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Contact Force Control of a Robotic Hand Using F/T Sensory Feedback with a Rigid Object.

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Abstract— **There have developed various robotic hands since the 1960's with the control theories. For a robotic hand, manipulating objects as human does is a quite difficult story and grasping or pinching objects should be preceded before manipulation. Those operations are based on interaction between robotic hand and arbitrary objects. It means how strongly a robotic hand grasps arbitrary object with stable and unbreaking motion when interactions occur. This paper attempts a grasping force control of a velocity controlled robotic hand using external Force/Torque (F/T) sensors. This control uses F/T sensor feedback and produces a command torque. Then, velocity-torque transformer converts a command torque into an input velocity to the robotic hand system. The algorithm is analyzed through an experiment that shows how a grasping force affects arbitrary objects and obtained competent results.**

I. INTRODUCTION

In decades, a variety of multi-fingered robotic hands were developed in some research institutes and universities. Most of researches have been so far on a motion planning for reaching and grasping from kinematic analysis. The great parts of those are coming from the computed torque feedforward control, inverse dynamics, and other model based controls. If the dynamics of a model of a robotic hand is known properly, enveloping forces on an object can be adequately input without any use of sensory feedback. However, those controls are not easy for multi-fingered robotic hands which have many degrees of freedom (DOFs). Robotic hands which are motivated from human have over 12 DOFs and most of them have disturbances from outside and nonlinearities. Consequently, there are difficulties to use those controls and expensive costs on computations. With that difficulty, controls without a model dynamics have been developed such as an impedance control by Hogan, et al. [1], [2], [3] and finger-thumb opposition for pinching objects by Arimoto, et al. [4], compliance control and so on.

For a robotic hand that has many control methods, a main issue is an interaction between an object and a robotic hand. On account of the reason that a robot should not break an object and manipulate it properly, safety problem has been focused since it has been developed. As a solution to this, there has been a variety of methods such as using current servo for the control mode, installing high performance servo motor for joint torque control [5] and compliance position control using external sensors [6] and so forth. The joint torque servo is too expensive although it can competently improve a performance of a robotic hand which is of over 12 DOFs. In the case of current servo, although it can be alternative for joint torque servo, it has difficulties in friction modeling. Hence, using force/torque (F/T) sensors on fingertips of a robotic hand can be considered to configure in less costly.

In a compliance control using F/T sensors, adequate results are shown from [6] that it is a previous research. It showed how a robotic hand can behave if disturbances are exerted on an F/T sensor during a manipulation. Although the control shows a robotic hand being compliant, it doesn't guarantee how much force is exerted on an object. Grasping an object has two properties that a robotic hand is not breaking an object and not dropping an object. Then, there comes an issue that how much force is appropriate for grasping an object. Before the issue is considered, there is another issue that it is possible to make the desired grasping force of a robotic hand to give it to an object. For a grasping force control, the virtual linkage method by Khatib et al. [7] is used and force decomposition by Bonitz [8] into its motion-inducing force and internal force is used. In addition, the biggest considerations in this paper are on a servo mode. Whether a current servo mode or a velocity servo mode, the proposed controller gives different interpretations and the velocity servo mode used in the robotic system is mainly focused in this paper.

This paper proposes a grasping force control of a velocity controlled robotic hand. Control law in previous research and proposed control law in velocity mode which plays important role in proposed method is introduced in section II. In addition, its experiments are presented in section III including a robot configuration and conclusion of this paper is followed in section IV.

II. CONTROL LAW

A. Control Law in Previous Research

Compliance control of a position controlled robotic hand was the purpose of previous research [6]. Consider a robotic hand which is grasping an object without the gravity shown in Fig. 1. Fingers are moving from a free space to a set position inside an object to grasp and interactions occur between an F/T sensor and the object. If the object surface and a grasping direction are not perpendicular, the fingers and object move until equilibrium state by a control torque τ.

Since KIST-Hand uses velocity mode as a main control scheme and each joint is assumed as a 1st order system, a computed control torque should be converted into an

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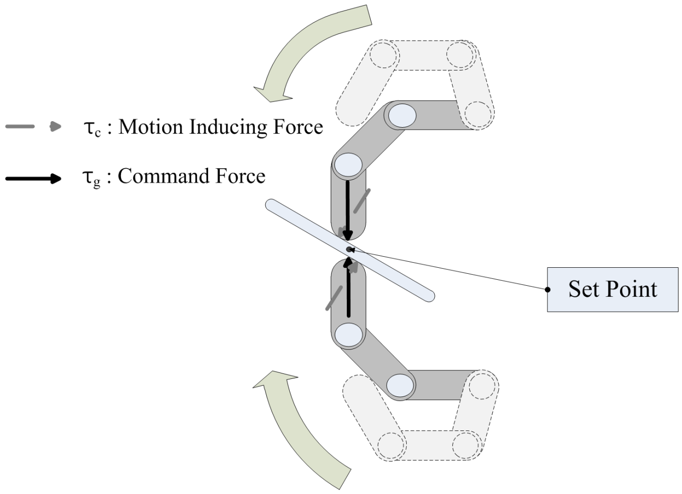


Fig. 1: Compliance control using external F/T sensors.

input velocity to the KIST-Hand. Hence, the robot controller computes the input joint velocity by

$$\dot{\boldsymbol{q}} = \frac{\boldsymbol{\tau}}{J_{eff}s + B_{eff}} \tag{1}$$

$\dot{\boldsymbol{q}}$ is an input velocity to the KIST-Hand and J_{eff} is an effective motor inertia defined as $J_{eff} = J_m N^2$ where J_m is a motor inertia and N is a gear ratio of the harmonic drive. B_{eff} is an effective damping coefficient defined as $B_{eff} = B_m N^2$ where B_m is a motor damping coefficient. Originally, dynamics should be computed in every control period for computing dynamics. However, computing the dynamics is more costly in time and not easy to solve. Hence, the effective inertia and damping are in use of getting velocities.

Then, the control torque consists of a grasping motion driving torque $\boldsymbol{\tau_g}$ and a internal torque $\boldsymbol{\tau_c}$ for compliant motion, and these can be combined as a superposition principle:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_g + \boldsymbol{\tau}_c \tag{2}$$

$\boldsymbol{\tau_g}$ is generated by a $\boldsymbol{f_h}$ which is a virtual spring-damper hypothesis [9]

$$\boldsymbol{\tau}_g = -\boldsymbol{J}_p^T(\boldsymbol{q})\boldsymbol{f}_h \tag{3}$$

where $\boldsymbol{J}_p^T(\boldsymbol{q})$ is a position jacobian transpose to convert a task space force to a joint space torque and $\boldsymbol{f}_h$ is given by

$$\boldsymbol{f_h} = C\dot{\boldsymbol{e}} + K\boldsymbol{e} \tag{4}$$

where $\boldsymbol{e}$ is a task-space position error defined as $\boldsymbol{e} = \boldsymbol{p} - \boldsymbol{p}_d$ and $\boldsymbol{p}_d$ is a desired position vector of fingertip for the path planning with respect to the base frame and $\boldsymbol{p} = [x\, y\, z]^T$ is a current position vector. In addition, C is a positive definite diagonal matrix of damping coefficients, and K is a positive definite diagonal matrix of spring stiffness coefficients.

While fingers are moving toward the object, a contact between an F/T sensor and an object occurs and the control

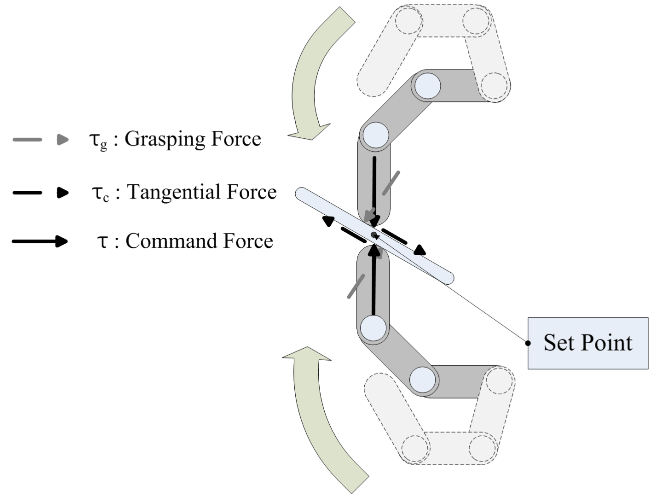


Fig. 2: Grasping force control using external F/T sensors with force decomposition to the normal direction and the tangential direction to an object surface.

is disturbed by an object. To a position controlled robot, if there is no compensation for the interactions, the robot would give forces to reduce the position error continuously to go on a set position while the robot and the object are in contact. Hence, the external F/T sensor is used to compensate the grasping forces. Then, a internal torque $\boldsymbol{\tau}_c$ is generated by the external force and moment $\boldsymbol{f}_{ext}$, $\boldsymbol{m}_{ext}$

$$\boldsymbol{\tau}_c = \boldsymbol{k}_{c,p}(\boldsymbol{J}_p^T(\boldsymbol{q})\boldsymbol{f}_{ext}) + \boldsymbol{k}_{c,o}(\boldsymbol{J}_o^T(\boldsymbol{q})\boldsymbol{m}_{ext}) \tag{5}$$

where $\boldsymbol{J}_o^T$ is an orientation jacobian transpose to convert the task space moment to a joint space torque, $\boldsymbol{k}_{c,p}$, $\boldsymbol{k}_{c,o}$ are a positive definite diagonal matrix of compliance coefficients of position and orientation, and $\boldsymbol{f}_{ext}$, $\boldsymbol{m}_{ext}$ from F/T sensor given by the vector

$$\boldsymbol{f}_{ext} = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix}, \boldsymbol{m}_{ext} = \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix}. \tag{6}$$

Therefore, input torque to the system is the sum of the motion driving torque and the internal torque. This control can show grasping motion with the compliant behavior. However controlling a grasping force is too difficult and if it is required, it can be obtained by adjusting coefficients of C, K, $k_{c,p}$, $k_{c,o}$. On that account, a grasping force control is inevitably desired.

B. Control Law for Grasping Force Control

Consider a robotic hand in contact with an arbitrary object for the grasping force control without the gravity shown in Fig. 2. As described in compliance control, the fingers and object move until those are in equilibrium state by control forces. Grasping force control is also uses velocity servo mode as a main control scheme.

In the case of current servo mode, computed control torque is converted into a current and it goes into the robot directly, so current is of some value if the computed torque

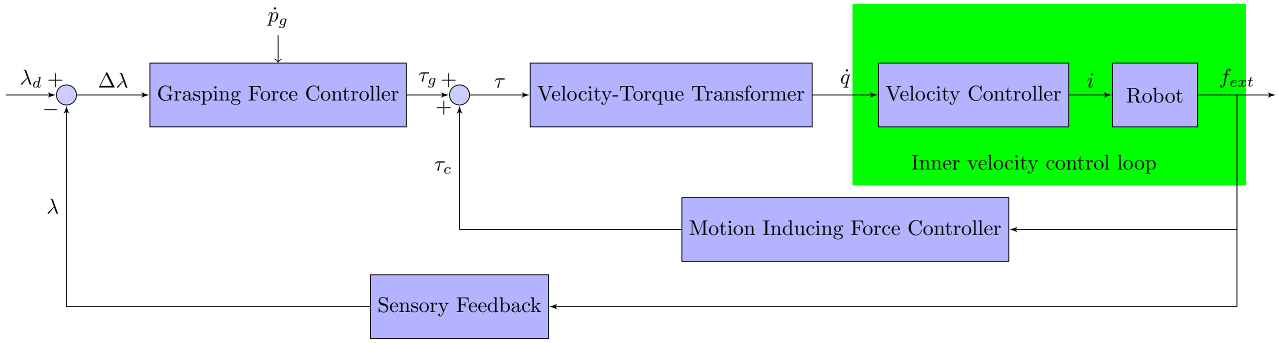


Fig. 3: Block diagram of proposed control method.

for grasping has some value. Hence, many of the force controllers have a form of feed-forward PI controller [10]:

$$\lambda_c = k_{f,p}\lambda_d + k_{f,i}\int_0^t \Delta\lambda dt \tag{7}$$

where $k_{f,p}$ and $k_{f,i}$ are positive definite values of proportional and integral coefficients. Moreover, $\Delta\lambda$ is a grasping force error defined as $\Delta\lambda = \lambda_d - \lambda$ and λ_d is a desired grasping force. In addition, a command force λ_c is converted into input torque and current, and transferred to the system and it has some value as much as the grasping force. In the force control level, high proportional coefficient can make the robot more unstable because of faster response than that of a velocity or a position servo. Hence, giving feed-forward term λ_d makes the grasping force error smaller and the robot difficult to diverge.

However, $\dot{q}$ in the velocity servo mode which is defined as (1) shows quite different meaning in grasping force control. $\boldsymbol{\tau}$ should converge to zero if the hand grasps the object with desired grasping force because $\Delta\dot{q} = 0$ in the PI controller of a inner velocity control loop shown in Fig. 3. $\Delta\dot{q} = 0$ makes $i = 0$ and the robot holding its position. Briefly, the input torque in current servo mode means the amplitude to make the grasping force and the input torque in velocity servo mode means the amplitude to make the joint velocity. All descriptions are shown by the block diagram in Fig. 3.

In that reason, velocity servo mode control is impossible to have the feed-forward term as current servo mode does because the feed-forward term λ_d makes an initial error bigger. The integral controller works to reduce the error, however, if k_i is small, response time is quite slow and if k_i is huge, the system diverges. Therefore, the grasping forces for the velocity controlled robotic hand can be designed as follows.

Control forces are decomposed into a grasping force or a command force $\boldsymbol{\tau_g}$ in a direction toward an each other finger and a internal force $\boldsymbol{\tau_c}$ in steady state in tangential direction to the object surface:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_g + \boldsymbol{\tau}_c \tag{8}$$

Two torques are combined by the superposition principle. Then, the grasping input torque $\boldsymbol{\tau}_g$ to the system is given by

$$\boldsymbol{\tau}_g = -\boldsymbol{J}^T(\lambda_c \frac{\boldsymbol{L}}{||\boldsymbol{L}||}) \tag{9}$$

where λ_c is a command force in the grasping direction and $\boldsymbol{L}$ is a vector defined as $\boldsymbol{L} = \boldsymbol{p}_{index} - \boldsymbol{p}_{thumb}$ which is used as the grasping direction from the thumb to the index. $\boldsymbol{p}_{index}$, $\boldsymbol{p}_{thumb}$ is a position of the index and thumb and $||\boldsymbol{L}||$ is the second Euclidean norm. $\frac{\boldsymbol{L}}{||\boldsymbol{L}||}$ means a unit vector from the thumb to the index and a grasping force, λ_c is determined by

$$\lambda_c = k_{g,p}\Delta\lambda + k_{g,i}\int_0^t \Delta\lambda dt - k_{g,d}\dot{p}_g \tag{10}$$

where $k_{g,p}$, $k_{g,i}$, $k_{g,d}$ are positive definite values of proportional, integral and damping coefficient and $\dot{p}_g$ is a grasping directional velocity in task-space. λ is a current grasping force computed from the F/T sensor by

$$\lambda = \left(\frac{\boldsymbol{L}}{||\boldsymbol{L}||}\right)^T \boldsymbol{f_{ext}}. \tag{11}$$

$\boldsymbol{f}_{ext}$ is projected on the grasping direction and results in a grasping force error in (10). The command force is computed in (10) and converted into command torque in (9).

In addition to this, the internal torque in tangential direction to the object surface $\boldsymbol{\tau}_c$ to the system is given by

$$\boldsymbol{\tau}_c = (\boldsymbol{E} - \boldsymbol{L}\boldsymbol{L}^{+T})\boldsymbol{f}_{ext} \tag{12}$$

where $\boldsymbol{E}$ is an identity matrix and $\boldsymbol{L}^+$ is a pseudo inverse of the grasping direction vector and (12) makes the robot compliant in the tangential direction to the object surface.

Through the controller, grasping force can be controlled by the desired values and also compliant motion can be derived during grasping the objects. In this paper, the internal torque for the compliance control in the tangential direction is not dealt. To validate the algorithm, experiments are performed in the next section and shows competent results.

III. EXPERIMENT

A. Hardware Description

The KIST-Hand is a multi-fingered dexterous robotic hand. It consists of four fingers with the thumb-fingers opposability. Each four fingers have three DOFs whose the third joint articulated by four-bar linkage at the distal joint respectively except the thumb as shown in Fig. 3. The fourth joint linked as the cross four-bar linkage moves in accordance with the third joint.

A force/torque sensor is installed at the fingertip for a force feedback. The sensor is a tiny force sensor (TFS) made by NITTA Co., Japan. The sensor signal has +5v of differential voltage excitation and its gain needs to be tuned by variable registers in an amp board. Each amp board has 6 variable registers for the voltage adjustment. Excitations of gain adjusted sensor data would be subtracted before multiplied with the calibration matrix. NITTA offers calibration matrices to transform the voltage signals to the force/torque data. Through computations of calibration matrix, a 6 by 1 vector whose first 3 by 1 vector is the force signal and another 3 by 1 vector is the torque signal is obtained.

The maximum range of sensor available measurement is different practically according to the coordinates. The maximum value of the sensor available range is limited as 25N for x and y-axis value in Table 1 for the safety problem. In addition, DAQ PCI board which has 12-bit of resolution is installed in an operating PC. Hence, the minimum force can be measured by the F/T sensor is $\frac{25\ N}{2^{12}} \approx 0.0061\ N$. The value change under 0.0061 is undetectable.

Real-time extension (RTX) is installed in the PC for the real time control in windows with 250Hz sampling rate and every computation is conducted within the control period. In addition, the KIST-Hand couldn't be operated by the current mode but by the velocity mode because the robotic hand is articulated by pulleys which generate a lot of nonlinearities. It means that the pulley causes a loss of energy when motor moves joints.

B. Experiment Setup

To show properly how the grasping force controller affects an object, the index of the KIST-Hand is used to perform the algorithm which is proposed in this paper. The object is fixed and the finger moves from the free space to the object surface for the interaction as shown in Fig. 4. When human grasps an object, the grasping forces are not huge as much as holing forces which are obtained from the arms and the palms of the human itself. As an experiment, the rigid object is assumed, $4.5N$ and $0.5N$ of grasping forces are given aperiodically to the object as the desired grasping force and the current grasping force is confirmed through the F/T sensor value feedback.

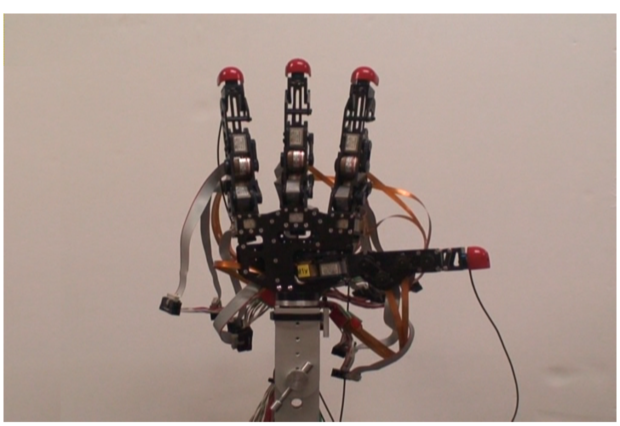


Fig. 4: KIST-Hand

TABLE I: F/T Sensor Specification

Model		TFS12-25
Rating	F_x, F_x, $[N]$	25
	F_z, $[N]$	50
	$M_x, M_y, [N{\cdot}cm]$	30
	M_z, $[N \cdot cm]$	30
Measurement		Diaphragm gauge
Amp board voltage/current consumption		DC 12 15 V ripple P-P less than 1.0 % / 47 mA
Sensor body weight [g]		7

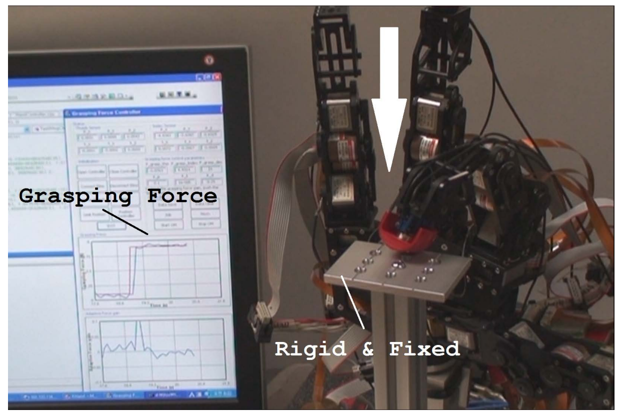
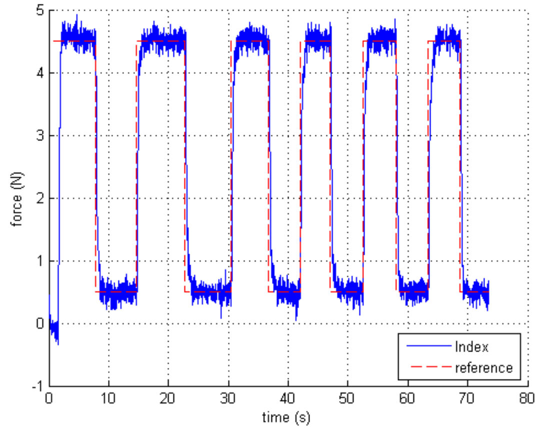


Fig. 5: The index of the KIST-Hand moves down toward the object which is fixed and pushes the object down as much as the desired grasping force are applied.

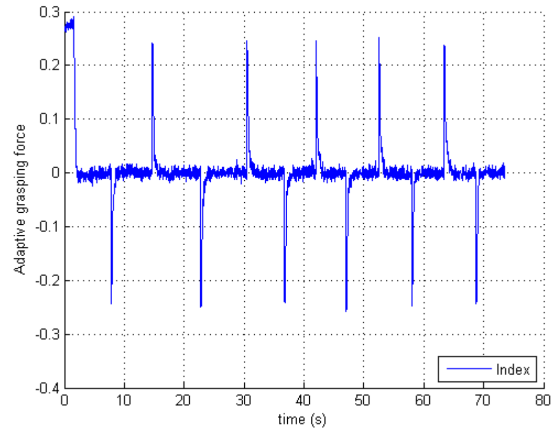
C. Experiment Result

In grasping an object, proper forces not to drop and not to break are important. The main issue is to show how fast the response of the controller is with small overshoot. The question how much the grasping force is necessary is another issue. If there is much overshoot, fragile or flexible objects are possible to be broken down or deformed. Hence, the robot should grasp the object with fast response and no overshoot.

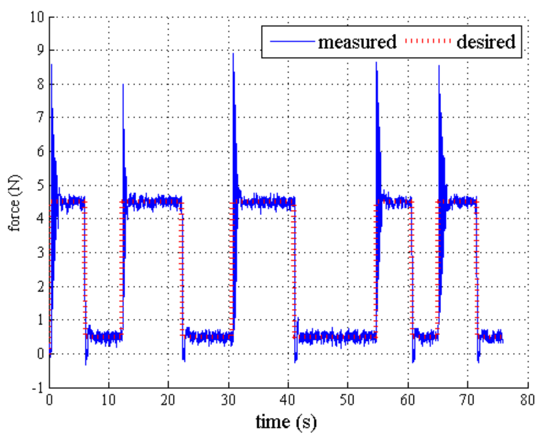
As a validation of the algorithm, two sets of the experiments are performed, and proper result and analysis are obtained through Fig. 6a to Fig. 6d. In accordance with three coefficients, $k_{g,p}$, $k_{g,i}$ and $k_{g,d}$, different force responses are obtained as shown in Fig. 6a and Fig. 6c. To compare the performance of the controller according to the coefficients, integral and damping coefficients are fixed with appropriate values and proportional coefficient is varied to see how the force response changes in the experiment. Without loss of generality, if $k_{g,p}$ increases, response time gets shorter and overshoot gets bigger, and if it deceases, response time gets longer and overshoot gets smaller. In that sense, Fig. 6a and



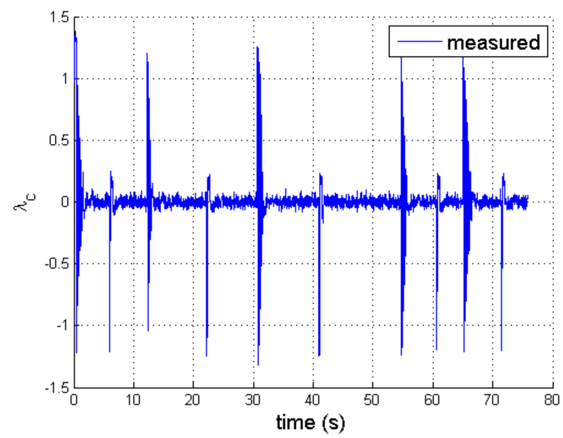
(a) Grasping force response by experiment set 1.



(b) Command grasping force response by experiment set 1.



(c) Grasping force response by experiment set 2.



(d) Command grasping force response by experiment set 2.

Fig. 6: Experiment set 1: $k_{g,p} = 0.1$, $k_{g,i} = 0.00001$, $k_{g,d} = 0.25$ and experiment set 2: $k_{g,p} = 0.3$, $k_{g,i} = 0.00001$, $k_{g,d} = 0.25$. Current grasping force response is shown in Fig. 6a and Fig. 6c. Red dotted line is the applied desired grasping force and blue solid line is the measured grasping force. The command grasping force is computed as shown in Fig. 6b and Fig. 6d and it generates the grasping force to follow the desired grasping force.

Fig. 6c shows grasping force control with varying desired grasping forces.

The red dotted line is the desired force which is given aperiodically and blue solid line is the current grasping force response which is measured from the F/T sensor and projected onto the grasping directional line. Fig. 6c has faster response time than that of Fig. 6a, however, it has too much overshoot compared to the Fig. 6a as analyzed. Hence, Fig. 6c is an appropriate control for the grasping force control. On the other hand, Fig. 6a shows a quite competent result that the response time is within one second and there is no overshoot as appeared in Fig. 6c. Meanwhile, the command grasping force is obtained in Fig. 6b and Fig. 6d. As explained in section II, if the current grasping force is not equal to the desired grasping force, command grasping force changes and if the current and desired grasping force is same, no command grasping force occurs. Appropriate results of the grasping force control of a velocity controlled robotic hand are shown in Fig. 6a and Fig. 6b. The ripple of Fig. 6a and Fig. 6b is within $\pm 0.15\ N$ and $\pm 0.015\ N$ in the steady state.

IV. CONCLUSION

The practical experiment of the grasping force control of a velocity controlled robotic hand using F/T sensors is conducted in this paper. The reason that the grasping force should be controlled is for the stable grasping with the desired grasping force. In that reason, grasping force controller is proposed and analyzed in the paper. In addition, the proposed grasping force controller works differently in the velocity servo mode compared to the current servo mode, and there is a meaning of the proposed controller for the velocity controlled robotic hand. The two properties of the grasping an object is not to drop and not to break down the object. For the stable grasping, proper grasping force controller is experimented and its result is analyzed. Of great importance is the grasping force control which is applied through the force feedback using F/T sensors.

If grasping force control is guaranteed, there are advanced issues to be considered in the dexterous robotic hand field based on it which is considered in this paper. Through the work conducted in this paper, competent results are achieved. Hence next considerations as a future work will be on how grasping force can be decided, manipulating the objects held by desired grasping forces and so on.

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