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Pre-shaping for Various Objects by the Robot Hand Equipped with Resistor Network Structure Proximity Sensors

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Abstract— **In this paper, we demonstrate a preliminary motion before grasping by a robot hand, for adjusting the object-fingertip distance and 2-axis postures simultaneously, using a Resistor Network Structure Proximity sensor (RNSP sensor). Through this motion (called "pre-shaping") and the grasping of an object, the surface of each fingertip is brought into contact with the object surface so that in the next stage grasping can be undertaken. In the next stage, a force can be applied from the fingertips onto the object surface directly. The pre-shaping enhances the reliability of the feedback control for the after-contact tactile sensors. To realize the pre-shaping, we use fingertips equipped with RNSP sensors, which can detect the distance between the fingertip and the object, to determine the relative position between fingertips and an object. The RNSP sensor has a fast response (<1 [ms]) and simple connectivity (only 6 wires), and can be mounted easily. Additionally, a characteristics of the RNSP sensor output can be designed by the arrangement of the sensor elements. To perform the pre-shaping by simple sensor feedback control based on the configuration between the fingertip and object, we designed the RNSP sensor so that it had the appropriate characteristics for the pre-shaping.**

I. Introduction

Objects have many forms, just as the word "apple" encompasses various shapes and sizes of the fruit, and it is impossible to prepare geometrical models for all of them. When trying to grasp these objects with a robot hand using a method that recognizes the object by fitting to the known models, cases of a poor grip or failure cannot be avoided. In this regard, a lot of grasping strategies have been proposed that use sensors (vision, tactile or proximity sensors) or self-adaptive mechanical hand.

Up to now, a number of studies using vision sensor have been tried [1][2][3][4][5]. Peter et al. have realized grasping various objects by approximating the objects detected by a camera as basic shapes(a triangular pyramid or a column) and using a simple rule set determined from the object shape and the geometry of the hand [6][7]. In many studies, a camera was used for vision sensor, because a camera image has abundant information about the objects (edge, surface, etc). However, missing information arise due to blind spots depends on the position or posture of the object. Moreover, the accuracy of feature extraction deteriorates according to differences in camera angle. Such information loss or deterioration in information quality causes the error in the posture or position of the object, then decreasing the certainty of the grasp.

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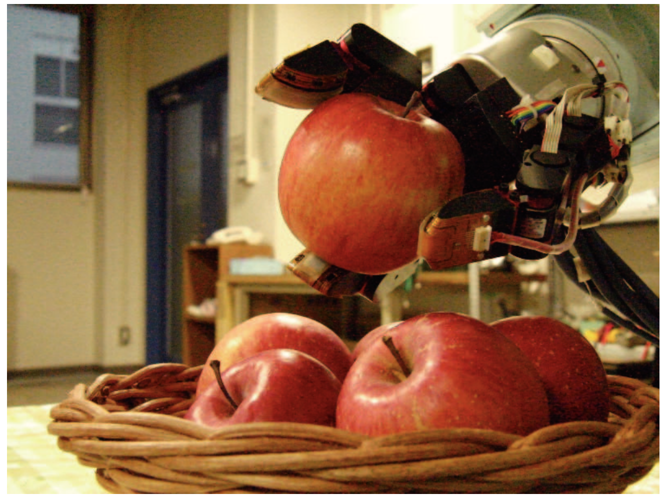

Fig. 1. Robot hand has to grasp various shapes and sizes of the objects in the human environment.

Therefore, techniques using tactile sensors mounted on the fingers have been proposed to carry out corrections to an appropriate grasp form [8][9][10][11]. However, it is difficult to grasp various objects reliably by tactile sensor feedback, because the whole surface of the finger must be covered by the sensors, and also the sensors are unable to get information until contact.

Recently, self-adaptive mechanical hands that adapt to the shape of object were presented[12][13][14]. These hands use passive joint compliance mechanisms or add special linkage mechanisms to fingers. Meijneke et.al. have been developed underactuated robot hand(DH-2) for industrial applications, having one actuator and no sensor[13]. Each finger is driven by a linkage mechanism. Low cost, simple design, all make the hand very attractive. However adaptive motion occurs after contact and also needs interaction force between finger and object, and so it seems that high speed grasping is difficult.

To grasp various objects reliably, a method has been proposed of mounting proximity sensors on fingertips, and detecting posture and position of an object prior to grasping [15][16][17]. Fujimoto et al. proposed a technique to detect the special points and posture of an object by active tracing operation using photo-reflector sensors mounted on the hand [15]. Mayton et al. realized adjusting robot hand position and posture to the object using electrostatic capacitance sensors with two different detection ranges mounted on fingers [16].

Hsiao et al. used photo-reflector sensors mounted on the

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fingertip[17]. Three sensors were arranged in a triangle on the face of the finger. Using each sensor output the distance and posture of the object near the fingertip were calculated. However, it is difficult to pack multiple detector elements into the limited space of the fingertip, and a number of wires increase.

With respect to this, we propose a Resistor Network-Structure Proximity sensor (RNSP sensor) that has characteristics of simple wiring, quick response, and easy installation in a small space [18][19][20]. The sensor acquires the position and distance of the object, within 1 ms, using 6 wires. Being composed of resistors and detection elements alone, the sensor is easily mounted in a small space and has appropriate features to mounting on the fingertips of a robot hand.

This paper demonstrates adjustment of the object-fingertip distance and 2-axis postures simultaneously, called it "pre-shaping", is realized by mounting the RNSP sensor on the fingertips. Through the pre-shaping, it is possible to apply fingertip force perpendicular to the object surface. Moreover, tactile sensors equipped on the fingertips could reliably detect tactile information. the RNSP sensor on the fingertips therefore enables the pre-shaping that achieve appropriate grasp form before contact, and improve the reliability of the object grasping.

To realize the pre-shaping by simple sensor feedback control alone, we designed the RNSP sensor which has appropriate characteristics for the pre-shaping.

II. Fingertip with the RNSP sensor

A. RNSP sensor

The circuitry of the RNSP sensor is shown in Fig. 2. The sensor is composed of photo-reflectors in a $m \times n$ matrix. The photo-reflectors consist of a coupled infrared light emitting diode (LED) and photo-transistor. The photo-transistors are connected by resistors and this composes an analog computing circuit. The infrared LED illuminates the object surface and the photo-transistor receives the reflected light. A photocurrent flows through each photo-transistor due to the reflected light, and a photocurrent distribution is generated in the matrix circuit.

the RNSP sensor can measure the central position of photocurrent distribution (x_c, y_c) and the total photocurrent I_{all} by measuring the voltage of four end points, applying the following equation.

$$x_c = \left(\frac{1}{R_0} + \frac{1}{r}\frac{2}{n-1}\right)\frac{V_{S2} - V_{S4}}{I_{all}} \quad (1)$$

$$y_c = \left(\frac{1}{R_0} + \frac{1}{r}\frac{2}{m-1}\right)\frac{V_{S1} - V_{S3}}{I_{all}} \quad (2)$$

$$I_{all} = \frac{2V_0 - V_{S1} - V_{S3}}{R_0} = \frac{2V_0 + V_{S2} + V_{S4}}{R_0} \quad (3)$$

The total photocurrent I_{all} increases as the objects approaches the sensor, and thereby it is possible to detect the distance to the object using I_{all}. The values of x_c and y_c are the central position of the current distribution in the x and y directions, taking the center of the sensor surface as the origin. The range of these values is normalized [-1, 1]. When an object is small compared with the RNSP sensor's size, the center position of the object is detected. On the other hand, if an object is large plane, the posture of the plane can be detected.

Usually a target object has a smooth surface, and its area is large compared with the sensor's size. Then, the fingertip with the RNSP sensor as shown in Fig. 2 can detect the object-fingertip posture error.

Figure 3(a)(b) shows the tilt detection in pitch of the fingertip. If the fingertip and an object surface is parallel as shown in Fig. 3(b), the photocurrents of each element is equal, then the center position of the current distribution become origin. Thus x_c is zero. When the object-fingertip tilt angle is not parallel, the current distribution inclines and the

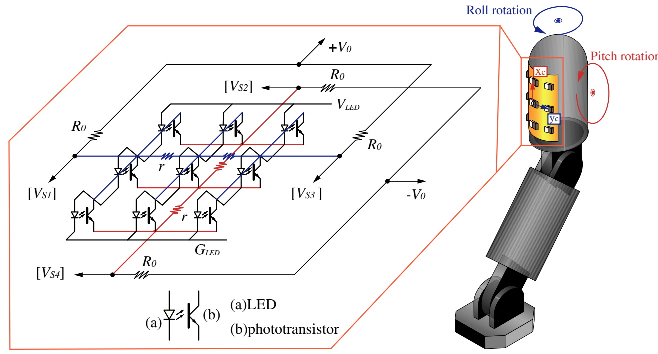


Fig. 2. Circuit diagram of the RNSP (Resistor Network-Structure Proximity) sensor mounted on the fingertips of a robot hand. 3×3 proximity sensing element array is shown in this example.

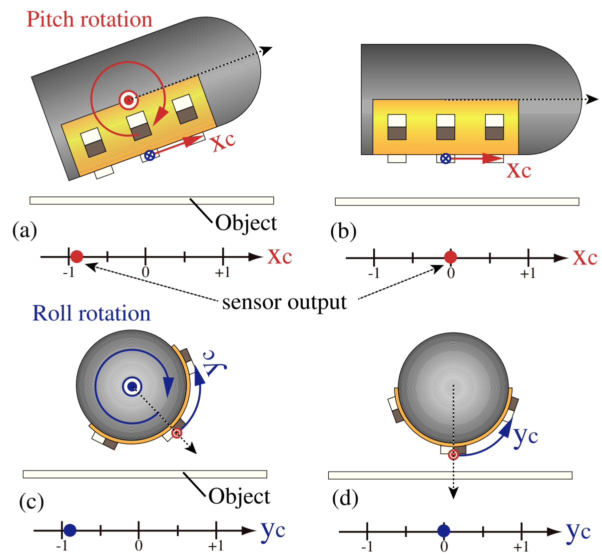


Fig. 3. Principle of tilt detection by using central position of the photocurrent distribution (x_c, y_c). If the fingertip and plane is parallel, photocurrent of each elements is equal, then the center position of the current distribution become origin.When the object-fingertip tilt angle changes, the current distribution inclines and the central point moves.

center position moves to the side in which distance to the object is shorter as shown in Fig. 3(a). Therefore the pitch angle error can be detected using x_c. Fig. 3(c)(d) also shows the case of roll angle. The object-fingertip roll angle error can be detected using y_c even through fingertip surface has curvature.

Accordingly, the object-fingertip posture error arising in the fingertip roll and pitch can be detected using (x_c, y_c). By using these characteristics, the fingertip can be correctly adjusted to the object by controlling the fingertip posture such that $(x_c,\ y_c) \Rightarrow (0,0)$. So we call it postural output(x_c, y_c).

B. Fingertip design

With regard to design of the robot hand fingertips, there are boundary conditions depending on overall dimensions of the hand, grasping method of the objects, and relationship between the size of the hand and the object. The maximum size of the fingertips mountable on the hand used in this study was 22×24×40 [mm]. To grasp objects of various sizes within these dimensions, a gentle curve was designed in the finger parts from the base to the top (Fig. 4(a)).

In order to mount a sheet-like tactile sensor and the RNSP sensor on the same fingertip, we designed the fingertip which has two surfaces (Fig. 4(b)). Small size photo-reflectors are arranged on the concave portion, and a sheet-like tactile sensor is mounted on the central portion.

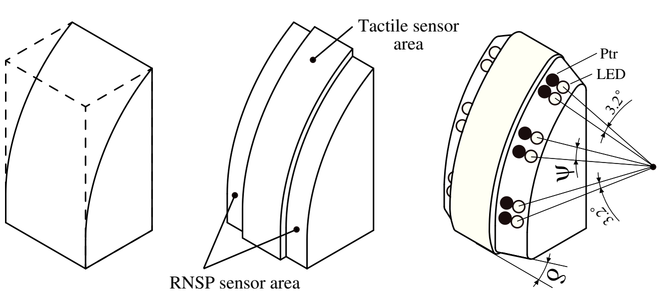
Here design parameters of the RNSP sensor are the interval and the angle at which the photo-reflectors are arranged on the mounting surface. These parameters are determined to have appropriate characteristics according to the application.

Design of the RNSP sensor characteristics

To realize pre-shaping in simple sensor feedback control, we designed the RNSP sensor on the fingertip to have following characteristics,

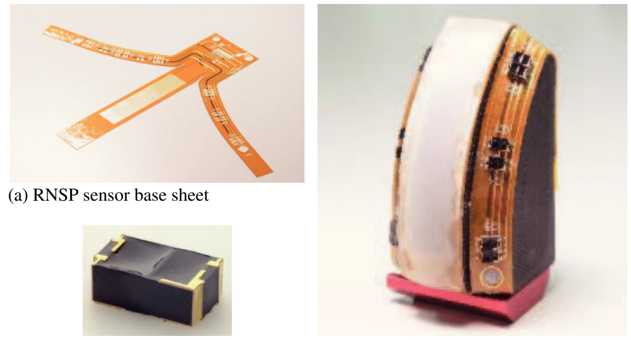
1) Postural output of roll angle y_c is high sensitive,
2) Total photocurrent I_{all} is independent of the pitch angle.

To achieve 1), we investigated the arrangement of elements in the width direction of the fingertip. In this direction, only two rows of photo-reflectors are arranged across the tactile sensor area. So the amount of light received may reduce when large roll angle error occurs, resulting in poor sensor feedback. Therefore, it is necessary to correct roll angle error quickly. For this reason, as for the RNSP sensor output y_c, it is desirable to detect this error by high sensitivity.



(a) (b) (c)

Fig. 4. Fingertip design: (a)To grasp various objects, a fingertip has a large curved surface. (b)To mount a sheet-like tactile sensor and the RNSP sensor, a fingertip has two surfaces. (c)To perform pre-shaping, the RNSP sensor elements are arranged appropriately.


(a) RNSP sensor base sheet

(b) Photoreflector : EE-SY1200

(c) Fingertip with RNSP sensor

Fig. 5. Overview of fingertip with the RNSP sensor

The design parameter that influences this sensitivity is the angle δ shown in Fig. 4(c). By inclining the angle δ of the optical axis of photo-reflectors, the photocurrent difference between the both sides increases in the same roll angle error, and y_c becomes high sensitive

To achieve 2), we investigated the arrangement of photo-reflectors in the direction along the base to the top of the fingertip. In order to adjust the fingertip posture and the object-fingertip distance simultaneously, uniformly irradiating light is necessary in this direction, because it is desirable that the distance detection characteristic is independent of pitch angle error. The design parameter that determines the distribution of this irradiation light is the interval and directivity of the photo-reflectors. We realized the uniform irradiation light by connecting two adjacent photo-reflectors in parallel. Adjusting the interval of these parallel-connected photo-reflectors change directivity of the photo-reflectors artificially. As shown Fig. 4(c), we determined the intervals near the base and the top of the fingertip is as close as possible (3.2 [°]), and the interval of central photo-reflectors is variable ψ.

The angles δ and ψ were decided using a proximity sensing ray-tracing simulator developed in our laboratory. This simulator can be simulate the RNSP sensor output in ideal condition. Simulation condition was as follows. An object detected by the RNSP sensor was a plane larger than size of the sensor surface. The plane and the RNSP sensor were face to face at the first, and then fingertip roll angle and pitch angle varied. We investigated the characteristics of the RNSP sensor output in each case of angle δ and ψ.

According to the simulation result of δ, the sensitivity of y_c improves as δ increases. In contrast, I_{all} decrease, because the irradiation light is diffused in wide direction. For this reason, there is a trade-off between the sensitivity of postural output y_c and the resolution of I_{all}. Here, we choose 25 [°] as δ where the resolution of I_{all} does not decrease excessively.

According to the simulation result of ψ, we choose 4.7 [°] as ψ, which minimizes the variation of I_{all} by the effect of the pitch angle error.

The form of the fingertip was determined based on the above investigation, and a sensor-base sheet was manufactured in accordance with this form (Fig. 5(a)). The RNSP sensor on the sensor-base sheet was constructed by mounting surface-mounted photo-reflectors (EE-SY1200 Omron, 3.2×1.9×1.1 mm) (Fig. 5(b)) and chip resistors. The fingertip with the RNSP sensor was developed by affixing this sheet to the fingertip surface (Fig. 5(c)).

C. Characteristics of the sensor

We describe two experiments to investigate the characteristics of the RNSP sensor on the fingertip. The first experiment focuses on characteristic of detecting posture error by the postural output (x_c, y_c), and the second experiment focuses on characteristic of the total photocurrent I_{all} when the pitch angle and distance varied. Through the experiments, we shows that the sensor characteristics designed in section II-B is fulfilled and the sensor is appropriate for the pre-shaping.

1) Characteristic of detecting posture error by the postural output (x_c, y_c): In this experiment, we investigated the sensitivity of the sensor outputs x_c and y_c when changing roll or pitch posture error and distance between the fingertip and a plane.

Fig. 6 shows the experimental apparatus. The fingertip with the RNSP sensor was placed d [mm] away from a plane (White-colored Kodak 90% gray card that is sufficiently larger than the sensor). y_c was measured under the condition that the fingertip was rotated with respect to the roll angle in the range of -45 [°] to 45 [°], and x_c was measured under the condition that the fingertip was rotated with respect to the pitch angle in the same range. The distance d between the sensor and the plane was 1.5, 4, 9, 14, 19, 24, and 29 [mm].

The results are shown in Fig. 7 and 8. Each graph shows roll or pitch posture error on the abscissa, and sensor output x_c or y_c on the ordinate in different colors according to the distance d. When the sensor and the plane face each other, roll angle and pitch angle are 0 [°]. These graph shows that (x_c, y_c) converges to almost zero in both of roll and pitch of 0 [°] regardless of the distance d. At any angle except 0 [°], (x_c, y_c) varies depending on the distance even in the same posture. taking a larger value at close distance. These results suggest that the pre-shaping, which adjusts posture of the fingertip to face to an object surface, is feasible irrespective of the distance by controlling the fingertip posture based on (x_c, y_c) $\Rightarrow$ (0,0). In addition, y_c is larger than x_c in the range of all angle, and a slope of the change of y_c is also larger. From the above, y_c of roll angle is high sensitive, and so it is possible to correct roll angle error quickly.

2) Characteristic of the total photocurrent I_{all}: In this experiment, we investigated a variation of total photocurrent by effect of the pitch posture error, and discuss the detection range of distance d by total photocurrent I_{all}.

I_{all} was measured under the condition that the sensor is rotated with respect to the pitch angle in the range of

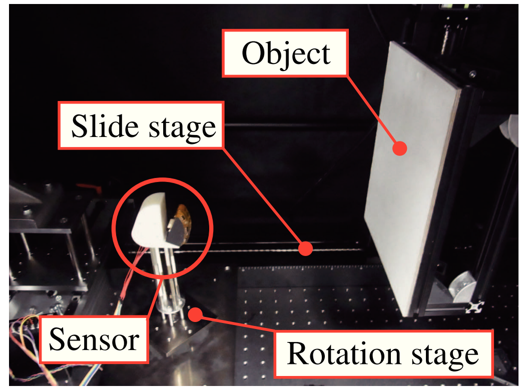


Fig. 6. Fingertip with the RNSP sensor experiment apparatus.

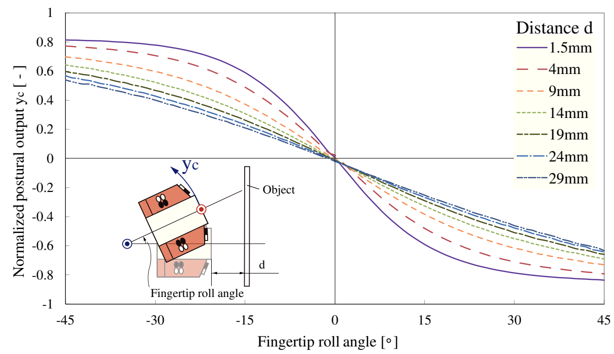


Fig. 7. Experimental results for postural output y_c vs. roll angle.

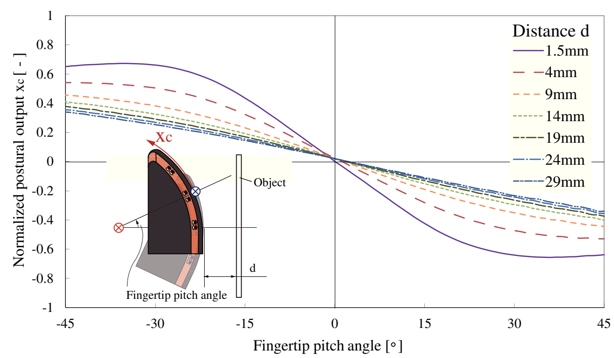
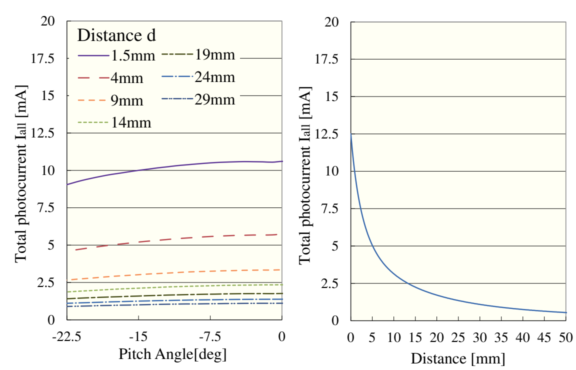


Fig. 8. Experimental results for postural output x_c vs. pitch angle.



(a) Total photocurrent I_{all} vs. Pitch angle (b) Total photocurrent I_{all} vs. distance

Fig. 9. Experimental results for I_{all} vs. pitch angle and I_{all} vs. distance.

-22.5 [°] to 22.5 [°], using the same experimental apparatus. The distance d between the sensor and the plane was in the range of 0 [mm] to 50 [mm].

The results are shown in Fig. 9(a) (distance is 1.5, 4, 9, 14, 19, 24, and 29 [mm]). This graph shows that the variation of I_{all} is small enough even if the fingertip pitch angle varies. Thus, there is little influence of pith angle in detecting distance d.

Fig. 9(b) shows the change of I_{all} when distance d is varied with both roll and pitch angles of 0 [°]. The maximum detection range for the sensor is determined by the S/N(signal-to-noise) ratio. We inferred from the result, distance sensing is feasible on a distance less than 50 [mm], where the I_{all} becomes 0.5 [mA]

Fig. 9(b) suggest that sensing is possible until a distance of 50 [mm], at which the I_{all} becomes around 0.5 [mA], and so the sensor has a sufficient range to carry out pre-shaping.

III. Control Method

In this section, we describe the pre-shaping control method using the fingertip with the RNSP sensor.

In this method, motion control of one finger is carried out by the RNSP sensor output on the fingertip. For this reason, the pre-shaping control is broken down into individual, independent controls for each finger, and can be applied to the grasping of complex objects.

In this study, a robot hand (developed by Harmonic Drive Systems Inc.) composed of three fingers is used (Fig. 10). Each finger has two flexion axises, and Finger 1 and Finger 3 additionally have a joints pivoting around the wrist of the hand at their base. Accordingly, Fingers 1 and 3 have three degrees of freedom whereas Finger 2 has two. the RNSP sensors are mounted on each of the three fingers of the robot hand, and the pre-shaping is carried out by the sensor feedback control of the finger joints. Specifically, feedback control of the joints uses sensor outputs as following:

1) The flexion axis of the fingertip by the sensor output x_{c} (Joint No.1)
2) The flexion axis of the base by the sensor output I_{all} (Joint No.2)
3) The pivot axis by the sensor output y_{c} (Pivot joint)

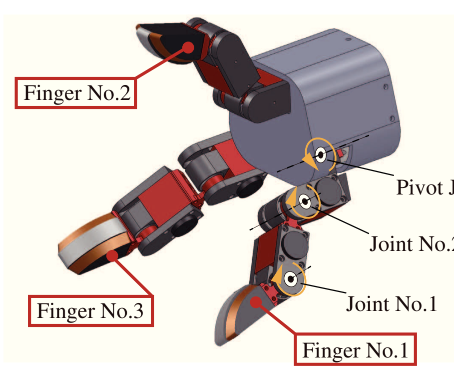


Fig. 10. Three-finger robot hand: Fingers 1 and 3 have three degrees of freedom. Finger 2 has two degrees of freedom.

The feedback control is carried out by the equation (4) to (6), using damping control typically utilized in force control.

$$\theta_{1-\mathrm{ref}} = \hat{\theta}_{1-\mathrm{ref}} + C_1 \int (I_{\mathrm{all}} - I_{\mathrm{ref}})\, dt \quad (4)$$

$$\theta_{2-\mathrm{ref}} = \hat{\theta}_{2-\mathrm{ref}} + C_2 \int x_{\mathrm{c}} dt \quad (5)$$

$$\theta_{\mathrm{p}-\mathrm{ref}} = \hat{\theta}_{\mathrm{p}-\mathrm{ref}} + C_3 \int y_{\mathrm{c}} dt \quad (6)$$

θ_{ref} is a target joint angle that is determined by sensor outputs, $\hat{\theta}_{\mathrm{ref}}$ is the joint angle at the start point of feedback control. C_1, C_2, and C_3 are appropriate gains. I_{ref} = 4.0 [mA] at which the object-fingertip distance is 10 [mm]. Due to individual difference of the photo-reflectors, the range of I_{all} value slightly change with respect to each sensor. So it is necessary to calibrate each sensor, in case of precision-grasp.

The feedback control starts when I_{all} exceeds 0.5 [mA], which is enough value to obtain efficient S/N ratio, in grasping motion rotating the flexion joints inward. Next section, the above control method is used in experiments.

IV. Pre-shaping Experiments

In this section, we describe two pre-shaping experiments, using above control method. First, the pre-shaping is performed by one finger, and second, the pre-shaping is performed by three fingers. Through these experiments, we show that the pre-shaping using the RNSP sensor can be performed for various objects.

A. Pre-shaping using one finger

In this experiment, we investigated the trajectory of one finger in the pre-shaping process by the finger to an inclined plane. Fig. 11 shows the experimental apparatus. Finger 3 approached to the plane (White-colored Kodak 90% gray card) tilted around roll angle. The angles of inclined plane are 0 to 65 [°]. The two-axis posture of the fingertip are adjusted to posture of inclined plane, and the distance between the plane and the fingertip is adjusted to 10 [mm], using above control method.

The results of time histories of roll angle, pitch angle, and distance are shown in Fig. 12, 13, 14, respectively. The time 0 [s] is at the feedback control start time. When the sensor and the plane face to each other, the roll and pitch angle are 0 [°]. The distance Fig. 14 means minimum value between the plane and the fingertip.

According to these graphs, the plane-fingertip distance converges to 10 [mm] within 0.35 [s], and the roll and pitch angle converge to 0 [°] within almost the same time, even if the angle of the inclined plane varies from 0 [°] to 65 [°].

From the above results, quick pre-shaping is achieved irrespective of the angle of inclined plane by above control method.

B. Pre-shaping using three fingers

In this experiment, we investigated whether the pre-shaping by three fingers is achievable for objects with 3D form (rectangular parallelepiped, cube, triangular prism, and

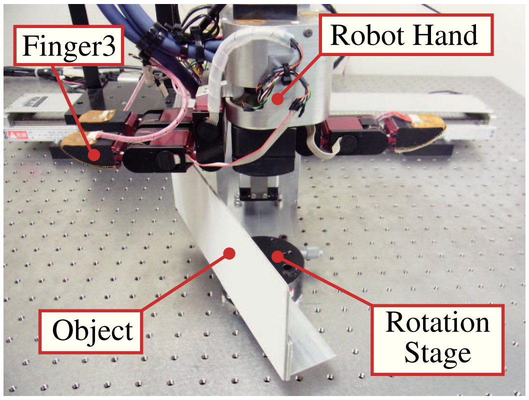


Fig. 11. Pre-shaping using only one finger.

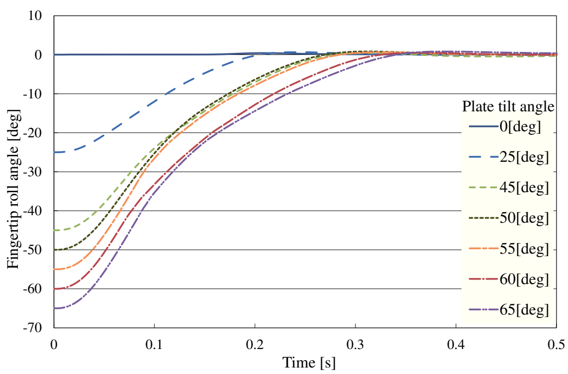


Fig. 12. Experimental results for fingertip roll angle.

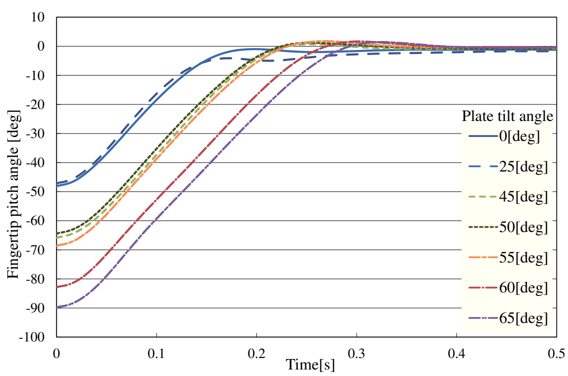


Fig. 13. Experimental results for fingertip pitch angle.

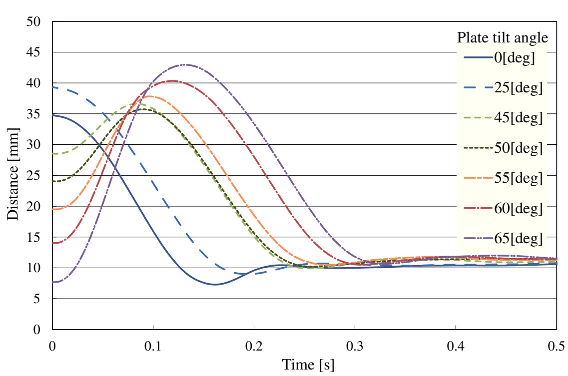
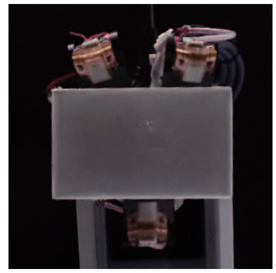
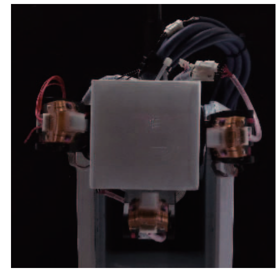


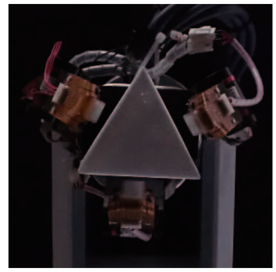
Fig. 14. Experimental results for distance between fingertip and object.



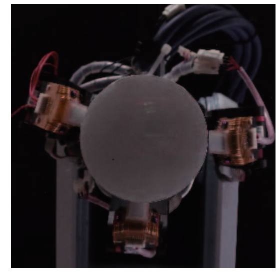
(a) rectangular parallelepiped



(b) cube



(c) triangular prism



(d) cylinder

Fig. 15. Pre-shaping for 3D objects. Each object was placed on a transparent table and photos were taken from under the table after the pre-shaping. Each finger converged to the condition shown in the photographs within 0.35 [s].

cylinder). Each object was placed on a transparent table and the pre-shaping was carried out for the objects. Fig. 15 shows photographs of the fingertips and objects taken from under the table after the pre-shaping performed. Similar to the result of the pre-shaping experiment with one finger, each fingers converged to the position and posture shown in the photographs within 0.35 [s] after control commenced.

According to Fig. 15(a), F_1 (Finger1), F_3 (Finger3) and the F_2 (Finger2) faced each other across the object for the pre-shaping to the rectangular. However, Fig. 15(b) shows that each of the three fingers is orthogonal for the pre-shaping to the cube. The deference of grasping forms between the rectangular and the cube is due to the relation between the width of the object and the width of two fingers (F_1 and F_3). Since the length of the longitudinal direction of the rectangular (100 [mm]) is longer than the width of two fingers (72 [mm]), the pre-shaping is carried out with regard to large surface. In contrast, since one side of the cube (60 [mm]) is shorter than the width of two fingers, the postural output does not converge on a surface in front of F_1, F_3, and F_1, F_3, move to neighboring surfaces. Thus, pre-shaping can be carried out adaptively to match the width of the object. In the rectangular, the posture of F_1 and F_3 converges to a state where they are slightly displaced from parallel alignment in the direction of the roll angle. This may be a result of the fingertip with the RNSP sensors of F_1 and F_3 having directly received irradiation light from each other. Such an issue occurs with the current system because the luminescence of the RNSP sensors is carried out simultaneously by the three fingers. This problem may be resolved by switching the luminescence of the sensor's LED in order.

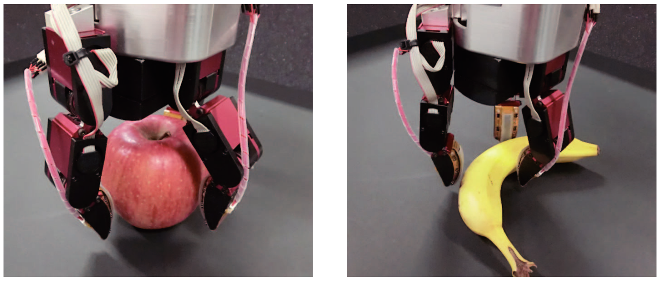


Fig. 16. Pre-shaping for novel objects (apple, banana).

According to Fig. 15(c) and (d), the pre-shaping was carried out with the three fingers each facing the center of the object for the triangular prism and the cylinder. It is considered that the pre-shaping worked well for grasping, because the convergence shape is in a mechanically closed form and advantageous for grasping the objects. From the above, the pre-shaping using three fingers with respect to the 3D objects was carried out successfully. Fig. 16 shows photographs of the cases the pre-shaping was carried out on novel objects (an apple and a banana). Even with respect to these novel objects, the hand can align the fingertips to match the surface. In this way, the pre-shaping is thought to be achievable by the RNSP sensor and proposed control method for novel objects.

V. Discussion and future work

According to the above experiments, the pre-shaping was achieved for the various objects. The control method was extremely simple, applying feedback control of a direct sensor output to each joint angle. Because of this, the pre-shaping was realized using a CPU of low processing-power. Accordingly, one idea is that the pre-shaping is performed by local feedback loop as lower control system, with upper control system giving orders for grasping. Here only the approximate posture and position of the object detected by a simple vision are send to the hand with the RNSP sensors control system, the hand is made to approach and also grasp the objects.

By carrying out pre-shaping and grasping with the proposed control system, it is possible to grasp the object with rough information about the object. Usually, with novel object grasping using visual sensors, it is necessary to obtain the position, posture, and shape via a visual sensor, and the time involved in the information processing and errors in information acquisition become an issue. In contrast, using the RNSP sensor on the fingertip and the control method of the low-computation load, there are advantages of reducing image processing time and facilitating the grasping of various objects.

VI. Summary

In this paper, we demonstrated the pre-shaping using the RNSP sensor, for adjusting the object-fingertip distance and 2-axis postures simultaneously. To realize the pre-shaping by simple feedback control, we designed and developed fingertip with the RNSP sensor, which has appropriate characteristics for the pre-shaping. Quick and stable pre-shaping was achieved for the various objects by simple sensor feedback control. Furthermore, the pre-shaping was also successfully appliance to novel objects such as an apple and a banana.

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