Grasping Force Control of a Robotic Hand based on a Torque-Velocity Transformation Using F/T Sensors with Gravity Compensation

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***Abstract*—In this paper, the grasping force control of a robotic hand based on a torque to velocity transformation using force/torque (F/T) sensors with gravity compensation is addressed. The force controller is designed and the task force is transformed into command torque. Then, the torque is converted into command velocity for the velocity servo control through torque to velocity transformation. Inner velocity controller is modeled, and the additional torque due to the gravity effect is augmented using superposition principle; then, the analysis of the overall system and controller is conducted through the grasping experiment. As a result of this, competent results are obtained.**

I. INTRODUCTION

Robotics researches have been on an industrial robot to work repeatable tasks, and most of tasks of industrial robots is pick and place. Hence, motion controlled robotic arm with a on/off gripper is developed. However, since service robots have developed, service robot interacts with an environment and does many tasks. In that reason, robotic hand has developed instead of gripper of industrial robot for the various manipulation.

In interaction control, reported interaction control can be classified into compliance control and force control. compliance control uses a dynamic relation to maintain an end-effector position [1], [2], [3]. Although compliance control can show a compliant motion during interaction [4], compliance control by sensory feedback does not guarantee a robotic hand to grasp an object with a desired grasping force. Hence, force control is used for a manipulation of a robotic hand and classified into three approaches: force control with inner position loop [5], force control with inner velocity loop and hybrid force/position control. Force control with inner velocity loop does not ensure reduction of a effect of the uncertainties [6]. In hybrid force/position control, force control and position control can be decomposed into workspace and complementary orthogonal workspace [7], [8], [9].

However, exact modeling of a system or sensory feedback control for torque control [10] is not easy for the industrial robots because torque control has a difficulty to compensate a nonlinearity of the system. Hence, this paper approaches velocity control of a multi-fingered robotic hand through torque to velocity transformation. Adaptive force control is studied by [11], however, the velocity controller is not modeled so, it has delay for the adaptation compared to a modeled case. Hence, the torque control using superposition principle [12] is used as a basic framework of the robot because the force of the other effect such as gravity or friction can be easily augmented in the physical sense, and modeling of the inner velocity controller is conducted. Interaction with an object is assumed as a frictional point contact, and finger-thumb opposition [13] and virtual linkage [10] are used to obtain a desired grasping force.

This paper presents the grasping force control of a robotic hand based on a torque to velocity transformation using force/torque (F/T) sensors with gravity compensation. The controller uses the force/torque sensory feedback on each fingertip of the robot, and computed grasping force is used to compute the command torque. Then, the torque is converted into the command joint velocity for velocity control, and suggested controller in a velocity servo system is analyzed. The main contribution of this paper is a synthesis of the control algorithm: grasping force controller and torque to velocity transformation under the gravity effect. For a practical validation of the controller, the experimental result is presented: an experiment of the grasping force control for a rigid object without and with gravity compensation. The remainder of this section provides an existing control literature and a motivation for the work.

This paper continues its control law proposed in section II and explained for the velocity servo mode. In addition, a robot system configuration and experiments of the grasping force control and gravity compensation are presented in section III, and section IV concludes this paper.

II. FORCE CONTROL IN A VELOCITY SERVO SYSTEM

Precise control at the contact point is important for the interaction control. In the case of joint position control, a loss of accuracy occurs in task space because of the model nonlinearities. If no precise information of the robot system and the object is given, the robot runs risk of breaking the object or itself because the inaccuracy causes a position error and the error generates a force to drive its position to the desired position. Hence, using task space control scheme, interaction between the robot and the object is considered.

Compliance control of a position controlled robotic hand was the purpose of previous research [4] to prevent the breakage. Although it shows a compliant motion while the robotic hand is interacting with the environment, control of desired grasping force is more difficult. Fine gain adjustments of the

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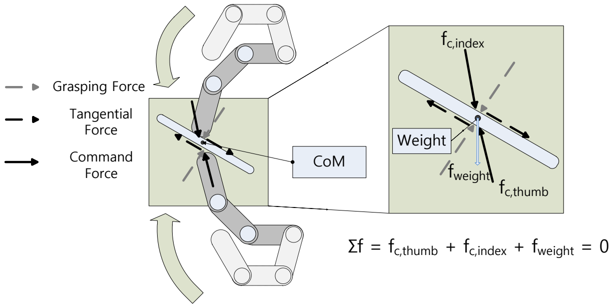


Fig. 1. Grasping force control using external F/T sensors.

controller coefficients should be conducted to get a grasping force, and other gains for other grasping forces so, grasping force control is unavoidably required. This study considers the grasping force control with the gravity compensation.

A. General grasping force control scheme

The force control scheme includes a position or velocity controller in the inner loop, and the force controller with inner velocity loop is generally designed as a form of proportional controller [6]:

$$\dot{\boldsymbol{p}} = k_{f,p}(\boldsymbol{f}_d - \boldsymbol{f}_c) \tag{1}$$

where $\dot{\boldsymbol{p}}$ is a velocity reference of the finger, $k_{f,p}$ is a proportional coefficient, $\boldsymbol{f}_d$ is a desired force, and $\boldsymbol{f}_c$ is a measured force. However, this force controller does not ensure reduction of the effect of the uncertainties [6]; hence Roy and Whitcomb proposed the force controller in [11] as

$$\dot{\boldsymbol{p}} = \hat{\gamma}\dot{\boldsymbol{f}}_d - k_{f,p}(\boldsymbol{f}_d - \boldsymbol{f}_c) \tag{2}$$

$$\hat{\gamma} = -\alpha \dot{f}_d \delta f \tag{3}$$

where $\hat{\gamma}$ is a time-varying estimate of the environment compliance, and α is a adaptive gain. The performance of the controller is decided by $\hat{\gamma}$, and the estimation always has a delay for adaptation. However, there is no need for estimation time if the form of the velocity controller is known, and modeling the inner velocity loop would improve control performance of a robotic hand because less uncertainty remain.

Hence, KIST-Hand is controlled by torque control framework and the torque to velocity transformation explained in the next sections. In this way, torque control based frame work for the algorithm is performed because the force of the other effect such as gravity or friction are easily augmented by superposition principle in the physical sense. Hence, the grasping force controller is designed as follows.

B. Grasping force control

The grasping force λ_c is proposed to make a command torque $\boldsymbol{\tau}$ by

$$\lambda_c = k_{g,p}\lambda_e + k_{g,i}\int_0^t \lambda_e dt - k_{g,d}\dot{\boldsymbol{L}} \tag{4}$$

$$\text{where} \quad \lambda_e = \lambda_d - \lambda, \quad \lambda = \left(\frac{\boldsymbol{L}}{||\boldsymbol{L}||}\right)^T \boldsymbol{f_{ext}} \tag{5}$$

where $k_{g,p}$, $k_{g,i}$, $k_{g,d}$ are positive definite values of proportional, integral and damping coefficients. In addition, $k_{g,d}\dot{\boldsymbol{L}}$ is a task space damping in the grasping direction, λ is a measured force in grasping direction and $\boldsymbol{f}_{ext}$ is a 3-dimensional measured force from the F/T sensor. $\boldsymbol{L} = \boldsymbol{p}_2 - \boldsymbol{p}_1$ and $\boldsymbol{p}_1, \boldsymbol{p}_2$ is a end-effector position of the thumb and finger. λ_c is converted into $\boldsymbol{\tau}$ by

$$\boldsymbol{\tau} = (-1)^i \boldsymbol{J}^T(\lambda_c \frac{\boldsymbol{L}}{||\boldsymbol{L}||}) \quad (i = 0, 1). \tag{6}$$

where $\boldsymbol{J}$ is the Jacobian which maps between end-effector force and joint torque. Then, computed $\boldsymbol{\tau}$ is applied to torque to velocity transformation to be converted to input velocity.

C. Torque control in a velocity servo system

KIST-Hand is operated in a velocity servo mode and has a inner velocity control loop including PI controller:

$$\boldsymbol{\tau} = k_d(\dot{\boldsymbol{q}}_d - \dot{\boldsymbol{q}}) + k_p \int_0^t (\dot{\boldsymbol{q}}_d - \dot{\boldsymbol{q}})dt \tag{7}$$

In frequency domain, the velocity controller can be represented as

$$\begin{aligned}\boldsymbol{\tau}(s) &= k_d(\dot{\boldsymbol{q}}_d(s) - \dot{\boldsymbol{q}}(s)) + \frac{1}{s}k_p(\dot{\boldsymbol{q}}_d(s) - \dot{\boldsymbol{q}}(s)) \\ &= \frac{1}{s}(k_p + sk_d)(\dot{\boldsymbol{q}}_d(s) - \dot{\boldsymbol{q}}(s))\end{aligned} \tag{8}$$

Hence, relation between the torque computed from the force controller and the velocity for the system input is obtained as

$$\begin{aligned}\dot{\boldsymbol{q}}_d(s) - \dot{\boldsymbol{q}}(s) &= \frac{s\boldsymbol{\tau}(s)}{k_p + sk_d} \\ &= \frac{1}{k_d}\left(1 - \frac{k_p}{k_p + sk_d}\right)\boldsymbol{\tau}(s) \\ &= \frac{1}{k_d}\boldsymbol{\tau}(s) - \frac{k_p/k_d}{k_p + sk_d}\boldsymbol{\tau}(s)\end{aligned} \tag{9}$$

By the final value theorem, the stability of the system is simply proved:

$$\begin{aligned}&\lim_{s\to 0} s(\dot{\boldsymbol{q}}_d(s) - \dot{\boldsymbol{q}}(s)) \\ &\quad = \lim_{s\to 0} s\left(\frac{1}{k_d}\boldsymbol{\tau}(s) - \frac{k_p/k_d}{k_p + sk_d}\boldsymbol{\tau}(s)\right) = 0\end{aligned} \tag{10}$$

If $t \to \infty$, $\lambda_e \to 0$ and $\boldsymbol{\tau} \to 0$ then, $\dot{q}_d(t) \to 0$. If the robotic hand grasps the object with the desired force, the robot should keep the position to give the force to the object. Therefore, a computed torque is transformed into an input velocity by $\dot{\boldsymbol{q}}_d(s)$:

$$\dot{\boldsymbol{q}}_d(s) = \dot{\boldsymbol{q}}(s) + \frac{s\boldsymbol{\tau}(s)}{k_p + sk_d}. \tag{11}$$

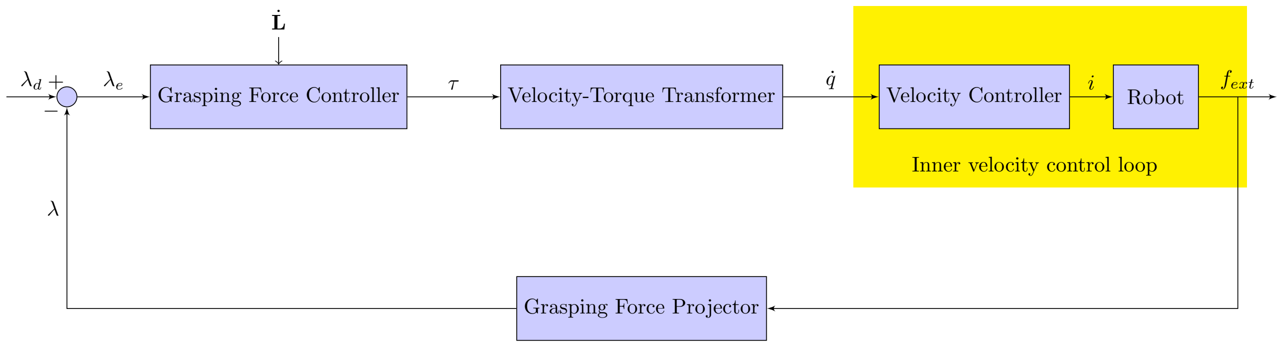


Fig. 2. Block diagram of grasping force control.

Fig. 2 describes a system block diagram of the proposed algorithm.

D. Gravity compensation

Meanwhile, if the gravity effect of the object is not considered during the interaction, the control can fail although the grasping force is appropriately controlled because the fingers go downward because of the object weight. Hence, gravity compensation needs to be implemented.

Fig. 1 provides consideration for a free body diagram of the system. The thumb is assumed as the lower finger in the system. Two opposite directional forces $\boldsymbol{f}_{c,thumb}$ and $\boldsymbol{f}_{c,index}$ are reactive forces, and the object weight remained to be added for force equilibrium. In other words, the fingers moves downward during the interaction of the hand and object system if no gravity effect is considered. Therefore, compensation force λ_g is added to the controller:

$$\begin{cases} \lambda_{d,upperfinger} &= \lambda_d \\ \lambda_{d,lowerfinger} &= \lambda_d + \lambda_g \end{cases} \tag{12}$$

$$\lambda_g = -\left(\frac{\boldsymbol{L}}{||\boldsymbol{L}||}\right)^T \boldsymbol{f}_g \tag{13}$$

$\lambda_{d,lowerfinger}$ is the desired grasping force of the robotic hand and λ_g is a gravity compensation force. $\boldsymbol{f}_g$ is the object gravity and it is projected in the grasping direction. Through this modification, the robot hold the object without position drift in spite of the object weight.

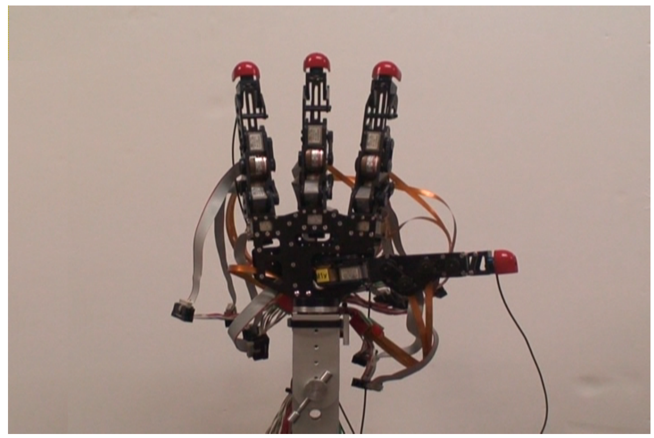


Fig. 3. KIST-Hand

TABLE I
F/T SENSOR SPECIFICATION

Model		TFS12-25
Rating	F_x, F_y, $[N]$	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

III. EXPERIMENT

A. Hardware description

To validate the control scheme, the grasping force control experiments are performed in the next section and brings competent results. The KIST-Hand in Fig. 3 is a four-fingered robotic hand which has 12 DOFs and a feature of a four-bar linkage at the distal joint at each finger except the thumb. The fourth joint moves accordingly to the third joint because of the four-bar linkage. In addition, F/T sensors are mounted on the fingertip of each finger for the sensory feedback control. The sensor signal is excited by +5v and it can be adjusted by the variable resistor in an amplifier. Amplified signals which have +5v of excitation should be subtracted by 5v for the calibration matrix multiplication. Through the multiplication of the calibration matrix and the sensor voltage signals, 6 axis F/T values are obtained. The maximum available sensing range is limited to 25N to prevent being damaged, and the sensor specification is shown in TABLE I. Moreover, the robotic hand is grounded to reduce the system noise affecting F/T sensors with irregular disturbances between the motor and the base frame, and between the base frame and the power supply.

The data acquisition board (DAQ) has a 12-bit of resolution, and the real-time extension (RTX) is used for faster and more stable control of 250Hz requency in Windows. Additionally, KIST-Hand is operated in the velocity servo mode because

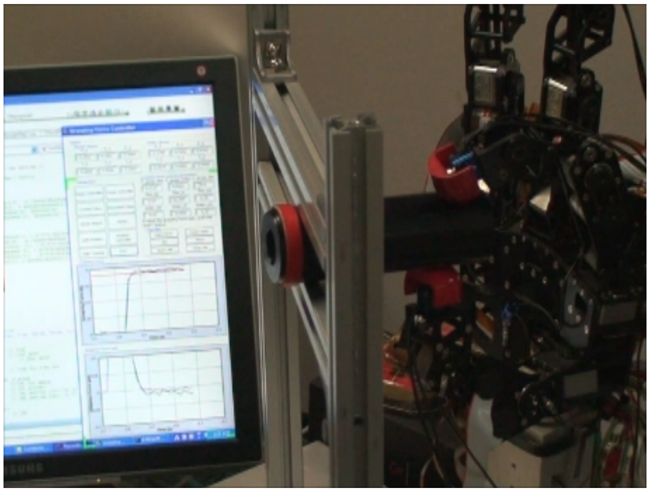


Fig. 4. Grasping force control experiment without gravity consideration.

of the pulleys connecting the motor and the harmonic drive of a 100:1 gear reduction ratio. The pulley generates the nonlinearities and causes a lot of energy loss between the motor and the joints, so it is difficult to use current servo mode.

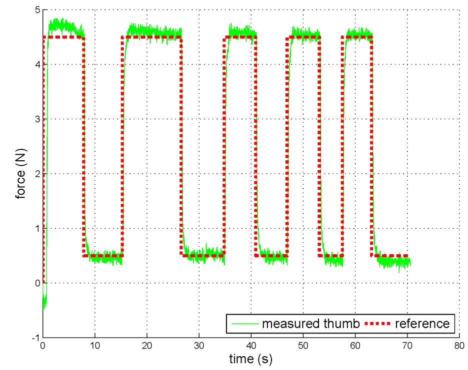
B. Grasping force control

1) Experiment setup: In this section, the goal is to demonstrate how the robotic hand grasps an object through the grasping force control. To show only the effect of the controller, the object is fixed to avoid introducing vibrations while the fingers and the object are in contact. The fingers move toward each fingertip and the object is fixed between the fingers as shown in Fig. 4. The object is sufficiently rigid, so fast and high overshoot reaction occurs if the control is not properly performed. Proper grasping is defined as to grasp an objet without dropping or breaking of the object. Hence, the coefficients of the controller are tuned to have a lower overshoot and a shorter settling time while the desired grasping force is controlled during the interaction. As an experiment, 4.5N and 0.5N of desired grasping forces are applied aperiodically and the grasping force is measured from the F/T sensors.

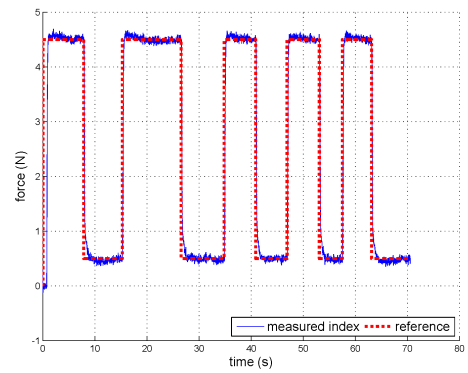
2) Experiment result: The experiment is repeated with the setup described above and the result is obtained in Fig. 5. The response of the robotic hand during the contact varies according to the coefficients. In this results, $k_{g,p} = 0.07$, $k_{g,i} = 0.00005$ and $k_{g,d} = 0.25$ are given for the control coefficients. Command grasping forces of the thumb and index have non-zero values if the desired grasping force changes during the movements as shown in Fig. 5c. Alternatively, command force is zero when the grasping force becomes same as the desired value; hence, the robotic hand maintains the position of the fingers to apply the desired forces.

C. Gravity compensation

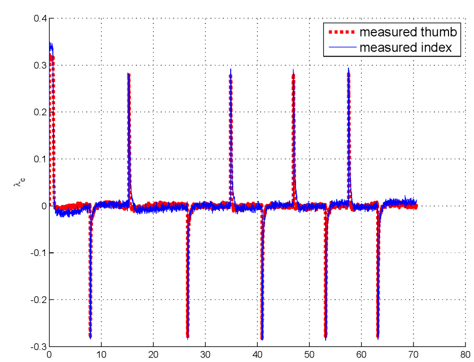
1) Experiment setup: To show the grasping force control under the gravity effect, the rigid box shape object is chosen



(a) Grasping force response of the thumb. Green solid line and red dotted line is the grasping force response of the thumb and the desired grasping force.



(b) Grasping force response of the index. Blue solid line and red dotted line is the grasping force response for the index and its desired grasping force.



(c) Command force response of the thumb and the index. The red dotted line and the blue solid line is the computed command force of the thumb and the index.

Fig. 5. Grasping force control experiment, and graphs show the response of the grasping force control. KIST-Hand grasps the object with desired grasping forces which vary its value aperiodically, and sensory feedback follows the desired grasping force. The settling time of the system is around 1-2 sec, and the measured force follows the desired force without high force overshoot. Gains are chosen as $k_{g,p} = 0.07$, $k_{g,i} = 0.00005$, $k_{g,d} = 0.25$.

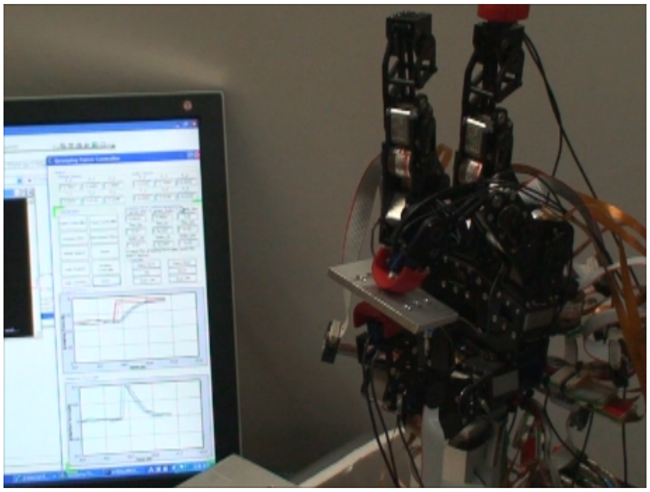


Fig. 6. Grasping force control experiment with gravity compensation.

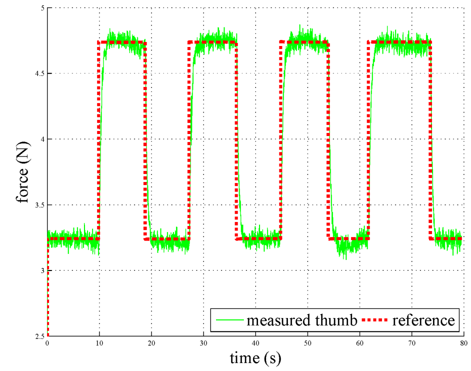
with the same control coefficients. In fact, configuration of KIST-Hand between the thumb and the index is designed to be tilted during the contact. Hence, different sides of the sensor are in contact when the fingers face each other. It makes the object tilted while it is grasped by the robotic hand. In addition, the object and the fingertip of the hand have low friction constants, so if enough force is not applied to the object and held the object closer to the center of mass, the object slips and rotates during in contact. Hence, the experiment is conducted under the stable configuration and enough desired force is assigned. In the experiment, 4.5N and 3N of desired grasping forces are chosen and applied to the object aperiodically during the interaction. Here, 29g of aluminum plate is used in the experiment. The overall setup for the experiment is shown in Fig. 6.

2) Experiment result: An experiment is conducted with the setup as described above and showed proper results for the gravity compensation in Fig. 7. The three coefficients are considered as same as III-B while the gravity is considered. Therefore, its result is shown in Fig. 7.

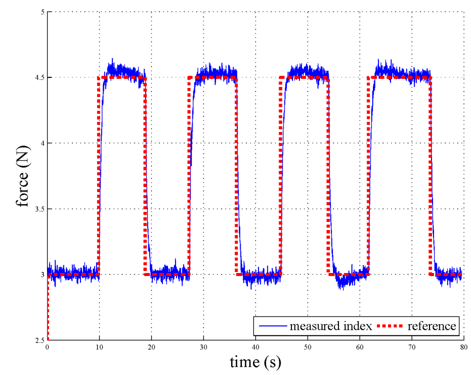
The gravity effect because of the mass is considered also in the desired grasping force as shown in Fig. 7a by adding 0.29N, the object weight. The gravity effect of the object is compensated during the grasping and its result is the same as the grasping force control. If the measured grasping force becomes the same value with desired grasping force, $\dot{\boldsymbol{q}}_c$ becomes zero as well, and the robot holds its position and delivers the desired grasping force to the object.

IV. CONCLUSION

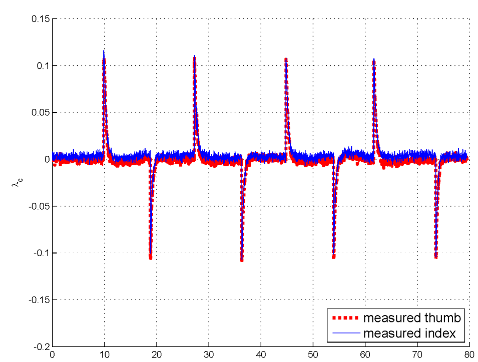
This paper presented the grasping force control of a velocity controlled robotic hand using F/T sensors with the gravity compensation. Although previous research verified an appropriate compliance control during the interaction with the environment, the control does not guarantee the grasping force that the robotic hand applies to the object. the virtual linkage is used to project the measured force on grasping force, and



(a) Grasping force response of the thumb. Green solid line and red dotted line is the grasping force response of the thumb and the desired grasping force.



(b) Grasping force response of the index. Blue solid line and red dotted line is the grasping force response for the index and its desired grasping force.



(c) Command force response of the thumb and the index. The red dotted line and the blue solid line is the computed command force of the thumb and the index.

Fig. 7. Grasping force control experiment under the gravity consideration, and the graphs show the response of the control. Gains are $\lambda_{d,thumb} = \lambda_d + \lambda_g$. $k_{g,p} = 0.07$, $k_{g,i} = 0.00005$, $k_{g,d} = 0.25$.

torque control of the grasping force is the basic framework to manipulate an object. The velocity controller for the torque to velocity transformation is addressed for the velocity controlled robotic hand, and the robot's behavior in the velocity servo mode is analyzed. In addition, the gravity compensation for the object weight is considered, and the experiments for the suggested algorithm is performed. Accordingly, appropriate results are obtained and the grasping force control is guaranteed through the designed control scheme. The following considerations will be on the next research topic: active decision of the desired grasping force, and manipulation of the fragile or deformable objects.

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