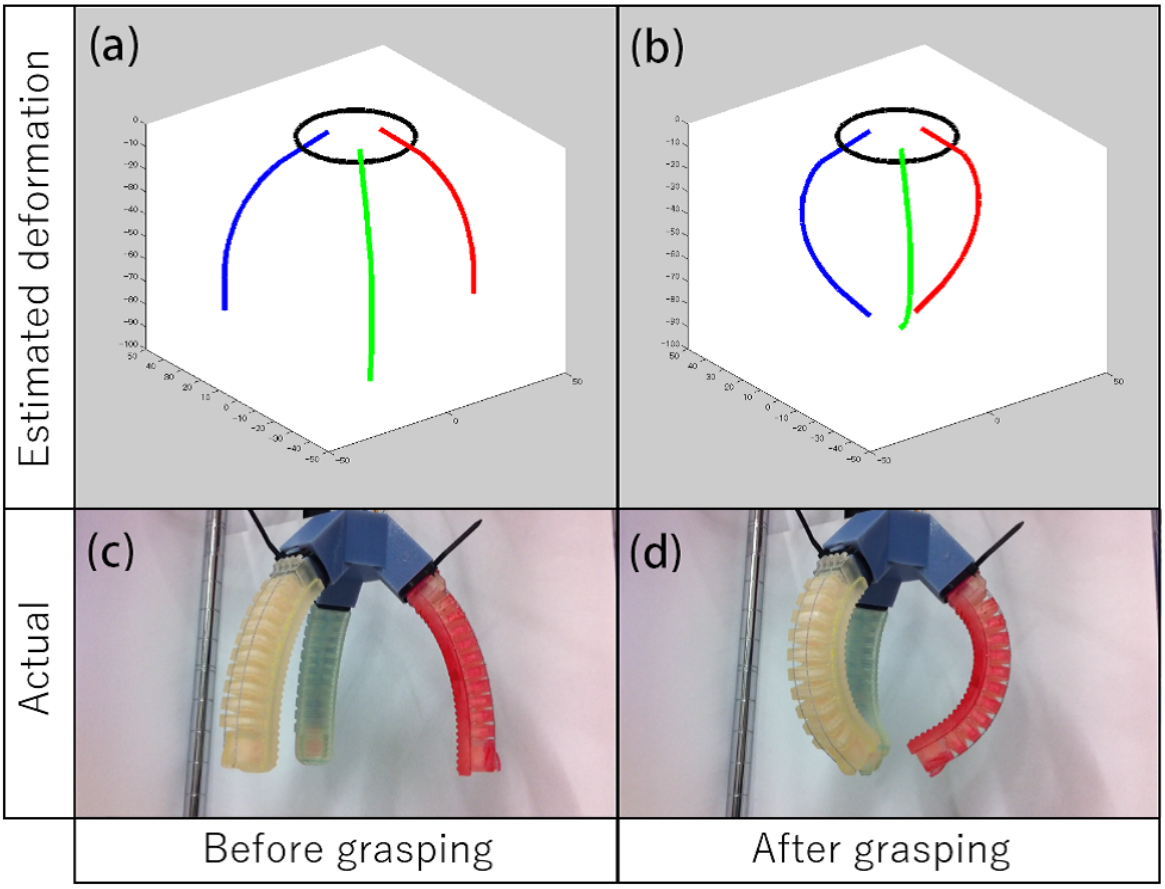

Fig. 9. Estimation of finger curvature with electro-conductive yarn.

soft gripper. Fig. 9 (a) and Fig. 9 (c) show before grasping, and Fig. 9 (b) and Fig. 9 (d) shows after grasping.

From experiment results, the estimated curvature from the resistance of the electro-conductive yarn are equivalent to the actual curvature of gripper. Therefore, the proposed method was successful when estimating the curvature of the printable soft gripper using the electro-conductive yarn.

V. CONCLUSION

In this paper, a novel method was presented for estimating the curvature of a printable soft gripper developed using electro-conductive yarn. Electro-conductive yarn is a conductive material. The resistance of the electro-conductive yarn is changed by stretching the strings. This characteristic is used for estimating the curvature of the printable soft gripper. It is less expensive than other sensors for measurement and bending. Additionally, it is simple to apply and disassemble a finger. Electro-conductive yarn is applied to top surface of a printable soft gripper. When a printable soft gripper is utilized for grasping, the electro-conductive yarn extends. Then, the resistance of the electro-conductive yarn changes. In our proposed estimation method, the curvature of the printable soft gripper is estimated from this resistance. The calibration method for the estimation setup is also proposed. Several types of polynomial functions are verified experimentally. Then, the estimation results are compared against the average error. From the comparison results, a linear equation is selected for the proposed calibration method. Finally, the electro-conductive yarn is applied to the prototype printable soft gripper, and our proposed estimation method is experimentally verified. From results of the experiment, the estimated curvature from resistance of the electro-conductive yarn was validated by the actual curvature of gripper. It was determined that the proposed method using the electro-conductive yarn was successful for estimating the curvature of the printable soft gripper using our proposed method.

APPENDIX

The size of the prototype printable soft gripper is shown in Fig. 10. Each link length l_n is decided as:

$$\begin{bmatrix} l_0 \\ l_1 \\ l_2 \\ \vdots \\ l_{10} \\ l_{11} \end{bmatrix} = \begin{bmatrix} 25 \\ 6 \\ 6 \\ \vdots \\ 6 \\ 15 \end{bmatrix}. \tag{11}$$

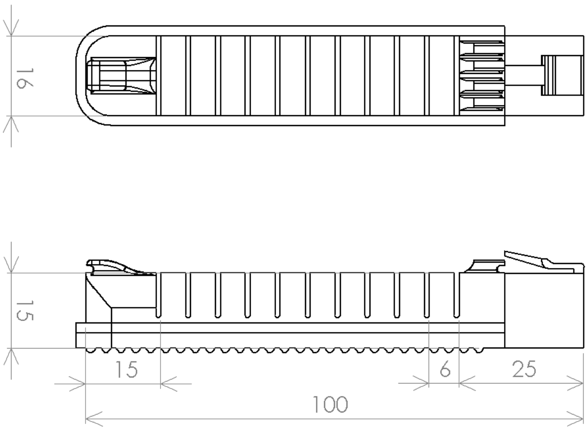

Fig. 10. Size of prototype printable soft gripper.

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