MASTER-SLAVE CONTROL METHOD WITH FORCE FEEDBACK FOR GRASPING SOFT OBJECTS USING A TELEOPERATION CONSTRUCTION ROBOT

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Abstract

The purpose of this research was to develop a control method that would provide an operator with a noticeable and reasonable sense of reaction force during slow grasping of a soft object. We examined a master-slave control system for a teleoperation construction robot comprised of two joysticks as the master that are used to manipulate the object from a remote location, and an excavator with four degrees of freedom consisting of a fork glove, swing, boom, and arm as the slave. In remote control systems, the operator must feel a reasonable sense of force from the fork glove feedback. We previously proposed a variable-gain velocity control system but found that the reaction force was insufficient and often undetectable to operators' sensory receptors in the initial stage of the grasping task, and the reaction force did not appear as a stepwise relation to the increased driving force when grasping a foam block at a slow speed. Based on these earlier problems, we proposed an improved method that provides a noticeable torque and variable gain that changes with the hardness of the task object. Its effectiveness was verified by a concrete block, tire, and sponge foam block grasping experiment.

Keywords: construction machinery, robot, hydraulic actuator, master-slave control, force feedback

1 Introduction

Remote-control robotics is an effective technique for accomplishing machine work in locations where it is difficult and/or dangerous for humans to enter, such as disaster sites, nuclear plants, and heavy machine manufacturing sites. In Japan, unmanned construction was first introduced at a practical level in the disaster recovery work after the eruption of Mt. Unzen Fugen Dake in 1990-1995, and numerous examples of practical application have been reported since that time. In 2001, the Ministry of Land, Infrastructure, and Transport (MLIT) worked out guidelines for the full-scale introduction of unmanned construction in public works projects. These trends suggest that unmanned construction will become increasingly common in the future (Muramatsu, 2002; FRICS, 2001).

In the teleoperation systems for construction machinery that are currently applied in practical use, the mainstream operating method includes feedback limited to visual information obtained by onboard cameras mounted on the construction machine. As expected, with this method, the operator's access to site information (presence) is limited, and it has been reported that work efficiency is considerably inferior to that occurring under direct operation (Kanno et al., 1994). To enable safe, steady, and high-level teleoperation work, it is important to supply the operator with a reasonable sense of force, or force feedback, in addition to visual information.

The authors have developed a master-slave control system for a teleoperation construction robot with force feedback. To achieve a sense of force feedback, we had previously proposed a variable-gain symmetric-position control method (Yamada et al., 2000). Because the operator was not able to feel a reasonable sense of the task force when grasping a soft object at a comparatively slow speed, a control method (Kato et al., 2002; Yamada et al., 2003) was proposed for the fork glove and swing using symmetric positioning and force reflection control methods. In addition, a method with gravitational compensation was proposed for the control of massive parts, that is, the boom and arm (Kato et al., 2003). However, the operators found moving the joystick by position-position control to be strange, because the most commonly used control for excavators

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sold in the market is position-velocity control. A variable-gain velocity control (Yamada et al., 2007), in which velocity is used as feedback instead of the position of the piston, has therefore been proposed.

Since the fork glove is regarded as the hand of the construction robot, the control for the fork glove is still the focus of our research. A force sensor or pressure sensor can be used to detect the reaction force. We used a pressure sensor in this research, since force sensors are easily damaged, hard to maintain, and not commonly used in hydraulic construction machinery. Pressure sensors are easily influenced by the effect of friction and cyclic loading, and although the operator's perception of change in the reaction force is reduced, particularly while grasping a foam block, we felt the sensitivity of pressure sensors outweighed this disadvantage. As there are many types of tasks dealing with different objects at disaster sites, nuclear plants, and other dangerous settings in real life, it will be useful for an operator to feel the task force generated by a soft object in teleoperation without crushing the object. Such a teleoperation system could, for example, be very useful during plumbing assembly without crushing the task object in nuclear plants.

We believe that our master-slave control should be available for handling the majority of soft objects, if an operator can perceive the sense of force while grasping foam blocks without crushing them. We therefore chose a piece of sponge foam as a task object for carrying out the grasping experiment by variable-gain velocity control (conventional control), and we found that the operator felt the task force only when the sponge foam block was almost completely crushed at a low speed. Consequently, in this research, we developed a control method capable of providing the operator with a noticeable and reasonable sense of reaction force without crushing the task object when grasping foam blocks.

We developed an algorithm for enhancing and magnifying the reaction force to develop a control method that would provide the operator with a noticeable and reasonable sense of the reaction force without crushing a foam block. In the remainder of this paper, we first examine the control of the teleoperation construction robot, and we then describe the algorithm of the reaction force by conventional control in the master-slave system and reveal the reason for the problem that occurs with conventional control when grasping a very soft object. Next, we introduce an improved control method to overcome this problem and provide the operator with a noticeable and reasonable sense of reaction force by adopting a noticeable torque and a variable gain. Finally, we conduct grasping experiments, analyze the experiment results, and present our conclusion.

2 Teleoperation Construction Robot

The schematic diagram of the teleoperation construction robot system used in this research is shown as Fig. 1. The system comprises two joysticks (Side Winder Feedback 2 manufactured by Microsoft Co., Ltd.) as the master and a construction robot (a commercially available backhoe modified based on Hitachi LandyKID-EX5) as the slave.

The joysticks enable forward/reverse and right/left movement. Joystick displacements are detected by position sensors, and the movement data is sent to a personal computer adapted to serve as the construction robot control computer. Two DC motors installed in each joystick enable the operator to feel the sense of grasping an object by the fork glove and the work reaction force (force sense) generated by the swing, boom, and arm.

In this system, a robot arm with four degrees of freedom is used, and manipulating the joysticks in four directions allows operation of the hydraulic cylinders (the fork glove, swing, boom, and arm) driving the construction robot. As a feature of the position-velocity control method in our teleoperation system, when the joystick is in the intermediate position, namely the displacement of the joystick is zero, the piston velocity of the hydraulic cylinders is also zero. The magnitude and direction of the piston velocity change along with the magnitude and direction of the joysticks. Hydraulic cylinders are controlled by proportional valves. Cylinder displacement is detected by magnetic stroke sensors, which are embedded in the pistons. Pressure sensors are installed on the cap end and rod end of the cylinder for detection of the cylinder's load pressure. These pressure signals can be used as force-sense signals, which are calculated by the personal computer and sent to the master side.

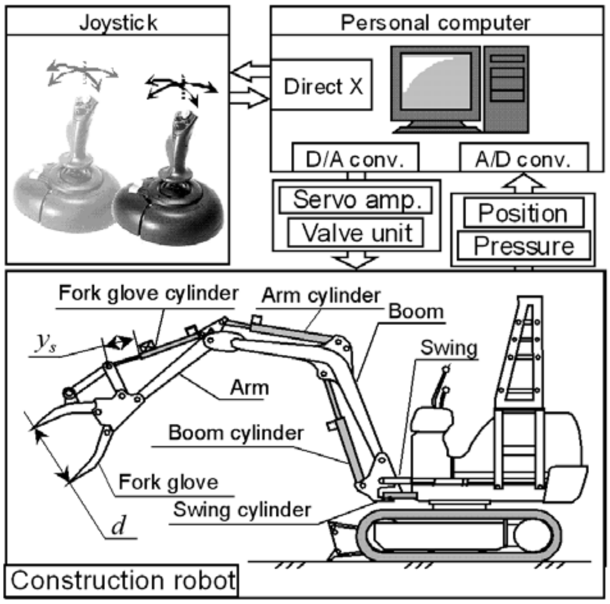


Fig. 1: *Schematic diagram of the experimental apparatus*

3 Master-Slave System

A conventional control was previously proposed for the fork glove, which enables reasonable representation of the feeling of grasping with the fork glove in a wide range of grasping tasks. The reaction of forces in the fork glove's cylinder under this control method is shown as Fig. 2. Omitting the fork glove, the equation of motion of the cylinder and the driving force acting on the cylinder (Yamada et al., 2003) during the grasping process can be expressed by

$$\begin{aligned} m\ddot{y}_s + b\dot{y}_s + f &= f_s \\ f_s &= a_c p_c - a_r p_r \end{aligned} \quad (1)$$

where b describes the viscous damping coefficient of the piston, and f is the sum of extraneous forces (except viscous friction and driving force) acting on the piston, e.g., gravitational force, Coriolis force, static friction, etc. The driving force, f_s, depends on the viscous force but also the gravitational force, Coriolis force, etc., according to Eq. 1.

The force feedback to the joystick, which is expressed by the reaction torque, τ_r, is made up of two items; one depends on the deviation between the velocity of the piston and the position of the joystick, and the other depends on f_s. τ_r occurs when the non-dimensional master overall gain, T, is more than zero, namely, when the fork glove is grasping an object. τ_r and T are represented by

$$\tau_r = T\{k_{pm}(Y_m - \dot{Y}_s) + k_{tm} f_s\} \quad (2)$$

$$T = \begin{cases} 0 & (|f_s| \le |f_{pre}|) \\ 0 < \dfrac{f_s - f_{pre}}{f_{e\_max} - f_{pre}} \le 1 & (f_s > 0 \cap f_s > f_{pre}) \\ 0 < \dfrac{f_s - f_{pre}}{f_{c\_max} - f_{pre}} \le 1 & (f_s < 0 \cap f_s < f_{pre}) \end{cases} . \quad (3)$$

Here, f_{e_max}, f_{c_max} express the maximum driving force of the piston in the expansion and contraction directions (f_{e_max}=11.7kN, f_{c_max}= -6.8kN), respectively, and f_{pre} denotes the threshold of the driving force when the piston is moving in free space (never reaching the limit position) without grasping anything, as shown in Fig. 3, while f_s is smaller than f_{pre}. Since cylinders are nonlinear systems in actual life, it is difficult to calculate f_s by a mathematical method. The relation between the driving force and the piston's velocity (velocity-driving force characteristic) can be measured by experiment.

First, we conducted a free grasping experiment (FGE), which measured the piston moving in free space without grasping anything. f_s was obtained when the construction robot (arm and fork glove) made various gestures at various velocities. The limit value of f_s with the corresponding velocity is shown as the black dot in Fig. 3. Since the driving forces of arm and boom are greatly affected by gravity, and the $\dot{y}_s$ - f_s characteristics form a curve, quadratic fit was chosen as the fitting method to observe the relation between the driving force and the velocity. Next, the FGE was conducted again using the $\dot{y}_s$ - f_s characteristics, to observe the value of the master overall gain, T. In this case, the gain, T, was greater than zero, due to the influence of oil temperature and the wear on cylinder. It was strange for the fork glove to not be grasping. A certain margin needs to be supplied for the $\dot{y}_s$ - f_s characteristics. A certain degree of vertical offset was therefore given to these lines, as seen in Fig. 3. The offset value was gradually increased, until the value of T always equalled zero. Finally, the functional equations for the threshold, f_{pre} (the curve in Fig. 3), are described by

$$\begin{cases} f_{pre} = (-150\dot{Y}_s^2 + 46\dot{Y}_s + 0.68)\times 10^3 & (\dot{Y}_s \ge 0) \\ f_{pre} = (1.1\dot{Y}_s^2 + 38.7\dot{Y}_s - 0.88)\times 10^3 & (\dot{Y}_s < 0) \end{cases} . \quad (4)$$

As seen in Fig. 3, the result of quadratic fit seems like a linear relationship between driving force and velocity, because the viscous friction has a great influence on the motion of the cylinder.

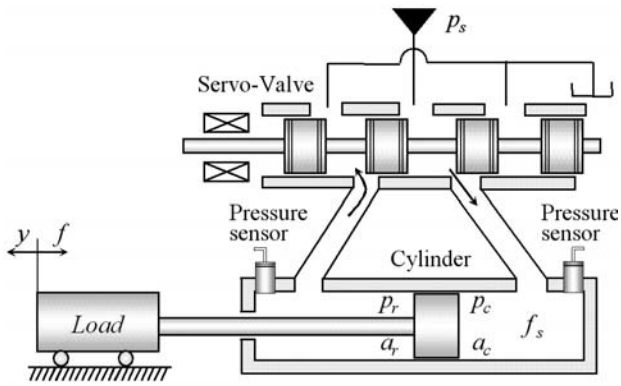


Fig. 2: *The reaction forces in the cylinder*

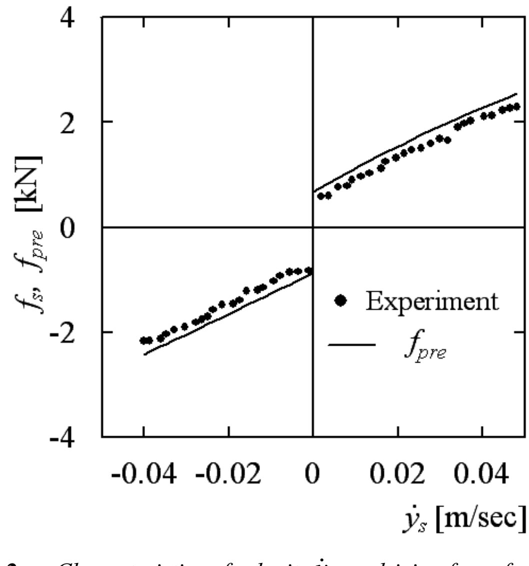


Fig. 3: *Characteristics of velocity $\dot{y}_s$ vs. driving force f_s*

As mentioned above, the conventional control has the advantage of position control with a feel of force, and the operator feels a reasonable sense of force when grasping both a soft object (e.g., a tire) relatively slowly and a rigid object (e.g., a concrete block).

We chose a sponge foam block as a task object for carrying out the grasping experiment by conventional control and found two problems. The first problem was that the operator did not feel the reaction torque in the initial stage of grasping the object, even though the reaction torque did appear judging by the experimental data. To avoid paying attention to the experimental data only while ignoring the operator's feeling, we gathered information on human perception in this study. The other problem was that the operator did not feel the reaction torque stepwise increase caused by stepwise grasping, and only felt the reaction torque when the foam block was almost completely crushed at a low speed.

These problems are considered to have occurred for the following reasons. For operational safety, the joystick returns to the zero position and the piston velocity equals zero when the operator releases the joystick during operation, so when the joystick is moved in free space without grasping an object, there is a reaction to the joystick. Another reason is that there is a disharmony between perception and stimulus for the operator. The operator perceives a physical stimulus only when the stimulus varies as a progression, and in this case the operator cannot notice any change in the reaction torque. This is because the external force on the fork glove changes slowly when the operator is grasping the sponge foam, and the reaction torque is also very small and is not felt as a stepwise change by conventional control.

4 An Improved Variable-Gain Velocity Control

To give prominence to the simple and practical construction robot teleoperation system in our lab, we made all improvements to existing equipment.

To overcome the problem of not feeling the reaction torque in the initial stage of grasping an object, we propose a noticeable τ_s, which suggests a threshold of human perception and provides a smaller and more noticeable difference between reactions to the joystick when grasping an object and when not grasping an object.

As shown in Fig. 1, the personal computer produces a reaction torque signal that was transmitted to the joysticks according to Eq. 1. To obtain τ_s, a simple experiment was conducted that simulated the reaction torque caused by the slave to transmit to the joysticks. Namely, the operator handled the two joysticks to slowly move them left and right, at the same time exerting a reaction torque to one of the two joysticks at a small fixed step by computer until the operator felt the reaction. Five data series were recorded, and the mean was τ_s ($0.17 \times \tau_{0r}$). In this experiment, the operator was able to feel the reaction torque from the fork glove in the initial stage of grasping, even though the force was small, by adopting a noticeable τ_s.

The reaction torque is now described by

$$\tau_r = T\{k_{pm}(Y_m - \dot{Y}_s) + k_{tm} f_s + \tau_s\}. \quad (5)$$

By applying this equation, we expect that although the feedback reactions are very small, they can reasonably be felt by the operator when slowly grasping a soft object.

In addition, because the external force on the fork glove changes slowly while grasping the sponge foam, the reaction torque does not significantly appear as a step-by-step change. To surmount this problem, we improved the variable-gain velocity control. In Eq. 2, k_{tm} is a constant value regardless of whether the object to be lifted is a concrete block, a tire, or a piece of sponge foam. We therefore set k_{tm} as a variable parameter to magnify the reaction from the driving force according to the type and hardness of an object.

To derive a calculation method for the variable k_{tm}, we researched the relationship between f_s and the distance change, delta d, as shown in Fig. 4, while slowly grasping a concrete block, a tire, and a sponge foam block. Here, d is the distance from the tip of the front fork to the tip of the back fork (finger distance), as shown in Fig. 1. Delta d is the change in d in the process of grasping an object perceived by the fork glove (delta $d = d^* - d$, d^* is the last moment's d before T_r appears in the process of grasping the task object). As shown in Fig. 4, during grasping of a hard object, f_s changes quickly. In contrast, during grasping of a soft object, due to the compressibility of the object, d changes quickly. We use d and f_s as the conditions for judging a hard object or a soft object.

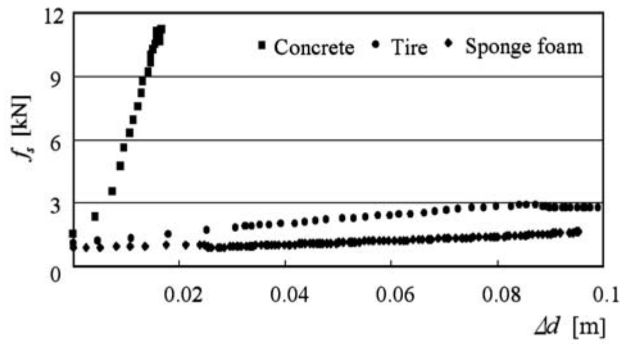


Fig. 4: *Relationship between delta d and f_s*

Naturally, f_s when grasping a tire is stronger than that when grasping a sponge foam block. For a softer object, we hope to get a stronger reaction, i.e., to get a bigger k_{tm}. Because T_r is very small by conventional control when grasping the sponge foam, k_{tm} is set by rounding (T_g / T_r) ($T_g \geq T_r$) to obtain a large value, and T_r is amplified to be easily perceived. T_g is a non-dimensional torque for k_{tm} calculation. The larger the value of T_g is, the larger k_{tm} is and the larger T_r is. If T_g is very large, T_r rapidly increases to a peak and is unable to appear as a stepwise change; it is therefore detrimental to the operator's judgment. In contrast, if the value of T_g is very small, T_r is enlarged without being clearly enhanced and is unable to be perceived by the operator. The flowchart of the improved variable-gain velocity control is shown as Fig. 5.

In Fig. 5, when T_r does not appear, the fork glove is not grasping an object and we save f_s^* d^*; otherwise, we use the conditions "$d^* - d > d_t$" and "$f_s - f_s^* > f_{st}$" to distinguish between soft and hard objects, respectively. If "$d^* - d > d_t$" is satisfied, the grasped object is a soft object, and k_{tm} is set to an integral value by rounding (T_g / T_r), in which case the experimental result will be more attractive to express the k_{tm} value. In contrast, if "$f_s - f_s^* > f_{st}$" is satisfied, the grasped object is a hard object, and k_{tm} is set to 1, which is the same as when using conventional control. If both of the conditions are not satisfied, the type of object cannot be distinguished and k_{tm} is set to a default value of 1. In this method, k_{tm}

is calculated while grasping an object at every turn. We use a fixed value, T_g, to obtain a larger k_{tm} value, and then a sufficient T_r appears. According to T_g / T_r, both k_{tm} and T_r will decrease in the next moment. Next, k_{tm} and T_r will increase again. This phenomenon will be repeated again and again in the initial stage of grasping, and the reaction torque will not be adequately amplified. The k_{tm} value is therefore set as a fixed value, and once k_{tm} is set, it will not be changed while grasping the object. According to the algorithm for soft objects, when the object is softer, k_{tm} is larger. To make k_{tm} exhibit a sufficient range according to the difference in the hardness of soft objects, T_g is set to 0.04 using a sponge foam block, a tire, and a concrete block by trial and error in this research.

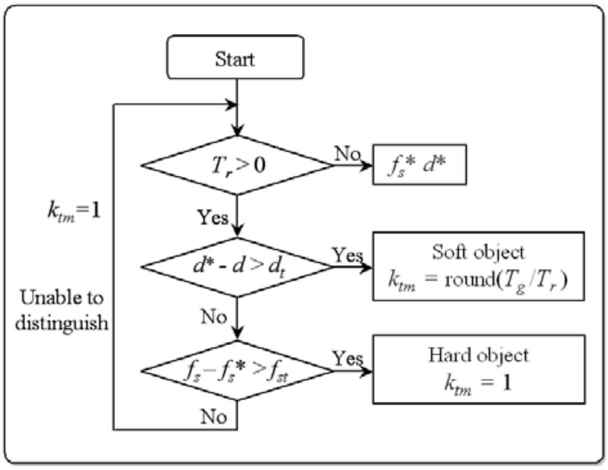


Fig. 5: *Flowchart of improved variable-gain velocity control*

In our improved variable-gain velocity control (improved control), τ_r is also defined as shown in Eq. 5. The variable threshold, f_{pre}, and variable-gain, k_{tm}, algorithms are described by Eq. 4 and Eq. 6, respectively. The block diagram of improved control is depicted as Fig. 6. By applying improved control, we expect the reaction torque to the joystick to strongly appear as stepwise in relation to the increasing driving force, and the operator will perceive a reasonable sense of reaction force variance changing with the deformation of the object during a grasping task. The type of grasped object can be recognized in the initial stage of grasping by changing the color of the object displayed in virtual space according to conditions "$d^* - d > d_t$" and "$f_s - f_s^* > f_{st}$". As shown in Fig. 7, the color of the object changes to red in the case of $k_{tm} = 1$ with a hard object grasped, namely "$f_s - f_s^* > f_{st}$"; the color of the object changes to pink on the condition of "$d^* - d > d_t$". This cuing is helpful for the operator to perform subsequent operations.

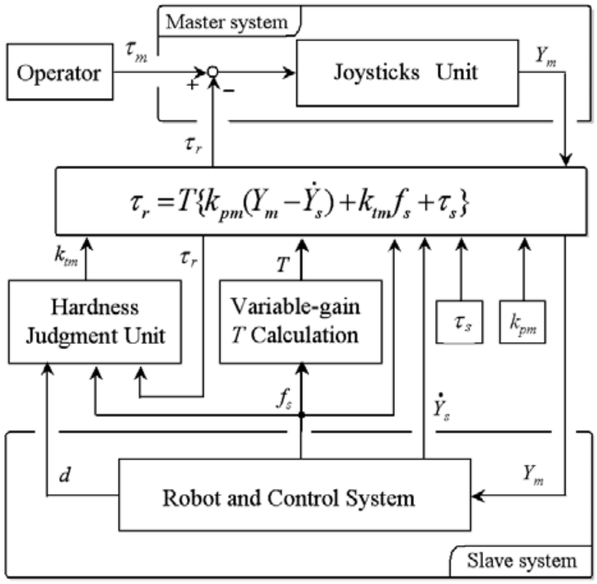


Fig. 6: *Block diagram of improved variable-gain velocity control*

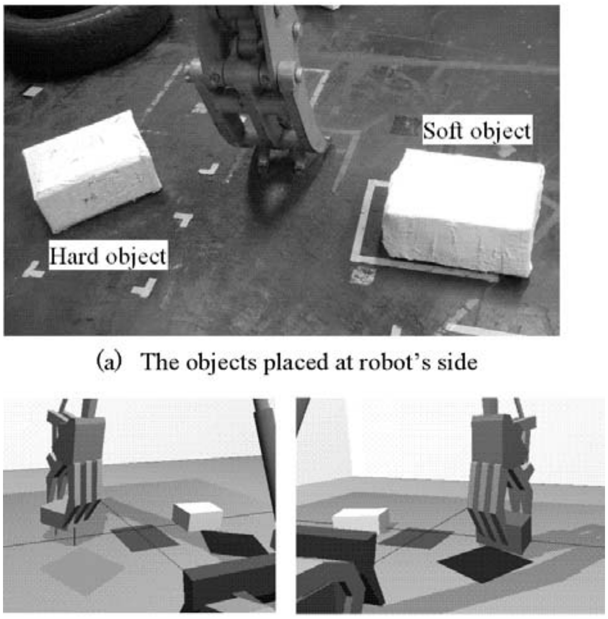
$$k_{tm} = \begin{cases} 1 & \text{(Hard object)} \\ round(0.04/T_r) & \text{(Soft object)} \end{cases} \tag{6}$$

5 Experiments

It is difficult for an operator to observe and judge the condition of the fork and task object due to poor image quality and large amounts of data gathered by the video cameras in the teleoperation system. At the same time, the operator may be confused, nervous, and/or worried by the lack of a sense of the reaction torque during the initial stage of grasping. We used a virtual reality system, as depicted in Fig. 7, for this involving a delicate robot model and a ground model. The gestures of the robot change with the displacement of the pistons, and the information about objects in the workspace is built in virtual space according to the data obtained by the vision sensor.

Simple grasping experiments were conducted to verify the effectiveness of the control method by using a block of sponge foam (approx. 330 mm × 160 mm × 200 mm), a tire (approx. Φ490 mm), and a concrete block (approx. 300 mm × 150 mm × 200 mm). The parameters d_t and f_{st} in Fig. 5 are determined by trial and error using these three objects. We set d_t = 0.02 m and f_{st} = 2 KN to carry out the experiment.

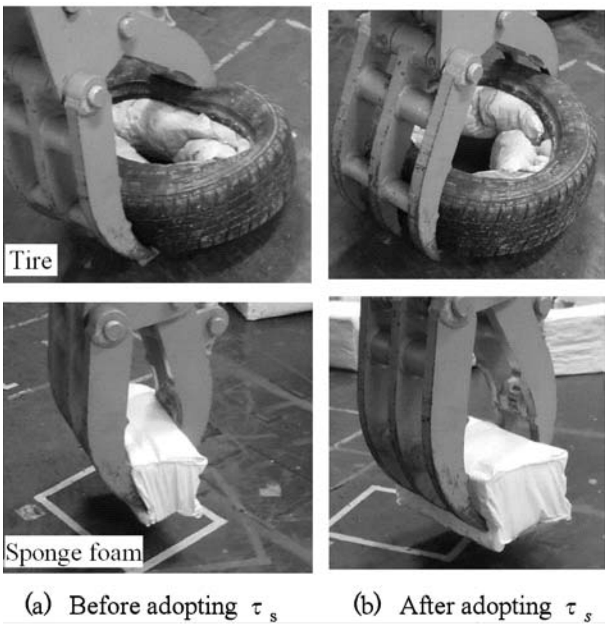
First, a simple grasping experiment was conducted to reveal the results of adopting a noticeable τ_s. The operator slowly grasped a tire and a sponge foam block, moving the joystick to the intermediate position while feeling the reaction torque. The results of images of the fork glove and objects obtained by digital camera are shown as Fig. 8.



(a) The objects placed at robot's side

(b) The objects placed at robot's side in virtual space

Fig. 7: *Visual prompting according to k_{tm} in virtual space*



(a) Before adopting τ_s (b) After adopting τ_s

Fig. 8: *A comparison of deformation before and after adopting τ_s*

After adopting τ_s, the operator felt the reaction torque while the soft objects were grasped lightly, and the deformation was indistinguishable to the naked eye. It is helpful for the operator to perceive the situation of the fork glove and objects in the initial stage of grasping objects, and it is helpful for teleoperation when very soft objects are conveyed with deformation required which must not be deformed. Our control system overcame the problems of operator misperception and provided the operator with a noticeable sense of reaction force in the initial stage of grasping.

We next conducted a grasping experiment by conventional control and improved control using a concrete block, a tire, and a sponge foam block. For comparison, a mark was used as a superscript (e.g., f'_s, T'_r) to indicate the experimental data obtained by conventional control. T'_r was calculated based on Eq. 2, but T_r was calculated based on Eq. 5. The corresponding experimental results are shown as Fig. 9 and 10.

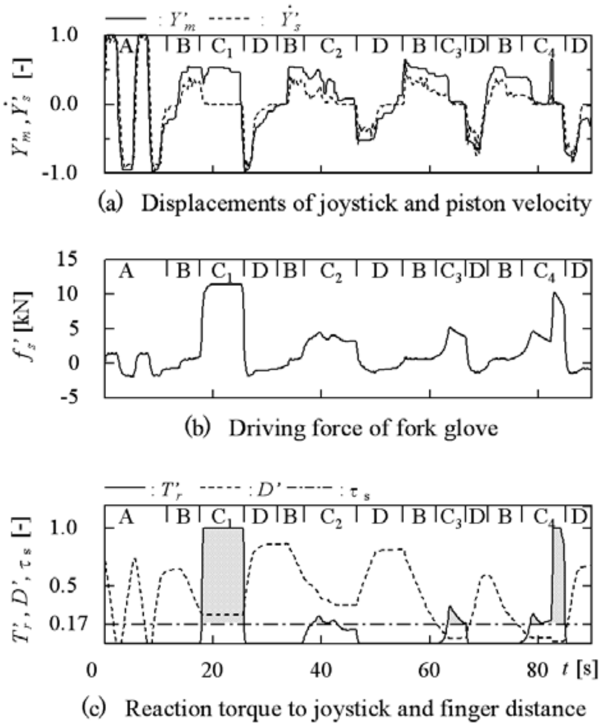


Fig. 9: *Grasping a concrete block, tire, and sponge foam block by conventional control*

In Fig. 9 and 10, A expresses moving the joystick in free space; B explains moving the joystick to grasp the objects; C_1, C_2, and C_3 describe grasping the concrete block, tire, and sponge foam block, respectively; C_4 describes the stepwise grasping of the sponge; and D expresses releasing the objects. In Fig. 9(c) and 10(c), the solid line expresses T_r. The broken line (D) is the non-dimensional quantity of the finger distance, d, which is calculated by the geometric relationship between d and the piston displacement, y_s. The smaller D is, the greater the contraction of the fork glove. The dot-dash line is the noticeable τ_s, which expresses a threshold of human perception. Humans can perceive the reaction torque only when it exceeds τ_s in our master-slave system (the shadow area in Fig. 9(c) and 10(c)).

In the experiment, the operator first moved the joystick in free space without grasping anything, and then grasped a concrete block, a tire, and a sponge foam block one by one until the operator felt the reaction torque. Last, the operator conducted a stepwise grasping of the sponge foam block until the maximum reaction torque could be felt.

In Fig. 9(c), since the hard object cannot be compressed during grasping (D' about 0.24), the driving force increases quickly in C_1 (f'_s about 11KN), and then the reaction T'_r changes quickly and peaks. The operator feels the reaction torque immediately when the concrete is completely grasped ($d^* - d' = 11$ mm, $f'_s - f_s^* = 8.5$ KN). The changes of T_r and D in Fig. 10(c) are the same as in Fig. 9(c).

When grasping the tire (C_2), the operator feels the feedback force while T'_r occurs and changes to 0.17 in Fig. 9(c) (d^* - d' = 75 mm, f'_s - f_s^* = 2.4 KN). At the same time, D' is about 0.35 and f'_s is about 3.8 KN. If we only consider the experimental data and neglect human perception, T'_r in Fig. 9(c) naturally expresses a very good experimental result. However, the operator cannot feel the feedback force, which is less than τ_s. After introducing a noticeable τ_s, when the operator perceives the T_r, D is about 0.55 and f_s is about 2.0 KN in Fig. 10(c) (d^* - d = 20 mm, f_s - f_s^* = 0.5 KN). The greater τ_s helped the operator to quickly feel the reaction torque, enhancing the operator's perception so that it matched the experimental data in the initial stage of grasping.

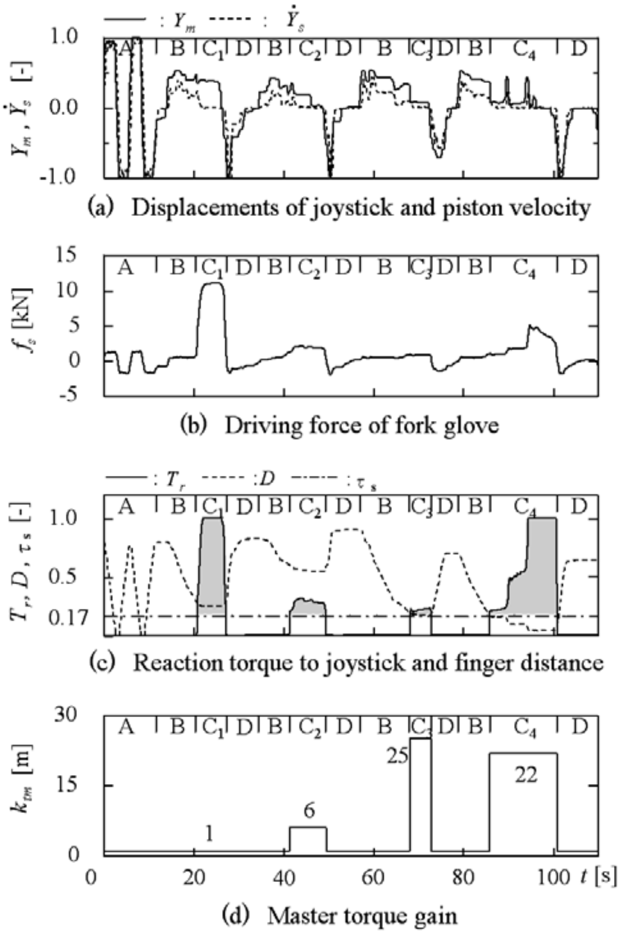


Fig. 10: *Grasping a concrete block, tire, and sponge foam block by improved control*

This function is more obvious while grasping a sponge foam block. When the operator feels the reaction torque, D' is about 0.05 and the block is almost completely crushed (d^* - d' = 98 mm, f'_s - f_s^* = 2.9 KN). In contrast, D is about 0.19 when the operator feels the reaction torque after introducing τ_s (d^* - d = 20 mm, f_s - f_s^* = 0.16 KN). The state of the fork glove and grasped object with improved control is shown as Fig. 8(b).

C_4 is the task of stepwise grasping of the sponge foam block, which is almost completely grasped when the operator feels T'_r. The sponge foam is completely crushed in the following stepped grasping. At this time the sponge foam is just like a hard object, so f'_s and T'_r rapidly increase in Fig. 9. In contrast, T_r describes a stepwise change, until about the 95 s mark, when the sponge foam is completely crushed, by adopting the variable gain k_{tm}.

When the task object is almost completely crushed, though the driving force changes slowly, T_r can become the largest value, 1, to provide the condition of the object for the operator. T_r appears to give satisfactory results.

Corresponding to Fig. 10(d), k_{tm} is 5 in the process of C_2, 25 in the process of C_3, and 22 in the process of C_4. The change is consistent with the k_{tm} algorithm. The experiment verified that the object is softer and k_{tm} is larger and k_{tm} is valid. Moreover, since the grasping speed and the gestures of the arm and fork glove vary, T_r cannot have the same value at every turn, and then k_{tm} varies, too.

In C_1, C_2, C_3, and C_4, the operator feels the actual force from the fork glove only, which coincides with the actual external force applied to the fork glove. The operator can distinguish between soft and hard objects by the reaction torque. For a very soft object, e.g., a sponge foam block, the operator also can identify the task object by the stepwise reaction change and visual prompting rather than only perceiving the reaction torque. Improved control is effective for grasping hard objects and soft objects.

Finally, a questionnaire survey about the improved control yielded the following conclusions:

- It is easy for an operator to perceive the moment that the reaction torque appears in the initial stage of grasping by improved control.
- It is helpful to perform the subsequent operation by introducing visual prompting based on k_{tm}.
- For a very soft object, it is useful to perceive the condition of the fork glove and task objects by adopting k_{tm} to magnify the reaction torque.

6 Conclusion

In a teleoperation construction robot, the operator must reasonably feel a sense of force coming from the fork glove. To overcome the lack of a noticeable and reasonable sense of reaction force when grasping a very soft object by conventional control, we enhanced and magnified the reaction force to develop a variable-gain velocity control, which can provide the operator with a noticeable sense of reaction force that harmonizes with the experimental data and a reasonable sense of reaction force variance changing with the deformation of object.

We experimentally verified that this control method improves operations. First, we verified the validity of τ_s by comparing the images of a fork glove and the objects obtained in grasping experiments. Next, we used a concrete block, a tire, and a sponge foam block as task objects that the operator grasped at a slow velocity. The experimental results confirmed the validity of τ_s and variable-gain k_{tm}. The results of a questionnaire survey suggest that the improved control is better than conventional control for soft object recognition by force feedback.

The proposed control reasonably presents the sense of force during slow grasping of a soft object, improves the performance of the construction robot manipulability, and extends the perceptible range of the construction robot grasping task. The results of the experiments demonstrate the feasibility of our proposal.

As a future work, we will conduct an operability evaluation experiment to verify the effectiveness of the control method in an actual task by behavioral measures (work efficiency and indexes expressing the danger level of an operation), subjective measure (measurement of mental strain using National Aeronautics and Space Administration Task Load Index), and physiological measure (measurement of physiology strain using heart rate variability).

Nomenclature

a_c, a_r	Cap and rod side of the cylinder's area	[m^2]
b	Viscous damping coefficient of piston	[Ns/m]
d	Distance from the tip of the front fork to the tip of the back fork [-0.135,0.76]	[m]
d^*	The last moment's d before T_r appears in the process of grasping an object	[m]
d_t	Threshold of soft object judgment	[m]
D	Non-dimensional quantity of d (= d / -0.135 in the negative direction; = d / 0.76 in the positive direction)	[-]
f	Sum of extraneous forces acting to the piston (except viscous friction and driving force)	[N]
f_{pre}	Threshold driving force for feedback regarding the reaction force	[N]
f_s	Slave force	[N]
f_s^*	Last moment's f_s before T_r appears in the process of grasping an object	[N]
f_{st}	Threshold of hard object judgment	[KN]
k_{pm}	Master proportional gain	[Nm]
k_{tm}	Master torque gain	[m]
m	Mass of the piston	[kg]
p_c, p_r	Cap and rod side of the cylinder's pressure	[Pa]
p_s	Hydraulic pressure supply	[Pa]
T	Master overall gain	[-]
y_m	Master displacement	[m]
y_{0m}	Standard master displacement ($y_{0m} = 0.06$)	[m]
Y_m	Non-dimensional quantity of y_m ($= y_m / y_{0m}$)	[-]
$y_s, \dot{y}_s$	Slave displacement/velocity	[m], m/s]
y_{0s}	Standard slave displacement ($y_{0s} = 0.3$)	[m]
$\dot{y}_{0s}$	Standard slave velocity ($\dot{y}_{0s} = 0.1$)	[m/s]
Y_s	Non-dimensional quantity of y_{0s} ($= y_s / y_{0s}$)	[-]
$\dot{Y}_s$	Non-dimensional quantity of $\dot{y}_s$ ($= \dot{y}_s / \dot{y}_{0s}$)	[-]
τ_m	Input torque (force) to joystick	[Nm]
τ_r	Reaction torque (force) to joystick while grasping an object	[Nm]
τ_s	Noticeable reaction torque (force) to joystick ($= 0.17 \times \tau_{0r}$)	[Nm]
τ_{0r}	Standard reaction torque to joystick ($\tau_{0r} = 0.57$)	[Nm]
T_g	Non-dimensional torque for k_{tm} calculation	[-]
T_r	Non-dimensional reaction torque (force) to joystick ($= \tau_r / \tau_{0r}$)	[-]

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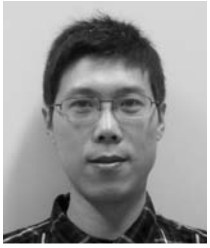

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