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TELEOPERATION OF HYDRAULIC CONSTRUCTION ROBOT USING VIRTUAL REALITY

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ABSTRACT

This research deals with master-slave control of a teleoperated hydraulic construction robot. In this system, the master consists of two joysticks, and the slave is the hydraulic construction robot (including the fork glove, boom, arm, and swing, driven by hydraulic actuators). In a previous research, the authors proposed a force feedback method based on position-velocity control, in which the cylinder velocity is proportional to the position of the joystick. The purpose of this research is to confirm the effectiveness of the force feedback method using behavioral measures and subjective indexes. An experiment was conducted to evaluate operational performance, confirming the effectiveness of the force feedback control system.

KEY WORDS

Key words, Construction Machinery, Robot, Hydraulic Actuator, Master-slave control, Force feedback

INTRODUCTION

The remote operation systems for construction machinery in general use adopt methods that give the operator only visual feedback, which is obtained by cameras mounted on the construction equipment. Naturally, the amount of information regarding the site provided to the operator by such methods is inadequate, and it has been reported that work efficiency is significantly inferior to that in direct operation.[1] In this case, if the operator could grasp various situations to the detailed level from the general condition of the work area, safe, precise work would be possible.

In previous research, the authors studied a master-slave system in which the master consisted of a pair of joysticks and the slave comprised all four actuators (fork glove, swing, boom, arm) of a hydraulic excavator (hereinafter, construction robot), using a position-position control system, in which the cylinder position of the construction robot displayed one-to-one correspondence with positional commands to the joystick. However, general construction machinery employs position-velocity control, in which the cylinder velocity is proportional to the position of the joystick. Therefore, in a previous report [2], we proposed a new master-slave control method (hereinafter, this control method) based on position-velocity control in order to approximate more closely the operating system in actual equipment. In this position-velocity control method, the cylinder velocity is proportional to the position of the joystick. Tests confirmed that accurate force representation was possible by this method.

On the other hand, in ordinary remote operation, there are limits on the number of visual sensors that can be installed at the site and the volume of data that can be transmitted. Furthermore, various factors (attitude of construction robot, change in attitude of front part) which occur during work create dead angles for cameras, making operation difficult and hindering work. It is considered possible to overcome the aforementioned problems of limits on the number of visual sensors and data transmission volume and camera dead angles by introducing an operation system mediated by virtual space constructed in a computer. However, the condition of the actual space and the work must be reflected satisfactorily in the virtual space. It can be assumed that work performed in a virtual space that does not satisfy this requirement will be difficult, like work in real space. Even when using a virtual space with these advantages and drawbacks as visual information, safe and precise work is expected to be possible if a feeling of force can be fed back to the operator, because the operator will be able to grasp the condition of the work intuitively.

Therefore, in this report, the position-velocity control type master-slave control system proposed by the authors was applied to a remote operation system mediated by virtual space constructed in a computer, and its effectiveness was verified from task efficiency, risk measurements, the success ratio, and subjective work load.

TELEOPERATED CONSTRUCTION ROBOT SYSTEM

Fig. 1 shows a schematic diagram of the experimental construction robot using the remote operation/virtual reality system which will be discussed in this paper. As shown in the figure, this system consists of two joysticks, which comprise the master, and a construction robot (Landy KID-EX5, manufactured by Hitachi Construction Machinery Co., Ltd.; weight: 0.5t), which is the slave. The joysticks form a bilateral pair, and can each be operated in the forward/back and right/left directions.

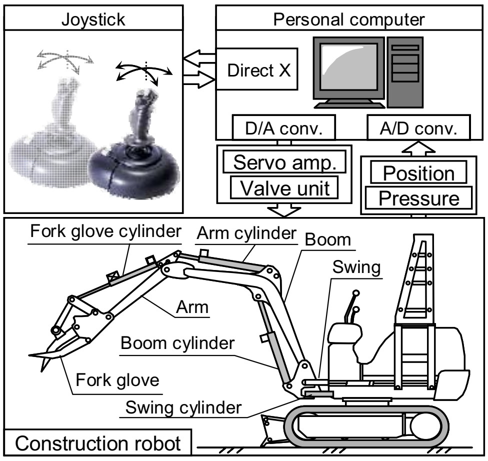

Figure 1 Schematic diagram of experimental apparatus

The mechanical system consists of a robot arm with four degrees of freedom. The hydraulic cylinders used as actuators for the fork glove (hereinafter, glove) at the end of the robot arm and the swing, boom, and arm are moved by operating the joysticks in these four directions. To give the operator a feeling of grasping objects with the glove and the work reaction force (force) generated during work by the swing, boom, and arm, two DC motors are incorporated in each of the joysticks. Feedback control by proportional control valves is used in the above-mentioned four cylinders (Stroke Sensing Cylinder, manufactured by KYB Co., Ltd.; resolution: 0.01mm). Force sensors are installed on the head side and cap side of each of the cylinders to detect load pressure. These pressure signals can be used as force signals, which are necessary on the master side.

POSITION-VELOCITY CONTROL IN MASTER-SLAVE SYSTEM

In this research, first, for the glove, a control method that enables satisfactory representation of grasping in a wide range of grasping tasks was proposed. The features of this control method are as follows[2].

① The threshold value f_{prei} for representing reaction force is variable, using measured velocity-drive force characteristics.

② Reaction force to the joystick comprises a term that depends on the position-velocity deviation of the master and slave, and a term that depends on piston drive force. (Symmetric positioning and force reflection control method are used in combination.)

The reaction force τ_{ri} on the joystick in this control method is given by Eq. (1). The subscript i in τ_{ri} and the other terms is i =1～2, corresponding to the fork glove or boom, respectively.

$$\tau_{ri} = T_i \left\{ k_{pmi} \left(Y_{mi} - V_{si} \right) + k_{tmi} f_i \right\} \tag{1}$$

Gain T is given by the following equation:

$$T_i = \begin{cases} 0 \quad ; & \left(\left| f_{si} \right| \le \left| f_{prei} \right| \right) \\ \dfrac{f_{si} - f_{prei}}{f_{e\_\max} - f_{prei}} \; ; & \left(f_{si} > 0 \cap f_{si} > f_{prei} \right) \\ \dfrac{f_{si} - f_{prei}}{f_{c\_\max} - f_{prei}} \; ; & \left(f_{si} < 0 \cap f_{si} < f_{prei} \right) \end{cases} \tag{2}$$

Here, Y_m, V_s are nondimensional displacement of the master and nondimensional velocity of the slave, f is piston drive force, and k_{pm}, k_{tm} are gain of the master system. f_{e_max}, f_{c_max} denote the maximum drive force of the piston in expansion and contraction (f_{e_max}=11.7kN, f_{c_max}= -6.8kN).[2]

Application of this control method, composed as described above, to this system makes it possible to give the operator a satisfactory feeling of the task, not only when grasping hard objects or opening and closing the glove without load, but also when grasping comparatively soft objects. In the case of the boom, external forces caused by gravity, etc. are included in the measured drive force. Therefore, when this control method is applied, the load force is estimated and subtracted from the measured drive force. In this research, the position-velocity control type master-slave control method was also applied to the boom for use in risk measurements, in addition to the fork glove. (In the previous report, application was limited to the glove.) Force feedback for the boom is expected to make it possible to avoid dangerous situations, such as overturning of the robot due to excessive pressure by the robot arm on the ground. In this report, this was also evaluated using the risk measurements.

EVALUATION OF OPERATIONAL PERFORMANCE

System Configuration

In this research, a system that displays CG of the work site to the operator was constructed assuming "block stacking by construction robot," which is frequently used in "mudslide countermeasure work by block stacking at disaster recovery sites." Fig. 2 shows the configuration of the object system used in an experiment to evaluate operational performance. The light gray arrows show the flow of signals for expressing the construction robot in virtual space; the dark gray arrows show the flow for the work object.

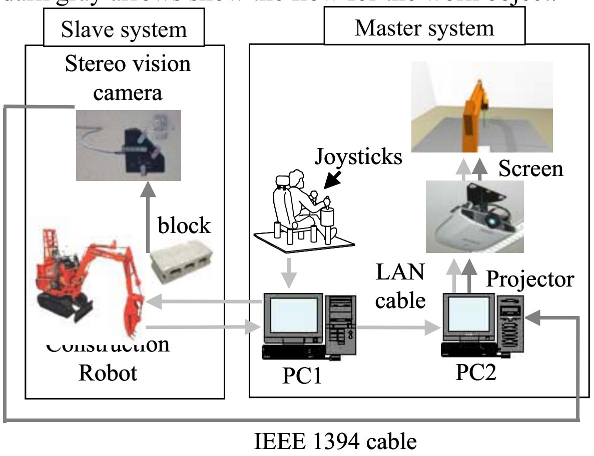

Figure 2 Experimental apparatus for evaluation of operational performance

PC1 is the computer which is used to control the construction robot. A master-slave system for feeding back the displacement of the joystick of the robot, which is the master, and the displacement of the piston of the robot, which is the slave, is configured using this computer. In addition to control of the construction robot, PC1 also transmits the cylinder displacement of the construction robot to PC2, which is the computer that creates the virtual space, using TCP/IP. Based on this information, PC2 draws the construction robot on the virtual space. In addition, distance and color information on the work object are sent to PC2 from a 3-dimensional shape input device using an IEEE1394 cable, and this information is used to draw the work object on the virtual space. The video images of the virtual space drawn in this manner are displayed on a screen using a projector. The 3D shape input device used is a 3D digital camera Color DIGICLOPS (manufactured by Point Grey Research; hereinafter, simply DIGICLOPS), which makes it possible to obtain 3-dimensional images in the field of view of the sensor.

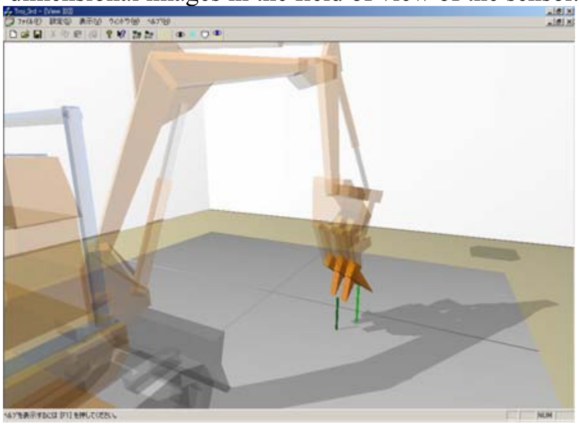

Figure 3 Example of created virtual space

The operator operates the robot while viewing the virtual space created by PC2. Fig. 3 shows an example of the virtual space displayed to the operator at this time. As illustrated here, the images displayed to the operator include the shadows of the construction robot and the object and a gauge showing the distance between the tip of the fork glove and the ground surface or object. The robot itself is semi-transparent. For easy operation with visual feedback using only one screen, an auto viewpoint move function is used. This function moves the viewpoint and reference point in response to the behavior of the swing and boom.

Content of Task

Two types of tasks (Task 1, 2) were adopted. These tasks involved sorting, movement, and stacking of blocks in the task area shown in Fig. 4, using four blocks with two different hardnesses (concrete blocks wrapped in sponge, hereinafter called hard blocks, and sponges, hereinafter called soft blocks). The contents of the respective tasks were as follows.

(1) Task 1

In the initial condition, one block each was arranged at point A and point C in Fig. 4, and 2 blocks were arranged at point B. The task was to grasp each block in order, beginning from the left as seen from the robot, and reply verbally as to whether the block was a hard block or soft block.

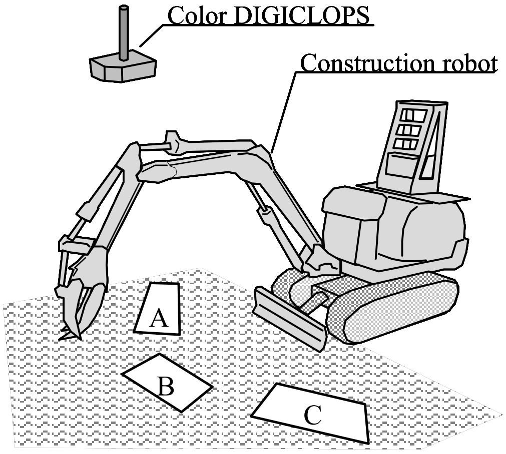

Figure 4 Task area for evaluation of operational performance

(2) Task 2

In the initial condition, two blocks each were arranged at point A and point C in Fig. 4. The task was to grasp each block in order, beginning from the left as seen from the robot, move the hard blocks to point B, and leave the soft blocks in the initial position. When two or more hard blocks were found, the operator was instructed to stack the blocks in accordance with the block arrangement plans in Fig. 5.

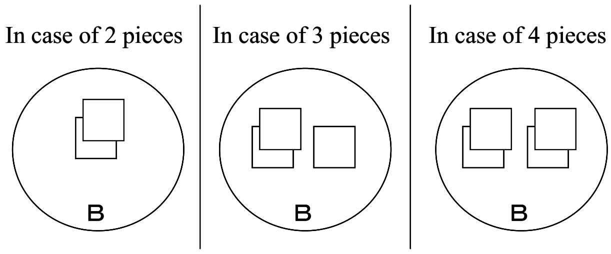

Figure 5 Block arrangement plans

Evaluation Indexes

A total of five evaluation methods were used. Three evaluation indexes were used to verify the effectiveness of the force feedback function by this control method, these being task efficiency, risk measurements, and success rate. These are objective behavioral measures. In addition, NASA-TLX and an evaluation questionnaire were also used as subjective indexes. The features of these various indexes are outlined below.

Behavioral measures refer primarily to objective task performance. These include the amount of work performed, error rate, etc. In the present research, task efficiency and risk measurements were used. The details of these items are as follows.

(1) Task efficiency

Task efficiency is an index that measures the number of blocks moved to the designated position and arranged in a unit of time [Obj./min].

(2) Risk measurements

The following two measures are used as indexes showing that the task is being performed irrespective of the fact that the robot is in an unstable condition.

① Time t_c during which the construction robot is in an unstable condition due to contact between the front part and the ground surface or object (hereinafter, contact time).

② Average value of force, F_c , generated in the boom, arm, and swing of the construction robot while the robot is in an unstable condition (hereinafter, average generated force).

Based on the action-reaction relationship, here, the excess force generated by the piston when in contact with the ground, etc. can be treated as equivalent to an external force acting on the piston. Introduction of the above-mentioned gain T enables nondimensional expression of the excess forces generated in each piston. The generated force Ft is obtained from the sum of these values. A threshold value is set for the generated force F_t obtained as described above, and conditions that exceed this value are considered unstable. Because the contact time tc shows the total time during which the generated force F_t exceeds the threshold value, the average generated force F_c is obtained by dividing the integrated value of Ft during this t_c counting time by the contact time t_c.

(3) Success rate

The success rate expresses the rate of success in correctly determining whether blocks are hard or soft. It is calculated by the percentage (%) of the number of blocks successfully judged among the total number of blocks.

SWAT (Subjective Workload Assessment Technique) and NASA-TLX (NASA Task Load Index) may be mentioned as psychological indexes in wide general use. In the present research, NASA-TLX was adopted as a subjective index, as there are many examples of application and it is easily introduced.

NASA-TLX consists of six measures, these being mental demand, physical demand, time demand, operational performance, effort, and frustration. The flow of evaluation by NASA-TLX consists mainly of three processes: ① paired comparisons of the various measures, ② work which is the object of the load evaluation (in this paper, block stacking work), and ③ evaluation of the load for each measure. Based on this procedure, it is possible to evaluate the size of the load for each measure, and to make an evaluation of the total load (WWL score: mean weighted workload score).

EXPERIMENTAL RESULTS
SYSTEM CONFIGURATION

This experiment was performed in order to verify the effectiveness of applying the force feedback function using this control method to actual work. Therefore, this chapter presents the results for the behavioral measures, subjective index and evaluation questionnaire when the block sorting and stacking tasks described above were performed. The subjects were 6 persons (all male, average age: 23.5 years), three of whom were inexperienced persons who received an explanation of operation of the construction robot prior to the start of the experiment to evaluate operational performance. All subjects were allowed sufficient time to practice operation of the construction robot prior to the experiment.

Behavioral measures

(1) Task efficiency

As task efficiency results, Fig. 6 shows the actual task efficiency and standard deviation by subject.

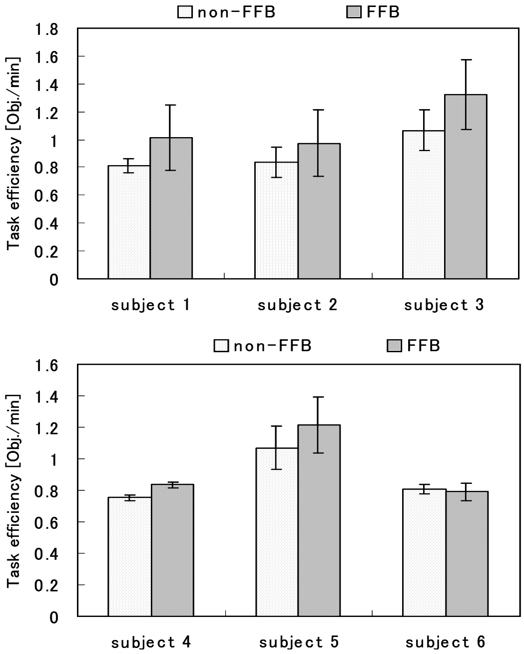

Figure 6 Task efficiency in behavioral measures

In this figure, "non-FFB" and "FFB" mean that operation was performed without or with force feedback, respectively. The *x*-axis shows the subjects, and the *y*-axis shows task efficiency [Obj./min]. Larger values on the *y*-axis mean higher task efficiency. Because the subjects were allowed to practice before the experiment, it was assumed that there would be little improvement in task efficiency as the subjects became more accustomed to operation of the robot. Therefore, no correction was made for this factor. According to Fig. 6, the task efficiency of almost all subjects as improved by using FFB. Accordingly, the results showed that the meaningful difference of force feedback in remote operation systems mediated by virtual space is not insignificant.

(2) Risk measurement

As risk measurement results, Fig. 7 shows contact time t_c and average generated force F_c by subject. In this figure, the left *y*-axis shows contact time t_c, and the right *y*-axis shows average generated force F_c. In both cases, smaller values mean that work can be performed more safely.

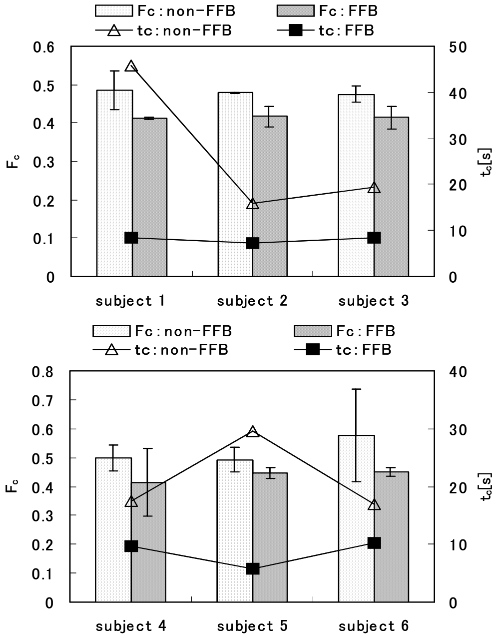

Figure 7 Risk measurement in behavioral measures

This figure shows that risk increases when force feedback is not provided. This is because the subjects could not judge contact with the floor due to the lack of reaction force. Conversely, with reaction force, the subjects could judge contact with the floor and move away immediately. These results confirmed that the condition of the construction robot can be grasped intuitively when force feedback is provided, and safer operation of the robot is possible.

(3) Success rate

Fig. 8 shows the results of the success rate by subject. In this figure, the x-axis shows the subjects, and the y-axis shows the success rate as a percentage. Because 8 blocks were used in all of the tasks in this experiment, the result is calculated as (number of blocks successfully judged) / 8. Larger values on the *y*-axis mean that a large number of blocks was judged successfully and errors were fewer.

According to Fig. 8, the success rate was higher when force feedback was provided. This is attributed to the fact that judgment is easier with force feedback because the task reaction force is communicated to the operator by way of the joystick. Conversely, when force feedback is not provided, judgments must be made based only on the CG, which does not show any change in the shape of the object. In this case, the operator must depend on his intuition, based on the condition of deformation of the task object.

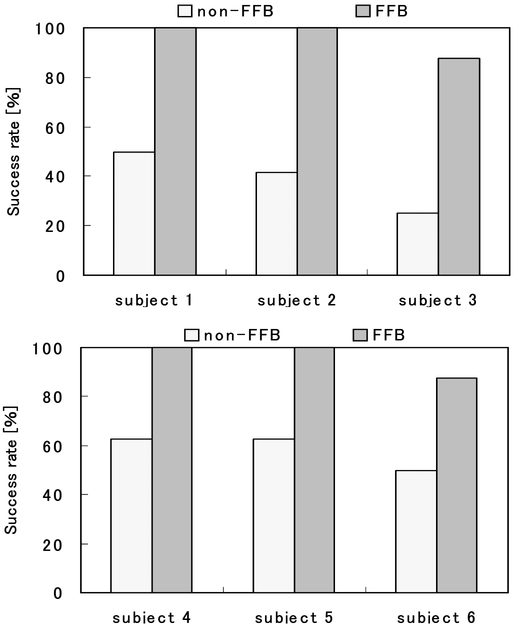

Figure 8 Success rate in behavioral measures

For this reason, there were considerable differences in the success rates of the subjects. The fact that in some cases the success rate was not 100% when force feedback was provided is attributed to locations where it was difficult to feel the reaction force due to the position where the block was grasped. Accordingly, it was found that accurate work is possible when force feedback is provided.

Subjective Index

Fig. 9 shows the results of NASA-TLX. It should be noted that, because NASA-TLX is a subjective evaluation method, the evaluation standard for each measure will differ depending on the habits and judgment standards of the respective subjects. For this reason, evaluation based on an average value for all subjects is difficult. Based on the results of the experiment, the results for the six subjects can be largely divided into two groups. Therefore, rather than showing the average values for all subjects, the figure shows the results for two subjects as representative examples. In this figure, the ■ mark shows the evaluation values for each measure without force feedback, while the Δ mark shows the case with force feedback. Smaller scores mean the load on the subject was lighter. Fig. 9 shows that both the respective evaluation values and the WWL score decreased when force feedback was provided. Accordingly, it can be understood that the mental load on subjects is reduced when force feedback is provided in comparison with the case where force feedback is not provided. Inferring from the tendencies of the two representative subjects, it was found that the loads for the measures mental demand (MD), effort (EF), frustration (FR), and operational performance (OP) were reduced with force feedback. However, one subject showed a slight increase in physical demand (PD). This is attributed to the increased load on the hands in joystick operation due to feedback of work reaction force. This seems to indicate that some persons may find operation more physically demanding with force feedback.

The results described above confirmed that, in situations where it is difficult to grasp the condition of the construction robot based on visual information alone, it is possible to supplement the visual information by providing force feedback, and this can lighten the mental load on the operator.

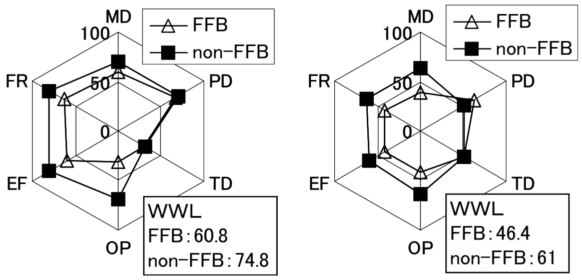

Figure 9 NASA-TLX in subjective measures

CONCLUSIONS

The objective of this research was to improve operational performance in work performed by teleoperation of construction robots. Using a general-purpose hydraulic excavator with a position-velocity control system proposed by the authors in previous work, force feedback was provided to operators and their operational performance was evaluated. These results show the effectiveness of the force feedback.

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