Construction Tele-robot System With Virtual Reality

Hironao Yamada
Department of Mechanical & Systems Engineering
Gifu University
Gifu, Japan
yamada@gifu-u.ac.jp

Ni Tao
Virtual System Laboratory
Gifu University
Gifu, Japan
ture_nitao@163.com

Zhao DingXuan
College of Mechanical Science and Engineering
Jilin University
Changchun, China
zdx@mail.jlu.edu.cn

***Abstract*—In this paper, a tele-robotics system for a construction machine is investigated. The system consists of a servo-controlled construction robot, two joysticks for controlling the robot, and a 3-dimensional virtual environment. Computer graphics (CG) of the robot and task objects are presented to the operator in virtual scene as a tool for assisting teleoperation. The operator performs remote operation of the construction robot by manipulating the graphic robot directly in virtual environment using the joysticks. The position and shape of the task objects in virtual world are updated in real time on basis of image information obtained by a stereo camera fixed in remote field. To improve the efficiency as well as security of teleoperation, and overcome the shortcomings (such as time-consuming judgement and mistaken selection of screen to be observed) of conventional three-screens visual display, the methods of auto point of view (APV) and semi-transparent object (STO) are introduced in this paper. Finally, A comparative study of a one-screen visual display combining APV and STO with the conventional three-screens visual display is carried out based on the results of evaluation experiments (task efficiency, risk indexes, questionnaire). These experiments confirmed that one-screen visual display combining APV and STO is superior in operability, safety, and reduction of stress.**

***Keywords*— virtual reality, computer graphics, teleoperation, tele-robotics**

I. INTRODUCTION

Due to the dangers associated with recovery work at disaster sites and work in extreme environments such as in space, under the sea, and deep underground, remote operation of work robots has become important. With conventional remote operation systems, there are limits on the number of sensors which can be installed and the volume of data which can be transmitted. Moreover, task efficiency is significantly reduced because the operator is unable to obtain adequate information regarding the actual site. Application of virtual reality (VR) technology offers the possibility of performing remote operation with greater safety and comfort in this kind of remote operation.

As a remote operation technology employing VR, in previous research, the authors improved the task efficiency of a conventional remote-operation construction robot system by using VR technology to give the operator a feeling of being at the actual work site in real time [1-6]. In that research, the system was constructed using a three dimensional shape input device (stereo camera) to obtain information on the remote site and computer graphics (CG). This previous work confirmed that tasks can be performed with high efficiency with this system even with a visual display consisting only of CG images. However, problems remained, including a lack of reproducibility of the task object and the construction robot on CG.

Therefore, the purposes of the present research are to solve the problems of the previously-reported remote-operation construction robot system and to improve its operability by incorporating improvements which give the operator an effective visual sense, while taking advantage of the distinctive features of VR. The usefulness of the system is also verified from the viewpoints of task efficiency and risk indexes.

II. TELE-ROBOT SYSTEM WITH VIRTUAL REALITY

Fig. 1 shows a schematic diagram of the construction tele-robot system used in this research. The system is of a bilateral type and is thus divided into two parts; the master system and the slave system. Here, the slave system is a construction robot equipped with a stereo camera. The master system is controlled by an operator and consists mainly of a manipulator and a screen.

The construction robot in remote field has four hydraulic actuators controlled by four servo valves through a computer (PC1). Acceleration sensors were attached to the robot for feeding back the robot's movement to the operator. The manipulator controlled by the operator is mainly composed of two joysticks with force feedback. Each joystick operates on an X and Y axis. The four angular displacements of the two joysticks are mapped onto the linear displacement of the construction robot's hydraulic cylinder of the swing, boom, arm and glove.

A stereo vision camera named "Digiclops", a product of Point Grey Research, Inc., is adopted as a tool for making a CG image of the task object. "Digiclops" is a color-stereo-vision system that provides real-time range images using stereo-computer vision technology. And "Digiclops" is accurately able to measure the distance to a task object in its field of view at a speed of up to 30 frames/second. In the developed presentation system, the operator can view CG images of the remote robot and the task object from all directions. The CG images of the robot and the task object are generated by a graphics computer (PC2) according to the signals received from the joysticks and the stereo vision camera "Digiclops".

Fig. 2 shows the arrangement of the experimental system as seen from above. In this research, experiments were conducted in two rooms separated by a sufficient distance to give the operator a real feeling of remote operation and prevent the operator from directly hearing any work sounds. The stereo "Digiclops" camera is set up just above the construction robot, and the optical axis of the "Digiclops" is made to intersect the floor perpendicularly.

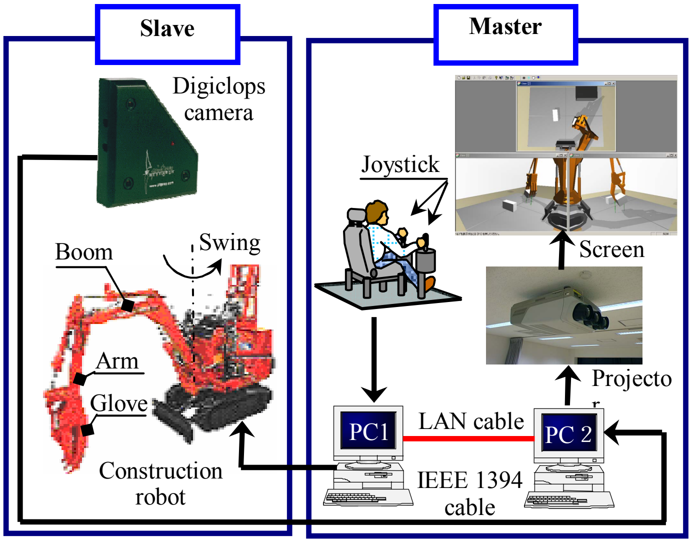

Figure 1. Construction tele-robot system with virtual reality

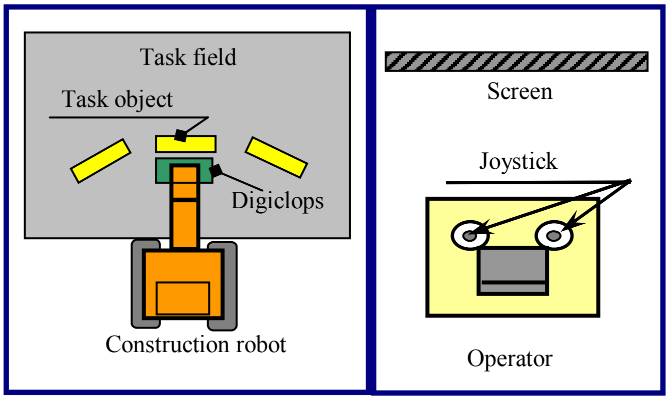

Figure 2. Arrangement of system

The operator performs remote operation of the construction robot using the joystick, watching the screen in front of him/her. Operational information from the joystick is input into a computer (PC1), which calculates operational signals for the servo valves of the robot using these command signals and outputs the signals to the servo amp on the construction robot. A computer (PC2) for use in displaying the virtual space creates images of the construction robot and the task objects in virtual space based on the operational information from the joystick and information on the position and shape of the task object obtained from the stereo camera, and transmits these video signals to a projector which projects the images on a screen.

Details about the implementation of CG images generated from stereo images are as follows. The CG image of the robot is generated according to the displacements, which are detected from sensors attached to the hydraulic cylinders. On the other hand, the CG images of the objects are generated using the "Digiclops". In this experiment, it is assumed that the robot handles only several concrete blocks as work objects and the other objects are neglected because of the limitation of the computer processing power. The shape of these objects is represented by a polygon element. The stereo algorithm, which is installed in the "Digiclops", is reliable enough for this application. Thus, the CG images of the objects are generated according to the following procedure.

(1) "Digiclops" measures the distance to a task object and also captures a video image in its field of view.

(2) The image of the robot arm is eliminated by using color data on the video image.

(3) After the image of the objects has been extracted from the distance data, a binary image of the objects is generated and labeling is executed.

(3) Small objects with a size less than 10x10 cm are eliminated.

(4) The shape of the objects is obtained by computing the polygon contour.

(5) The information of objects (including shape and position) is sent to OpenGL contex and rendered in real time.

The animated CG image of the objects is generated by repeating above from (1) to (5). The moment at which an object is grasped by the robot is detected from the relationship between the measured displacements of the robot arm and the size of the object. While the robot is holding the object, a CG image of the robot and the held object are generated by using the information on the moment at which it was grasped. After the robot releases the object, the object is recognized again by using the above process.

III. VISUAL DISPLAY IN VIRTUAL SPACE

In this research, as supplementary information in the virtual space, the shadows of the construction robot and task objects (blocks) were drawn and a gauge from the fork glove part was drawn perpendicular to the ground surface or block in order to improve operability and safety. The shadows were drawn in darker colors when the projected object are close to the ground or objects and in lighter colors when being more distant to provide a more realistic sense of vertical distance.

The visual display to the operator normally consists of three screens (upper, left, right). Although this type of visual display has the advantage of a small dead angle, judgment as to which of the three screens should be observed while performing operations causes lost time, and there are many cases where this becomes a marked problem, particularly in the case of inexperienced operators. Moreover, a mistaken selection of the screen which is to be observed can result in a dangerous inclined orientation of the construction robot.

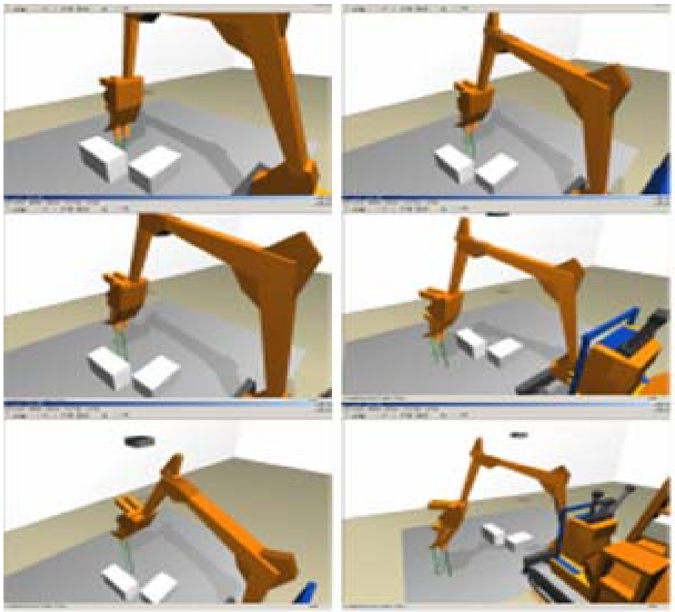

Figure 3. The auto point of view

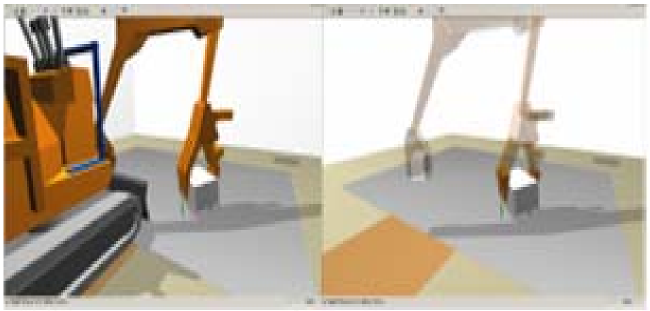

Figure 4. The semitransparent object

To prevent these problems, in this research, a function (auto point of view: APV) which moves the point of view and reference point in response to the behavior of the swing and boom was added so as to facilitate work when using a single-screen display. However, the remote site was assumed to be flat and blocks were not stacked more than 3 high. In setting the point of view, it is necessary to set the parameters of the point of view (X_1, Y_1, Z_1) and the reference point (X_2, Y_2, Z_2). Equations (1) and (2) show the point of view (X_1, Y_1)and reference point (X_2, Y_2),which are moved depending on the joint angle θ of the swing. Equations (3) and (4) show the point of view (Y_1, Z_1)and reference point (Y_2, Z_2), which are moved depending on the joint angle ϕ. To make it easier to grasp the blocks, arbitrary constants ($a_{1,2,3,4}$, $b_{1,2,3,4}$, $c_{1,2,3,4}$, $d_{1,2,3,4}$,) were decided considering the fact that the point of view is inclined with respect to the arm and the ability to command a view of the entire scene.

$$\begin{bmatrix} X_1' \\ Y_1' \end{bmatrix} = \begin{bmatrix} X_1 \\ Y_1 \end{bmatrix} + \begin{bmatrix} a_1 \\ c_1 \end{bmatrix}\theta + \begin{bmatrix} b_1 \\ d_1 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} X_2' \\ Y_2' \end{bmatrix} = \begin{bmatrix} X_2 \\ Y_2 \end{bmatrix} + \begin{bmatrix} a_2 \\ c_2 \end{bmatrix}\theta + \begin{bmatrix} b_2 \\ d_2 \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} Y_1' \\ Z_1' \end{bmatrix} = \begin{bmatrix} Y_1 \\ Z_1 \end{bmatrix} + \begin{bmatrix} a_3 \\ c_3 \end{bmatrix}\varphi + \begin{bmatrix} b_3 \\ d_3 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} Y_2' \\ Z_2' \end{bmatrix} = \begin{bmatrix} Y_2 \\ Z_2 \end{bmatrix} + \begin{bmatrix} a_4 \\ c_4 \end{bmatrix}\varphi + \begin{bmatrix} b_4 \\ d_4 \end{bmatrix} \tag{4}$$

As shown in Fig. 3, these parameters cause the viewpoint to move to the left or right corresponding to the lateral-direction behavior of the construction robot and upward or downward corresponding to its vertical-direction behavior. Because this enables natural spatial recognition of the operator while performing tasks, it can be expected to increase judgment speed and improve safety. Furthermore, in the operation of actual construction robots, as well as in the operation of CG robots, there are cases where the task object is hidden behind the arm or boom of the construction robot itself,. This is not only a hindrance to operation, but is also an operator stress factor. Therefore, a function (semi-transparent object: STO) which expresses the robot as semi-transparent was added, as shown in Fig. 4, by setting the degree of transparency when creating CG. A function for removing the body of the construction robot (base part) from the CG was also added. Because this reduces the dead angle, it can be expected to alleviate the stress experienced by the operator.

IV. EXPERIMENTS AND DISCUSSION

In experiments, operators performed specified tasks by operating the construction robot with the joystick. The virtual space display system is still in the process of development and has not reached a stage where it can reproduce complex conditions faithfully. Accordingly, when the current virtual space display system is used as a visual display system, the task content must unavoidably be simplified to a certain extent. Therefore, in the present experiment, three types of tasks (Task 1 ~ 3) which included transportation and stacking in the working area of construction robots using 2 or 3 concrete blocks (approx. 200mm x 260mm x 100mm; called "blocks" in the following) were adopted, as illustrated in Fig. 5. The content of each task is as follows.

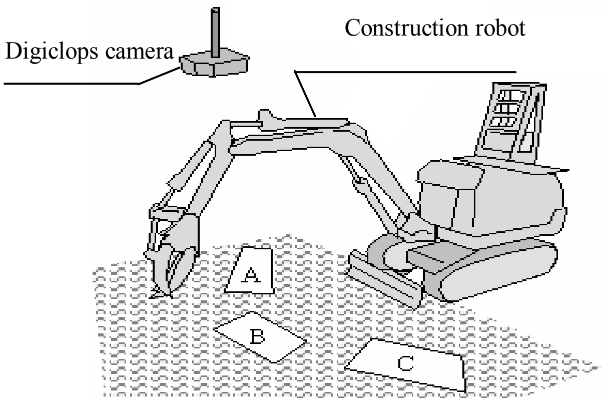

Figure 5. Task area for evaluation of operation

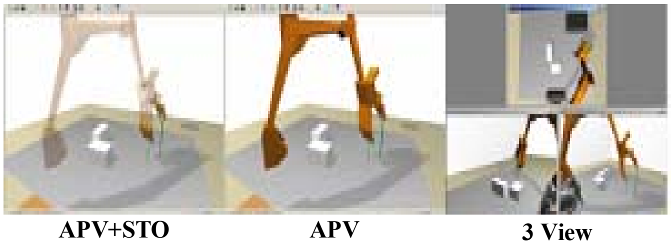

Figure 6. Experimental condition

(1) Task 1

In the initial condition in Task 1, the blocks are arranged with one block each at points B and C in Fig. 5. First, the block at point C is transported to point A. Next, the block at point B is stacked on the block which is already at point A.

(2) Task 2

In the initial condition in Task 2, the blocks are arranged with one block each at points A, B, and C in Fig. 5. First, the block at point A is stacked on the block at point B. Next, the block at point C is transported to point A. Finally, the upper block of the two blocks stacked at point B is transported to point C.

(3) Task 3

In the initial condition in Task 3, the blocks are arranged with one block each at point B and C in Fig. 5. First, the block at point C is transported to point A. Next, the block at point B is transported to point C. Then, the block at point A is moved to point B. The blocks are transported to the empty point among points A, B, and C in this manner a total of 8 times.

The experiment was performed under three visual conditions. As shown in Fig. 6, these were an “APV+STO” condition, in which the task is performed using one screen with moving auto point of view and a semitransparent polygonal object, “APV,” in which the task is performed using one screen with APV and an opaque polygon, and “3 view,” in which the task is performed with the conventional three screens. The time required to complete the task under each set of conditions and the time and force of contact between the construction robot and the floor are measured. After the experiment, the subjects were asked to complete a simple questionnaire. The subjects were 8 males, 22～24 years of age, who were adequately familiar with the operation of the construction robot.

Fig. 7 shows the averaged results of the number of block movements which the subjects completed in 1 minute, together with the standard deviation. The abscissa shows the visual conditions used in the experiment, and the ordinate shows task efficiency (objects/minute). Larger values on the ordinate indicate higher task efficiency.

With APV+STO, the number of block movements per minute increased by approximately 0.8 in comparison with the 3 view method. With the 3 view method, because the task is displayed on 3 screens, time is lost in selecting the screen to be viewed. On the other hand, with APV+STO, it is considered that judgments could be made quickly because the dead angle is small and spatial recognition is possible simultaneously with the task.

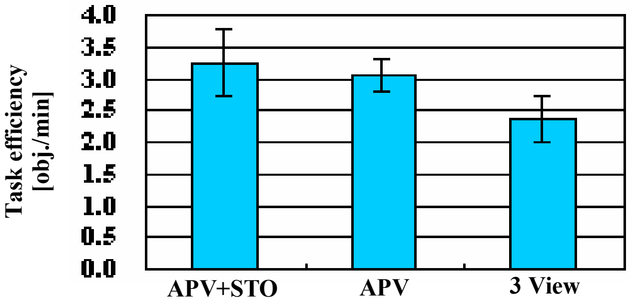

Figure 7. Task efficiency

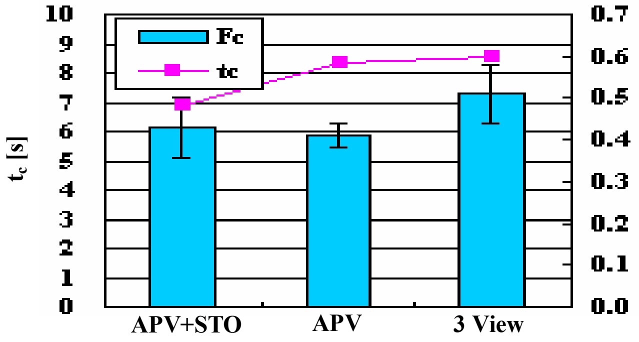

Figure 8. Risk measurement

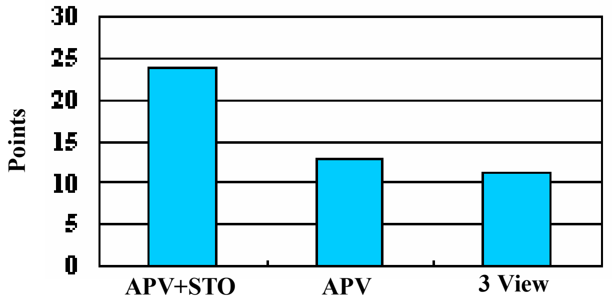

Figure 9. Questionnaire result

Fig. 8 shows the averaged results of the time and force of contact between the construction robot and floor. As above, the abscissa shows the visual conditions. The left ordinate shows the time of contact with the floor, t_c in seconds, and the right ordinate shows the dimensionless force F_c obtained from the average force generated by the boom, arm, and swing. On both the right and left axes, larger values indicate risk. The fact that natural spatial recognition with APV has an effect on safety can be understood from this figure. Moreover, with the 3 view method, there were numerous cases in which both t_c and F_c showed high values when the subject erred in selecting the screen which should be viewed.

Fig. 9 shows the results of the subjects' ranking of the operability of the construction robot and stress experienced, where 3 is the most favorable response. The abscissa shows the visual conditions in the experiment, and the ordinate shows the score. Higher scores indicate easier operation. Comparing APV+STO and APV, APV+STO clearly has a higher score. This shows that semi-transparency has a favorable effect. Furthermore, in comparison with 3-screen display, in 1-screen display with APV, the large size per screen and natural spatial recognition resulting from the moving point of view appear to have a positive effect on operability and stress experienced.

V. CONCLUSION

In this research, a remote operation system was constructed by introducing virtual reality (VR) technology and adding a virtual space display using computer graphics. In contrast to the conventional 3-screen visual display, effective visual display was possible while taking advantage of the distinctive features of VR. Tasks were performed by linking a construction robot in virtual space with an actual robot, and a comparative study was carried out for various VR visual conditions. A comparative study of a 1-screen visual display combining automatic movement of the point of view and reference point (APV) and semi-transparency (STO) and a conventional 3-screen visual display was carried out based on the results of evaluation experiments (task efficiency, risk indexes, questionnaire). These experiments confirmed that 1-screen visual display combining APV and STO is superior in operability, safety, and reduction of stress.

As future subjects, study of an improved point of view and virtual space display method and introduction of dynamic characteristics for movement more closely approximating that of real objects may be mentioned.

Other future objectives include the construction of a system which enables measurement of the position and shape of objects using a camera, rangefinder, etc. and reflection of this information in the displayed image by computer graphics.

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REFERENCES

[1] Yamada, H., Muto, T. and Ohashi, G., "Development of a telerobotics system for construction robot using virtual reality," Proceedings (CD-ROM) of European Control Conference ECC'99, F1000-6, Germany, 1999, in press.

[2] Yamada, H., Kato, H. and Muto, T., "Master-slave control for construction robot teleoperation," Journal of Robotics and Mechatronics, vol. 15, pp. 54-60, 2003, in press.

[3] Zhao, D., Xia, Y., Yamada, H., and Muto, T., "Presentation of realistic motion to the operator in operating a tele-operated construction robot," Journal of Robotics and Mechatronics, vol. 14, pp. 98-104, 2002, in press.

[4] Zhao, D., Xia, Y., Yamada, H., and Muto, T., "Control method for realistic motions in a construction tele-robotic system with a 3-DOF parallel mechanism," Journal of Robotics and Mechatronics, vol. 15, pp. 361-368, 2003, in press.

[5] Yamada, H. and Muto, T., "Development of a hydraulic tele-operated construction robot using virtual reality - new master-slave control method and an evaluation of a visual feedback system," International Journal of Fluid Power, vol. 4, pp. 35-42, 2003, in press.

[6] Yamada, H., Sugimoto, H. and Muto, T., "Construction tele-robotic system with virtual reality (CG presentation of virtual robot and task object using stereo vision system)," Proceedings of the 5th JFPS International Symposium on Fluid Power, pp. 831-836, 2002, in press.