

ANALYSIS OF TACTILE SLIPPAGE CONTROL ALGORITHM FOR ROBOTIC HAND PERFORMING GRASP-MOVE-TWIST MOTIONS

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Abstract- This paper presents an analysis result of grasp-move-and-twist motions of robotic hands equipped with optical three-axis tactile sensor to evaluate performance of a new control algorithm based on tactile slippage sensation. The optical three-axis tactile sensor is capable of defining normal and shear forces simultaneously. The proposed algorithm consists of robot arm and hand controls based on parameters of normal and shear force, and slippage detection. To improve performance during grasp, move and twist motions, we present analysis of slippage direction and classify the control algorithm in two phases: grasp-move-release and grasp-twist. We present detailed explanation of the control algorithm based on the existing robot arm control system. The experiment is conducted using a bottle cap, and the analysis results show that the slippage control parameters enhanced performance of grasp control in simultaneous robot tasks. Experimental results revealed good performance of the proposed control algorithm to accomplish the proposed grasp-move-and-twist motions.

Index terms: Tactile sensor, robot hand, tactile slippage sensation, slippage detection, control algorithm, grasp-move-twist motion, normal and shear force, slippage measurement.

I. INTRODUCTION

The sensorization of artificial robot hands has been widely studied from both engineering and biological points of view. This paper presents the continuity of the research to develop an intelligent tactile sensing device and its control algorithm for application in robotic hands. The

purpose is to archive human-like sensing ability in dexterous manipulation tasks. The rationale for this endeavor was multifold. First, the growing interest in and rapid development of intelligent robotic hands such as the Gifu Hand III [1] and the high-speed robot hand [2] produced at the University of Tokyo, which perform impressive acts of dexterity and skillful manipulation, have urged the development of reliable tactile sensing devices and control algorithms to merge perfectly with the robot controller. In addition, such a sensing system can be used as an experimental apparatus to explore control strategies in dexterous robot manipulation [3]. Finally, and not less important, an artificial robot hand with a tactile sensing system may find a place in the rehabilitation of hand amputees, and replace humans in dangerous, dirty or time-consuming tasks.

Tactile sensors offer great potential for improving the grasp synthesis in robot manipulation due to their extreme sensitivity and capability for measuring contact forces distribution. In previous work, the authors produced a unique tactile sensor system based on the optical waveguide transduction method for application to humanoid robot hands [4][5]. The optical waveguide sensing principle used in this tactile sensor comparatively provides better sensing accuracy to detect contact phenomena from acquisition of three axial directions of forces [6]. Therefore, it is capable of measuring both normal and shear force simultaneously and suitable for application in robotic hands. For development and analysis of the control algorithm, the optical three axis tactile sensors are mounted on fingertips of a robot arm as shown in Fig. 1. The robot arm consists of 11-dofs: 2-dofs at the shoulder joint, 1-dof at the elbow joint, 2-dofs at the wrist joint, and 2 units of 3-dof robot hands functioning as fingers for the arm.

We have analyzed the active tactile sensing data in the robot arm control system to conduct a simple object handling tasks [7]. Furthermore, we analyzed grasp synthesis from distribution of normal and shear force to compile a control algorithm based on the tactile sensation. The analysis results were evaluated in an experiment of robot hand grasp and transfer of an object located at an arbitrary position [8]. From these analysis and experimental results, we realized that not only the tactile sensing is required to generate optimum grasp, but the slippage sensation is also important to support the control of grasp pressure for improvement of grasp quality during object manipulation.

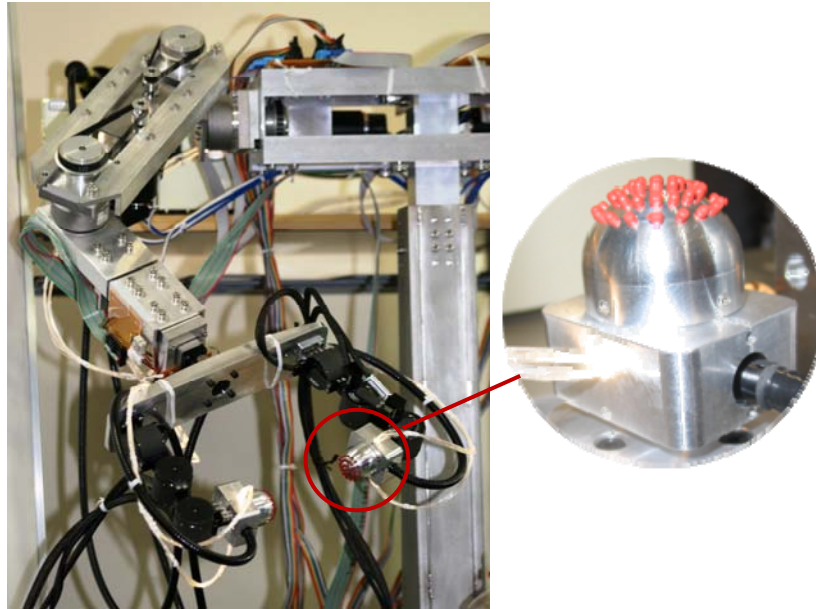


Figure 1. An 11-dofs multi-fingered robot arm mounted with optical three-axis tactile sensors at fingertips.

Since slippage detection is very important in tactile sensor principles for safe grasping of an object, optimization of robot and sensor control algorithm combining tactile and slippage sensation is the key point for dexterous and robust manipulation. Basically tactile feedback must derived the robot to respond very fast when slippage was detected by the tactile sensor so that the object will not slip out. Any delay may also cause imperfect grip or overload grip that will damage the object.

In human neurophysiology, it is known that human fingers start reacting just before the object starts slipping. This situation is called incipient slip. Several researchers have tried to clarify incipient slip terminology in their tactile sensor system such as the ultrasonic tactile sensor presented by Shinoda and Ando [9] that realized slippage sensation from computation of cell deformation along three orthogonal axes. It was followed by Jockush et al. [10] that proposed a new sensor composed by a piezoresistive semiconductor (FSR) and a piezoelectric material (PVF2). The sensor is used to measure contact force, object position and slippage detection.

Holweg et al. [11] proposed two interesting techniques for slippage detection with a rubber-based tactile matrix sensor. The first technique is based on a frequency analysis of the position of the center of force distribution to detect micro movement of the object due to the elasticity of the rubber. By implementing Fast Fourier Transform (FFT) method, the slip is identified before it practically occurs. The second approach is based on the principle that the normal forces measured

by the tactile sensor fluctuate with a certain frequency during slip because of the rubber elasticity. This fluctuation is due to a “stick and slip” effect. By testing the frequency domain of the normal force a slip condition can be detected.

Tactile slippage control algorithm in robotic system is the main essence in field of fine grasp. Previously, Maekawa et al. [12] designed a two-fingers gripper equipped with tactile sensors and they presented an algorithm for moving an object along a desired track. For each elementary movement, the object location and orientation are defined, while a tactile sensor detects the contact point. The joint location of the fingers is controlled based on kinematic analysis, so that the object does not change orientation when moving along the desired track.

Further interesting result was presented by Glossas and Aspragathos [13] using fuzzy logic to determine minimal required force without measurement of this force. The proposed control algorithm adjusts the motion of two-fingers gripper using tactile feedback, so that a fragile and delicate objects is grasped safely. The controller receives the object velocity, acceleration and the detection of incipient slippage to adjust fingers motion. The main advantage of this method is that the designed controller is quite robust because knowledge concerning the size, the weight or the surface texture of the grasped object is not required.

In current research, we conduct analysis to clarify the performance of the object manipulation task when tactile and slippage sensations were both integrated in the same robot control platform. To optimize the investigation, we create an experimental case study for the robot arm to complete and then we analyze the tactile slippage data. About the experimental task, humans commonly use their hands for a range of behaviors including power grips, fine manipulation, and communicative gestures. In order to closely describe these human behaviors in robotic experiments, we choose grasp, move and screw motions to evaluate our system. In this experiment the high accuracy of shear force detection of our tactile sensor system has provided a great opportunity to evaluate the slippage sensation occurred at the robot hands.

II. SLIPPAGE MEASUREMENT IN OPTICAL THREE-AXIS TACTILE SENSOR

a. Hardware Structure and Measurement Principle of Optical Three-Axis Tactile Sensor

The hardware structure of the optical three-axis tactile sensor, as shown in Fig. 2, consists of an acrylic hemispherical dome, an array of 41 pieces of sensing elements made from silicon rubber,

a light source, an optical fiber scope, and a CCD camera. The optical fiber-scope is connected to the CCD camera to acquire the images of sensing elements touching the acrylic dome inside the sensor. The silicone rubber sensing element is comprised of one columnar feeler and eight conical feelers that remain in contact with the acrylic surface.

The light emitted from the light source is directed towards the edge of the hemispherical acrylic dome through optical fibers. 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. The contact phenomena, which consist of bright spots caused by the collapse of the feelers, are observed as image data, retrieved by the optical fiber scope connected to the CCD camera, and transmitted to the computer.

In the measurement process, the normal force of the F_x , F_y and F_z values is calculated using integrated gray-scale value G , while shearing force is based on horizontal center point displacement. The displacement of gray-scale distribution \mathbf{u} is defined in equation (1), where \mathbf{i} and \mathbf{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. Finally, each force component is defined in equation (2).

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

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

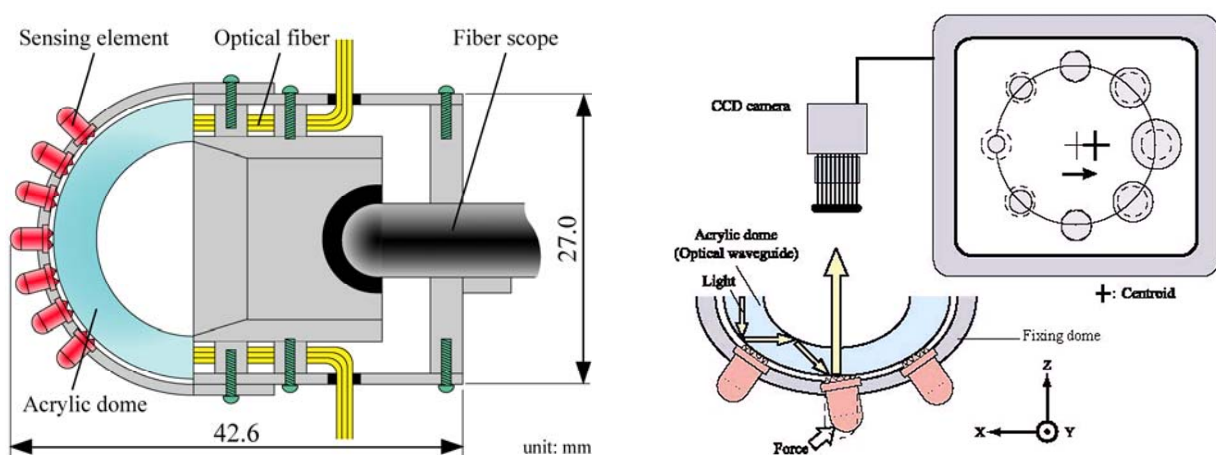


Figure 2. Hardware structure of optical three-axis tactile sensor and sensing principle of shear force detection.

b. Slippage Measurement

In the shearing force detection, basically when the tangential force is applied to the sensing element, it collapses according to the applied load direction. At the same time, the centroid point of the bright spot is also shifted. Therefore, the shearing force can be calculated based on the horizontal displacement of this centroid point. In this study, due to the cylindrical shape of the sensing elements, slippage normally occurs when the grasped object surface alternates between sticking to the sensing element and sliding over the sensing element. This ‘stick and slip’ phenomenon can be measured by calculation of time derivation of centroid point displacement in shear force detection. Since the present control algorithm allows robot hands to refine their grasp pressure when slippage is detected, the robot hands will be able to handle various types of objects by adjusting the parameter value of the centroid point displacement threshold. It also been useful to classify stiffness of an object for safe and effective manipulation.

The calculation of the centroid position, which is measured based on the center point of the bright spot area that equals the center position of the integrated gray-scale measurement area, is conducted when tangential force is applied to the sensor element or when slippage occurs. At this moment, the conical feeler’s contact area at the sensing element with the acryl surface is shifted horizontally. To define the shearing force, we measure the horizontal centroid point displacement at the x and y axes. In shear force measurement, by applying the increment of integrated gray-scale value $\Delta g(x,y)$, the centroid positions at the xy -axes, which are described as x_G and y_G are defined within the measurement area of the integrated gray-scale value, as shown in Eqs. (3) and (4), respectively:

$$x_G = \frac{\int_S \Delta g(x,y) x dS}{\int_S \Delta g(x,y) dS} \quad (3)$$

$$y_G = \frac{\int_S \Delta g(x,y) y dS}{\int_S \Delta g(x,y) dS} \quad (4)$$

Based on the above equations, the displacement of the centroid point at the xy -axes in time t is defined as follows:

$$dx_G^{(t)} = x_G^{(t)} - x_G^{(t-1)} \quad (5)$$

$$dy_G^{(t)} = y_G^{(t)} - y_G^{(t-1)} \quad (6)$$

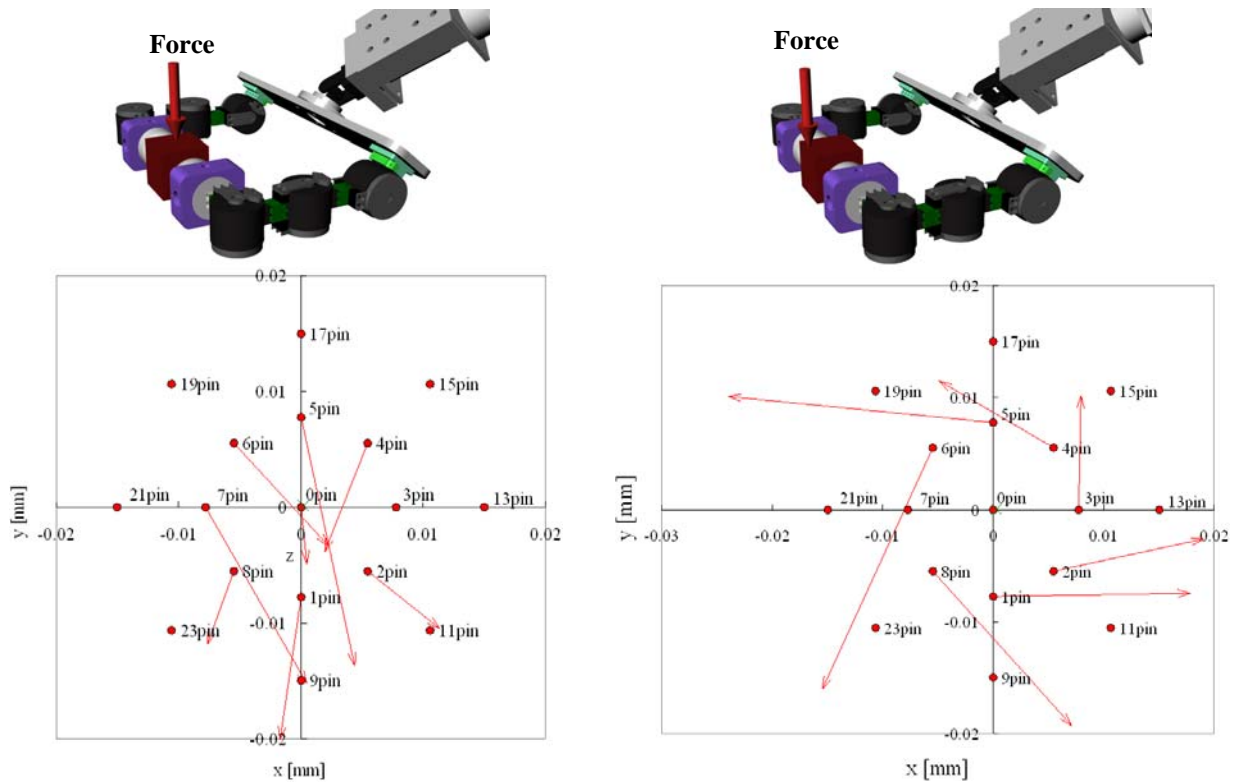


Figure 3. Centroid displacement of tactile sensor elements in analysis of shear force and slippage direction when force is applied at object's center (left) and object's edge (right).

III. ANALYSIS OF SLIPPAGE DIRECTION

In object manipulation, when the robot arm is in the static condition and only the robot hand is performing motion, slippage normally occurs during the incipient grasp and when the object is in contact with the ground or another object surface. During the incipient grasp, the main reason for slippage is the object's surface condition and weight. However, it is possible to manipulate this condition for improvement of the task control. In order to find a suitable solution, we analyze the slippage direction of the optical three-axis tactile sensor.

In this study, we intended to use the slippage direction so that the robot system could achieve the autonomous grasping condition and define accurate timing to lift and release the object. In order to analyze slippage direction, we conducted a simple experiment in which the robot finger held a cube-shaped object as illustrated in Fig. 3. First, we applied force to the center of the object, as shown in the figure left side, and then at its edge as shown in the figure right side, which caused the object to slightly rotate. We defined the shear force characteristics and distribution by

calculating the centroid point displacement of the sensing elements, as indicated in the graphs for both experiments.

The graphs in Fig. 3 left show that the directions of the centroid displacements of the related tactile sensor elements are toward the applied force direction. In Fig. 3 right, the directions of the centroid displacement for the tactile sensor elements are according to the object's rotation direction. From both experiment results, we conclude that the shear force direction is according to the applied force direction. Therefore, slippage direction can be used as a control parameter in the robot arm control system to distinguish incipient grasp and release motion.

IV. TACTILE SLIPPAGE BASED CONTROL ALGORITHM

The objective of this paper is to evaluate the application of slippage control in the present robot arm control algorithm based on the tri-axial tactile sensing data. In order to accomplish the objective of the present case study, we classified the control algorithm into two phases. Phase one is for grasp, move and release motions. Phase two is for grasp and screw motions during the screwing task. The control system structure of the robot hand controller is shown in Fig. 4. It is comprised of three modules: a Connection Module, Thinking Routines, and a Hand Control Module. The most important part is the Thinking Routines in which calculation of tri-axial tactile data and decision of velocity and motion control are conducted.

In the present robot hand control system, the robot hand is controlled according to velocity control. Meanwhile, the hand motion is divided into two modes. First is "search mode" to make fingers approach an object. After fingers touch the object, the hand status enters "move mode" to manipulate the object. During both search and move modes, when absolute time derivative of shearing force of a sensing element exceeds a threshold dr , this system achieved the condition as slippage. Furthermore, to prevent the hands from dropping the object due to the slippage, recompressive velocity is defined to move the hands along counter direction of applied force. In addition, to define optimum grasp pressure toward the object, we fixed two layers of normal force threshold F_1 and F_2 . When normal force exceeds F_1 , the robot hands will stop the gripping motion and hold its position. F_2 is for emergency stop to prevent the robot hands from crushing the object or damaging the sensor elements.

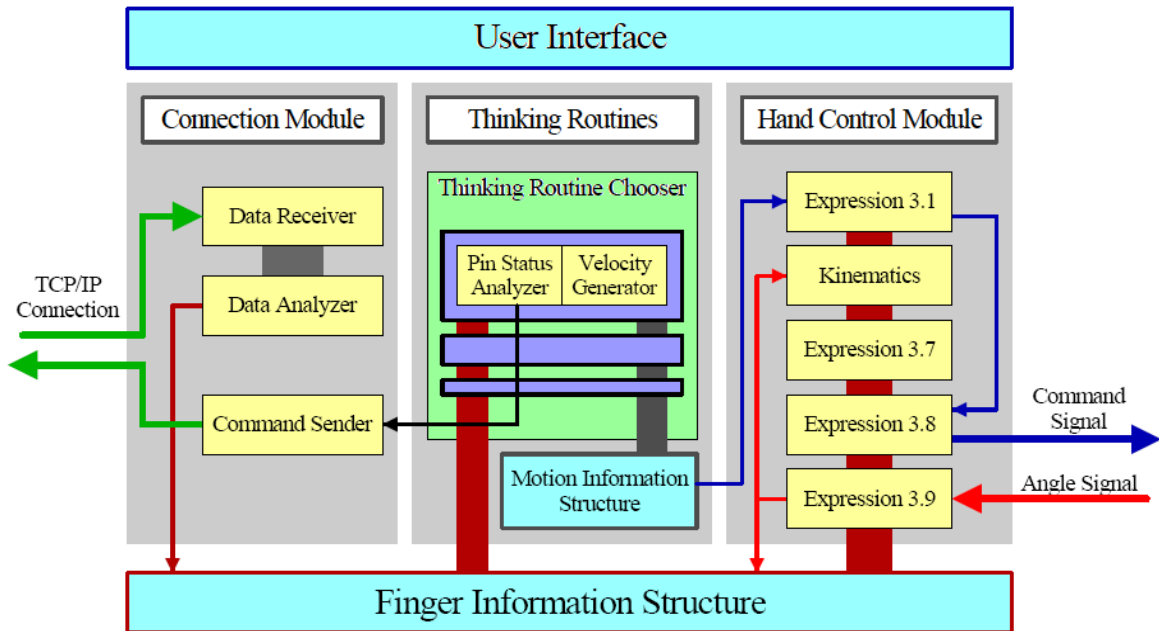


Figure 4. Control system structure of robot hand controller.

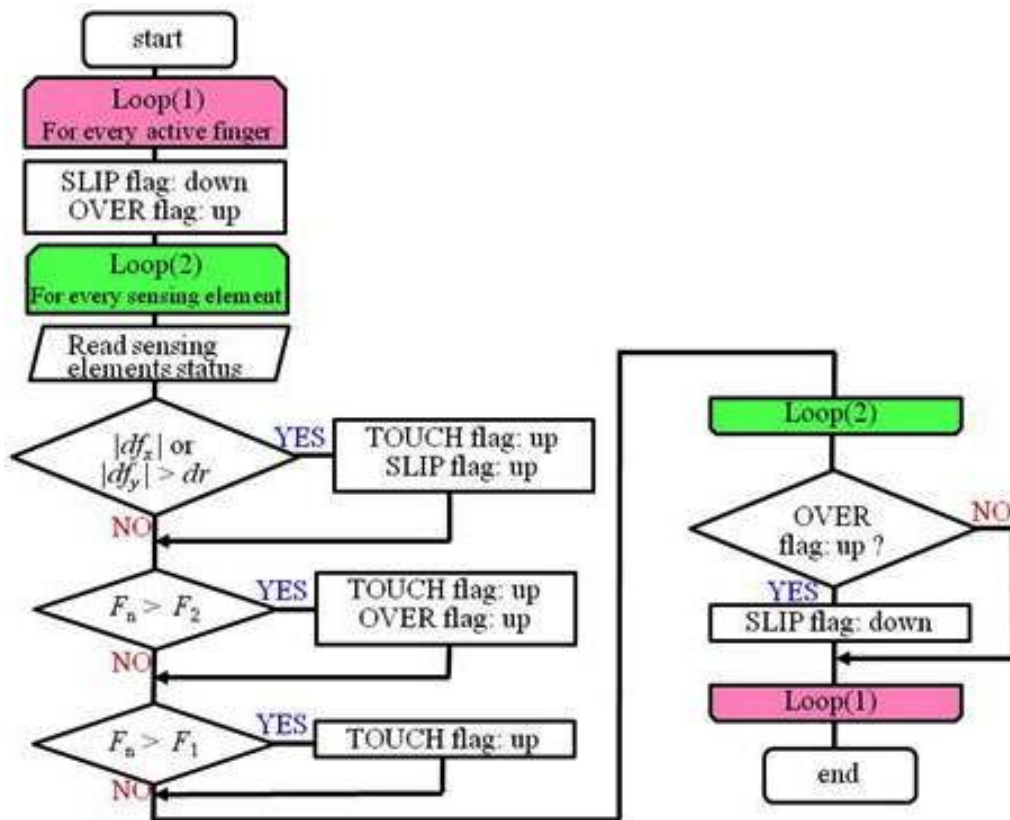


Figure 5. Algorithm of flag analyzer.

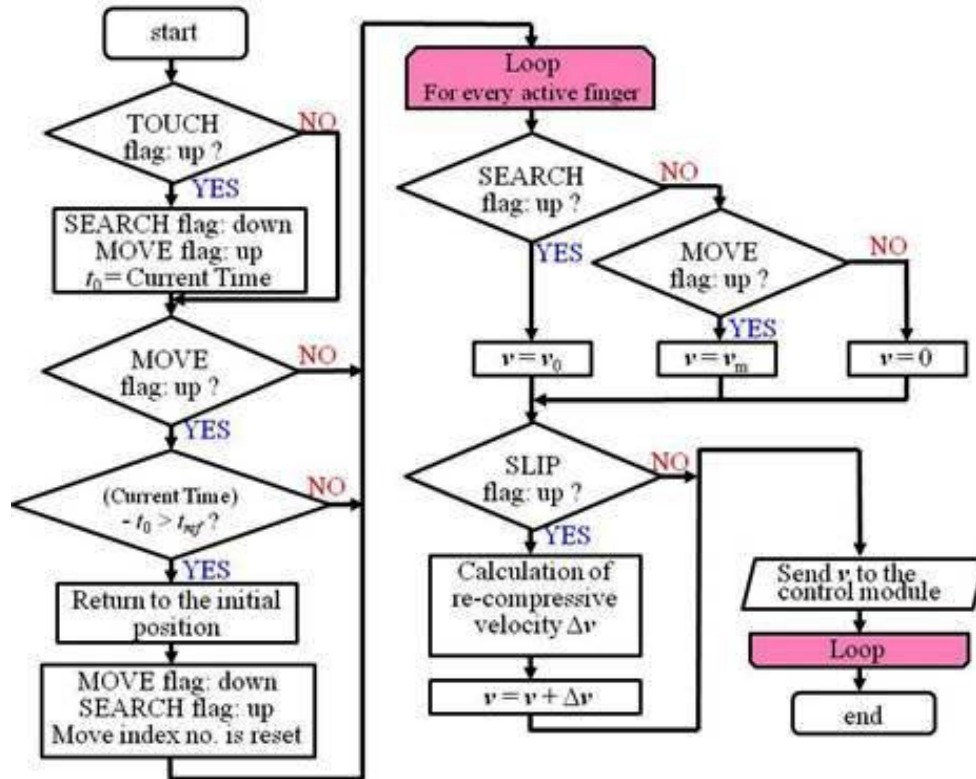


Figure 6. Algorithm of finger speed estimator.

In our system, the sensor control program and hand control program are executed in different computers because CPU time is efficiently consumed using the multi-task program method. These programs are synchronized as the following five flags according to the tri-axial tactile data and finger motions:

SEARCH: Hands search for an object until normal force of a sensing element exceeds a threshold F_1 or a Slip flag is raised.

MOVE: This flag is raised whenever the robotic hand manipulates an object.

TOUCH: This flag is raised whenever one of the fingers touches an object.

SLIP: This flag is raised whenever time derivative of shear force exceeds a threshold dr .

OVER: This flag is raised when normal force of a sensing element exceeds a threshold F_2 .

Figure 5 shows the algorithm of the flag analyzer in the control system. The outputs of this algorithm are TOUCH, SLIP and OVER flags. In the flag analyzer, the robot control system realizes the status as touching an object when normal force of a sensing element exceeds F_1 or absolute time derivative of shearing force exceeds dr (SLIP flag is raised). At this moment, the

TOUCH flag is raised. The OVER flag is raised when normal force of a sensing element exceeds F_2 to prevent over squeezing toward the object. Figure 6 shows the algorithm of the velocity generator inside the Thinking Routines. The velocity of the finger tip is determined based on the five flag values. Whenever the SLIP flag is raised, a sensing element of the largest normal force is identified and re-compressive velocity of the finger is determined as an inward normal line of the sensing element. The re-compressive velocity is added to the current velocity, and the resultant velocity is applied to the control module.

b. Phase I: Grasp-Move-Release

The first phase of the control algorithm is for grasp, move and release motions. Initially, based on the slippage direction analysis presented in the previous section, when the direction of centroid displacement is at the positive side, the control system will classify the condition as a grasp motion. If the direction is at the negative side, the system will classify it as a release motion.

We compiled the communications between the robot arm and hand/finger controllers in the proposed algorithm as shown in Fig. 7. In this flowchart, 'MOVE1~6' are the motion trajectory commands. 'Grasping' and 'Releasing' are the main functions for this algorithm. The slippage direction algorithm is embedded in 'Assess slip' and 'Vertical slip' functions that decide whether to hold or release the object.

During grasping motion, when the fingers have defined a suitable grasp pressure on an object, the finger controller sends a 'Grasping Ended' instruction to the arm controller so that the arm can start to lift and move the object. At this time, when slippage caused by the movement of the arm or the object's weight is detected, the finger controls the grip by re-compressing the object so that the object will not drop.

Next, the arm moves to the targeted position while maintaining its orientation holding the object. Then the arm controller sends an instruction to the finger controller to start the process of releasing the object. At this time, both hands move to the lower position toward the ground. Finally, the object comes into contact with the ground where slippage is detected due to the object contacting the ground surface.

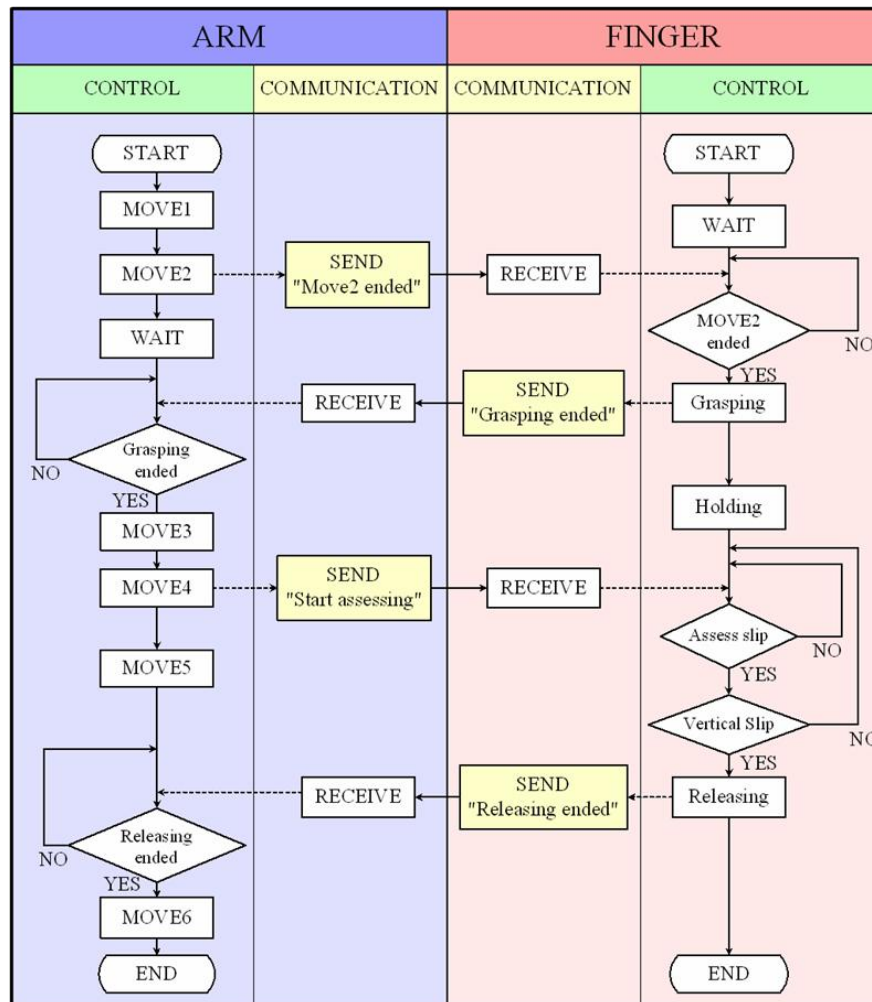


Figure 7. Algorithm flowchart of communication between robot arm and hand.

At this time, the hand controller chooses only one sensor element that shows the maximum normal force value among sensor elements where slippage was detected. This sensor element is used as a coordinate point to define the direction of slippage. The reason for this selection method is that the object seems to rotate when it comes into contact with the ground, and the sensor pin that has shown the maximum normal force value has become the center point of this rotation. After the direction of slippage is confirmed, the robot hands will gently release the object.

c. Phase II: Grasp-Twist

The second phase is for grasp and screw motions during the twisting task. Since turning motion is different from grasp and release motion, the control algorithm of slippage direction is not

considered in this motion control. We only considered the increment of time derivative of shearing force together with increment of normal force. Hence, the control parameters involved are dr , F_1 and F_2 . Furthermore, since the screwing cap problem requires touch and release motion, MOVE and SEARCH flags are controlled according to TOUCH and SLIP flags and spending time.

A motion trajectory was generated for both hands to perform movement as shown in Fig. 8. This figure shows hand motion in one cycle of the screwing task. At first, robot fingers grasp the object, move in the turning direction, and return back again to the initial grasping position to repeat the twisting task. The grasp pressure is controlled by the aforementioned parameters. During twisting motion, the important point is to decide how and when to finish the motion. In the case of closing the bottle cap, we fixed two control conditions. First is when the detected data of displacement in the shear force detection (slippage detection) exceeds the threshold dr at specified times (Ns) in one cycle of the twist task. Second is when the slippage detection exceeds the threshold dr in two continuous cycles of the twist task. The robot control system will realize the cap is fully tightened when either one of the above conditions is satisfied. The robot hand can stop the twist task when the cap is fully tightened.

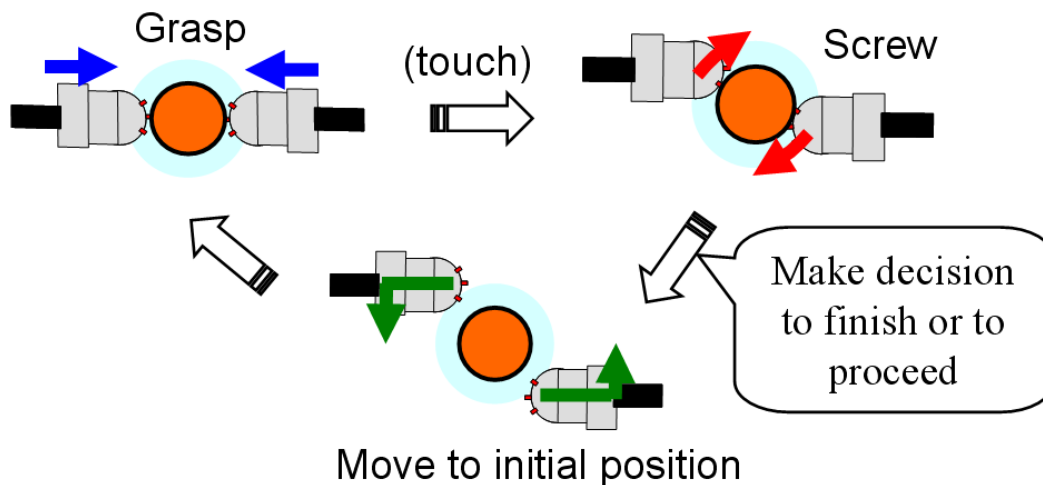


Figure 8. One cycle of motion trajectory in twisting task.

V. EXPERIMENT AND RESULT

We conducted an experiment to evaluate the performance of the proposed tactile slippage control algorithm using the humanoid robot arm equipped with a tactile sensor. The motion planning is done according to the proposed case study of grasp, move and screw motions, and the object is a mineral water bottle cap. In this experiment, the cap and bottle are located at the place where only the geometrical positions of the x - and y -axes are primarily defined. The height at the z -axis is not specified. This is to evaluate the proposed slippage direction control in grasp and release motions. In the screw task, the robot hand will use the reference coordinate during release motion. At this time, N_s value is fixed at 8 times based on experimental experience. The dr value is 0.004 [mm] for the whole tasks except for screw task which was increased 1.3 times so that the tactile sensor can optimize slippage detection to justify the cap tighten condition.

Figure 9 shows pictures of the experimental condition of grasp, move and screw motions. The robot arm managed to perform all motions smoothly. Figure 10 shows the relationship between shear force displacement data at the y -axis and the fingertip position of the robot hand at the x -axis.

First, the robot hands grasp the object and adjust its grasp pressure. At this moment, since the first detected shear force direction that exceeded the dr value is at the positive side, the robot arm continues lifting the object and moves to the bottle position. During the move motion, slippage was detected probably due to vibration of the arm. At this moment, robot hands re-compress the cap to keep it from dropping. When the robot hand moves toward the bottle, the cap touched the bottle head surface causing great slippage due to rotation of the cap. Since the first detected slippage direction that exceeded dr value is at the negative side, the robot hands gently release the cap. Next, the robot hands performed screw tasks. At the third cycle of the tasks, the robot controller realized that the cap was already tightened because the slippage detection exceeded the fixed N_s value.

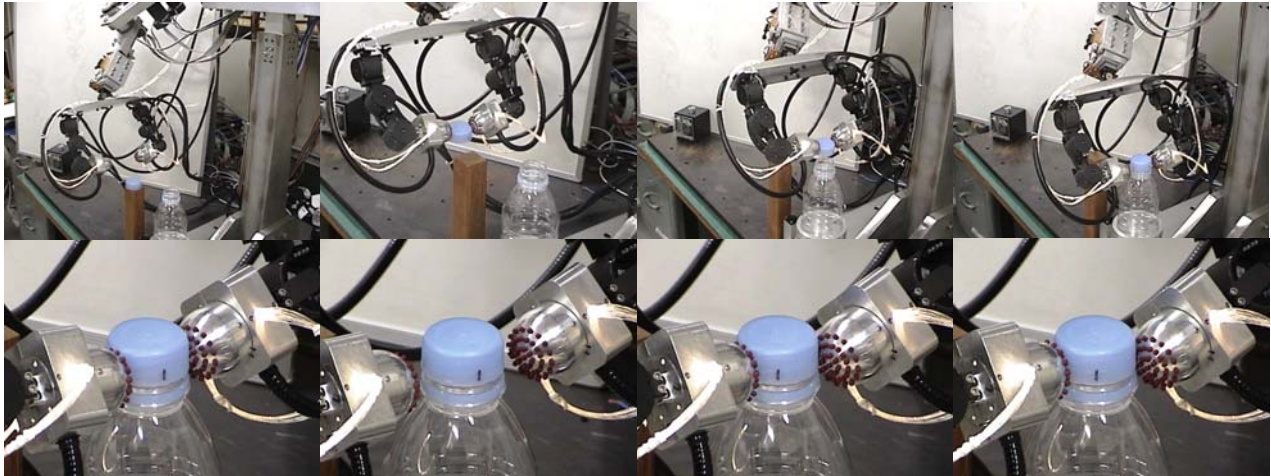


Figure 9. Sequential photographs in the experiment of grasp-move-and-screw motion using humanoid robot arm with optical three-axis tactile sensor.

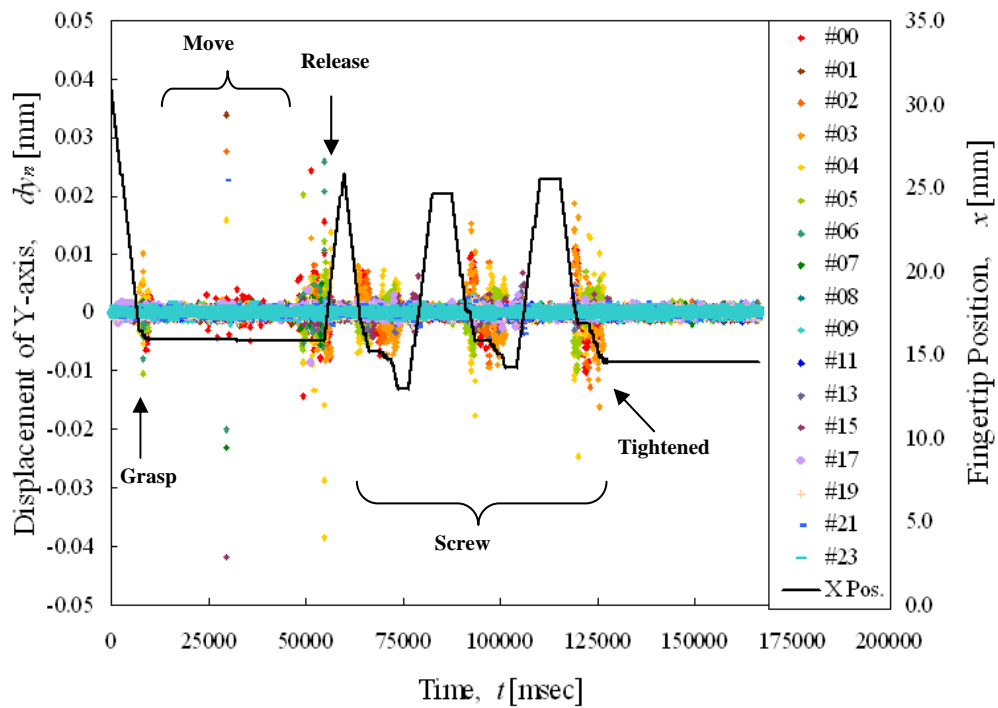


Figure 10. Relationship between displacement of y-directional centroid change and x-directional fingertip position.

VI. CONCLUSIONS

In this report, we proposed a new control algorithm in a robot arm based on tri-axial forces and slippage detection parameters. Analysis of normal and shear forces detection was conducted to define suitable parameters in the robot hand control system that equipped with optical three-axis tactile sensor mounted on fingertips of the robot hands. Since the proposed tactile sensor provide high accuracy detection of normal and shear force simultaneously, the sensing principle of shear force detection was used to define slippage sensation at object surface during grasping task.

The proposed algorithm was evaluated in an experimental case study of grasp, move and twist motions. Prior to the experiment, we presented the methodology of slippage measurement and conducted analysis of slippage direction to improve performance of the proposed algorithm. Analysis result shows that slippage direction can be used as a control parameter in the robot arm control system to distinguish incipient grasp and release motion.

To satisfy the proposed case study, the algorithm was classified in two phases, grasp-move-release and grasp-screw. The experimental results using a bottle cap revealed good performance of the proposed algorithm for future application in a real artificial robot hand. This result shows that integration of tactile and slippage sensation in a robot control system could contribute a better maneuvering of the robot arm-finger system when handling an object, particularly when the geometrical orientation of the object is unknown.

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