OPERABILITY OF A CONTROL METHOD FOR GRASPING SOFT OBJECTS IN A CONSTRUCTION TELEOPERATION ROBOT TESTED IN VIRTUAL REALITY

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Abstract

The purpose of this research was to evaluate an operation system that includes a control method of feedback previously proposed by our lab, in a virtual reality setting. Specifically, we examined a master-slave control system for a teleoperation construction robot. The master comprises two joysticks adopted to manipulate objects from a remote location, and the slave corresponds to an excavator with four degrees of freedom, regarded as a construction robot. The authors previously proposed a control method to provide an operator with a realistic sensation of grasping by introducing a noticeable reaction torque to the joystick's handling and a variable master torque gain according to an object's hardness when the robot moves slowly to grasp a soft object. In this research, an operability test was conducted when the control method was introduced to actual tasks, including grasping, conveying and classifying tasks using concrete blocks and sponge foam blocks. Measurement of mental strain using NASA-TLX and measurement of physiology strain using heart rate variability were recommended as evaluation methods in addition to the use of task efficiency and danger indices. According to statistical analysis of the experimental results, we verified that the control method used in the operation system could contribute to improving efficiency and safety during teleoperation work as well as alleviating the operator's mental fatigue and stress.

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

1 Introduction

A teleoperation system enables a human operator to implement given tasks in a remote manner or enhance his/her capability to handle both the macro and the micro worlds. Such a system's various applications can be found in fields as diverse as space exploration, nuclear reactor operations and underwater operations (Hung, et al. (2003)). Other potentially applicable areas are in construction, forestry, mining, disaster sites and many others. Because the site information that can be gathered with visual feedback is limited in a teleoperation system, it is important to supply an operator with a realistic sense of force or force feedback for safe, steady and high-level teleoperation work. Such force feedback in addition to visual feedback is especially crucial in cases where a soft object could be completely crushed by a manipulator.

In our lab, an excavator modified with a fork glove in the front end as a hand for grasping task objects is applied as a construction robot in the slave system, and two joysticks are introduced to operate the construction robot from a remote place in the master system. In the master-slave control system, the authors proposed control methods by which the operator could feel a realistic sense of task force generated from the feedback force of the fork glove (Kato (2002, 2003), Yamada (2000, 2003)). However, the operators found moving the joystick by position-position control to be strange, because the most commonly used control for excavators sold in the market is position-velocity control. A variable-gain velocity control (conventional control), in which velocity is used as feedback instead of the position of the piston, has therefore been proposed (Yamada, et al. (2006)).

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. Pres-

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sure sensors are easily influenced by the effect of friction and cyclic loading, and the operator's perception of change in the reaction force is reduced, particularly while grasping a foam block. For example, a disadvantage in conventional control was that the operator felt the task force only when an object softer than a tire, i.e., a sponge foam block, was almost completely crushed at a low speed. However, the sensitivity of pressure sensors has eliminated this disadvantage by providing an improved variable-gain velocity control (new control), to which a noticeable reaction torque to the joystick and a variable master torque gain in terms of the object's hardness have been introduced (Lingtao, et al. (2012)).

Since it is easy to change the visual information provided to the operator about the construction robot, its environment, and objects in virtual space, and since the use of virtual reality can solve the problem of a camera's blind spot, we set up a master-slave operation with the new control method in a computerized virtual environment as the primary method of visual prompting, and real images obtained by a USB camera as the secondary method of visual prompting. In addition, we varied the virtual visual information with the situation between the construction robot and the environment or the objects, to enable precise and safe teleoperation work.

To verify that the new control method could contribute to improving the operation and reducing the strain on the operator in the operation system while grasping soft objects in an actual task, we first examine the master-slave control, then describe the master-slave operation system, and then explain our experimental method, including grasping, conveying, and classifying tasks as well as an evaluation method comprising the measurement of mental strain using NASA-TLX and the measurement of physiology strain using heart rate variability in addition to work efficiency and danger indices. Finally, we discuss the experimental results obtained by applying the above-mentioned evaluation method. We also present our statistical analysis, in which we verify the validity of the experimental data.

We expect that the new control method for grasping soft objects could improve the operability in construction robot teleportation, since the control method shortens the operation time for judging object-types in the grasping process.

2 Master-Slave Control

Figure 1 is a schematic diagram of the experimental apparatus used in this research. The system comprises two joysticks (Side Winder Feedback 2 manufactured by Microsoft Co., Ltd.) as the master, a construction robot (a commercially available backhoe modified based on Hitachi LandyKID-EX5) as the slave, and a personal computer that is introduced to mange the system by master-slave control. The joysticks enable forward/reverse and right/left movement. Joystick displacements are detected by position sensors. To 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, two DC motors are installed in each joystick. In this system a robot arm with four degrees of freedom is used. Manipulating the joysticks in four directions can operate the hydraulic cylinders (the fork glove, swing, boom, and arm) driving the construction robot. Hydraulic cylinders are controlled by proportional valves. Cylinder displacements are detected by magnetic stroke sensors, which are embedded in the pistons. Pressure sensors are installed on the rod side and cap side of each cylinder for detection of the load pressure. These pressure signals can be used to calculate the reaction force to the joysticks in the master-slave control.

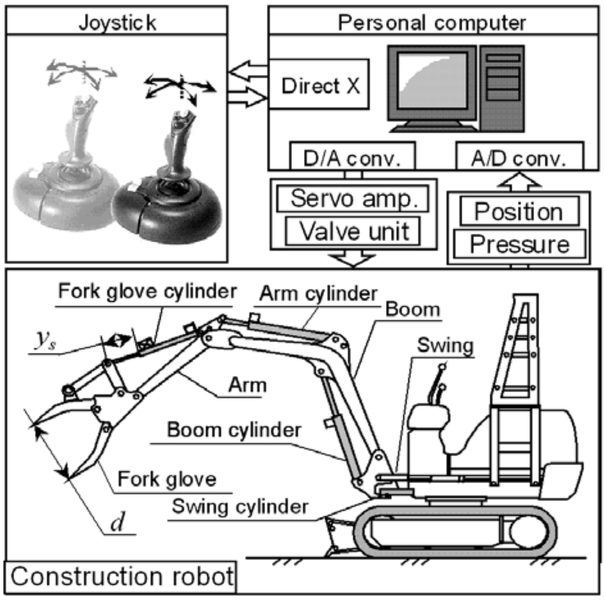


Fig. 1: *Schematic diagram of the experimental apparatus*

The above-mentioned conventional control and the new control are both master-slave control methods. However, the new control method provides the operator with a realistic force sense of grasping from the fork glove, during grasping not only a hard object but also a very soft object, i.e., a sponge foam block. The features of the new control method are briefly described as follows:

(1) A variable threshold driving force, f_{pre}, of the reaction torque to the joystick, τ_r, is introduced, which changes continuously in terms of the actuator drive condition using measured velocity-driving force characteristics.

(2) An offset value, τ_s, is adopted in the new control method to supply the operator with a realistic feeling of force, even though feedback reactions from external force are very small in the beginning of slowly grasping a very soft object.

(3) A variable parameter, k_{tm}, to magnify the reaction from the driving force ensures that the reaction torque to the joystick significantly appears in a step-by-step relation to the increasing driving force, during slow grasping of a soft object.

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 (2003)) during the grasping process can be expressed by

$$m\ddot{y}_{\rm s} + b\dot{y}_{\rm s} + f = f_{\rm s}$$
$$f_{\rm s} = a_{\rm c} p_{\rm c} - a_{\rm r} p_{\rm r} \quad (1)$$

Actually, the driving force f_s is just the pressure force, as described by Eq. (1)-bottom; then, f_s relates to the sum of extraneous forces f, as defined by Eq. (1)-top.

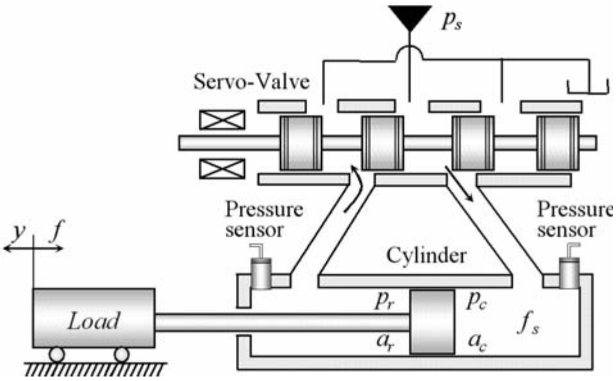


Fig. 2: *The reaction forces in the cylinder*

The force feedback to the joystick, which is expressed by the reaction torque, τ_r, is composed of three items; one depends on the deviation between the position of the joystick and the velocity of the piston (non-dimensional quantities $\dot{Y}_s$ and Y_m), the second one depends on f_s, and the last one is the noticeable reaction torque, τ_s. τ_r occurs when the non-dimensional master overall gain, T, is more than zero, i.e., when the fork glove is grasping an object. τ_r and T are defined by

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

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

Here, $f_{\rm e\_max}$=11.7 kN and $f_{\rm c\_max}$=-6.8 kN. $f_{\rm pre}$, which derives from the velocity of piston and driving force characteristic, denotes the threshold of the driving force when the piston is moving in free space (never reaching the limit position) without grasping anything (Lingtao, et al. (2012)). Gain T depends on threshold $f_{\rm pre}$, as defined in Eq. (3). If the driving force, $f_{\rm s}$, exceeds the threshold driving force, $f_{\rm pre}$, the deviation between these two values is regarded as an external force on the fork glove caused grasping an object, and corresponding reaction torque to the joystick is generated. The master torque gain is defined as follows:

$$k_{tm} = \begin{cases} 1 & \text{(Hard object)} \\ round(0.04/T_r) & \text{(Soft object)} \end{cases} \quad (4)$$

$k_{\rm tm}$ is a variable parameter depending on the type of object being manipulated. If the object grasped by the fork glove is a hard object, $k_{\rm tm}$ will be set to 1. If the object is a soft object, $k_{\rm tm}$ will be set to round $(0.04/T_r)$ according to the hardness of the soft object. $T_{\rm r}$ is the non-dimensional reaction force to joystick. Here, d and f_s are used as parameters for judging whether a grasped object is a hard object or a soft object (Lingtao, et al. (2012)). If the amount of $f_{\rm s}$ changes gradually as d decreases, the object is a soft object; if the amount of $f_{\rm s}$ changes rapidly as d decreases, the object is a hard object. Otherwise, the grasped object cannot be judged and the comparison continues. The type of the grasped object is determined, and then $k_{\rm tm}$ is obtained.

An offset value, $\tau_{\rm s}$, is introduced to provide the operator with a realistic sense of the reaction force, even though feedback reactions from external force are very small while grasping a soft object. The operator handles two joysticks to move left and right slowly, and at the same time reaction torque is exerted to one of the two joysticks at a small fixed step by the computer, to simulate the actual force from the slave, until the operator feels the reaction. Five data series were recorded, and the mean was 0.0969 Nm ($0.17\times\tau_{0\rm r}$), which was introduced as the value of $\tau_{\rm s}$.

Compared with Eq. (2), the differences from calculating the force feedback to joysticks with conventional control are that the value of $k_{\rm tm}$ is constant and there is no $\tau_{\rm s}$.

Figure 3 illustrates the master-slave control in which the new control method is used. The operator operates the joysticks to control the construction robot by feeling the reaction force calculated as described above, as well as seeing the virtual and real images built in the master-slave operation system.

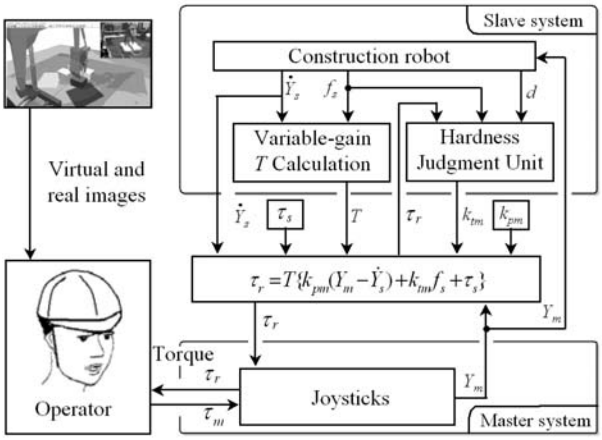


Fig. 3: *Master-slave control in the new control method*

3 Master-Slave Operation System

The master-slave operation system (Fig. 4) consists of three computers (PC 1~3), and PC 3 is connected with PC 1 and PC 2 by the TCP/IP (Transmission Control Protocol/Internet Protocol) model.

3.1 Construction Robot Side

The construction robot side comprises PC 1, which is introduced to manage the master-slave system for the construction robot and the joysticks, and PC 2, which is adopted to process the image of the construction robot side obtained by the USB camera and vision sensor. The vision sensor is a 3D digital camera (ColorDIGI-

CLOPS, manufactured by Point Grey Research, hereafter DICICLOPS), which can obtain three-dimensional images. To obtain a three-dimensional image of the entire workspace, DIGICLOPS is installed about 2 m above the construction robot. The information about objects placed in the workspace, such as position, color, shape, and size, are calculated by processing the three-dimensional image of the entire workspace. To easily calculate the size of objects (especial the height), DIGICLOPS is established to hold the photographic plane parallel to the ground. Since there are some deviations between objects built in virtual space and those placed in the workspace, we obtained real images with a USB camera located at an angle to the right of the construction robot as an aided approach to provide information about the workspace to the operator.

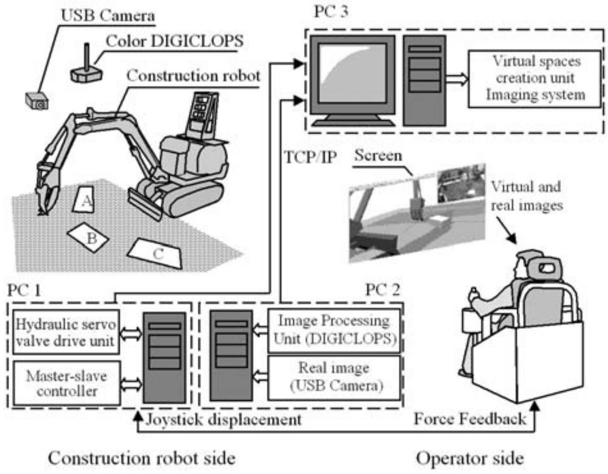
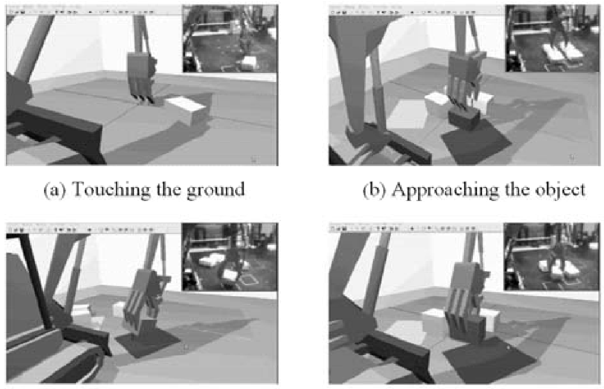


Fig. 4: *Schematic diagram of the master-slave operation system*

3.2 Operator Side

The operator side consists of PC 3, which provides the operator with the visual information, joysticks, a screen, and the images obtained by the USB camera and built in virtual space. The basic model of virtual space built by PC 3 comprises the robot model built according to the drawings of the construction robot in the slave system, and the ground model. To present the information about objects in the workspace and the construction robot's posture in the virtual space, PC 3 receives information about the displacement of the construction robot's cylinder and the objects in real time via the network with PC 1 and PC 2, and it also receives the real image obtained by the USB camera. The operator moves the joysticks to operate the construction robot as guided by visual information and the reaction force calculated in the master-slave control system.

To enable precise and safe teleoperation work, the supplementary information is appended to virtual space in the master-slave operation system. Since a color change is able to immediately and directly prompt the operator, the color change is introduced as a presentation method for supplementary information in virtual space in this research. For example, as shown in Fig. 5, (a) is the case in which the ground's color changes to red when the construction robot touches the ground; (b) shows the situation where the object's color changes to blue when the construction robot stays above the object and approaches the object, and while the smallest distance between the tip of the fork and the object is less than a threshold; and (c) and (d) express the cases in which the object's color changes to red and purple, respectively, while the construction robot is grasping a hard and a soft object, respectively. We believe this method avoids having the construction robot fall into an unstable situation.



(a) Touching the ground (b) Approaching the object

(c) Grasping a hard object (d) Grasping a soft object

Fig. 5: *Supplementary information in virtual space*

4 Experimental Setting

4.1 Experimental Method

The experiments of grasping, conveying, and classifying concrete (approx. 300 mm × 150 mm × 220 mm, 8.6 kg) or sponge foam blocks (approx. 300 mm × 160 mm × 210 mm, 0.8 kg) placed in the construction robot side were conducted in this research. When the operators judged object's types, the objects were placed on the work field and the fork glove grasped the objects almost in an upright position. Therefore the influence of the fork glove's gravity and the object's gravity on the force feedback can be omitted in the judging process.

(a) Task 1 (Grasping)

Initially, one sponge foam block is placed on A in Fig. 4. To easily calculate the experimental time, we set the fork glove's color to blue, while the non-dimensional quantity of the fork glove's displacement, Y_s, is less than 0.4. Y_s increases in the process of grasping. The starting time of a grasping is the moment that the fork glove's color changes from blue to its original color. The operator controls the construction robot to slowly grasp the block. The fork glove is opened when the operator feels the reaction force in the process of grasping the object, and it stays open until the fork glove's color changes to blue (the finishing time of grasping). This grasping operation is repeated 10 times.

(b) Task 2 (Conveying)

Initially, two sponge foam blocks are placed on A and C in Fig. 4, respectively. First, the block on A is conveyed to B; second, the block placed on C is conveyed to A; finally, the block on B is conveyed to C. This series of tasks is performed twice.

(c) Task 3 (Classifying)

Initially, two sponge foam blocks and two concrete foam blocks are arranged at B in Fig. 4. The blocks are covered in white tape, so it is impossible to distinguish them by their appearance. The operator must distinguish between the soft objects and hard objects based on the reaction force to the joystick and then convey hard objects to A and soft objects to C.

4.2 Evaluation Method

The evaluation method used to verify the effectiveness of the new control method in the operation system is described in the following sections.

4.2.1 Behavioral Measures

Behavioral measures describe mainly the task performance. In this research, task efficiency and danger indices are used as behavioral measures and explained as follows:

(1) Task efficiency

The number of blocks conveyed and arranged per unit of time (Obj. / min) is used as an index of task efficiency. To minimize the effect of familiarity with the conditions, time compensation is adopted in this research. Because the experiment was carried out at low speed grasping, grasping time of fork glove was dominant ratio in the experiment time, and we regarded the speed of the fork glove as a standard. The average speed of the fork glove is $v_o = Y_o / t_o$ and $v_n = Y_n / t_n$ by using conventional control and new control, respectively. The compensated experiment time t_s, is calculated by $t_s = t_o \times v_n / v_o$. t_o and t_s are introduced as the experiment time to calculate task efficiency by the conventional control and the new control, respectively.

(2) Danger indices

The danger indices used in this research are the contact time, t_c, and the average force, F_c, generated by the boom, arm, and swing of the construction robot while the construction robot continues work in an unstable condition. This unstable condition occurs in cases where the fork glove forcibly presses the ground or the other drive axis is operated while the construction robot is working in a pressing condition, which frequently occurs during the process of grasping the task object.

According to the law of action-reaction, the excess force generated by the piston while the robot is in unstable conditions can be treated as an external force individually acting on the piston. Therefore, the excess forces generated in each cylinder can be expressed as a non-dimensional quantity by introducing the above-mentioned gain, T, and a generated force, F, is obtained as the sum of these individual forces. A threshold is set for F, and the conditions that exceed the threshold are regarded as unstable conditions. The generated force F_t is obtained as the sum of these excess forces generated in each cylinder above the set threshold, and the contact time, t_c, can be obtained as the sum of the times in unstable conditions. The average force, F_c, is obtained by dividing F_t by t_c.

4.2.2 Subjective Measure

The best-known methods of mental strain evaluation are SWAT (Subjective Workload Assessment Technique (Reid and Nygren (1988)) and NASA-TLX (NASA Task Load Index (Hart and Staveland (1988)). Because Nygren (1991) suggested that NASA-TLX is superior to SWAT according to sensitivity especially for low mental workloads and introduction of NASA-TLX is comparatively easy, NASA-TLX is introduced as the measurement of mental strain in this research.

NASA-TLX comprises 6 criteria: mental demand (MD), physical demand (PD), temporal demand (TD), own performance (OP), effort (EF), and frustration level (FR). The procedure of NASA-TLX is as follows: 1) a pairwise comparison test; 2) execution of an evaluation experiment; 3) evaluation of each criterion. The evaluation scores for 6 criteria and the mean weighted workload (WWL) score, which is recommended as a result of evaluation of workload by the NASA-TLX technique, are assigned and calculated.

4.2.3 Physiological Measure

The physiological responses such as heartbeat, brainwave, respiration, and peripheral skin temperature change when human beings bear a mental burden. Heart rate variability among them is considered to accurately reflect the mental burden. The R-R interval is the inverse of heart rate, and its value derived from electrocardiogram waveforms shows large fluctuation under the resting state and small fluctuation in a tense and agitated state.

To capture the motion of the heart based on electrocardiogram waveforms, coefficient of variation of the R-R interval, $CV_{\text{R-R}}$, is adopted as the physiological measure in this research. $CV_{\text{R-R}}$ expressed by standard deviation (SD)/mean appears as a large value under resting state and a small value in a tense and agitated state (Toichia, M. et al., 1997). In addition, due to $CV_{\text{R-R}}$ changes with age and individual, a normalized $CV'_{\text{R-R}}$ based on Eq. (5) is recommended as the physiological measure in this research.

$$CV'_{\text{R-R}} = \frac{CV_{\text{R-R}} - CV_{\min}}{CV_{\text{R-R}} - CV_{\max}} \tag{5}$$

Here, $CV_{\max}$ and $CV_{\min}$ express the extremum of $CV_{\text{R-R}}$ measured under the resting state and tense state, respectively.

4.2.4 Statistical Analysis

Ten males with a mean age of 25.8 years (range from 22 to 33 years) were enrolled in this research. Descriptive statistics expressed as the mean ± SD described the main features of the experimental data obtained by evaluation methods. Results of the evaluation methods before and after using the new method are compared by using paired t tests (p values < 0.05 are regarded as statistically significant), which is generally used when measurements are taken from the same subject before and after some manipulation (Paulo, et al. (2010)). The degree of freedom for the sample is 9.

According to Student's t distribution, the probability that t is less than 2.262 is 90 % ($t(9) = 2.262$, $p = 0.05$) for a two-tail test. If $t(9) > 2.262$, $p < 0.05$, it is considered that there is a significant difference between the means of the two variables obtained in this research, the experimental data are not accidental data, and the new control method plays a role in the measurement.

5 Experiment

5.1 Grasping experiment

Before performing the evaluation experiment described in Section 4.1, a simple grasping experiment is introduced. The experimental results of grasping a piece of sponge foam (approx. 350 mm×160 mm×240 mm) and a concrete block are shown as Fig. 6.

Figure 6(a) shows the change over time in the displacement of the joystick, Y_m, and the non-dimensional quantity of the fork glove's velocity, $\dot{Y}_s$. A_1 and A_2 show grasping of the sponge foam and concrete, respectively. Figure 6(b) reveals the change in the driving force, f_s, of the fork glove. f_s increases in steps accompanying the sponge foam grasping operation, reaches a large value at about 42 s in A_1, and then reaches a peak quickly in A_2. Figure 6(d) expresses the feedback force, T_r, and the non-dimensional quantity of the fork glove's displacement, Y_s. In A_1, the reaction force, T_r, shows a stepwise change, as the fork glove grasps the sponge foam step-by-step, until at about 42 s the sponge foam is almost completely crushed. Though the driving force on the fork glove changes slowly, T_r can become the largest value, 1, to provide feedback on the condition of the object with the operator. We therefore concluded that the master-slave control method is available for handling the majority of soft objects in practical use. A_2 is the task of grasping concrete, in which the reaction force to the joystick changes quickly and peaks corresponding to the reaction force. In Fig. 6(c), k_{tm} is 38 in the process of A_1 and 1 in the process of A_2. The change is consistent with the k_{tm} algorithm.

The experiments described in Section 4.1 were conducted to verify the effectiveness of the new control method in the operation system. Before starting the operational evaluation experiment, we first briefed the subjects regarding the operation of the construction robot, and they then had sufficient practice performing the operations. The experiment was carried out after the subjects were familiar with the operation of the construction robot. The results of behavioral measures are explicitly described in the following section. Finally, statistics are used to describe the main features of the experimental data quantitatively, and a paired t test was conducted to determine whether the difference of measurements was due to an effect of the new control method or just a coincidence of random sampling. "Constant" and "Variable" shown in the results implies the experimental methods of the conventional control and new control, respectively.

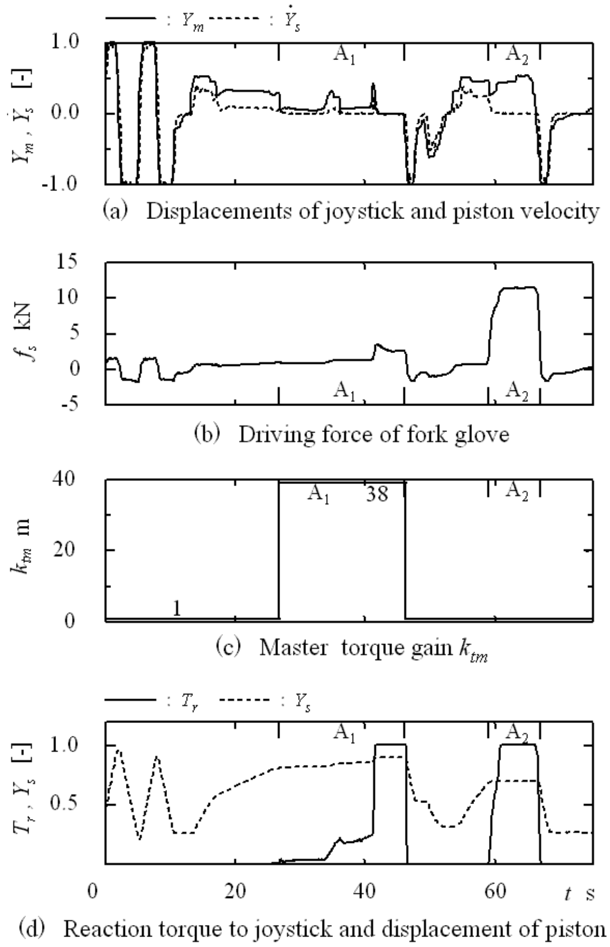


Fig. 6: *Grasping a piece of sponge foam and a concrete block*

5.2 Behavioral Measures

Task Efficiency

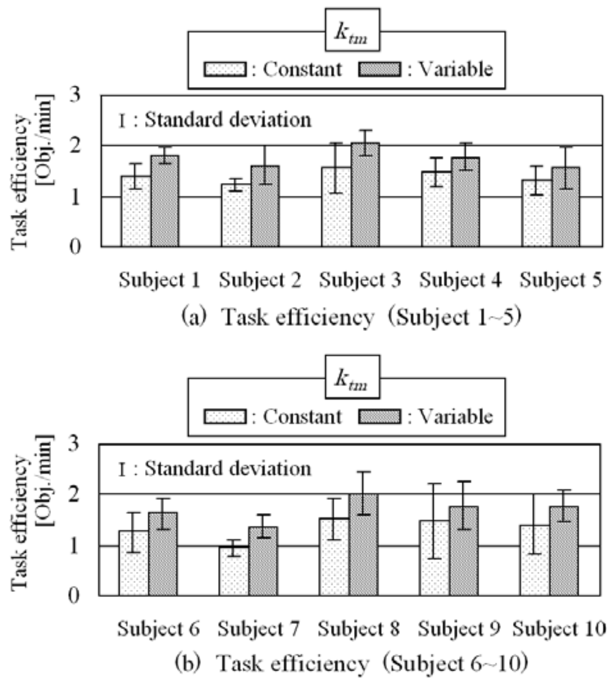


Fig. 7: *Task efficiency in behavioral measures*

Figure 7 explains the task efficiency results for all subjects. The task efficiency signifies the average of the three types of task described in Section 4.4. The standard deviation defines a standard deviation of the efficiency for each task. I.e., the standard deviation indicates a variation in efficiency between the three types of task. In this figure, the horizontal axis shows the subjects, and the vertical axis shows the task efficiency expressed by [Obj./min]. The larger the values in the vertical axis are, the higher the task efficiency. According to this figure, task efficiency has been clearly improved by the new control method. The effectiveness of our proposed control method is verified by task efficiency.

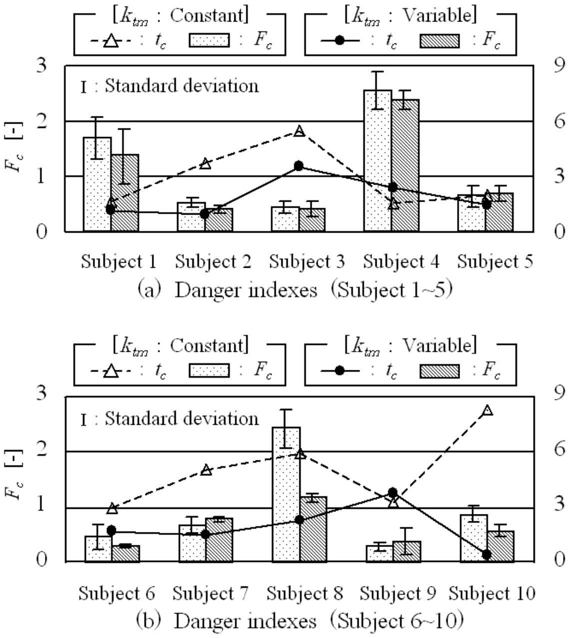


Fig. 8: *Danger indices in behavioral measures*

(2) Danger Indices

The results of danger indices, the contact time, t_c, and the average force, F_c (non-dimensional quantity [0 - 10], 1 corresponds to 0.057 Nm) are shown as Fig. 8. The right vertical axis shows the contact time, t_c, while the construction robot is in unstable conditions; the left vertical axis represents the average force, F_c, generated by actuators during t_c. The smaller values of t_c and F_c indicate safer conditions. The difference in F_c by the two methods was very small, and hence no meaningful difference brought by use of the new control method was found, but t_c was evidently decreased by use of the new control method, based on Fig. 8. We believe this difference was caused by one of the following two points:

(1) As a result of applying supplementary information in virtual space with the new control method, the construction robot does not fall into an unstable state.

(2) The unstable conditions can easily occur in the process of grasping a task object. Because the period during which the operator perceives the feedback reaction from the fork glove by the new control method in the process of grasping the task object is shorter than that by conventional control, the construction robot falls into unstable conditions less often when the new control method is employed. Therefore, the operator can intuitively perceive the construction robot's situation and the safety of the teleoperation work is improved by the new control method.

5.3 Subjective Measure

The results of the mental strain evaluation using NASA-TLX are shown in Fig. 9. Because NASA-TLX is a subjective evaluation method, evaluation criteria and evaluation scores vary greatly depending on the subject. Because the 10 subjects' evaluation scores of 6 criteria and WWL are basically identical, the criteria results of subject 5 and subject 8 as typical examples are shown as Fig. 9(a) and Fig. 9(b), and the results for WWL are shown as Fig. 9(c) and Fig. 9(d). The lower the scores of the 6 criteria and WWL, the lower the mental strain. In Fig. 9(a) and Fig. 9(b), the triangles (Δ) and black circles (●) show the scores for 6 criteria by conventional control and the new control method, and the scores for most individual items are lower with the new control. In Fig. 9(c) and Fig. 9(d), the scores for WWL are also lower in the case of the new control. We therefore concluded that the mental strain on the operator will be alleviated with the new control method.

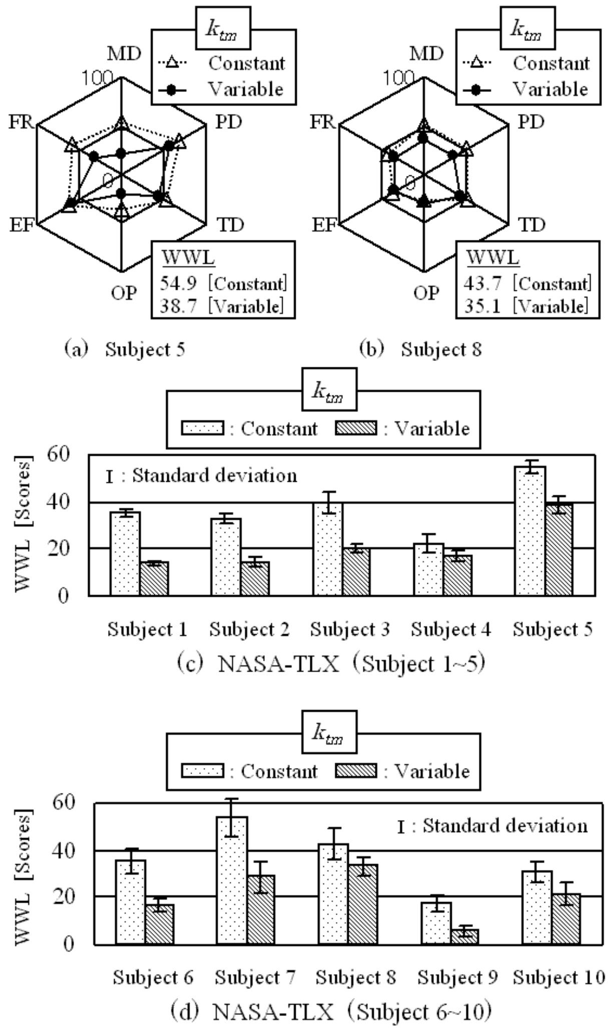


Fig. 9: *NASA-TLX subjective measure*

5.4 Physiological Measure

Figure 10 shows the results of coefficient of variation of the R-R interval, $CV'_{\text{R-R}}$, which shows subjects on the horizontal axis and $CV'_{\text{R-R}}$ on the vertical axis. The lower the values on the vertical axis, the more nervous the subject became. According to Fig. 10, $CV'_{\text{R-R}}$ was slightly increased when the new control method was introduced. We believe the reason for the difference is that with conventional control it takes a long time before the operator feels the feedback reaction force in the process of grasping the task object, and the operator will become more and more nervous until he/she realistically feels the feedback reaction force. The operator's mental strain will therefore be alleviated using the new control method. The effectiveness of the new control method is thus verified by physiological measure.

5.5 Statistical Analysis

The descriptive statistics results of behavioral measures, subjective measure and physiological measure, and the result of the paired *t* test are shown as Table 1. As shown in the table, the results of the various evaluation methods (task efficiency, average force, contact time, NASA-TLX, and coefficient of variation of R-R interval) were all improved after introduction of the new control method. Statistically significant results in task efficiency, contact time, NASA-TLX, and $CV'_{\text{R-R}}$ are revealed according to *p* values. Viewing the situation as a whole, we believe that the experimental data do not represent a coincidence of random sampling, but rather that the difference of the measurements reflects a true difference due to introducing the new control method. The conclusions described in Sections 5.2 - 5.4 are consistent with statistical analysis.

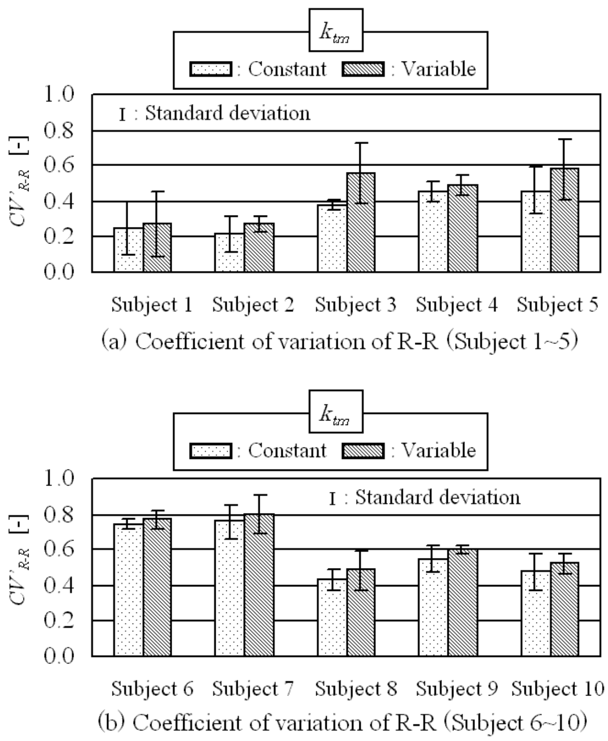


Fig. 10: *Coefficient of variation of R-R as a physiological measure*

Table 1: Descriptive statistics of evaluation and paired t test

	Conventional control mean ± SD	New control mean ± SD	*p*
Task efficiency [Obj./min] A	1.36 ± 0.18	1.88 ± 0.10	$2.0e^{-5}$*
Average force F_c [-] B	1.06 ± 0.85	0.85 ± 0.64	$1.3e^{-1}$
Contact time t_c [s] B	4.02 ± 2.17	1.93 ± 1.10	$3.0e^{-2}$*
NASA-TLX [Scores] B	36.51 ± 11.86	21.09 ± 9.85	$2.3e^{-5}$*
$CV'_{\text{R-R}}$ [-] A	0.47 ± 0.18	0.54 ± 0.18	$2.9e^{-3}$*

A: If the mean value is larger, the result is better.
B: If the mean value is smaller, the result is better.
The *p* value is a non-dimensional value. *: $p<0.05$

6 Conclusions

A master-slave operation system was proposed with virtual reality built in a virtual surrounding system as the primary visual prompting, using a real image obtained by a USB camera as secondary visual information. The virtual visual information can be varied with the information between the construction robot and the environment and objects. Operability experiments were objectively conducted to verify the effectiveness of the new control method in this operation system. Grasping, conveying, and classifying tasks were chosen for the experiments. In addition, due to the high adaptability of human subjects, there are cases where operability cannot be adequately evaluated on the basis of work efficiency or work results alone, and therefore, in addition to the grasping, conveying, and classifying tasks, we also performed the following measurements:

(1) Task efficiency and danger indices were used as the behavioral measures in this research. Task efficiency was evidently improved and the contact time, t_c, was evidently decreased by use of the new control method. The period during which the operator perceived the feedback reaction from the fork glove by the new control method in the process of grasping the task object was shorter than that by conventional control. The efficiency and safety in teleoperation work was therefore improved with force feedback from the fork glove by the new control introduced as the supplementary information for visual information.

(2) NASA-TLX was introduced as the subjective measure in this research. The results of NASA-TLX showed that the mental strain on the operator was decreased by the force feedback from the fork glove in the new control method. The construction robot's working conditions were easily and distinctly perceived with the force feedback by the new control method and the visual prompting. Therefore, it was confirmed that using the new control method could contribute to decreasing the mental strain on the operator.

(3) The coefficient of variation of R-R, $CV'_{\text{R-R}}$, was recommended as the physiological measure in this research. $CV'_{\text{R-R}}$ was increased, indicating that the mental strain on the operator was alleviated by the new control method. The measurement was taken for a short time while the operator felt the feedback reaction force in the process of grasping the task object by the new control method. Consequently, the operator felt more relaxed and the mental strain on the operator was therefore alleviated by the new control method.

Statistical analysis verified the validity of the experimental results, showing that not only did the construction robot perform more safely, but also the mental burden on the operator was alleviated with the feedback force by the new control method. The results of the experiment proved the feasibility and validity of using the new control method in the operation system. Also, the influence of grasped object's gravity in the process of transferring is regarded as our further research.

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Nomenclature

a_c, a_r	Cap and rod side of the cylinder's area	[m^2]
b	Viscous damping coefficient of the piston	[Ns/m]
$CV_{\text{R-R}}$	Coefficient of variation of the R-R interval	[-]
$CV'_{\text{R-R}}$	Normalized $CV_{\text{R-R}}$	[-]
d	Distance from the tip of the front fork to the tip of the back fork [-0.135,0.76]	[m]
f	Sum of extraneous forces acting on the piston (except viscous friction and driving force)	[N]
f_{c_max}, f_{e_max}	Maximum driving force in the contraction/expansion direction	[kN]
f_{pre}	Threshold driving force for feedback	[N]
f_s	Slave force	[N]
F_c	Average force	[-]
p_c, p_r	Cap and rod side of the cylinder's pressure	[Pa]
k_{pm}	Master proportional gain	[Nm]
k_{tm}	Master torque gain	[m]
t_n	Experiment time by new control	[s]
t_o	Experiment time by convention control	[s]
t_s	Compensated experiment time	[s]
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_n	Displacement of fork glove during t_n	[m]
y_o	Displacement of fork glove during t_o	[m]
y_s	Slave displacement	[m]
$\dot{y}_s$	Slave velocity	[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 the joystick	[Nm]
τ_r	Reaction torque (force) to the joystick while grasping an object	[Nm]
τ_s	Noticeable reaction torque (force) to the joystick ($= 0.17 \times \tau_{0r}$)	[Nm]
τ_{0r}	Reference quantity of reaction torque to the joystick ($\tau_{0r} = 0.57$)	[Nm]
t_c	Contact time	[s]
T_r	Non-dimensional reaction torque (force) to the joystick ($= \tau_r / \tau_{0r}$)	[-]
v_n	Average speed of fork glove during t_n	[m/s]
v_o	Average speed of fork glove during t_o	[m/s]

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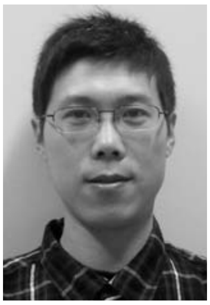

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