2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Development of Intelligent Robot Hand using Proximity, Contact and Slip sensing

Hiroaki Hasegawa*[1], Yoshitomo Mizoguchi*[2], Kenjiro tadakuma*[3],
Aiguo Ming*[1], Masatoshi Ishikawa*[4] and Makoto Shimojo*[1]

Abstract— **To achieve the skillful task like the human, many researchers have been working on robot hand. An interaction with vision and tactile information are indispensable for realization of skillful tasks. In the existing research, the method using a camera to get the vision information is often found. But, in the boundary area of a non-contact phase and a contact phase, there are problem that lack of sensor information because the influence of occlusion comes up to surface. We devise to introduce the proximity sensor in this area. And we call the robot hand which is equipped with proximity, tactile and slip sensor "intelligent robot hand".**

In this research, we show the constitution example of the intelligent robot hand and propose the method to realize Pick&Place as concrete task.

I. INTRODUCTION

In recent years, the engineered reproduction of dexterous fingers similar to those of the human hand has been targeted, and research relating to robot hands has been enthusiastically carried out. In the realization of skillful operations by means of this hand, the employment of visual and tactile information is indispensible. By way of existing applications of visual information, Namiki et al.[1][2] used high-speed vision and implemented a series of operations from approach to the target object to grasping it, and further showed that visual information is effective for grasp/manipulation operations by performing tasks such as the manipulation of tools and the tying of string. However, in the case a camera is used for the acquisition of visual information, there is an issue of information lacking in the region where the separation of the hand and target object is exceedingly small due to concealment, etc. A method used in response to this issue is a proximity sensor to detect short distances of a few centimeters from the contact surface[3] [4]. A faster approach and softer contact is made possible by reliably detecting short distances according to a proximity sense.

Meanwhile, position and force of contact and detection of slippage are important as tactile information. Many proposals have been made for tactile sensors that detect position and strength of contact[5][6]. However, the important point in a practical application is the treatment of the wiring from the sensor and high-speed responsiveness. The minimization of wiring is particularly necessary when sensors are installed in confined parts such as the fingertips. Also, a response speed of within 1ms is desirable in the 1kHz control loop used for robot control in order to facilitate responsiveness. In the application of tactile information to hand control, there are such examples as the high-speed rotation control of a pen-shaped object by a three-fingered hand with a sensor that could rapidly detect contact information, as achieved by Ishihara et al.[7], and the grasping of objects of unknown friction coefficient and varying weights using a slip sensor and slip control, as achieved by Gunji et al.[11]

Now, we believe that an integrated system of visual, proximity, tactile and slip sensor groups as shown in Fig.1 is essential in the realization of high-speed handling by a robot hand. However, there is nothing in the way of research concerning integrated systems of visual, proximity, tactile and slip sensor groups with the exception of that by Shimoyama et al.[8] They embedded an ultra-small three-axis tactile sensor and a proximity sensor, etc. on a gripper-type hand and carried out handling of tableware as an example of handling in coordination with visual information. The position of the object was visually estimated with grasp direction adjustments in the vicinity of the object carried out next by a proximity sensor. After contact, slip control, etc. of the grasped object was carried out by the three-axis tactile sensor, but since there is no report on the entire system as yet, the details are not clearly known.

As in this example, the grasping, transportation and placement of the object are fundamental grasp operations performed by a robot hand. In addition to each process of grasping, transportation and placement, processes that

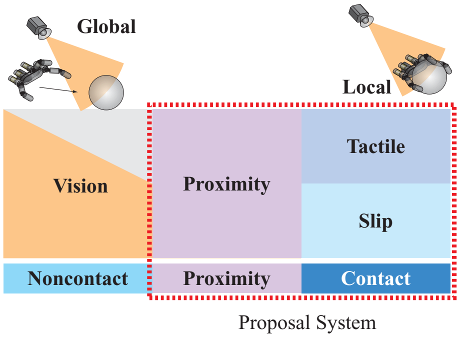


Fig. 1. Proposed sensor configuration for a robot hand

---

*1 Department of Mechanical Engineering and Intelligent Systems, the University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo, 182-8585 Japan

*2 Harmonic Drive Systems Inc.

*3 Department of Mechanical Engineering, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, 565-0871, Japan

*4 Department of Information Physics and Computing, Graduate School of Information Science and Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

978-1-4244-5040-4/10/$26.00 ©2010 IEEE

establish the grasp (i.e. the approach to the target object and grasp attitude control) are necessary. On this occasion, we also considered the abovementioned grasping, transportation and placement as examples of fundamental operations for high-speed handling by a robotic hand.

For example, object position information is necessary in order to grasp and can be measured by standard vision, but error exists and measurement is not possible at short distances due to concealment of the object. For this reason, it is necessary to perform safe and reliable grasping through using a proximity sense at short distances. Also, configuration of the grasp strength in accordance with the object is necessary when grasping. If the grasp strength is excessive, it will result in damage to the object or overloading of the engine. If it is insufficient, the target object will be dropped. For this reason, it is necessary to implement a grasp strength that does not let the object slip and drop and yet is as small as possible.

Next, the prevention of the target object falling, etc. by appropriate grasp strength control is essential in the same way as in both the transport and placement processes, as various interferences such as inertia forces and vibrations increase during transportation. In the final placement operation, it is necessary to arrest the slippage generated from the contact between the floor and the object, and release the object in order to avoid the danger of pushing the object into the floor or dropping it.

We have already developed a net-structure proximity sensor and tactile and slip sensors. These sensors all have a responsiveness of within 1ms as they have the reduced wiring of 6 wires or less and are analogue circuitry networks. In this research, we seamlessly detect from proximity to contact and achieve a safe and reliable grasp through the integration of sensor groups with these characteristics in a three-fingered hand, and propose an appropriate grasp strength control derived from slippage information during grasping, transport and placement processes. Robot hands possessing this kind of sensor group and faculty are called intelligent robot hands. Furthermore, object placement was visually estimated and handled using the proximity, tactile and slip sense information shown in Fig.1.

In this article, we describe the system structure of an intelligent robot hand and experimental results relating to the fundamental operations of approach, grasp attitude, transportation and placement carried out using this system.

II. TACTILE/SLIP/PROXIMITY INTEGRATED SENSOR

In this section we describe the sensor used in the robot hand and the method of mounting in the hand.

A. *Tactile/Slip/Proximity Integrated Sensor*

The sensor employed was a center of pressure type tactile sensor (CoP sensor)[9].This sensor is a three-layer structure composed of a layer of pressure sensitive conductive rubber inserted between two layers of conductive film. It outputs the central position of the load distribution applied to the sensor and the sum total of that force. As it is composed of soft material, it is possible to mount by wrapping around the fingertip. Also, in addition to possessing high-speed responsiveness of 1ms, it also has the feature of reduced wiring, with just four wires, regardless of sensor surface area.

This sensor reacts to the force tangential to the sensor [10]. Experimental results are shown in Fig.2.The upper graph shows CoP sensor force output, the middle graph shows object displacement and the lower graph shows the force in the tangential direction measured by the load cell. In the diagram, the sudden decline of the sensor force output accompanying the increase of the tangential force can be seen in region II. Slippage prediction/detection is carried out according to this. The following two conditions are introduced as slippage detection conditions. In the case either of these conditions is fulfilled, the system judges slippage have occurred.[11].

$$\text{Condition 1:} \qquad \Delta V > V_{th} \tag{1}$$

$$OR$$

$$\text{Condition 2:} \qquad \frac{d}{dt}\Delta V < c \tag{2}$$

Here, ΔV is the decline in sensor force output from that of static state. And V_{th} and c are thresholds.

B. *Net-structure Proximity Sensor*

The proximity sensor used was a net-structure proximity sensor we developed[12][13]. Fig.3 shows its structure. The sensor uses photo-reflectors as detection elements.The photo-reflector is composed of a luminescent infrared LED and a phototransistor as infrared detector.Infrared rays from LEDs reflect on the surface of object, then phototransistors detect and transform them into currents.Reflected IRs decline as detecting object is distant, so output of elements are approximately inversely proportional to distance.

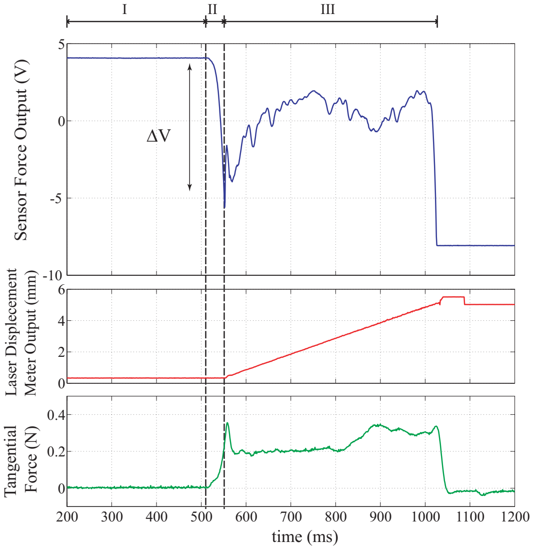


Fig. 2. Tangential force characteristic of the CoP sensor. Initially, CoP sensor is pressed at constant force. In region II, tangential force is increasing, then sensor output drops by ΔV. And during slippage (region III), the stick-slip between sensor and surface of objecgt makes sensor output vibrational.

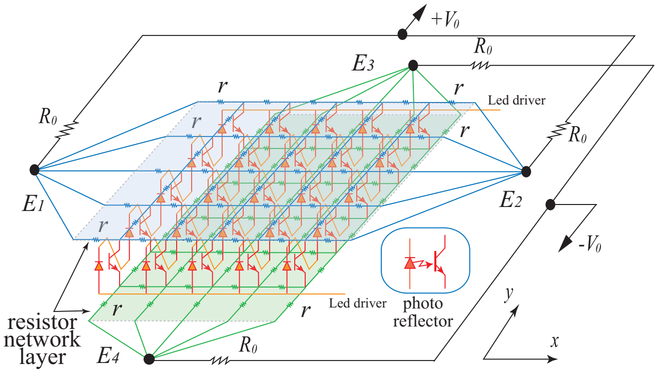


Fig. 3. Structure of the net-structure proximity sensor

The sensor structure is such that the node intervals of the 2-layer $m \times n$ resistance matrix are connected by phototransistors. There are output lines from the matrix for each of the four nodes E1, E2, E3, E4 and two to drive the luminescent LED, giving a total of just six wires. Also, the sensor is an analogue circuitry network and so has the characteristic of an almost constant response speed independent of number and placement of detection elements and of sensor surface area. The sensor outputs the central position of the illuminance distribution produced when infrared light from the luminescent LED is reflected by the target object and the sum total of said illuminance. Unless especially heteromorphous objects are targeted, the central position of the illuminance distribution shows the 2-dimensional central position of the target object on the sensor surface and the sum total of the illuminance corresponds to the distance between the target object and sensor surface.

C. Realization of Integrated Tactile/Proximity Sensor

As it is necessary for both the tactile sensor and proximity sensor to be on the hand surface in order to make measurements during the approach until contact with the target object from the same surface, the geometric arrangement of the sensors becomes an issue. In response, we devised a method using a CoP sensor with a through-hole established. The coexistence of both sensors was devised by establishing a through-hole in the CoP sensor as shown in Fig.6, and exposing the receptive surface of the proximity sensor by this aperture.

For this reason, it is necessary to investigate the change in characteristics of the CoP sensor due to this through-hole processing. Accordingly, position and load output was measured for the case when a 6-mm hole was made in the center of the CoP sensor ($60mm \times 30mm$).The position output results are shown in Fig.4.The position output test measured the sensor output for the case where pressure was applied to the punched CoP sensor at 5-mm intervals from the edge. It can be seen from Fig.4 that position output in the vicinity of the through-hole is displaced radially outwards from the hole. However, this error is around 2mm at maximum and so insignificant. It was also verified that there was almost no disparity in the load output.

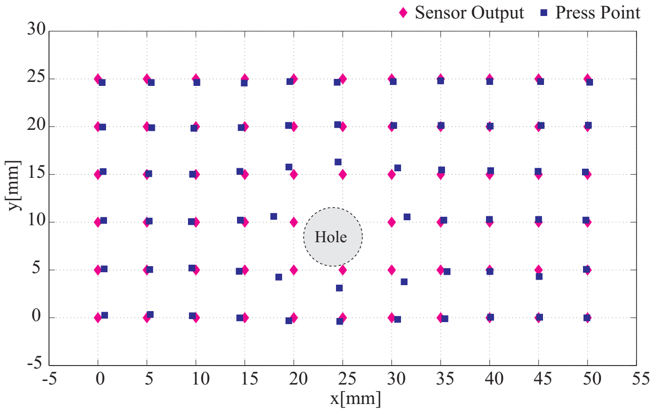


Fig. 4. Position output characteristic of the CoP sensor with the hole. Pressed at every 5-mm intervals (blue plot), the position outputs of the sensor (magenta) is deiplaced outwards from the hole

III. CONFIGURATION OF THE INTELLIGENT ROBOT HAND

Fig.5 shows an image of the entire system. A three-fingered hand with eight degrees of freedom (manufactured by Harmonic Drive Systems) was used for a platform on which to compose the robot hand. The hand was mounted on an XZ stage to give a configuration of one degree of freedom in both the vertical and horizontal directions. A complete image of the hand is shown in Fig.6.Proximity, tactile and slip sensors are mounted on each fingertip and the matrix-structure proximity sensor on the palm. ART-Linux was employed for the control OS and a 1-ms control loop implemented.

A. Configuration of the Fingertips

In mounting an integrated tactile and proximity sensor in a small part such as a fingertip, a photo reflector RPR-220 (manufactured by ROHM) of long detection range was employed as the detection element with just one element installed in each tip. The proximity sensor element was embedded in the fingertip prior to molding from two-liquid type hard urethane resin. Holes 6mm in diameter were established in corresponding positions on the CoP sensors,

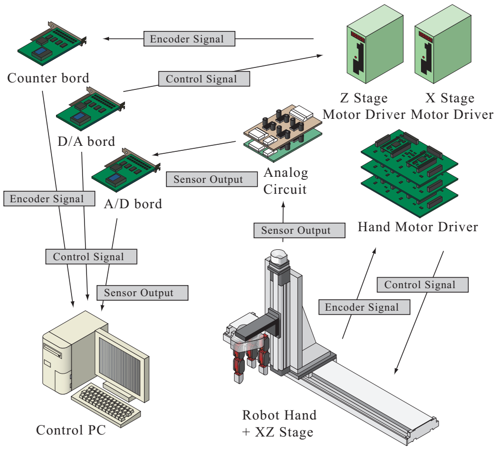


Fig. 5. Outline of the intelligent hand system

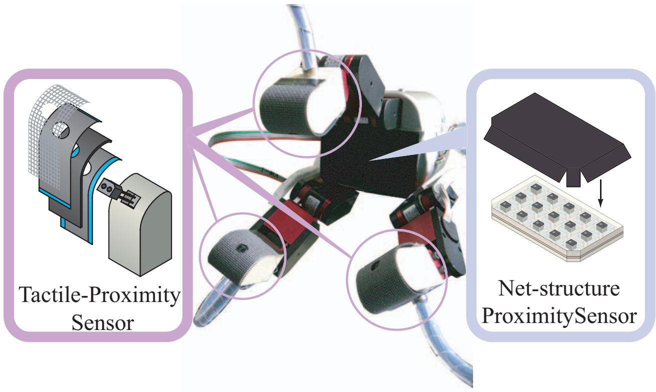


Fig. 6. Intelligent hand with proximity and tactile sensors

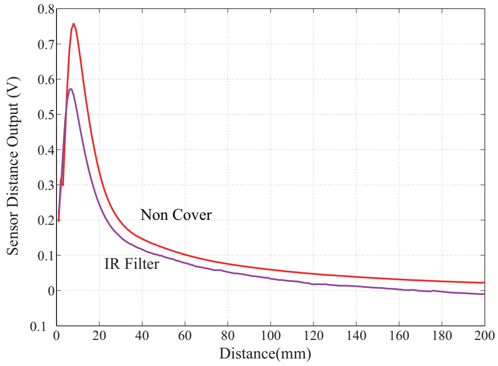


Fig. 7. Distance output characteristic of the palm's proximity sensor

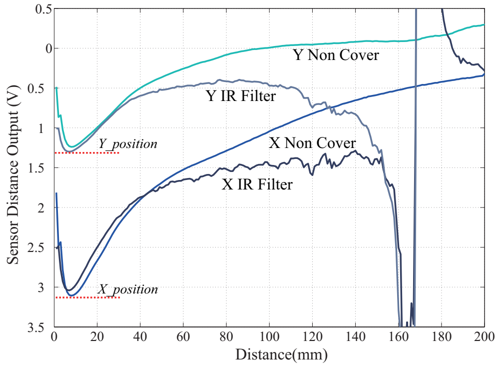


Fig. 8. Position output characteristic of the palm's proximity sensor

and they were mounted on the fingertips. Also, the sensor surface was covered by a protective mesh.

B. *Configuration of the Palm Proximity Sensor*

An RPR-220 identical to that used in the fingertips was used for the net-structure proximity sensor mounted in the palm and was a 3 × 5 matrix configuration. The resistance between elements, which is a circuit constant, and selection of the external resistance was measured using a circuit simulator. The sensors were arranged on a printed circuit board as shown in Fig.6, and the space between sensor elements plugged with urethane resin. The entire sensor surface was given a protective IR filter covering. Due to this the functionality as a palm, contact surface could be preserved. The manufactured sensor characteristic test results are shown in Figs.7 and 8. In the test, a circular-shaped white piece of paper was placed directly in front of the sensor top-left element and the output measured from a start condition of contact to a point of separation.

It can be seen from Fig.7 that the sensor separation output is a waveform possessing one peak. This is a reflection of the characteristics of the proximity sensor element. Meanwhile, as shown in Fig. 8, the sensor position output becomes large in the vicinity of the focal length and is asymptotic to the center as separation increases. At close distances the sensor output tends to the object position as the sensor outputs the central position of the reflected light distribution. However, in accordance with an increase in separation, the reflected light incident on the sensor surface becomes uniform as the light reflected from the object diffuses and the sensor output becomes asymptotic to the center position. Also, the position and distance outputs both decline in the case the sensor is covered by the IR filter.

IV. PICK & PLACE BY THE ROBOT HAND

The Pick & Place operation was implemented as a specific task using the hand under the conditions of 1) the target object weight/shape/friction conditions are unknown, and 2) an installation error exists. In order to fulfill; the task under these conditions, a grasping strategy with each of the following processes was adopted according to the following kind of operation primitive combination 1) Approach: Placement error handling by palm proximity sensor. 2) Grasp attitude control: fingertip contact timing by fingertip proximity sense. 3) Grasping/transportation/placement: Placement based on anti-slip control and slip detection by tactile and slip sensors. The details are described below.

A. *Handling of Placement Error by Palm Proximity Sensor*

As an initial approach operation, handling is carried out for the case the object is displaced from the assumed position. The object position is estimated by sight if the robot has such a sense, or a position is specified if the robot is part of an assembly process in a factory. However, to consider that a position error exists is standard in either case. It is therefore desirable to absorb this placement error with a reliable and safe grasp. On this occasion, this operation was carried out by the net-structure proximity sensor attached to the palm of the hand. The issue here is that the sensor depends on the surface properties of the target object as it utilizes infrared light reflection. Accordingly, this issue was dealt with by the following method. Firstly, the sensor distance output for the control of the distance direction depends on the target object, and that output varies. However, the sensor output for all target objects has one peak, and that distance is around 6mm, the focal length of the proximity sensor element. For this reason, it is possible to approach up to the focal length with no dependence on the target object through controlling the distance direction such that the distance output peaks.

Next is the control for positioning. The objective of this positioning control is the movement of the center of the palm of the hand to directly about the target object. As the center of the sensor is coincident with the center of the palm of the hand, it is acceptable to control such that the sensor position output becomes 0. With this convenience, the position output accurately reflects the target position as the sensor in the palm of the hand approaches the target object to grasp it, as shown in Fig.9, and when directly above the target object it can trace a smooth approach trajectory.

B. Fingertip Contact Timing by Fingertip Proximity Sensor

Next, we will describe the fingertip contact timing. In general, there is the possibility of a discrepancy in fingertip contact timing even when the palm of the hand is deployed above the center of the object due to the shape of the object, etc. For this reason, tilting or toppling of the object occurs and a safe, reliable grasp is not possible. The contact timing of each finger was made to coincide by using the proximity sensor of each fingertip and deploying all the fingertips a few millimeters from the target object. Specifically, the fingertip position was controlled such that the distance output of the fingertip proximity sensor became a maximum. Fingertip placement control was carried out as shown by the following equation.

$$\boldsymbol{\tau} \;=\; \boldsymbol{J(q)K_p(p_d - p) - J(q)K_d\dot{p}} \tag{3}$$

Here J(q) is the Jacobian, pd is the target fingertip position and p is the fingertip position. Kp and Kd are gains.

Also, the trajectory of the fingertips was constant in the vertical direction with movement allowed in the horizontal direction and the swing joints of the first and third fingers fixed.

C. Force Control for the Grasp

Next, we move to the contact phase. First, the object is grasped. The grasp attitude was a 2 vs 1 arrangement grasp, with grasp force control carried out by controlling the contact force of the 2nd finger that opposes the fixed 1st and 3rd fingers. Position based force control shown by the following equation was used for the force control.

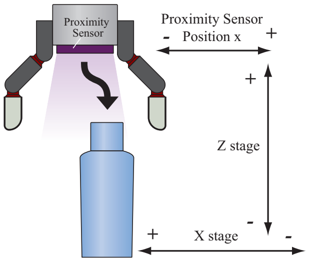


Fig. 9. Response to the initial position error using the proximity sensor

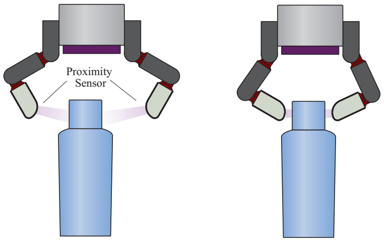


Fig. 10. Contact timing control by the finger's proximity sensor

$$\begin{aligned} \boldsymbol{\tau} &= \boldsymbol{J(q)K_p(\hat{p}_d - p) - J(q)K_d\dot{p}} \quad (4)\\ \boldsymbol{\hat{p}_d} &= \boldsymbol{p_d + K_{fp}(f_d - f) - K_{fd}\dot{f}} \quad (5) \end{aligned}$$

f_d is the target contact force, f is the contact force. K_{fp} and K_{fd} are gains. The issue when grasping a target object is the determination of a grasp strength suitable to the target object. If the grasp strength is excessive, it will result in damage to the target object or overloading of the engine. If it is insufficient, the target object will be dropped. For this reason, the ideal grasp strength is one that does not let the object slip and fall and yet is as small as possible. On this occasion, the implementation of a grasp force that does not allow the target object to slip and fall was targeted through configuring the grasp force based on slip detection. Specifically, the target grasp force fd was updated in the following way based on slip determination.

$$\begin{aligned} \text{Slip detected} \quad \hat{f}_d &= f_d + \alpha \quad (6)\\ \text{Slip not detected} \quad \hat{f}_d &= f_d \quad (7) \end{aligned}$$

D. Anti-Slip/Interference Control for Transportation

After the grasp is completed, the robot moves into transportation. At this point, various interferences such as inertia force and the vibration of the higher order joints irregularly act on the grasped target object. Considerations to prevent the dropping of the target object are made in response to these through appropriately increasing the grasp force. Because this grasp is achieved based on the force output of the tactile sensor, interference such as that which hinders the grasp is materialized as a decline in CoP sensor output. Meanwhile, it can be considered that the aforementioned slippage according to characteristics of the CoP sensor also materializes as a decline in force output. For this reason, it is possible to handle the various interferences by means of regulating the CoP sensor force output[14].

E. Placement Using Slip Detection

Finally, we have the placement operation. It is possible to estimate a target object release position from wrist position, etc.; however, doing so results in the risk of pressing the target object into the floor or dropping it due to the accumulative error of the joints and environmental variations, etc. In order to prevent this it is desirable to be able to detect the placement of the target object and the floor. Accordingly, determination of slippage was carried out when the wrist descended, the slippage that occurs due to the contact between the floor and the target object was captured and the target object released.

V. EXPERIMENT

The practical Pick & Place operation was carried out with the above controls implemented[15]. The details of the experiment were for the case the weight of the target object was varied in 50-g increments from 50g to 200g and for the case the target object placement position was varied by units of 10mm within a range of ±70mm.The grasped target object was a cuboid made of cardboard and its weight was adjusted by packing the inside with weights.

A. Experiment Results

1) Handling Deployment Error: First, we describe the experiment results of the deployment error in Fig.11. The upper graph shows the Z position of the wrist of the hand, the middle shows the X position of the wrist of the hand and the lower shows the distance and position outputs of the proximity sensor in the palm of the hand. From this it can be seen that the Z position of the wrist of the hand is controlled such that the distance output of the net-structure proximity sensor mounted on the palm of the hand is roughly a maximum value, that is, a distance of around 6mm from the object. Meanwhile, the X position of the wrist of the hand is controlled such that the position output of the palm sensor is almost asymptotic with 0, that is, to approach directly above the object.

Also, the range of placement error handling is around ±50 mm as shown in Fig.12. This is also dependent on the shape of the upper edges of the grasped target object but shows that the handling of a detected area around that of the proximity sensor in the palm of the hand can be expected.

2) Control of Contact Timing: Next, we describe the deployment of the fingertips. The upper graph of Fig.13 shows the distance output of the fingertip proximity sensors and the lower graph shows the displacement from the initial attitude of each fingertip. From this it is seen that the proximity sensor output for all of the fingertips becomes a maximum and the fingertips are deployed at a position of a few millimeters from the surface of the target object. Also, in this case, it can be seen that the fingers are deployed in the order of finger 1, finger 3, finger 2 and coincidence of contact timing is being attempted.

3) Grasping, Transportation and Placement: Fig.14 shows the CoP sensor output regarding the grasp, the 2nd finger joint torque and the wrist joint position. The upper graph shows the force output of the CoP sensor, the middle graph shows the directed torque value for the 1st and 2nd finger joints of the 2nd finger and the lower graph shows the position of the hand establishment stage in the Z and X directions. In range I-II, the rising of the hand in the Z axis direction commences and an increase in torque in response to the accompanying slippage is observed. The grasp force that was configured to a small value in the initial state is renewed to a large value in accordance with the rising of the hand, and its configuration to a specified value can be seen. Fig.15 is a summary of the configured grasp forces when the weight is varied. The configured grasp force becomes large as the target object weight becomes large and the adaptive configuration of the grasp strength can be seen. In the range II-IV, transportation of the grasped object is carried out. At this point, the effect of the anti-slipping/anti-interference control is notable, realized in the range i-ii. In this range, a large inertia force is applied to the target object as the transport direction of the hand completely changes. At this point, the finger joint torque increases and the anti-interference effect can be seen. The actual appearance of the operation is shown in Fig.16.

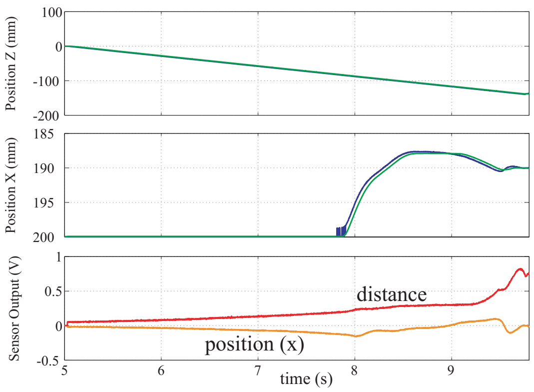


Fig. 11. Displacement of a wrist joint, and the output of a proximity sensor

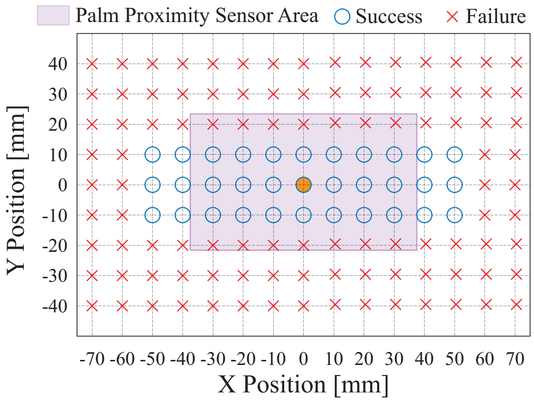


Fig. 12. Covering range of the initial position error.

VI. DISCUSSION

1) The position error correction using the palm of the hand proximity sensor could guide the wrist position to directly above the target object through simple control. As can also be seen from Fig.16, the position relation of the hand and the target object when approaching the target object makes

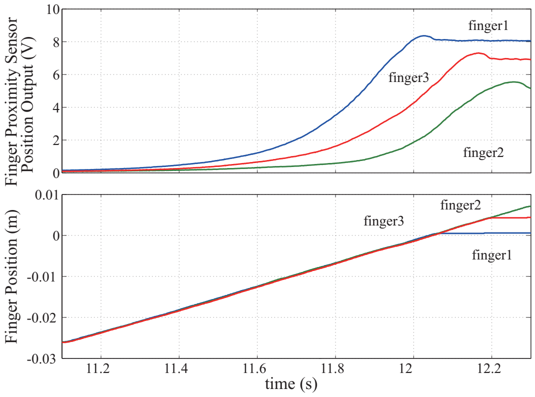


Fig. 13. Proximity sensor output and fingertip displacement

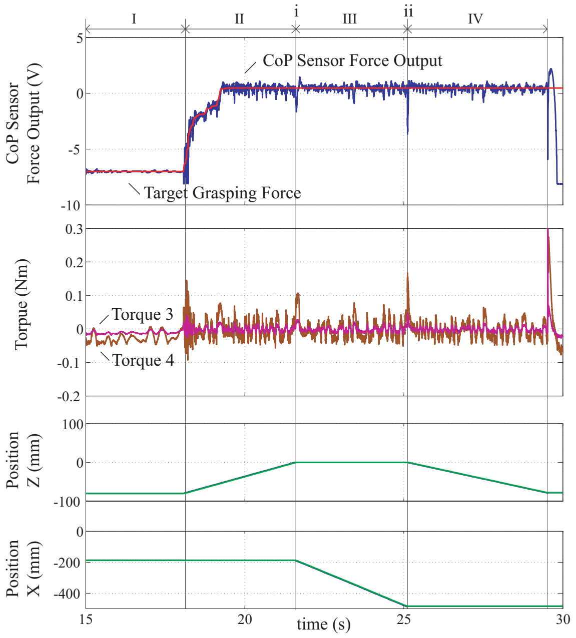


Fig. 14. CoP sensor force output and the 2nd joint torque

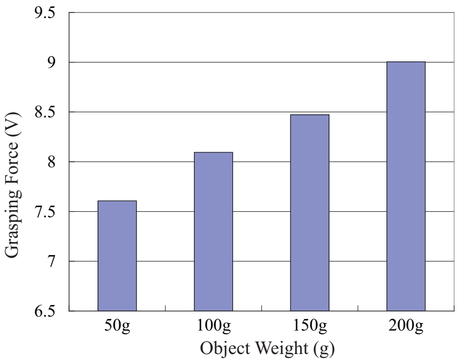


Fig. 15. Relationship between object weight and realized grasping force

guidance by the traditional technique of using a camera difficult as it is hard to avoid concealing the object with fingers, etc. and it can be said that the mounting of the proximity sensor was exceedingly effective. Also, as the handling of the placement error within the range of the proximity sensor of the palm of the hand can be expected, the achievement of a grasp is possible even when the precision of the approach from the global range to the target object by camera, etc. is relatively low and so the acceleration and optimization of tasks can be attempted. However, according to this technique, deployment of the palm directly above the target object may not always be possible in the case that the upper edges of the target object do not directly oppose the proximity sensor of the palm of the hand or for the case the object is heteromorphous. In this case, it may be possible to acquire shape information for the target object in advance by use of a camera, etc. and appropriately configure the target value of the proximity sensor in the palm of the hand.

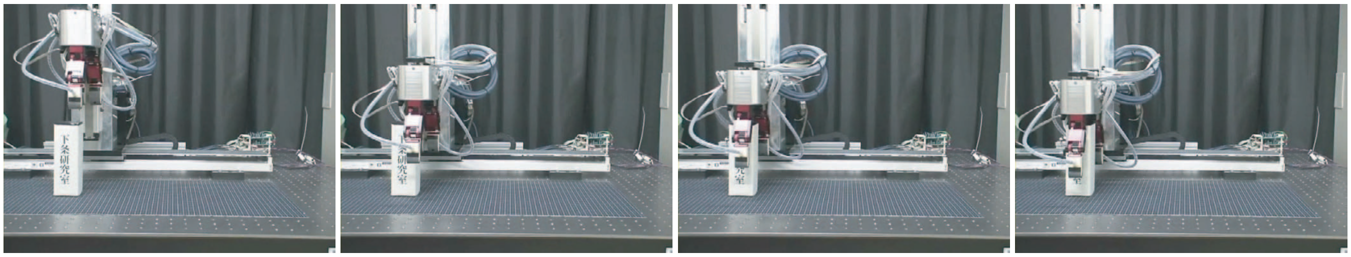
2) The determination operation of the grasp attitude using the fingertip proximity sensors also greatly contributed to the achievement of grasp. Even in a simple grasp attitude such as a pinching the target object from both sides, the contact timing of the fingertips does not coincide due to attitude error of the target object or initial attitude displacement when repetitive tasks are performed. As a dead band exists in the tactile sensor, the attitude of the target object is altered by the first fingertip to contact, leading to cases where grasping fails and so the importance of coinciding contact timing in the achievement of grasp was seen. This fingertip trajectory control was simple with a fixed height direction and control in the horizontal direction only. However, through achievement of grasp attitude and trajectory control based on the fingertip proximity sensors in response to the target object shape, it may be possible to realize a precise grasp in response to various shaped objects. Furthermore, the selection of a grasp attitude in response to the target object may not be possible to determine from just the information from the proximity sensor of the palm of the hand, in which case it may be necessary to use visual information such as from a camera, etc. complimentarily.

3) Dynamic grasp force control was achieved, realizing a grasp force that did not allow the object to fall while not being excessive. Even if the same object is grasped, a grasp strength configured in advance can be insufficient because variations in friction conditions result from changes in the contact surface and differences in contact position in each test operation and so an adaptive grasp strength based on slippage was extremely effective. Furthermore, in circumstances where the reception of the tangential force of the CoP sensor force output is used, separation of the tangential and normal vector forces is not possible for the slip detection applied here. For this reason, the inability to measure a precise normal vector force is an issue and the investigation of this characteristic or combined usage with another sensor must be considered.

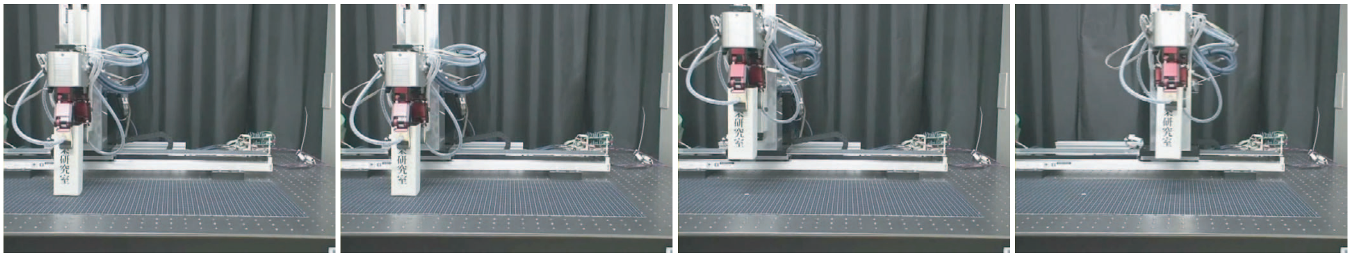
4) As it is not necessary to assign a position to release the target object in advance and variations in placement position can be handled, a placement operation based on slip detection may be expanded to delivery to humans or other robots, etc. However, in order that the contact patch detection is determined by threshold, it may be necessary to consider limiting the placement operation range in practice, as the possibility exists for the target object to be mistakenly dropped in the case a rush interference is generated. An intelligent robot as proposed above would make a grasp operation configuration possible that is resilient to environmental changes by means of sensor integration. Also, although the proposed sensor group does not necessarily provide an abundance of high speed information, it showed sufficient effectiveness through its appropriate usage.

VII. CONCLUSION

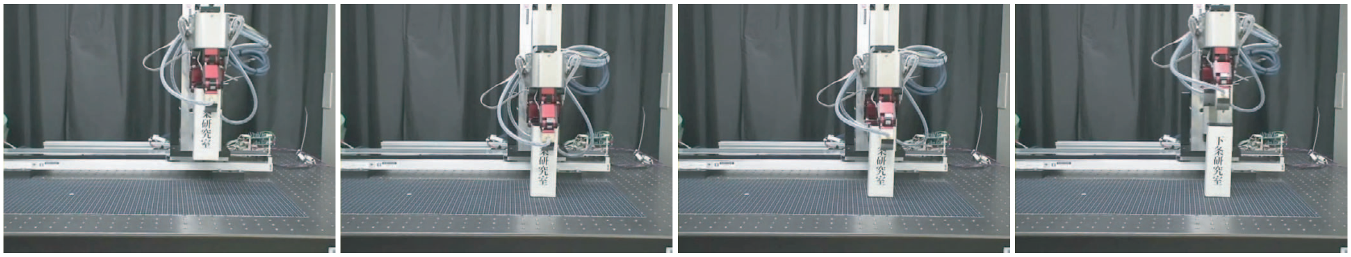
Through integrating proximity, tactile and slip senses, detection from approach to contact was seamlessly carried out, and an intelligent robot hand that could reliably grasp/seize was proposed. In moving towards this materialization, an integrated tactile and proximity sensor was proposed by means of a punched CoP and an intelligent robot hand was



(1) Initial Position (2) Wrist goes down (3) Adjustment of Position Error (4) Completion of Position Error Adjustment



(5) Moving to Grasping Position (6) Grasping (7) Wrist Rising / Grasping Force Control (8) Wrist Moving



(9) Wrist goes down (10) Landing Detection (11) Releasing Object (12) Completion Pick & Place

Fig. 16. Pick & Place operation of the robot hand

composed by actually mounting the sensor in it. Furthermore, Pick & Place was adopted as a practical task using the hand, and was successful in implementation under the conditions of 1) weight/shape/friction conditions are unknown and 2) placement error exists. Although the sensor group did not necessarily provide an abundance of precise information, it showed sufficient effectiveness through its appropriate usage. Hereafter, it is planned to include a proximity sense in the whole area of the fingertips through the miniaturization of a net-structure proximity sensor and aim for an increase in capability of handling the grasped object by increasing the operational degrees of freedom of the robot.

REFERENCES

[1] N. Furukawa, A. Namiki, T. Senoo and M. Ishikawa, Dynamic Regrasping Using a High-speed Multifingered Hand and a High-speed Vision System, IEEE Int. Conf. on Robotics and Automation, 181/187, 2006

[2] Yuji Yamakawa, Akio Namiki, Masatoshi Ishikawa, and Makoto Shimojo, One-handed Knotting of a Flexible Rope with a High-speed Multifingered Hand having Tactile Sensors, 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems/pp.703-708, 2007

[3] K. Hsiao, P. Nangeroni, M. Huber, A. Saxena, A. Y Ng, Reactive Grasping Using Optical Proximity Sensors, IEEE Int. Conf. on Robotics and Automation, 2098/2105, 2009

[4] R. Wistort, J.R. Smith, Electric Field Servoing for Robotic Manipulation, IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, 494/499, 2008

[5] H.R. Nicholls, M.H. Lee: A Survey of Robot Tactile Sensing Technology, Int.J. Robotics Research, 8-3,3/30, 1989

[6] M.H. Lee, H.R. Nicholls,Tactile Sensing for Mechatronics- A State of the Art Survey,Mechatronics, 9, 1/31, 1999

[7] T. Ishihara, A. Namiki, M. Ishikawa, M. Shimojo, Dynamic Pen Spinning Using a High-speed Multifingered Hand with High-speed Tactile Sensor, 2006 IEEE RAS Int. Conf. on Humanoid Robots, 258/263, 2006

[8] Information and Robot Technology Reserch Initiative, the University of Tokyo, Announcing ”Technology that supports dish washing with kitchen robots”,
http://www.irt.i.u-tokyo.ac.jp/news/kitchenrelease081217.pdf

[9] M. Ishikawa, M.Shimojo, A Method for Measuring the Center Position of a Two Dimensional Load Using Pressure-Conductive Rubber, The Society of Instrument and Control Engineers, vol.18, no.7, pp.730-735, 1982

[10] S. Teshigawara, K. Tadakuma, A. Ming, M. Ishikawa, and M. Shimojo: High Speed and High Sensitivity Slip Sensor Utilizing Characteristics of Conducive Rubber, Journal of Robotics and Mechatronics, vol.21, no.2, 200-208, 2009

[11] D. Gunji, Y. Mizoguchi, and M. Shimojo: Grasping Force Control of Multi-fingered Robot Hand based on Slip Detection with Tactile Sensor, Proc. of IEEE Int. Conf. on Robotics and Automation 2008,2605/2610, 2008

[12] S. Amamoto, M. Shimojo, Y. Shibasaki, M. Ishikawa: Object recognition of a robot by using a proximity sensor network system, 8th SICE System Integration Division Annual Conferince, pp. 493-494, 2007

[13] M. Shimojo, T. Araki, S. Teshigawara, A. Ming, M. Ishikawa: A Net-structure tactile sensor covering freeform surface and ensuring high-speed response, IEEE/RSJ (IROS2007),670/675, 2007

[14] Y. Mizoguchi, S. Teshigawara, A. Namiki, M. Ishikawa, A. Ming, M. Shimojo, Pick & Place Task Based on Slip Detection, 8th SICE System Integration Division Annual Conferince, pp. 57-58, 2007

[15] Y. Mizoguchi, K. Tadakuma, M.Ishikawa, A. Ming, M. SHimojo: Development of Inelligent Robot Hand - Control of Capture and Grasp using Tactile-Proximity sensor -, 9th SICE System Integration Division Annual Conferince, pp. 991-992, 2008