Application of Stiffness Control Algorithm for Dexterous Robot Grasping using Optical Three-Axis Tactile Sensor System

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Abstract:

This paper presents analysis and experiments to define object stiffness control algorithm using a prototype optical three-axis tactile sensor for improvement of dexterous grasping tasks in robotic fingers. We proposed a low force control scheme and conducted a series of calibration experiments with soft and hard objects. We analyzed normal and shearing forces data detected in the experiments. To correlate the normal force characteristics of soft and hard objects, we measured the increment of maximum normal force in specific progress time to classify the stiffness of objects. The shearing force is utilized to define re-pushes velocity of the robot fingers when grasping the object. We compiled the parameters in an algorithm inside the robot control system to control fingertips movements by defining optimum grasp pressure and perform re-push movement when slippage was detected. Verification experiments were conducted which result revealed that robot fingers managed to recognize the stiffness of objects and safely manipulate it.

1. Introduction

Grasping is a typical human ability that is widely studied from both biological and engineering points of view. In robotics, grasping has been studied from its biological aspects, principles and sensory based design and control. Primarily, robot grasping is synthesized by the ability of robot grippers to measure and detect sensation of touch, pressure, slippage and stiffness of object [1]. Since defining distribution of force and slip sensation are no longer a critical issue in current tactile sensors [2][3], the critical problem to be solve for synthesizing the real-time grasp is to develop a control algorithm to measure stiffness of object based on data acquired by the tactile sensor.

In our research lab, we have successfully developed a unique tactile sensor system based on optical waveguide transduction method for application in humanoid robot hands [4][5]. The optical three axis tactile sensor is capable of measuring both normal and shear force simultaneously. The optical waveguide sensing principle is comparatively provides better sensing accuracy to detect contact phenomena from acquisition of three axial directions of forces [6]. The optical three axis tactile sensors are mounted on fingertips of humanoid robot arm as shown in Fig. 1, which also shows the structure of the tactile sensor.

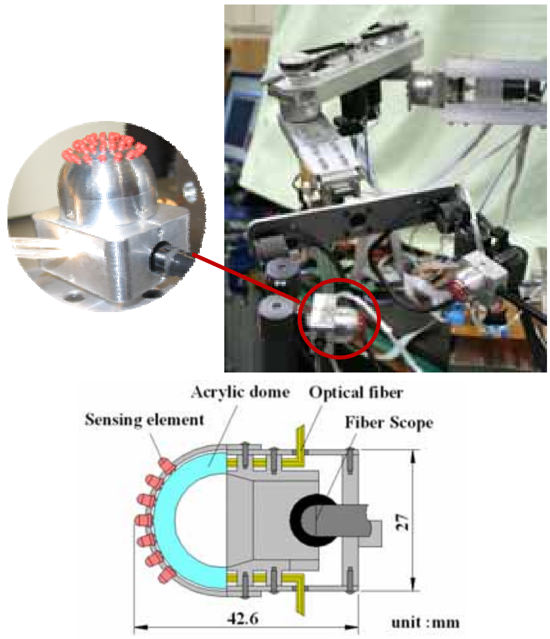

Fig.1. A multi-fingered humanoid arm mounted with optical three-axis tactile sensors at fingertips, and the structure of the tactile sensor.

In order to improve sensing performance and robustness of the optical three axis tactile sensor tactile sensor system during real-time object manipulation tasks, we conducted analysis to define suitable object stiffness measurement. We utilized normal force, shearing force, and slippage sensation acquired by the tactile sensor in the robot finger system to distinguish the stiffness of unknown objects during manipulation tasks. At current stage, we defined stiffness of unknown objects from qualitative point of view and we classified the objects as hard, medium and soft. We do not yet perform quantitative measurement of object stiffness because it will require high volume of measurements on various types of objects, which will require huge database that will impose a burden to the existing control system. However, after reliability of stiffness measurement at current used system was verified, it is necessary to clarify the quantitative measurement issue in the current system.

We have proposed a low force control scheme [7] so that the robot finger could perform soft touch on object surface in order to measure the object stiffness before performing grasp and manipulation task. We conducted a series of calibration experiments with soft and hard objects to verify the performance of the optical tactile sensor system and determine the important stiffness control parameter values in the robot arm control system.

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2. DETERMINATION OF IMPORTANT PARAMETERS

To successfully manipulate objects in the real world, robot systems require some form of tactile feedback to distinguish the object's stiffness. Unfortunately, so far, no specific parameters in developmental robots can measure the stiffness sensation. In this research to define suitable parameters value in current robot arm system, we conducted a series of calibration experiments with soft and hard objects using the multi-fingered robotic system. The purpose are to verify the performance of the optical tactile sensor system and determine the important parameters in the robot arm control system based on the proposed low force control scheme for object stiffness 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. 2. 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. The parameters considered in this experiment are shown in Table 1. Experimental results for both hard and soft objects are indicated in Figs. 3 and 4. Both figures show the detected normal and shear forces graphs for right finger.

In the experiment with aluminum block, the reaction force applied toward the tactile sensor elements is high due to the hard surface. This cause the detected normal force to increased drastically. However, the weight of the object caused slippage. For paper box, small reaction force is applied to the sensing elements because of the soft surface. Accordingly, the detected normal force becomes low. Therefore, to correlate the hardness distinction of these hard and soft objects, we utilized the maximum increment of normal force ΔF, which was calculated within a specified progress time, as a hardness distinction parameter.

To comply with the slippage that normally 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 specified *dr* value, the finger re-pushes toward the object to prevent it from slip.

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 F_1 and F_2. If the normal force is over the F_1 value, both fingers will not further re-push toward the object. F_2 is used for emergency stops in case of over push towards the object occurred.

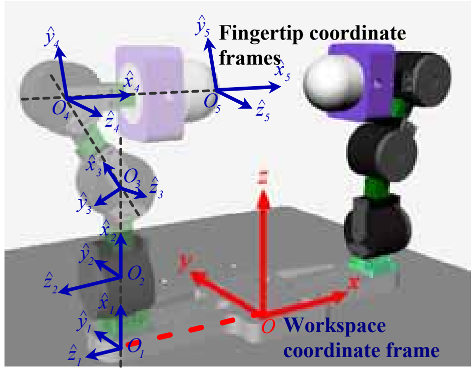

Fig. 2. Coordinate frames at robot finger and workspace.

Table 1. Parameters considered in calibration experiments.

Category of Parameters	
Interval for sampling	Sensor Finger
Threshold of normal force	F_1 ,F_2
Threshold of centroid change	*dr*
Velocity of repush	v_p
Increment of normal force	ΔF
Progress time	Δt

Table 2. Parameters for stiffness distinction from calibration results.

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 of shearing force	*dr*	0.004 mm
Velocity of re-push	v_p	2 mm/s
Velocity ratio	(Soft, Medium,Hard)	(0.25,1.00,1.25)
Increment of normal force	ΔF	soft< 0.08 N <hard
Progress time	Δt	0.1 s

From the experimental results, it was shown that the optical three axis tactile sensor system is capable to detect a very low force applied to the sensing elements. The tactile sensor responds according to the contact condition between the sensing elements and the object surface. The sensing principle, which utilized an optical waveguide transduction method, permits highly sensitive force detection. However, at current level due to some variations caused by measurement of brightness at the gray-scale value using current measurement equipments, the lowest reliable normal force detection is 0.1 [N]. For shearing force, the force detection resolution is estimated about 0.001 [N].

After analyzing the calibration experiment results, we determined the parameter values shown in Table 2. These low force control parameters are enable the finger system to

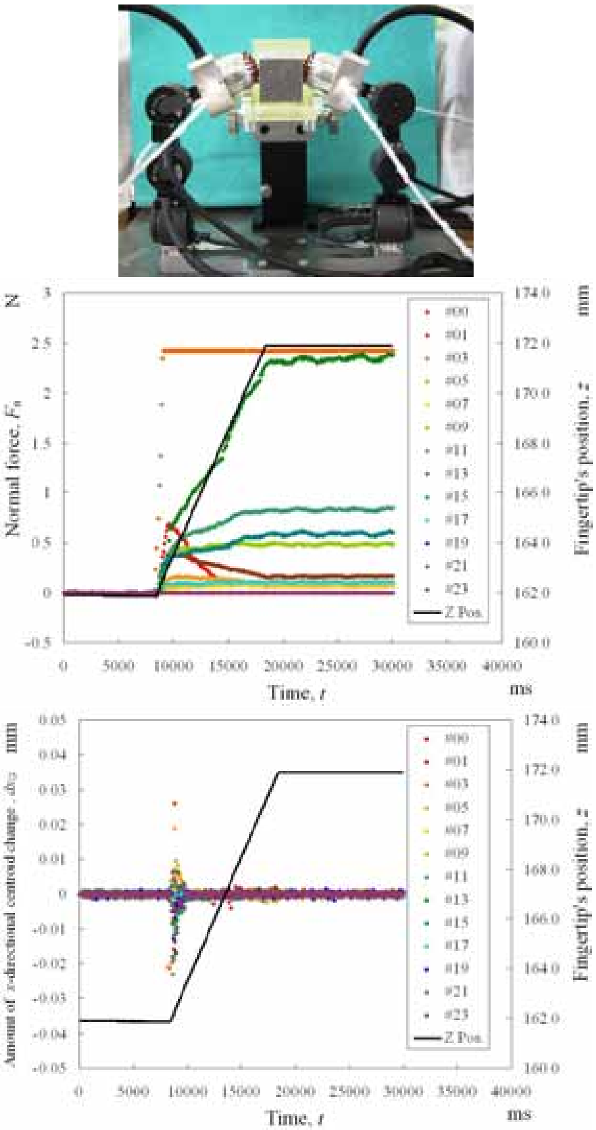

Fig. 3. Relationship between normal (*top*) and shearing (*bottom*) forces with fingertip position at *z*-axis for experiment with aluminum block at right finger.

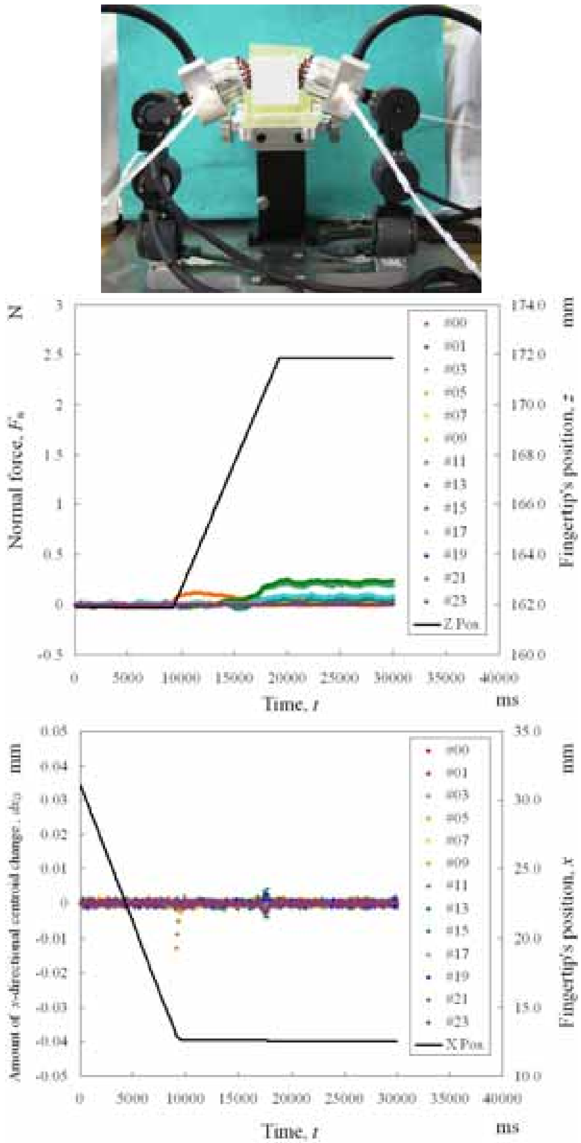

Fig. 4. Relationship between normal (*top*) and shearing (*bottom*) forces with fingertip position at *z*-axis for experiment with paper box at right finger.

realize object stiffness, even when the detected forces are very low, and then to precisely adjust the grasp pressure to manipulate the object. These parameters are applied in the control algorithm of the robot finger controller.

3. Control Algorithm

According to the qualitative approach applied in this research, it is necessary to classify the stiffness of object to optimize the control of robot fingers based on the tactile sensor data. Since the stiffness of objects can be estimate by the maximum increments of normal force, we classified the object into three classifications: Soft, Medium, and Hard to define optimum grasping pressure.

These classifications are used to select velocity ratio for velocity of re-push motion v_p, and threshold of normal force F_1 and F_2 to control finger movement during grasping and manipulating objects.

In the sensing algorithm, at first the control system sees the threshold of centroid change *dr* before performing hardness distinction using the increment of normal force ΔF. Then the fingers reinforce the grasping pressure to re-push the object according to the velocity ratio. Regarding the threshold of normal force, if the object was detected as soft object, the finger will no longer re-push the object when the normal force detected exceeds F_1. Meanwhile, F_2 is used for emergency case so that the finger will not over-push the object, especially when handling hard object.

The maximum increment of normal force $\triangle F$ is basically used to classify the object stiffness. During stiffness distinction process, if the difference between maximum normal force F_{max} and reference maximum normal force F_{ref} within $\triangle t$ exceeds threshold of $\triangle F$, the object is classified as hard object. If the different value is lower than $\triangle F$, the object is classified as soft object. This process is conducted every time the slippage sensation is detected exceeding the threshold of centroid change *dr*.

However for safety purpose, once the object was classified as soft object, the system will not further check for hard or middle object (this restriction will be released when the system is reset back). Furthermore, stiffness distinction process of each finger was conducted separately. If comparison of the final hardness distinction result for these two fingers was not indicating the same object classification, the control system will choose to classify the object as soft object. This severe selection process of object hardness classification will avoid the finger from damaging the object or the sensor elements due to mistake in choosing velocity ratio to re-push the object. Next, the control system will proceed to re-push on the object.

During re-push motion, selection of threshold of normal force F_1 and F_2 are decided according to object hardness classification. Based on the thresholds of normal force, velocity ratio to re-push towards the object and decision to stop the re-push motion were defined. Velocity of re-push motion v_p is according to object hardness classifications of Soft, Medium, and Hard, where velocity ratio for each object hardness is shown in Table 3. Since the threshold of normal force in this system is divided into two, for Soft and Medium objects are respect to F_1, meanwhile Hard object is respect to F_2. The finger will stop the re-push motion when the detected normal force F_n exceeds these threshold values with respect to each object hardness classification.

4. Verification Experiment

We conduct verification experiments based on the results of calibration experiment as shown in Table 2. We used the robot fingers equipped with the optical three-axis tactile sensors which mounted on a test jig. The fingers orientation is about horizontal with table surface.

4.1 Experiment I

The first experiment is using paper box where the robot fingers grasp it and perform twisting motion. Figure 5 show photographs of the robotic fingers motion. Both fingers move along *x*-axis direction to grasp the paper box. The robot recognized stiffness of the object, and then both fingers lift up the paper box along *y*-axis. Then the fingers perform the twisting motion. In this experiment, the fingers managed to manipulate the paper box without crushing it.

Table 3. Relationship between stiffness classifications with control parameters of velocity ratio and threshold of normal force.

Parameter	Object Hardness Classification		
	Soft	Medium	Hard
Velocity of re-push v_p	2 mm/s	2 mm/s	2 mm/s
Velocity Ratio	0.25	1.00	1.25
Threshold of normal force	F_1	F_1	F_2

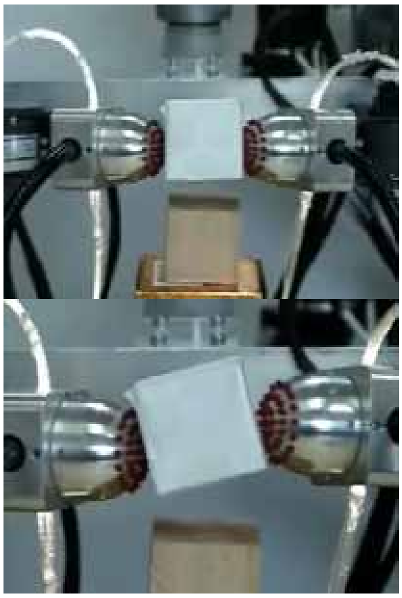

Fig. 5. Verification experiment I: Robot fingers grasp and twist paper box.

4.2 Experiment II

The second experiment is to verify the control algorithm during a sudden object weight change. 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 80 sec of the progress time. At 40 sec we poured 60 ml of water into the cup, then after 55 sec we poured another 30 ml, and finally 20 ml after about 70 sec. This is to analyze the control system performance against sudden changes of the object's weight.

In the second experiment, at first both fingers softly touch the cup to recognize its stiffness and define the optimum grasping pressure. Based on the proposed control algorithm defined in the previous section, the control system recognized stiffness of the paper cup. When optimum gripping pressure is satisfied, the fingers manipulate the paper cup by lifting it without crushing it. At this moment, the re-push movement increases the detected normal force, while 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.

Fig. 6 show photographs of this experiment. When water is poured into the cup, slippage was detected by tactile sensors and resulting centroid changes at the *x*-directional of the sensor elements. The finger system responds by adjusting the fingertips position to tighten the grip so that the paper cup will not slip out. The proposed control algorithm managed to define object stiffness and prevent object from drop when the object weight is suddenly increased.

5. CONCLUSION

In this paper, we have presented analysis and experiments to define object stiffness control algorithm using a prototype optical three-axis tactile sensor for improvement of dexterous grasping tasks in robotic fingers. The optical three axis tactile sensor presented in this research is capable of measuring both normal and shear force simultaneously.

We proposed a low force control scheme to define important parameter values in robot control system based on tactile sensing data. We conducted calibration experiments using hard and soft objects, and then analyzed the normal and shearing forces data detected in the experiments. To correlate the normal force characteristics of soft and hard objects, we measured the increment of maximum normal force in specific progress time to classify the stiffness of objects. Meanwhile, the shearing force is utilized to define re-pushes velocity of the robot fingers when grasping the object. From qualitative point of view, we classified stiffness of object into hard, medium and soft. This classification is used to select suitable velocity ration of re-push motion and the threshold of normal force.

Verification experiment using robotic fingers to manipulate soft object was conducted whose result revealed that the finger's system managed to recognize the stiffness and safely manipulate the object. These results also verified that the proposed control algorithm can define optimum grasp synthesis and respond to the changes of object weight during object manipulation based on the tactile sensing. The proposed stiffness control algorithm is particularly effective to prevent damaging the object or the tactile sensing elements during object manipulation tasks. It is anticipated that using this novel control algorithm with tactile sensing technology will help advance the evolution of real-time object manipulation.

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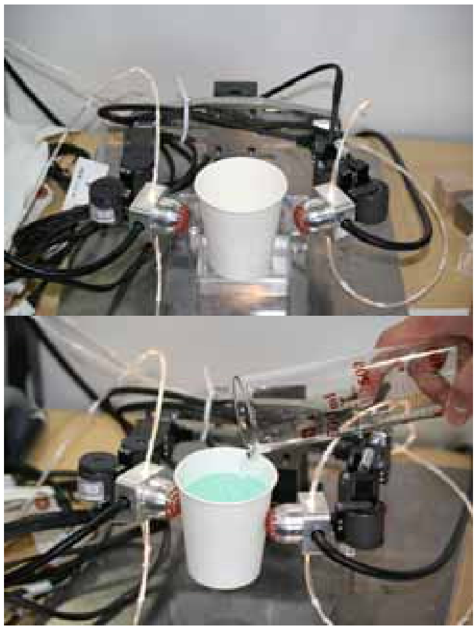

Fig. 6. Verification experiment II: Robot fingers grasp an empty cup and then water is poured inside it.

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