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Low Force Control Scheme for Object Hardness Distinction in Robot Manipulation Based on Tactile Sensing

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***Abstract*—This paper presents an application of a low force interaction method in a control scheme of robot manipulation based on tactile sensing. Our aim is to develop an intelligent control system that can distinguish the hardness of unknown objects so that robotic fingers can effectively explore the object's surface without altering its physical properties or causing damage. Initially we developed a novel optical three-axis tactile sensor system based on an optical waveguide transduction method capable of acquiring normal and shearing forces. The sensors are mounted on the fingertips of the multi-fingered humanoid robot arm. We proposed a new control scheme applying low force interaction to distinguish the hardness of unknown objects in robot manipulation tasks based on tactile sensing. The scheme utilized new control parameters obtained by calibration experiments using hard and soft objects that enable robot fingers to precisely control grasp pressure and define the slippage sensation of the given object. Finally, verification experiments of the proposed control scheme using a humanoid robot arm were conducted whose results revealed that the finger's system managed to recognize the hardness of unknown objects and complied with sudden changes of the object's weight during object manipulation tasks.**

I. INTRODUCTION

THE sense of touch or tactile sensing is the process of determining physical properties and events through contact with objects in the world. As one of the five main sensing modalities in humans besides sight, sound, smell, and taste, the sense of touch will play an important role in robotic paradigms toward effective manipulation and collaboration with humans in built-for-human environments. In robot manipulation, the ability to sense hardness and/or softness will be particularly important in future applications of developmental robots that apply tactile sensing.

In daily life, humans regularly apply tactile sensing to support motions and perform tasks. However, in a developmental robot, tactile sensors are especially appropriate sensing devices that have too often been neglected in favor of vision-based approaches. To date, while much research has developed visual and auditory sensors, comparatively little progress has been made on sensors that translate the sense of touch. This apparent neglect reflects the complexity of tactile sensing itself, because tactile sensing through the skin is not a simple transduction of one physical property into electronic signals. Furthermore tactile sensing is difficult to imitate, unlike sight and sound, which are well-defined physical quantities. In addition, the fact that a tactile signal is distributed over a much wider area and lacks such localized sensory organs as eyes and ears complicates the developmental of artificial sensory devices.

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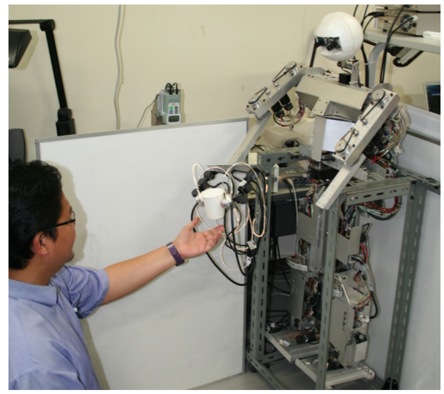

Fig. 1. Humanoid robot *Bonten-Maru II* collaborates with human in object manipulation tasks. Its arm is equipped with two robotic fingers mounted with optical three-axis tactile sensor at each fingertip.

Nonetheless, realizing that the development of intelligent tactile sensors will help advance the evolution of human and robots working together in real life is encouraging. Indeed, researchers have recently agreed that a tactile sensor system is an essential sensory device to support the robot control system, particularly for object manipulation tasks [1-3]. This agreement reflects the tactile sensor's capability to simultaneously sense normal force, shearing force, and slippage, thus offering exciting possibilities for determining object shape, texture, and property in real environments. To successfully manipulate objects in the real world, robot systems require some form of tactile feedback to distinguish the object's hardness. Unfortunately, the parameters of human fingers involved in sensing an object's hardness have not been fully researched. So far, no specific parameters in developmental robots or even in the human nervous system can measure the hardness sensation.

A. Robot Manipulation Based on Tactile Sensing

Robot manipulation fundamentally relies on contact interaction between the robot and the world. As blind people convincingly demonstrate, tactile sensing alone can support extremely sophisticated manipulation. Therefore in this research we focus on robot manipulation based on tactile sensing. However, serious issues exist in object manipulation based on tactile sensing. First, the robot must use low force interactions to explore the object surface without altering its physical properties or causing damage. Second, during the manipulation task when suddenly the object's weight is changes, the robot will have trouble controlling the exact grasping pressure. The third issue is related to mechanical structure and material strength; tactile sensor elements, which are normally made from soft and elastic materials such as silicon rubber, reduce robustness for handling strong impact and pressure during object manipulation tasks.

Researchers are addressing these problems through a novel sensor design that considers intelligent object exploration algorithms [4][5]. However, it seems insufficient since so far manipulation tasks have only been demonstrated using solid and hard objects, and questions of low force interaction and hardness distinction for the safe manipulation of soft and fragile objects have still not been fully researched. We believe that besides the development of a novel tactile sensor system that can precisely measure forces, developing of a precision control scheme to distinguish object hardness is also inevitable. Therefore, in this research we aim to develop a control scheme for robotic fingers to distinguish the hardness of unknown objects for safe and effective robot manipulation in real environments.

B. Current State-of-the-Art Survey of Tactile Sensing in Humanoid Robot Manipulation

Tactile sensors offer exciting possibilities for applications in robotics for determining object shape, texture, hardness, etc. Humanoid robotics has generated the most interest recently regarding tactile sensor applications because humanoid robots are practically suitable to coexist with humans due to their anthropomorphism, human friendly design, and locomotive ability. Indeed, to effectively work in built-for-human environments, a humanoid robot requires sensing devices that can measure physical properties and recognizes the shapes of objects through contact interaction to allow the robot to generate suitable trajectories for safely handling them.

Recently, researchers have focused on developing intelligent tactile sensor systems that are compatible with humanoid robot platforms [2][5]. Several achievements have already been reported including a protruding-shape tactile sensor developed at MIT [6] that can estimate the magnitude and direction of applied forces with great sensitivity by measuring the deformation of a compliant dome. The sensor system has been applied in a compliant hand of a humanoid robot called *Obrero*. Another interesting example is the skin-type conformable and scalable tactile sensor developed by a research team at Tokyo University [7]. The tactile sensing element consists of a photoreflector covered by

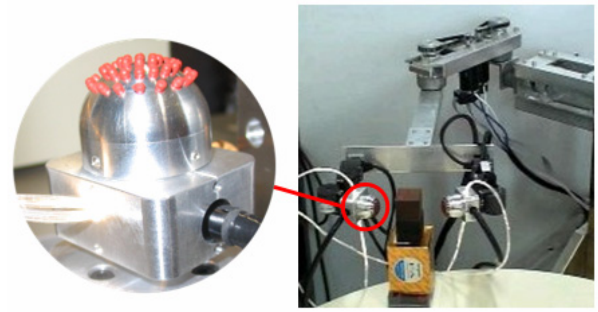

Fig. 2. Multi-fingered humanoid robot arm mounted with optical three-axis tactile sensors at fingertips.

urethane foam and organized as a network of self-contained modules that communicate through a serial bus. The novelty of this tactile sensor includes connectivity, cuttability, and bendability, allowing for easy attachment to the robot body to realize whole-body movements. This tactile sensor has been applied in adult-size humanoid robot bodies to perform a dynamic roll-and-rise motion [8]. However, this tactile sensor seems unsuitable for use in object manipulation, particularly to define low force interaction and determine slippage sensation.

In this research, we initialized a humanoid robot project toward effective working collaboration of humans and humanoids in real life. For this purpose, we developed a research prototype humanoid robot called *Bonten-Maru II*, as shown in Fig. 1 that is 1.25-m tall, weights 32.5 kg, and has a total of 21 dofs: six for each leg, three for each arm, one for the waist, and two for the head. The robot arm has two robotic fingers with 3-dof for each finger. The newly developed optical three-axis tactile sensors are mounted on each finger as shown in Fig. 2, for analysis of object manipulation tasks based on tactile sensing. In this report, we present the development and analysis of object manipulation in a humanoid robot based on tactile sensing. We applied low force interaction in the robot's control system so that the robotic fingers can initially perform soft touch on the object to distinguish its hardness before continuing to manipulate it more safely and effectively.

II. Optical Three-Axis Tactile Sensor

A tactile sensor is a device that can measure a given property of an object or contact event through physical contact between the sensor and the object. Research on tactile sensor is basically motivated by the tactile sensing system of the human skin. In humans, the skin's structure provides a mechanism to simultaneously sense static and dynamic pressure with extremely high accuracy. Meanwhile in robotics, several tactile sensing principles are commonly used, such as capacitive, piezoelectrical and optoelectrical sensors [3]. In this research, to establish object manipulation ability in a real humanoid robot, we developed an optical three-axis tactile sensor capable of acquiring normal and shearing forces to mount on the fingertips of the humanoid robot arm. This tactile sensor uses an optical waveguide transduction method

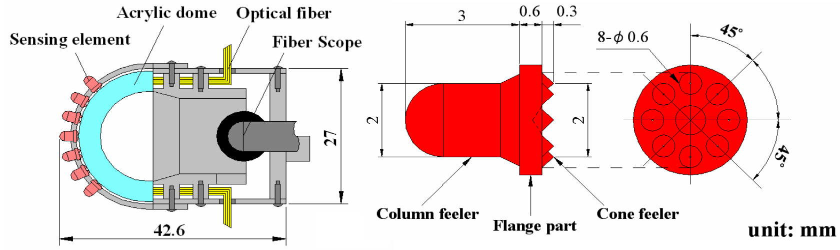

Fig. 3. Structure of hemispherical optical three-axis tactile sensor and sensing element.

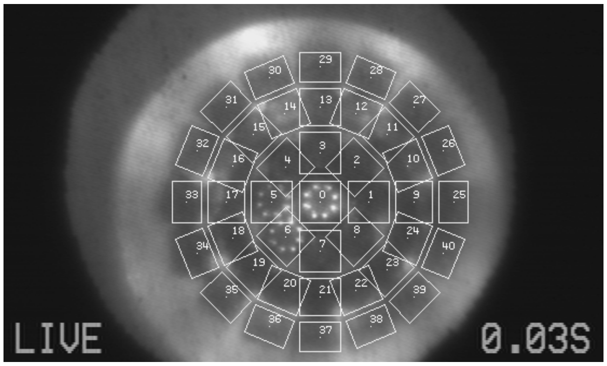

Fig. 4. CCD camera-captured image of contact phenomenon in the optical three-axis tactile sensor.

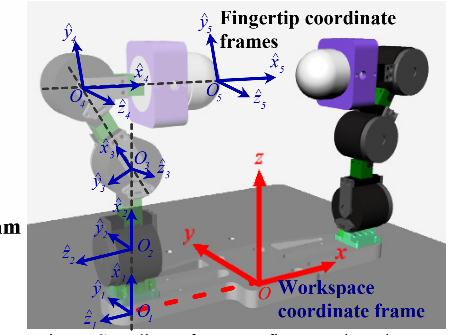

Fig. 5. Coordinate frames at finger and workspace.

and applies image processing techniques. Such a sensing principle is expected to provide better sensing accuracy to realize contact phenomena by acquiring the three axial directions of the forces, so that normal and shearing forces can be measured simultaneously.

The optical three-axis tactile sensor is designed in a hemispherical dome shape that consists of an array of sensing elements. This shape is to mimics the structure of human fingertips for easy compliance with various shapes of objects. The hardware novelty consists of an acrylic hemispherical dome, an array of 41 pieces of sensing elements made from silicon rubber, a light source, an optical fibre-scope, and a CCD camera, as shown in Fig. 3. Here, light emitted from the light source is directed toward the edge of the hemispherical acrylic dome through optical fibers.

Meanwhile, the silicone rubber sensing element is comprised of one columnar feeler and eight conical feelers (Fig. 3) which remain in contact with the acrylic surface while the tip of the columnar feeler touches an object. The sensing elements are arranged on the hemispherical acrylic dome in a concentric configuration with 41 sub-regions as shown in Fig. 4. When an object contacts the columnar feelers, resulting in contact pressure, the feelers collapse.

At the points where the conical feelers collapse, light is diffusely reflected out of the reverse surface of the acrylic surface because the rubber has a higher reflective index. Contact phenomena consisting of bright spots caused by the collapse of the feelers are observed as image data, which are retrieved by the optical fibre-scope connected to the CCD camera and transmitted to the computer. Fig. 4 shows the image data of contact phenomenon acquired by the CCD camera. The dividing procedure, digital filtering, integrated gray-scale value and centroid displacement are controlled on the PC using auto analysis programme. In this situation, the normal force of the *Fx*, *Fy* and *Fz* values are calculated using integrated gray-scale value *G*, while shearing force is based on horizontal centroid displacement. The displacement of gray-scale distribution $\boldsymbol{u}$ is defined in (1), where $\boldsymbol{i}$ and $\boldsymbol{j}$ are the orthogonal base vectors of the *x*- and *y*-axes of a Cartesian coordinate, respectively. This equation is based on calibration experiments, and material functions are identified with piecewise approximate curves [9]. Consequently, each force component is defined in (2).

$$\boldsymbol{u} = u_x\boldsymbol{i} + u_y\boldsymbol{j} \quad (1)$$

$$F_x = f(u_x),\ F_y = f(u_y),\ F_z = g(G) \quad (2)$$

In the tactile sensor controller, since the image was warped due to projection from a hemispherical surface (Fig. 4), software Cosmos32 installed in the computer modifies the warped image data and calculates G, u_x and u_y to obtain the applied three-axis force at the sensing element using (2).

III. Low Force Control Scheme

A. Control System Structure

The hardware system structure consists of robotic fingers, an optical three-axis tactile sensor, and a humanoid robot arm. The robotic finger system is comprised of two articulated fingers, each of which has 3-dof with micro-actuators that are used in each joint. Fig. 5 shows the coordinate frames of the fingers with tactile sensors and a workspace coordinate frame. Trajectory generation by kinematical analysis and formulations of coordinate transformation between fingers and tactile sensor are defined in [10] and [11].

Fig. 6 shows the control system structure of the multi-fingered humanoid robot arm with robotic fingers and an optical three-axis tactile sensor used in this research. This system is comprised of three main controllers: arm controller, finger controller and tactile sensor controller. Each of these controllers is connected to the others using TCP/IP protocols by the internet. The arm controller consists of two main modules: robot controller and motion instructor. The control system architecture of the robot finger controller, which is based on tactile sensing, is shown in Fig. 7. This controller is comprised of three modules: connection module, thinking routines, and finger control module.

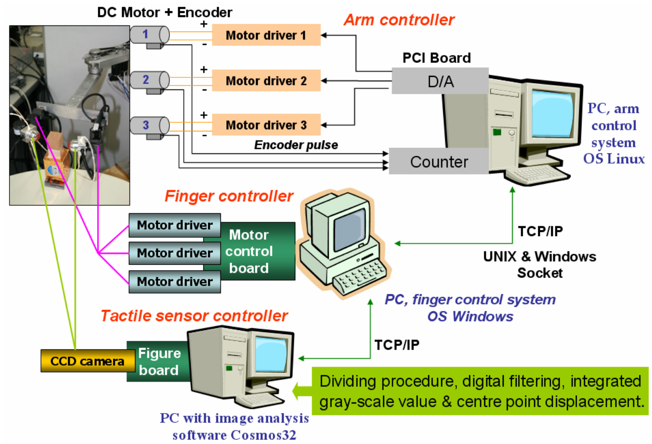

Fig. 6. Control system structure of multi-fingered humanoid robot arm with optical three-axis tactile sensor.

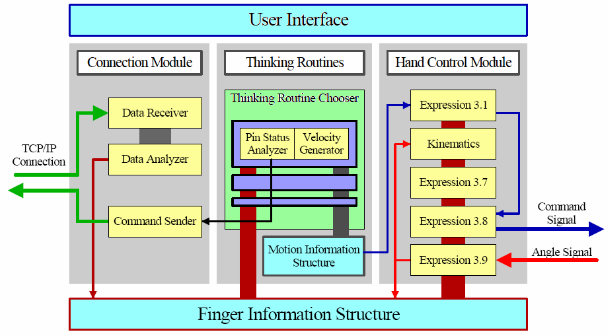

Fig. 7. System conception diagram of finger controller.

B. Methodology for object hardness distinction

As explained in the previous section, the optical three-axis tactile sensor can acquire normal and shearing forces and slippage sensation. To distinguish the hardness of unknown objects in our manipulation tasks, we utilized normal force, shearing force, and slippage sensation in the finger's control system. In the current object manipulation scheme, motion planning is divided into two modes: grasping and moving. In the grasping mode, both fingers move slowly to grasp the object to define the optimum grasp pressure, while controlling the pushing velocity of both fingers to grip the object. When the optimum grasp pressure is defined, both fingers are automatically shifted to the moving mode and togather manipulate the object.

In the proposed control scheme to define hardness distinction, specifying control parameters in the finger control system is necessary so that the fingers can respond correctly to any objects with different hardness conditions. However, serious conflicts remain to specify such parameters, particularly during contact point changes. To solve this problem, first the finger must perform a soft touch on the object's surface and detect forces that occurred during the soft contact event. During soft contact, the detected forces are definitely low and difficult to measure. However, this low force must be utilized to distinguish the object's hardness so that the finger control system can conduct grasping motions without crushing the object or damaging the sensor elements. Therefore, the tactile sensor must be highly sensitive enough to detect a very low force. Furthermore, the sensor system must be able to detect not only normal force but also shearing force so that a slippage sensation that may occur during soft contact can be detected. The optical three-axis tactile sensor used in this research can satisfy the above requirements because the sensing principle, which utilized an optical waveguide transduction method, permits highly sensitive force detection from the acquisition of the three axial directions of forces; thus normal force and shearing force can be measured simultaneously with high accuracy.

C. Determination of Important Parameters

We conducted a series of calibration experiments with soft and hard objects using a multi-fingered robotic system to determine the important parameters in our proposed low force control scheme for hardness distinction. The hard object was an aluminum block, and the soft object was a paper box. The fingers and workspace coordination are indicated in Fig. 5. In this experiment, both fingers move along the x-axis to grip the object and define the optimum grasp pressure for the grasping mode. Then both fingers lift up the object along the z-axis in the moving mode.

In the experiment with the hard object, the reaction force applied toward the tactile sensor elements is big because the elasticity coefficient for the hard object is high. Therefore, the detected normal force becomes high. However, the weight of the hard object caused great slippage. For soft objects, small reaction force is applied to the sensing elements because the elasticity coefficient for soft objects is low. Accordingly, the detected normal force becomes low. Therefore, to correlate the hardness distinction of these hard and soft objects, we utilized the increment of normal force ΔF, which was calculated within a specified progress time, as a hardness distinction parameter. To comply with the slippage that particularly occurred for hard objects, we considered the amount of centroid change dr for x-directional (dx_G) and y-directional (dy_G) of the fingertip coordinate frame, by means of shearing force distribution. If slippage is over the dr value, the finger re-pushes toward the object to prevent it from slipping. However, if the detected ΔF was lower than a specified value (i.e., a soft object), the finger system uses the dr value to control the finger's re-push velocity so that the grasping motion becomes gentler and finally stops when the centroid change is over a specified dr value. On the other hand, the fingertips movements are basically controlled by the thresholds of normal force $F1$ and $F2$. If the normal force is over the $F1$ value, both fingers will not further re-push toward the object. $F2$ is used for emergency stops.

Based on the above control scheme, the results of calibration experiments were compiled in graphs and analyzed to define suitable parameters values. For example the relationship between normal force and shearing force with fingertips movements for the left finger are shown in Fig. 8 for the aluminum and Fig. 9 for the paper box.

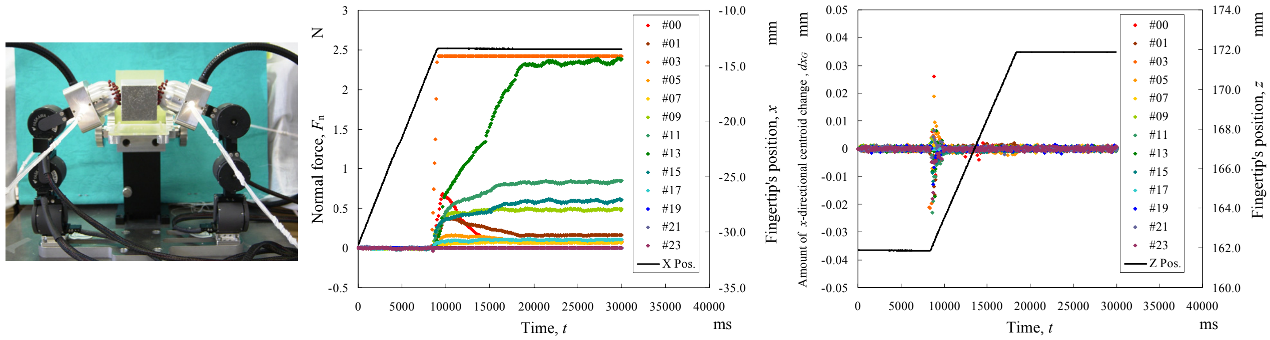

Fig. 8. Robot fingers grasp and manipulate aluminum block *(left)*. Relationship between normal force and x-directional fingertip position for left finger *(middle)*. Relationship between amount of x-directional centroid change and z-directional fingertip position for left finger *(Right)*.

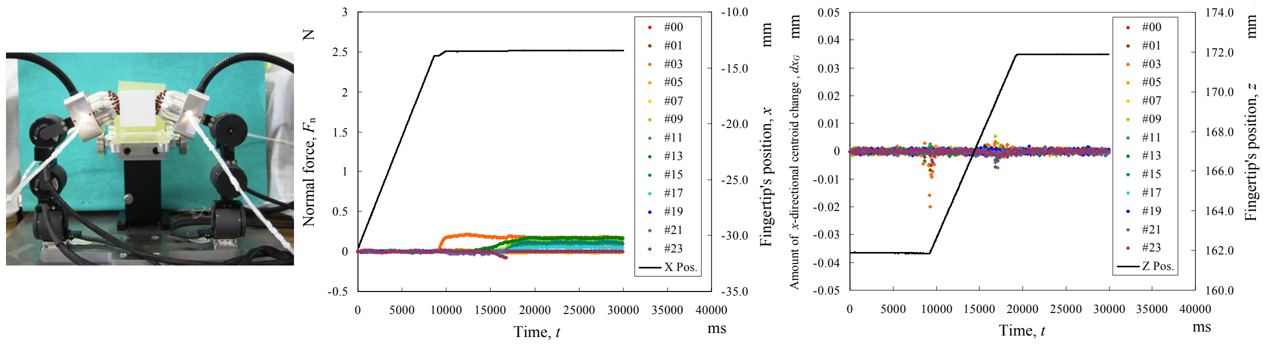

Fig. 9. Robot fingers grasp and manipulate paper box *(left)*. Relationship between normal force and x-directional fingertip position for left finger *(middle)*. Relationship between amount of x-directional centroid change and z-directional fingertip position for left finger *(Right)*.

In these graphs, dx_G and dy_G are calculated within the fingertip coordinate frames, and the fingertip position is always calculated in the workspace coordinate frames. After analyzing the calibration experiment results, we determined the parameter values shown in Table 1. These low force control parameters enable the finger system to realize object hardness, even when the detected forces are very low, and then to precisely adjust the grasp pressure to manipulate the object. The above control scheme is particularly effective to prevent damaging the object or the tactile sensing elements in object manipulation tasks. These parameters are applied in the control algorithm of the robot finger controller at the thinking routine module (Fig. 7).

Table 1. Parameters for hardness distinction from calibration experiments

Category		Parameter
Sampling interval	Sensor	100 ms
	Finger	25 ms
Threshold of normal force	F_1	0.5 N
	F_2	1.8 N
Threshold centroid change	dr	0.004 mm
Velocity of re-push	v_p	2 mm/s
Velocity ratio	(soft, normal, hard)	(0.25,1.00,1.25)
Increment of normal force	ΔF	soft< 0.08 N <hard
Progress time	Δt	0.1 s

IV. Verification Experiment

The ability to distinguish object hardness and to respond to sudden changes of object weight during manipulation tasks is crucial for successful applications of robot manipulation in the real world. Therefore, we conducted a set of experiments to verify the performance of the proposed control scheme by recognizing the hardness of unknown objects and responding to changes of object weight during object manipulation tasks. The experiment was conducted using *Bonten-Maru II*, and optical three-axis tactile sensors were mounted on the fingertips of its multi-fingered arm. The object was an empty paper cup that weighed about 4 grams.

Motion planning was designed so that both fingers could move along the x-axis direction to grip the cup, lifting it up along the y-axis direction within 60 sec of the progress time. At 30 sec, we poured 50 ml of water into the cup, as shown in Fig. 10 to analyze the control system performance against sudden changes of the object's weight.

In this experiment, both fingers softly touch the cup to recognize its hardness and define the optimum grasping pressure. Based on the proposed control parameters defined in the previous section (see Table 1), the control system recognized the cup as a soft object. When optimum gripping pressure is satisfied, the fingers manipulate the paper cup by lifting it without crushing it. The fingertip movements and the detected normal force and centroid change data of both fingers are compiled in graphs for analysis. For example, the movement of the right fingertip at the xy-axes against the detected normal and shearing forces can be observed in Figs. 11(a)~(c). In this experiment, when water is poured into the cup, slippage was detected by tactile sensors and in resulting centroid changes at the x-directional and y-directional of the sensor elements, as shown in Figs. 11(b) and (c), respectively.

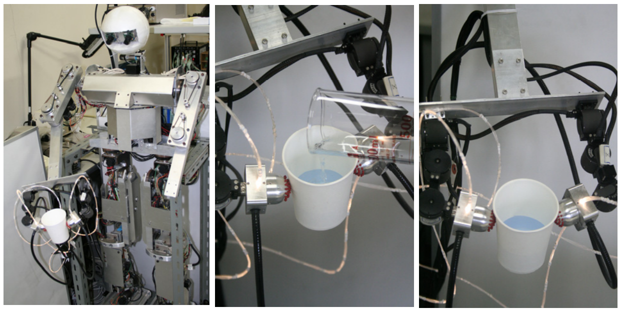

Fig. 10. *Bonten-Maru II* manipulated a paper cup with sudden weight change.

Based on these experiment results, the finger control system managed to respond effectively to the sudden change of object weight by moving both fingers to re-push the cup to tighten its grip and prevent the cup from slipping. The re-push movement increases the detected normal force, as shown in Fig. 11(a). At the same time, the parameters of *F1* and *F2* are used to control the grip force so that the fingers do not crush the paper cup. These results verified that the proposed low force control scheme can define object hardness and respond to the changes of object weight during object manipulation based on tactile sensing. Further experiments gradually increased the amount of water poured into the cup to 70 ml and showed that by simply adjusting parameter value of *F1*, the finger system managed to maintain its grip on the cup without dropping it.

V. Conclusion

In this report, we presented the application of a low force control scheme to distinguish object hardness in a robot manipulation task based on tactile sensing. The optical three-axis tactile sensor provided valuable tactile information for the robot control system to recognize contact interaction. The low force control parameters defined in the calibration experiments enabled the robot finger system to recognize object hardness and safely perform object manipulation. Finally, the performance of the proposed control scheme was evaluated in experiments with real objects, and results revealed good performance for the robot fingers in recognizing object hardness and responding to sudden changes of object weight during the object manipulation task.

The low force control scheme proposed in this research is capable of clearly distinguishing hard and soft objects and responding to the sudden change of object weight during object manipulation. In addition, this control scheme can be used to solve material strength problems of tactile sensor elements. It is anticipated that using this novel control scheme with tactile sensing technology will help advance the evolution of humans and robots working together in real life.

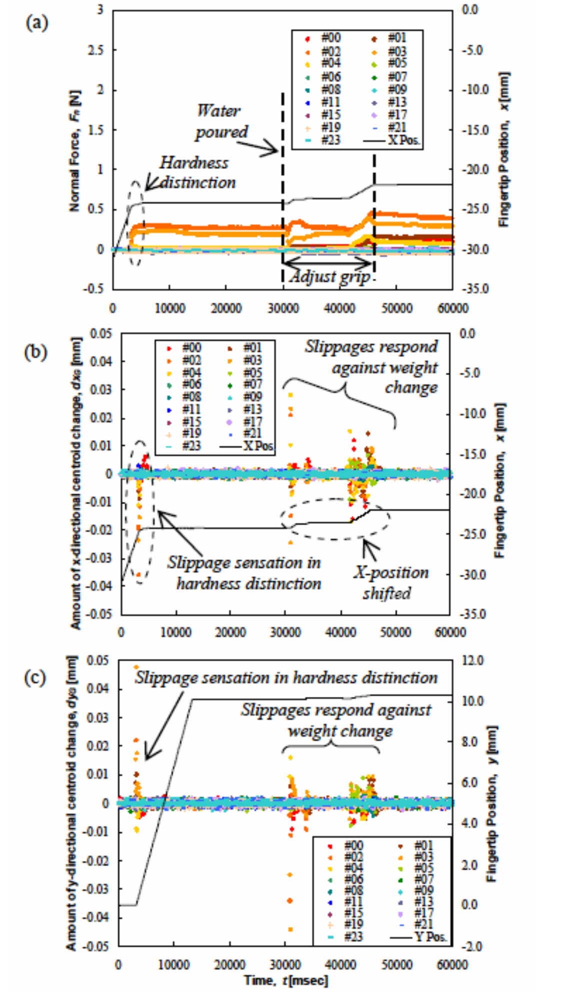

Fig. 11. (a) Relationship between normal force and *x*-directional fingertip position. (b) Relationship between amount of *x*-directional centroid change and *x*-directional fingertip position. (c) Relationship between *y*-directional centroid change and *y*-directional fingertip position.

References

[1] S. Omata, Y. Murayama and C.E. Constantinou, "Real time robotic tactile sensor system for determination of the physical properties of biomaterials," *J. Sensors and Actuators A*, 112(2-3), 2004, pp 278-285.

[2] O. Kerpa, K. Weiss and H. Worn, "Development of a flexible tactile sensor system for a humanoid robot," in *Proc. IROS2003*, vol. 1, Oct. 2003, Las Vegas, USA, pp. 1-6.

[3] M.H. Lee and H.R. Nicholls, "Tactile sensing for mechatronics: a state of the art survey," *Journal Mechatronics*, 9(1), 1999, pp 1-31.

[4] A. Edsinger and C. Kemp, "Manipulation in human environments," in *Proc. Int. Conf. on Humanoid Robotics (Humanoids06)*, Italy, 2006.

[5] P. A. Schmidt and E. Mael, "A sensor for dynamic tactile information with applications in human-robot interaction and object exploration," *J. Robotics & Autonomous Systems*, vol. 54, 2006, pp. 1005-1014.

[6] L. Natale and E. Torres-Jara, "A sensitive approach to grasping," in *Proc. 6th Int. Conference on Epigenetic Robotics*, Sept. 2006, France.

[7] Y. Ohmura, Y. Kuniyoshi, and A. Nagakubo, "Conformable and scalable tactile sensor skin for curved surfaces," in *Proc. ICRA2006,* Orlando, Florida, 2006, pp. 1348-1353.

[8] Y. Kuniyoshi, Y. Ohmura, and K. Terada, "Embodied basis of invariant features in execution and perception of whole-body dynamic actions – knacks and focuses of roll-and-rise motion," *J. Robotics and Autonomous Systems*, vol. 48, 2004, pp. 189-201.

[9] M. Ohka, H. Kobayashi and Y. Mitsuya, "Sensing precision of an optical three-axis tactile sensor for a robotic finger," in *Proc. 15th RO-MAN06*, Sept. 2006, Hatfield, United Kingdom, pp. 220-225.

[10] M. Ohka, J. Takata, H. Kobayashi, H. Yussof, and Y. Mitsuya, "Object handling with a robotic hand equipped with optical three-axis tactile sensors," in *proc. 13th RA07*, August, 2007, Germany.

[11] H. Yussof, M. Ohka, H. Suzuki, N. Morisawa, and J. Takata, "Control scheme of object manipulation based on tactile sensing in humanoid robot arm," in *proc. WCECS07 Int. Conf. on Intelligent Automation and Robotics (ICIAR07)*, October, 2007, San Francisco, USA.