Universal Robot Hand Equipped with Tactile and Joint Torque Sensors - Development and Experiments on Stiffness Control and Object Recognition -

Hiroyuki NAKAMOTO
Hyogo Pref. Institute of Technology
3-1-12 Yukihira-cho, Suma-ku
KOBE, 654-0037, JAPAN

Futoshi KOBAYASHI
and Fumio KOJIMA
Dept. of Mechanical and Systems
Engineering, Kobe University
1-1, Rokkodai-cho, Nada-ku
KOBE, 657-8501, JAPAN

Nobuaki IMAMURA
Kobe City College of Technology
8-3 Gakuen-Higashimachi, Nishi-ku
KOBE, 651-2194, JAPAN

Hidenori SHIRASAWA
The Advanced Materials Processing
Institute Kinki Japan
7-1-8 Doi-cho
AMAGASAKI,660-0807,JAPAN

ABSTRACT

Various humanoid robots have been developed and multifunction robot hands which are able to attach those robots like human hand is needed. But a useful robot hand has not been depeveloped, because there are a lot of problems such as control method of many degrees of freedom and processing method of enormous sensor outputs. Realizing such robot hand, we have developed five-finger robot hand. In this paper, the detailed structure of developed robot hand is described. The robot hand we developed has five fingers of multi-joint that is equipped with joint torque sensors and tactile sensors. We report experimental results of a stiffness control with the developed robot hand. Those results show that it is possible to change the stiffness of joints. Moreover we propose an object recognition method with the tactile sensor. The validity of that method is assured by experimental results.

Keywords: Robot Hand, Tactile Sensor, Joint Torque Sensor, Stiffness Control, Object Recognition

1. INTRODUCTION

Recently, various humanoid robots to help human works in human living environment have been developed [1]-[3]. However, these robots can not work like the human, because there are still many elements that should advance research and development. One of them is a robot hand that can do various jobs. Considering to work in human living environment and to use same tools as the human uses, the robot hand is required that size and number of robot finger are equal to those of human hand.

A human hand has five multi-joint fingers, and a finger has various sensor including tactile perception and kinesthetic sense. Realizing such robot hand, multi-fingered robot hands have been researched [4]-[10]. The Utah/MIT Dextrous Hand [4] has four fingers with four joints driven with tendon cables by pneumatic actuators. A full tactile sensing suite has been also developed for this hand. This sensor is comprised of capacitance sensing and is capable for use in contact force control [9]. However, it is difficult to maintain the high accuracy of the position control, because the tendon cable has a tendency to stretch. The Gifu Hand [5] and the KH Hand type S [6] have 20 joints with 16 DOF and 20 joints with 15 DOF, respectively. These robot hands weigh light and are equipped with the six-axes force sensors and the tactile sensors used the conductive ink. The six-axes force sensors are mainly used to control the robot hand[7] However, the tactile sensor is not actively used to control these robot hands. There are many problems to realize dexterous motions effectively using the tactile sensors yet. The hardware with high accuracy and the software using the information obtained by the sensors are important in control of such multi-fingered robot hands like human hands.

Therefore we proceed with the study about robot hands from both sides of hardware and software. Five-fingered robot hand we developed (hereinafter called Universal Robot Hand) has five multi-joint fingers that is equipped with joint torque sensors and tactile sensors. This report deals with the structure of the fingers and the tactile sensors. The results of stiffness control show that the developed finger can drive with high accuracy. Moreover we propose an object recognition method with tactile sensor which measures a pressure distribution. The validity of that method is assured by experimental results.

2. UNIVERSAL ROBOT HAND

Mechanism of Finger and Control System

The mechanism of finger is shown in Figure 1 and the specification of finger is shown in Table 1. This finger has four joints and three degrees of freedom. Each joint is driven by miniaturized DC motor and reduction gears (manufactured by Harmonic Drive Systems CO.) built-in each link. In addition, two joints of fingertip, Joint3 and Joint4, drive at equal ratio as a human finger. Each joint has a joint torque sensor and each DC motor has a rotary encoder. The tactile sensors are attached in ventral side

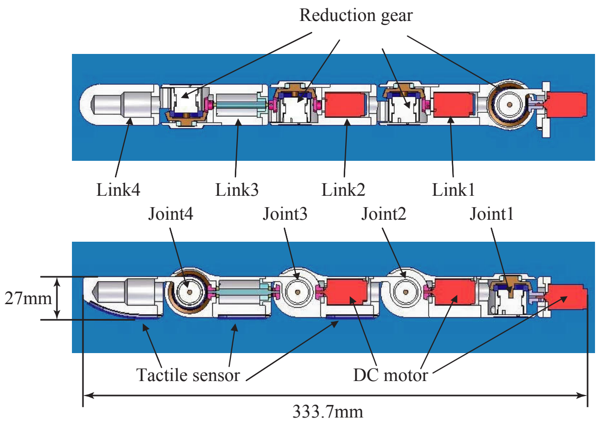

Fig. 1 Finger mechanism

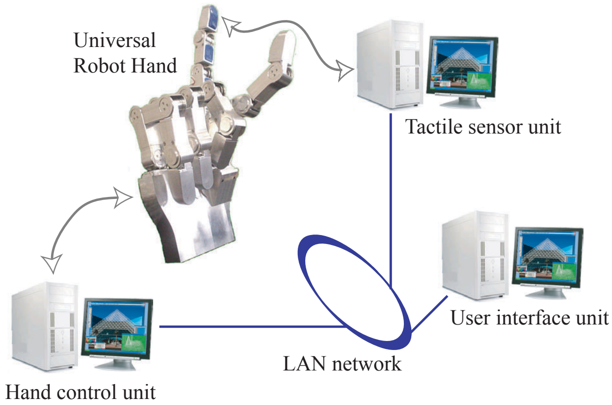

Fig. 2 Control system

number of joint	4
actuator	3(DC micro motor)
angle range	-10 $\leq$ J1 $\leq$ 10[degees] 0 $\leq$ J2,J3,J4 $\leq$ 90[degees]
speed	J1-J4 : 29[rpm]max
torque	J1-J4 : 1100[Nmm]max

Table 1 Specification of finger

of each link. The finger is 333.7mm length.
The control system of Universal Robot Hand is shown in Figure 2. Generally, such as a robot hand system controls with processing outputs of rotary encoders, tactile sensors and torque sensors. However, amount of processing outputs becomes higher as increasing joints and sensors. Then it is difficult to control a robot hand in real time. The control system of Universal Robot Hand has three units which are a hand control unit, a tactile sensor control unit and a user interface unit. All units are driven on RT-Linux and are linked with LAN. The hand control unit processes outputs of motor's rotary encoders and torque sensors and controls the finger joints. The tactile sensor control unit controls all tactile sensors. The user interface unit shows conditions of the Universal Robot Hand. An operator is able to control the Universal Robot Hand with this unit.

Stiffness Control

When the Universal Robot Hand grasps or manipulates an object, it is necessary to adaptively control the finger posture according to the shape of the object. Therefore, it has been studied to control the relation between the tip position of the finger and its torque. Recently, it is studied about the stiffness control that controls the relation between torque and position. It is thought that the stiffness control is a very effective method to control complex mechanism with many degrees of freedom like the Universal Robot Hand. In this report, we applied the stiffness control modeled by Imamura [11] to the Universal Robot Hand. This model is expressed by eq.(1) and is able to arbitrarily adjust the joint stiffness by changing positional control gain K_p.

$$\begin{aligned} EM &= K_t(t_r - t_a) \\ t_r &= K_p(\theta_r - \theta_a) \end{aligned} \quad (1)$$

where EM represents the torque signal to joint, K_t and K_p represent the torque control and the position control gain, respectively, and t_r, t_a, θ_r, θ_a represent the target torque, the measured torque, the target angle, the mesured torque, respectively.

Experiments of Stiffness Control

The control characteristic of the Universal Robot Hand was experimentally evaluated. Firstly Figure 3 shows results of the step response with PD control of 1 milliseconds control cycle. The target values were 30 and 60 degrees. The finger operation times ware about 600 milliseconds in case of 30 degrees and about 1050 milliseconds in case of 60 degrees. It was confirmed that the error margin was within 0.3 degrees in any case and the position of high accuracy was able to control in 1 milliseconds period. Accordingly, it was confirmed that the Universal Robot Hand was able to control with a position of high accuracy. Next, the performance evaluation experiment of the stiffness control was implemented. The target torque was set 0 degree. When the positional control gain changed as K_p=5, 10 and 15, relations between the joint angle and the external torque was measured. Figure 3 shows experimental results. In the figure, the horizontal axis shows the joint angle and the vertical axis shows the external torque. The joint stiffness was in proportion to the positional control gain. The results shows that it is possible to control the joint stiffness control by adjusting the gain K_p. However, the hysteresis loop is seen between the joint torque and the angle. It is thought that the offset by the friction of reduction gears causes the hysteresis loop.

3. TACTILE SENSOR

Structure

The developed tactile sensor is shown in Figure 5. This sensor is three-layer structure; urethane gel (manufactured by EXSEAL CO.), pressure sensitive rubber (man-

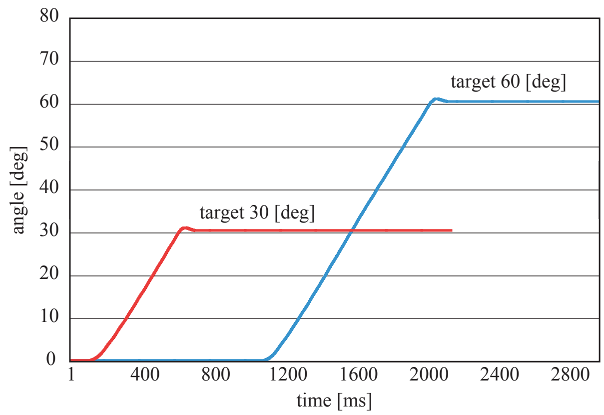

Fig. 3 Step responses

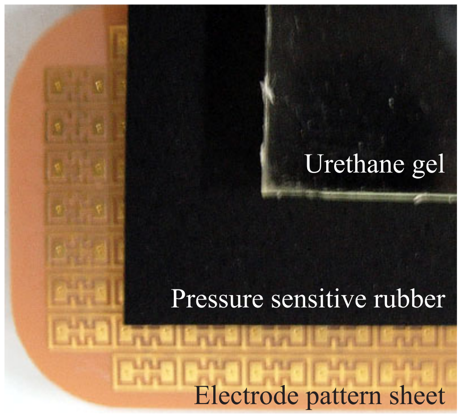

Fig. 5 Structure of tactile sensor

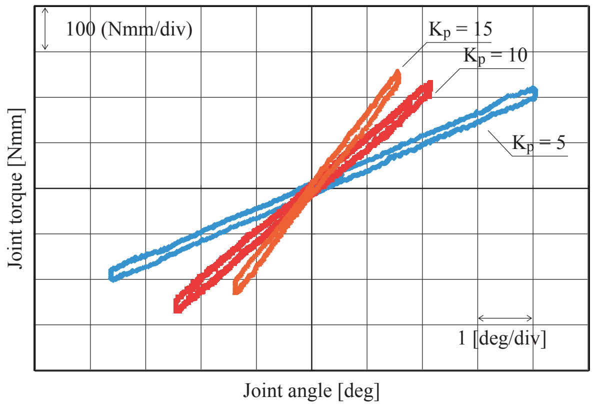

Fig. 4 Stiffness control responses

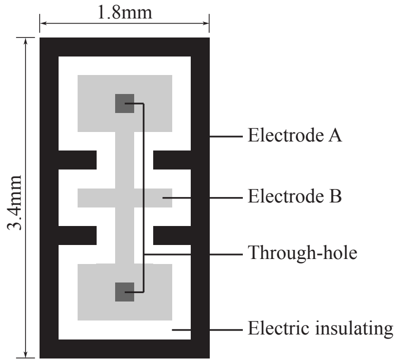

Fig. 6 Electrode pattern unit

ufactured by INABA RUBBER CO.) and electrode pattern sheet from the top. It is easy to product the sensors and replace of the urethane gel which often wears because of simple three-layer structure. The hardness of urethane gel is 15 and its thickness is 2.5mm. When an object contacts this sensor, force and shape of contact surface deforms the urethane gel. This deformation makes pressure distribution for the pressure sensitive rubber. The pressure sensitive rubber is about 0.5mm thick and contains electric conduction particles. When the pressure sensitive rubber receives pressure and becomes thin, electric resistance of the region drops, because the electric conduction particles contact in the pressure sensitive rubber. Consequently, measuring this electric resistance, it is possible to calculate the pressure which is added to the region. Measuring electric resistance of pressure sensitive rubber, the two electrodes is needed in a electrode pattern. One (hereinafter called electrode A) impresses voltage and the other (hereinafter called electrode B) receives current. We designed these electrodes on a multi-layer flexible board of the polyimide material to simplify the sensor structure.

A electrode pattern unit is shown in Figure 6. In the figure, the black outside shows the electrode A and the gray inside shows the electrode B. An electrode B has two through-holes which wired to the inner layer of the flexible sheet. An electrode pattern is size of 3.4 x 1.8mm and becomes a measurement point. As the pressure sensitive rubber is placed over the pattern, the measuring area of the sensor is the pressure sensitive rubber upper the white insulation area between the electrode A and B. Deforming the pressure sensitive rubber makes many conductive paths because the electric conduction particles contact. If the more of the conductive paths, the resisitance changes substantially and the sensitivity of the tactile sensor becomes higher. It is nessesary to reduce the insulation's width to get near these electrodes and to make longer the insulation's length. Then we designed that the width of the insulation is 0.2mm and both electrodes are complicated.

The electrode pattern sheet is shown in Figure 7 . In the sheet, the number of the electrode A is 9 in the vertical direction and the number of the electrode B is 8 in the horizontal direction. As the sheet has 70 units shown in Figure 6, the tactile sensor has 70 measurement points. We also designed 0.2mm gap between measurement points to reduce the insensitive area of the sensor. The ratio of the measurement area to the senor area is about 82 percent.

Attaching to Universal Robot Hand

The Universal Robot Hand which is attached the tactile sensor is shown in Figure 8. The tactile sensors are attached in ventral side of each link of the finger and there are three sensors per one finger. The number of measurement point of the fingertip is 102 points, the other 2 parts is 70 points. Wiring from the tactile sensor is connected to the tactile sensor unit via the sensor control circuit which consists of the amplifier and the multiplexer cir-

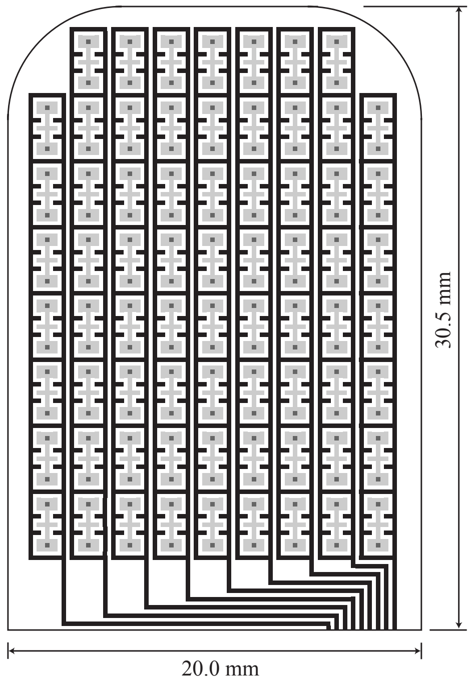

Fig. 7 Electrode pattern sheet

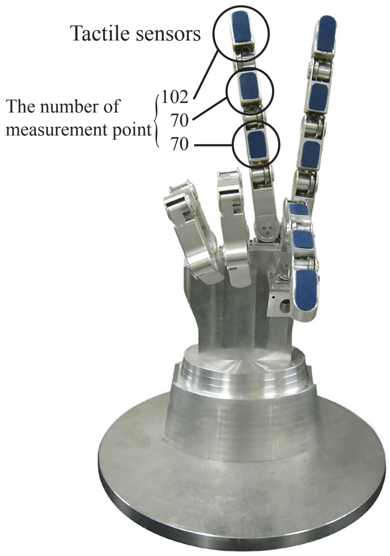

Fig. 8 Universal Robot Hand with tactile sensors

cuit. The tactile sensor unit selects the measurement point via the sensor control circuit and measures outputs of the measurement point in the range of voltage 0-10V, through the AD conversion board with the resolution of 12 bits. The range of this voltage is correspond to 20M-5K Ohms with change of electric resistance of the pressure sensitive rubber.

Method of Object Shape Recognition

We suppose that the robot hand recognizes the grasping object's shape with the pressure distribution which is measured by the tactile sensors. In particular, we have an assumption that the Universal Robot Hand with the plural tactile sensors as shown in Figure 8, grasps an object by using the whole of the finger. In this case, the robot hand recognizes the shapes of the contact surface with tactile sensors, then the hand recognizes the whole shape by combining those results. It is effective to recognize with these two steps. In this paper, we introduce that the shape recognition method regarding the convexity of the contact surface with one pressure distribution in the first step.

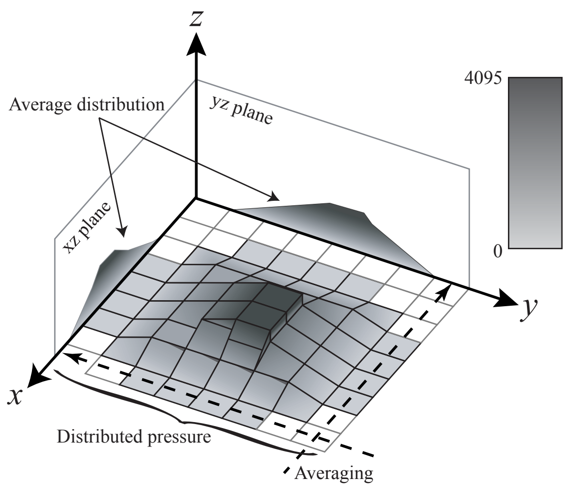

Fig. 9 Example of pressure distribution and average distributions

The tactile sensor measures a pressure distribution as shown in Figure 9. This pressure distribution is based on the shape of the contact surface and the total force. Here we assume that environmental condition such as temperature and humidity is constant. When the added force to the contact surface is constant, the pressure distribution depends on the shape of the contact surface. If the shape of the contact surface has the convexity like sphere, the pressure distribution becomes sharp, if the surface is flat, the distribution becomes low. Under the above hypothesis, the shape recognition of the contact surface is done as follows: As Figure 9 shows, the axes of coordinates are set to pressure distribution. The average distribution which takes the average of pressure value of y-axis direction in regard to xz-plane is found. In the same way average distribution is found in regard to yz-plane. Next, each average distribution is regarded frequency distribution, that kurtosis γ is culculated by eq.(2)

$$\gamma = \sum_{i=1}^{N} z_i (c_i - \mu)^4 / (N\sigma^4) \qquad (2)$$

In eq.(2), $z_i(i = 1..N)$ are data of distribution, $c_i(i = 1..N)$ are class values of the data, N is the number of data, μ is average, σ is standard deviation. If the distribution becomes sharp, the kurtosis becomes high and if distribution is flat, the kurtosis becomes low. We thought it is suitable for the shape recognition of the contact surface, because kurtosis is able to express at one value of the sharp condition of pressure distribution.

Experiments

We carried out some experiments about the shape recognition. The test pieces were placed in front of the Universal Robot Hand and touched to the tactile sensor by driving finger joints. We used five different test pieces as shown in Figure 10. The dotted lines as shown in Figure 10 represent the contact surface of each test piece.

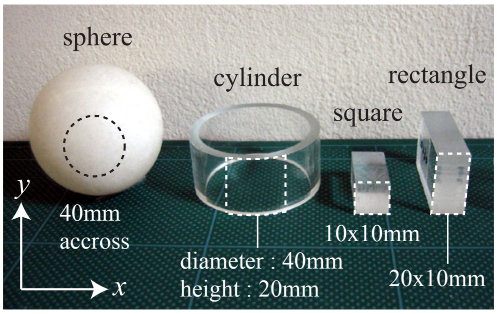

Fig. 10 Test pieces

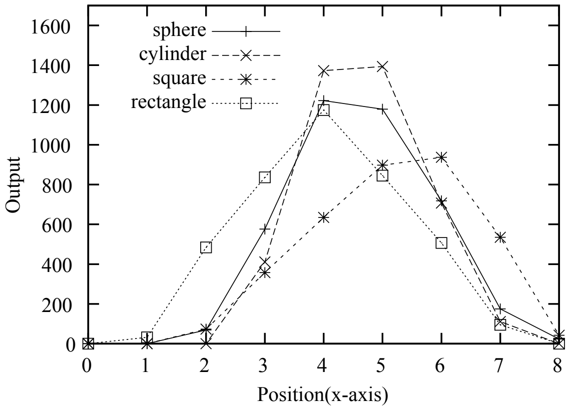

Fig. 11 Average distribution of xz-plane

Average distributions of xz-plane of test pieces are shown in Figure 11, that of yz-plane are shown in Figure 12. They were acquired from pressure distributions when the sum total of measurement points was 30000. The number of electrodes of the tactile sensor was 9 in x-axis and 8 in y-axis. Therefore, a horizontal axis in Figure 11 had 9 elements and that in Figure 12 had 8 elements. A vertical axis of each graph was outputs by the AD conversion board. In Figure 11, as sphere and cylinder had the curved shape of 40mm diameter, thier distributions became approximately the same shape. In Figure 12, as cylinder and rectangle had the flat shape of 20mm length, thier distributions became approximately the same distribution, too. These results showed that the developed tactile sensor was able to measure the pressure distribution responding to the shape of the contact surface.

Next, averages and standard deviations of kurtosis in each distribution of each test piece is shown in Table 2. These are averages and standard deviations of five measurement. It was shown that the difference in the kurtosis of each average distribution was small between planes whose contours of contact surfaces were similar, xy- and yz-plane of the sphere and xz-plane of the cylinder, yz-plane of the cylinder and the rectangle, xz- and yz-plane of the square and xz-plane of the rectangle. Moreover, standard deviations were also smaller than 3% of each average. These values showed kurtosis was higher reliability. The contour of the contact surface was reflected to the kurtosis.

4. CONCLUSION

In this paper, we reported the detailed structure of the Universal Robot Hand. The experimental results of a stiffness control showed that it was possible to change the stiffness of joints. We also reported the structure and feature of the tactile sensor. The experimental results showed that kurtosis was available for the shape recognition of the contact surface. We will study about understanding of grasping state and recognition of grasping object with tactile sensors, joint torque sensors and rotary encoders. Additionally, research about the control method of the Universal Robot Hand will be advanced.

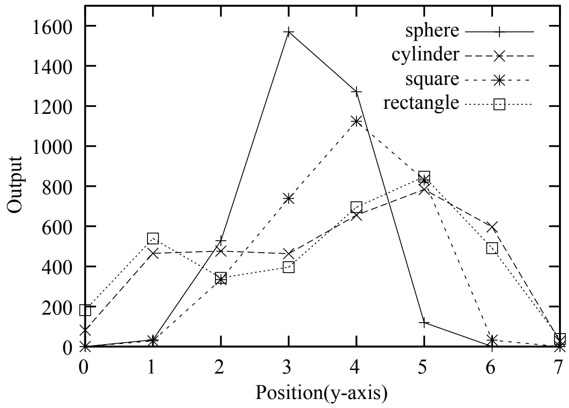

Fig. 12 Average distribution of yz-plane

Table 2 Averages and standard deviations of kurtosis of average distributions

test piece		sphere	cylinder	square	rectangle
xz	AVE	2.67	2.68	2.40	2.38
	SD	0.026	0.057	0.032	0.011
yz	AVE	2.71	1.96	2.38	1.94
	SD	0.081	0.026	0.067	0.045

5. REFERENCES

[1] K. Kaneko, F. Kanehiro, S. Kajita, K. Yokoyama, K. Akachi, T. Kawasaki, S. Ota, and T. Isozumi, "Design of Prototype Humanoid Robotics Platform for HRP", **Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems**, 2002, 2431-2436.

[2] Honda Motor Co., "ASIMO OFFICIAL SITE", **"http://www.honda.co.jp/ASIMO/"**, (in Japanese).

[3] Mitsubishi Heavy Industries, "wakamaru", **"http://www.mhi.co.jp/kobe/wakamaru /english/"**.

[4] John M. Hollerbach, and Stephen C. Jacobsen, "Anthropomorphic robots and human interactions", **Proceedings of 1st International Symposium on Humanoid Robots**, 1996, 83-91.

[5] T. Mouri, H. Kawasaki, K. Yoshikawa, J. Takai, and S. Ito, "Anthropomorphic Robot Hand: Gifu Hand III", **Proceedings of International Conference ICCAS2002**, 2002, 1288-1293.

[6] T. Mouri, H. Kawasaki, and K. Umebayashi, "Developments of New Anthropomorphic Robot Hand and its Master Slave System", **Proceedings of the 2005 IEEE/RSJ International Conference on**

Intelligent Robots and Systems, 2005, 3474-3479.

[7] S. Ueki, H. Kawasaki, and T. Mouri, "Adaptive Coordinated Control of Multi-Fingered Hands with Rolling Contact", **Proceedings of SICE Annual Conference 2005 in Okayama**, 2005, 852-857.

[8] S. Schulz, C. Pylatiuk, and G. Bretthauer, "A New Ultralight Anthropomorphic Hand", **Proceedings of the 2001 IEEE International Conference on Robotics and Automation**, volume 3, 2001, 2437-2441

[9] D. Johnston, P. Zhang, J. Hollerbach, and S. Jacobsen, "A Full Tactile Sensing Suite for Dextrous Robot Hands and Use in Contact Force Control", **Proceedings of the 1996 IEEE International Conference on Robotics and Automation**, 1996, 661-666.

[10] J. Jockusch, J. Walter, and H. Ritter, "A Tactile Sensor System for a Three-Fingered Robot Manipulator", **Proceedings of IEEEE International Conference on Robotics and Automation**, 1997, 3080-3086.

[11] N. Imamura, M. Kaneko, K. Yokoi, and K. Tanie, "Development of a two-fingered robot hand with compliance adjustment capability", **Symposium of flexible automation (ISCIE)**, 1990, 997-1004.