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Construction Tele-Robotic System with Virtual Reality (CG Presentation of Virtual Robot and Task Object Using Stereo Vision System)

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1. Introduction

A remote-control robotic system using bilateral control is useful for performing restoration in damaged areas, and also in extreme environments such as space, the seabed, and deep underground.

In this study, we investigated a tele-robotics system for a construction machine. The system consists of a servo-controlled construction robot, two joysticks for operating the robot from a remote place, and a 3-degrees-of-freedom motion base. The operator of the robot sits on the motion base and controls the robot bilaterally from a remote place. The role of the motion base is to realistically simulate the motion of the robot.

In order to improve the controllability of the system, we examined (1) the master and slave control method between joysticks and robot arms (Yamada et al., 1999, 2003a), (2) a presentation method for the motion base (Zhao et al., 2002, 2003), and (3) the visual presentation of the task field for an operator (Yamada et al., 2003b). Because the visual presentation is the information most essential to the operator, in this study we focused on the presentation method of the operation field of a remote place.

The world's first remote control system was a mechanical master-slave manipulator called ANL Model M1 developed by Goertz (Goertz, 1952). Since its introduction, the field of tele-operation has expanded its scope. For example, tele-operation has been used in the handling of radioactive materials, sub-sea exploration, and servicing. Its use has also been demonstrated in space, construction, forestry, and mining. As an advanced form of tele-operation, the concept of "telepresence" was proposed by Minsky (Minsky, 1980). Telepresence enables a human operator to remotely perform tasks with dexterity, providing the user with the feeling that she/he is present in the remote location. About the same time, "telexistence", a similar concept, was proposed by Tachi (Tachi et al., 1996).

Incidentally, practical restoration systems using tele-operation have been tested in Japan, because volcanic or earthquake disasters occur frequently. For example, unmanned construction was introduced in recovery work after the disastrous eruption of Mount Unzen Fugen Lake in 1994 and was used in a disastrous eruption on Miyakejima, which was made uninhabitable due to lava flows and toxic volcanic gas. In these tele-operation systems, however, simple stereo video image feedback was adopted; there remains some room for improvement in the details of telepresence.

As an application for excavator control, bilateral matched-impedance tele-operation was developed at the University of British Columbia (Tafazoli et al. 1999; Salcudean et al., 1999). They have also developed a virtual excavator simulator suitable for experimentation with user interfaces, control strategies, and operator training (DiMaio et al., 1998). This simulator comprises machine dynamics as an impedance model, a ground-bucket interaction model, and a graphical display sub-system. In their experiment, an actual excavator is operated by a bilateral control method. However, they did not evaluate the effectiveness of the visual display system with the computer graphics image for real time teleoperation.

With regard to the method of visual presentation for tele-operation, augmented reality (AR) has lately become of major interest (Azuma, 1997). AR enhances a user's perception of and interaction with the real world. For example, stereoscopic AR, which is called "ARGOS", was adopted for robot path planning by Milgram (Milgram et al., 1993). Others have used registered overlays with telepresence systems (Kim et al. 1996; Tharp et al., 1994). It is expected that effectiveness of display method can be improved by using an AR system. However, registration and sensing errors are serious problems in building practical AR systems, and these errors may make the working efficiency lower.

In our previous paper, we proposed a presentation method that used a mixed image of stereo video and the CG image of the robot, and clarified that the task efficiency was improved (Yamada et al., 2003b). At this stage, however, because the position and the shape of the task object have not been presented to the operator, the operator cannot help feeling inconvenienced. In this study, therefore, a full CG presentation system, which enables presentation not only of the robot but also of the position and the shape of a task object, was newly developed. The proposed display method enables the operator to choose the view point of the camera freely and thereby presumably improve the task efficiency. This "virtualized reality" system, proposed by Kanade (Kanade et al., 1997), is perhaps similar in spirit to the CG presentation system that we proposed, although it is not currently a real-time system. They use many cameras in order to extract models of dynamic scenes. Our system uses a single stereo vision camera for practical tele-operation. Another CG presentation system, "Networked Telexistence" has been proposed by Tachi (Tachi, 1998), but the task efficiency was not evaluated in the proposal. Utsumi developed a CG display method for an underwater teleoperation system (Utsumi et al., 2002). He clarified that the visualization of the haptic image is effective for the grasping operation under conditions of poor visibility. However, the CG image is generated based on a force sensor attached to a slave manipulator, and thus no detailed CG image of task objects can be presented. In our system, the CG image is generated based on a stereo vision camera, so it is possible to display task objects clearly.

In this study, a full CG presentation system, which enables presentation not only of the robot but also of the position and the shape of a task object, was newly developed. Application of the method was expected to increase the task efficiency. To confirm this, a CG of a virtual robot was created, and its effectiveness for the task of carrying an object was determined. The results of the experiment clarified that tasking time was shortened effectively even for amateur operators. Thus, the usefulness of the developed CG system was confirmed.

2. Tele-robotic system using CG presentation

Fig. 1 shows a schematic diagram of the tele-robotic system that was developed in the course of this research (Yamada et al., 2003a). 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 pair of stereo CCD cameras. The master system is controlled by an operator and consists mainly of a manipulator and a screen. The robot has four hydraulic actuators controlled by four servo valves through a computer (PC). Acceleration sensors were attached to the robot for feeding back the robot's movement to the operator.

The manipulator controlled by the operator consists of two joysticks and a motion base on which a seat is set for the operator. The motion base provides 3 degrees of freedom and can move in accordance with the motion of the robot. This means that the operator is able to feel the movement of the robot as if she/he were sitting on the seat of the robot.

The joysticks can be operated in two directions; along the X- and Y-axes. The displacements of the joysticks are detected by position sensors, while the displacements of the actuators are detected by magnetic stroke sensors embedded in the pistons.

A stereo video image captured by the CCD cameras is transmitted to a 3D converter then projected onto the screen by a projector. Simultaneously, a signal synchronized with the video image is generated by the 3D converter and transmitted to an infrared unit. This signal enables the liquid crystal shutter glasses to alternately block out light coming toward the left and right eyes. Thus, the operator's remote vision is stereoscopic.

In the previous paper (Yamada et al., 2003b), a CG image of robot motion (without a CG image of the task object) was additionally presented; i.e., with the video image from the CCD cameras. In that case, the operator had to watch both the CG and the video image at the same time, which was tiring.

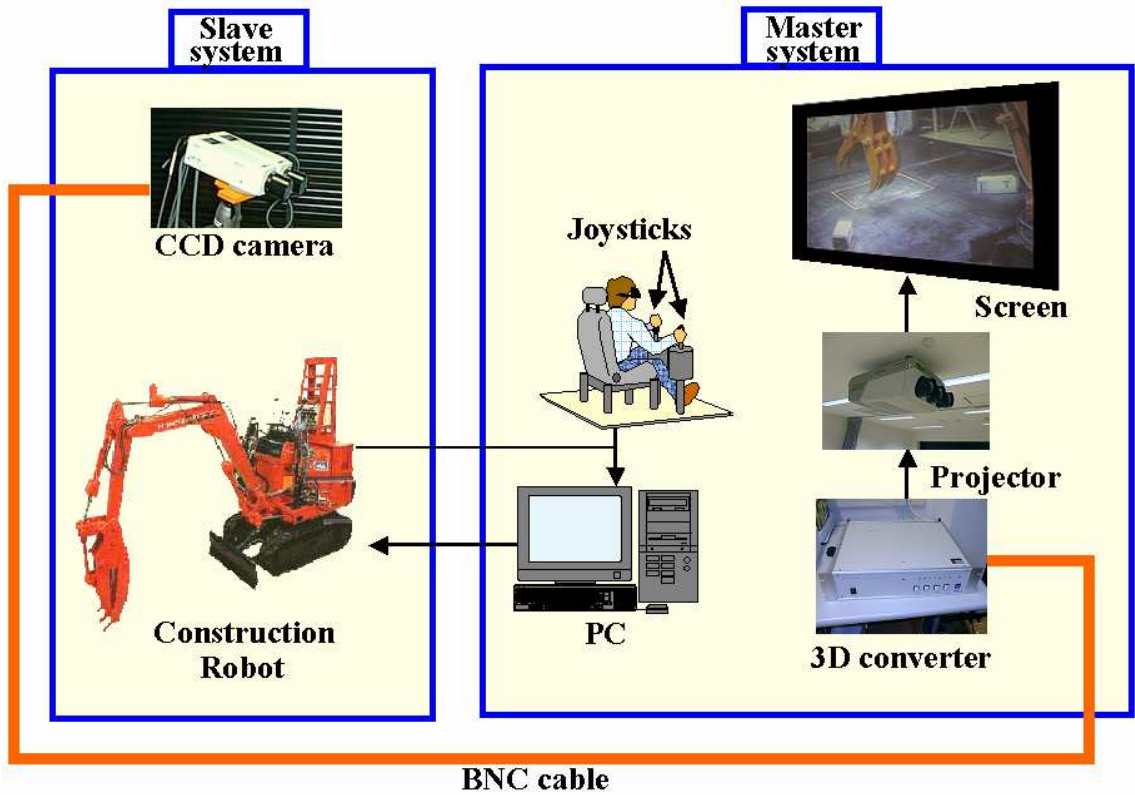


Fig. 1. Construction Tele-Robot System using CCD camera

In this study, we developed a visual presentation system for producing two CG images; one is the robot, the other the task object. As a tool for making a CG image of the task object, we adopted a stereo vision camera named “Digiclops” (Fig.2), a product of Point Grey Research, Inc.

Digiclops is a color-stereo-vision system that provides real-time range images using stereo-computer vision technology. The system consists of a three-calibrated-colors camera module, which is connected to a Pentium PC. 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

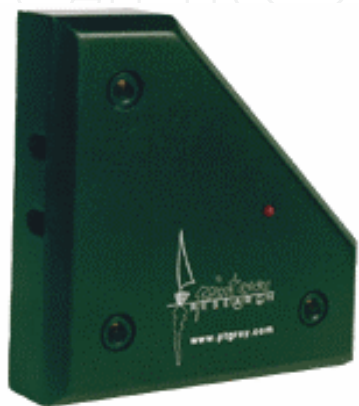


Fig. 2. Stereo vision camera “Digiclops”

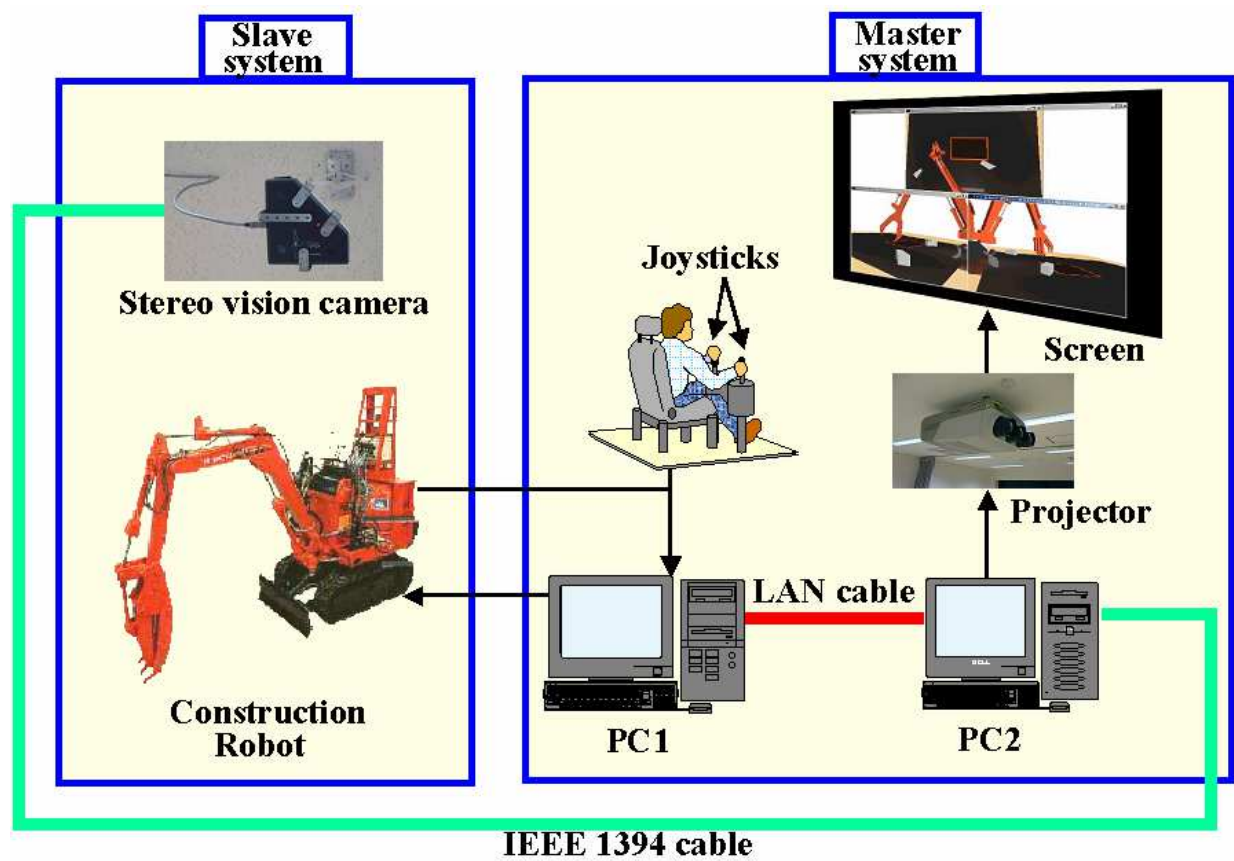


Fig. 3. Construction Tele-Robot System using stereo vision camera

the task object from all directions. Fig. 3 shows a schematic diagram of the developed tele-robotic system with CG presentation. In the figure., PC1 has the same role as the PC in Fig.1. 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.s 4 and 5 show the arrangement of the experimental setup and a top view of the tele-robotic system, respectively. The robot is set on the left-hand side of the operation site. The operator controls the joysticks, watching the screen in front of him/her. The stereo CCD video cameras are arranged at the back left side of the robot; thus, the operator observes the operation field from a back oblique angle through the screen. When the operator looks directly at the robot, he/she is actually looking from the right-hand side. In this study, the video image of the virtual robot was produced using a graphics library called Open-GL. The produced virtual robot is 1/200th the size of the real one; is composed of ca. 350 polygons; and is able to move in real time.

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 convex polygon element. The Digiclops is set up just above the robot as shown in Fig.4. The optical axis of the Digiclops is made to intersect the floor perpendicularly. 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.

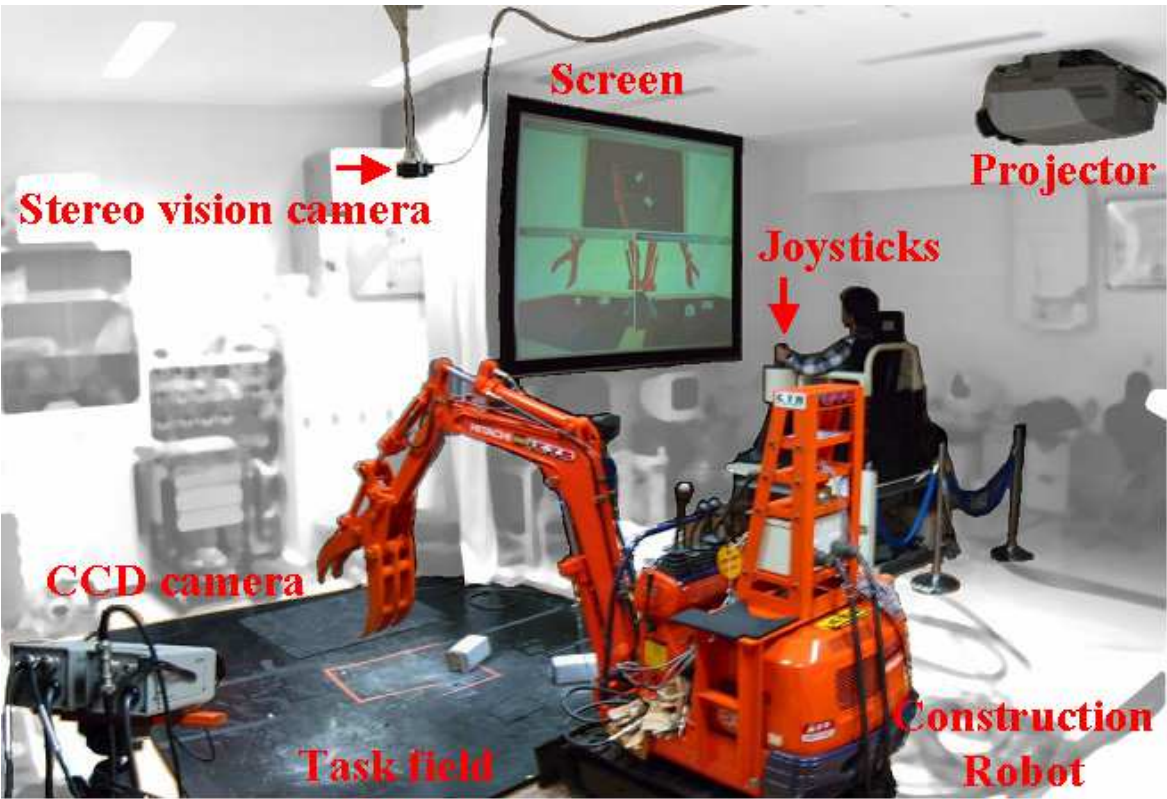


Fig. 4. Arrangement of system

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.
4. Small objects with a size less than 10x10 cm are eliminated.
5. The shape of the objects is obtained by computing the convex hull.

The animated CG image of the objects is generated by repeating above (1)-(4). 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. The experiment was conducted in an indoor environment. As to the generation algorithm of the CG image of the objects, the elimination of the robot from the camera image is robust enough to conduct the experiment under various interior lighting conditions. (We have not yet executed the outdoor experiment. The outdoor experiment is planned as future work.)

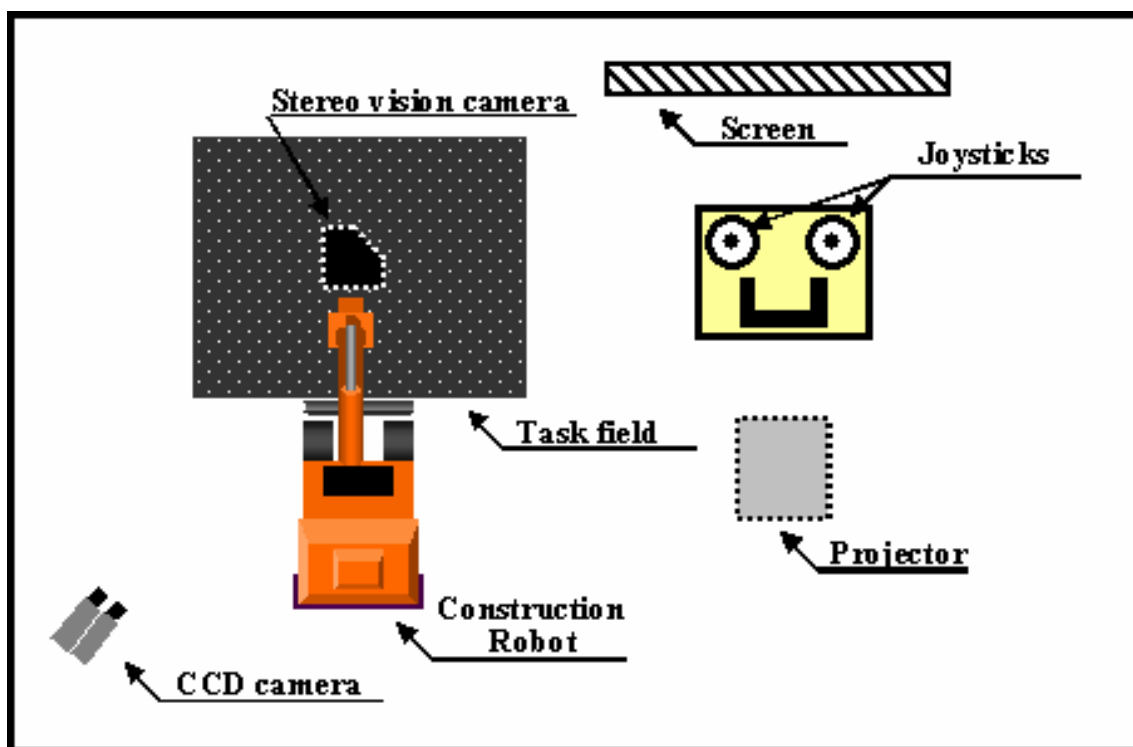


Fig. 5. Arrangement of the system (top view)

3. Experimental results

In the experiment, the operator controls the robot by using the joysticks according to predetermined tasks. In the beginning, the robot is set at the neutral position (Fig.6), and two concrete blocks are placed on a pair of the marked places each other (Fig.7). The operator grasps one of the concrete blocks set in a marked place, then carries it to the center marked place and releases it. Subsequently, and in a similar fashion, the operator grasps and carries the other block.

As control conditions for the operator, three types of visual presentation, shown in Table 1, are set. That is, “Stereo Video” corresponds to the stereo vision presentation given by stereo CCD cameras. In this case, the operator observes the operation field from a back oblique angle through the screen because the stereo CCD video cameras are arranged to the back left side of the robot. (In the case in which the stereo CCD cameras are arranged on the construction robot, the visibility is poor because the operation field is hidden by the robot arm. Therefore, the best viewpoint is found by trial and error.) “CG” corresponds to the presentation of the virtual robot and task objects by Computer Graphics, and “Direct” corresponds to watching the task field directly. In this case, the operator is actually looking from the right-hand side because the operation platform is set up to the right of the robot as shown in Fig.5.

In the experiments, three kinds of CG video images of the virtual robot are simultaneously presented to the operator. The first is a lateral view from the left-hand side; the second a lateral view from the right-hand side; and the third a top view. These view angles were selected so that the operator could effectively confirm the position of two concrete blocks. Fig. 8 shows a projected image presented to the operator.



Fig. 6. Task field



Fig. 7. Image from CCD camera

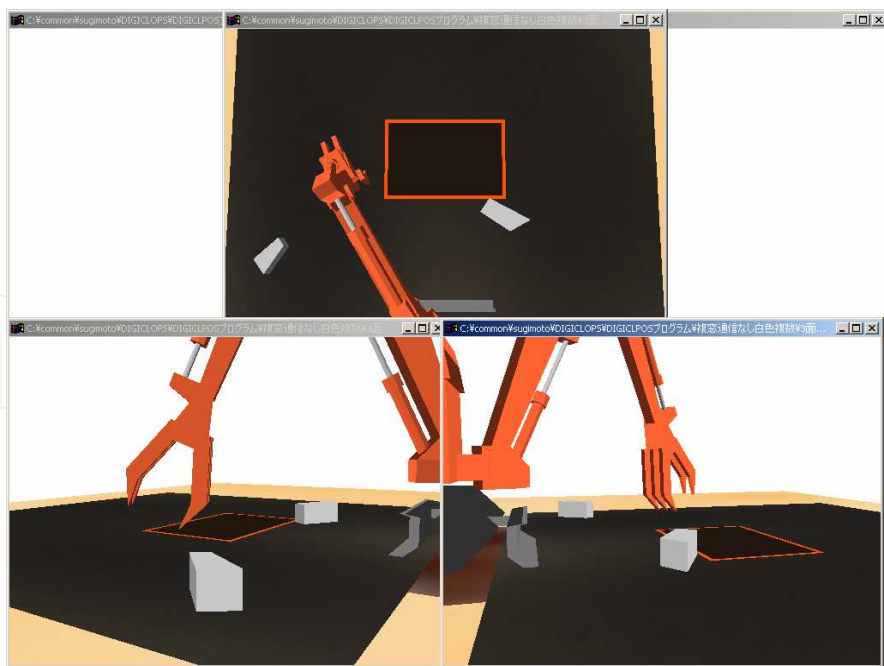


Fig. 8. CG image

Thirty-three subjects served as respective operators of the robot, and we measured the time it took each subject to complete the task. Moreover, we counted the number of failed attempts – that is, when a subject could not succeed in completing a task.

Abbreviation	Conditions
Stereo Video	Operator observes in stereo vision provided by stereo CCD cameras.
CG	Virtual robot and task object are presented solely by Computer Graphics.
Direct	Operator controls the robot while watching the task field directly.

Table 1. Control conditions for the operator

Fig. 9 shows the average values of the tasking times it took the 33 subjects to complete the assigned tasks. The average tasking time in “Stereo Video” was longer than that in “CG” or “Direct”. This is thought to be due to the difficulty the operator has in observing the operation field only from a back oblique angle through the screen in the case of “Stereo Video”. In the case of “CG”, however, the operator has access to a VR image of the robot, even when the robot is at a dead angle; thus, the tasking times in this case is considered to nearly coincide with those in “Direct”.

Fig. 10 shows the ratio of tasking time of direct control to that of each experiment. Based on this result, the efficiency in “Stereo Video” is approximately 40%. To date, several types of telerobotic construction systems have been tested by construction companies in Japan, and it was reported that their working efficiency of remote operation by using stereo video was from 30% to 50% of that in direct operation. Therefore, our result is quite similar to the efficiency of ‘Stereo Video’ illustrated in Fig.10. On the other hand, the efficiency in “CG” amounts to nearly 80%. These results confirm the usefulness of the VR image.

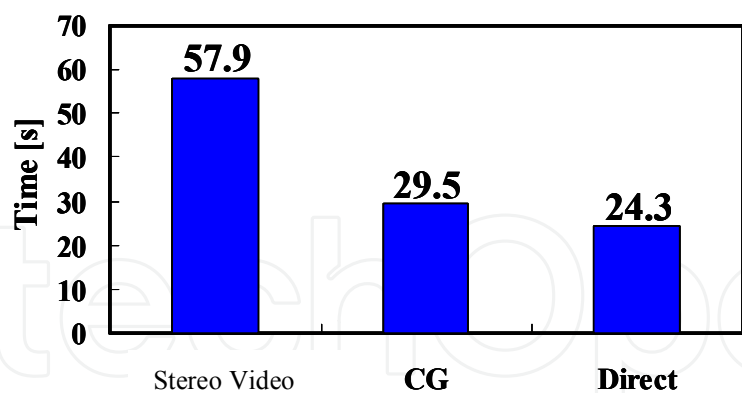


Fig. 9. Average values of tasking times

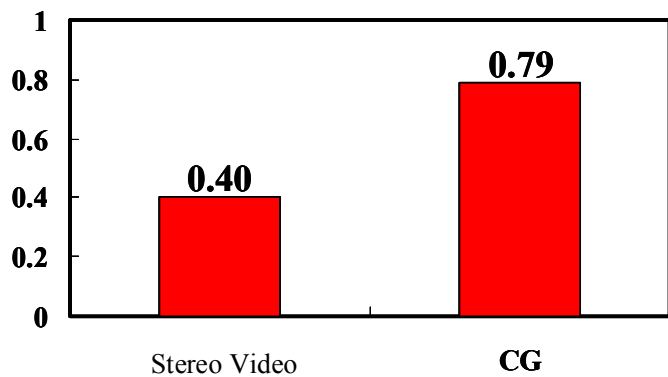


Fig. 10. The ratio of tasking time of direct control to that of each experiment

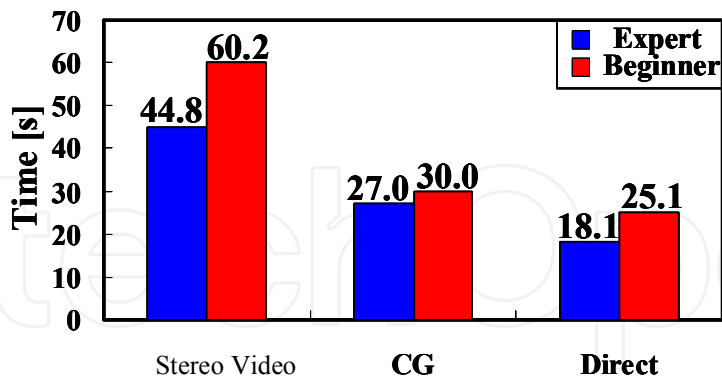


Fig. 11. The time required by an expert and that by a beginner

Fig. 11 shows the time required by experts (operators who had operated the tele-robot system several times before) and that by beginners (operators operating the tele-robot system for the first time). In our study, there were 5 experts and 26 beginners. In this figure, it can be seen that the graphs of experts and beginners show nearly the same shape. However, the tasking time of the beginners is longer than that of the experts. The difference in tasking time between the beginners and the experts is the smallest in the case of “CG”, indicating that CG presentation is most effective for beginners.

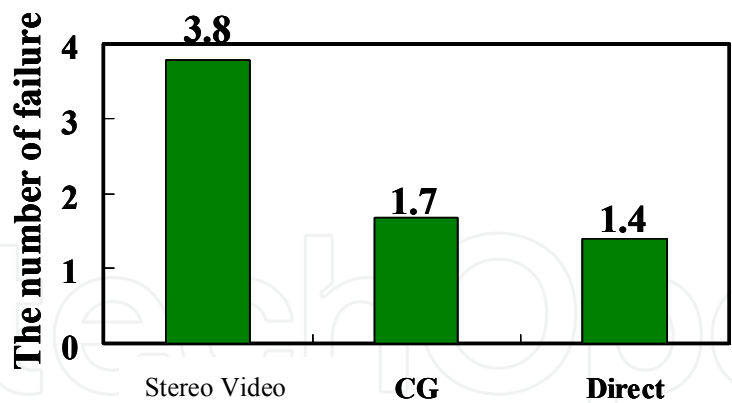


Fig. 12. The average of the number of failed attempts

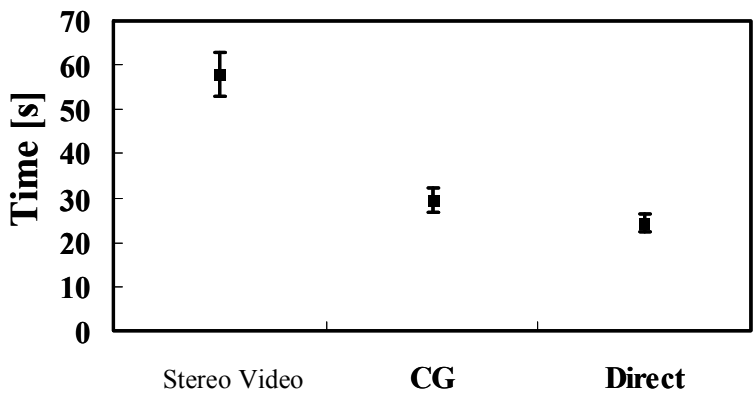


Fig. 13. Standard deviation

Fig. 12 shows the average number of failed attempts. We can see in the figure that the number of failed attempts in “CG” is less than half that in “Stereo Video”. This is because in the former, the operators could recognize the end position of the robot arm accurately, via the CG image. We will add the function of “zoom-in with CG and view only the interesting parts” in future work. Use of that function is expected to reduce the number of failed attempts.

Fig. 13 shows the dispersion of the tasking times with standard deviation. From the figure, it can be seen that the tasking times in “Stereo Video” vary relatively widely. In the case of “CG” or “Direct”, on the other hand, the dispersion is small, as a result of the stability of the tasks.

Another task, one in which the robot piles up blocks, was also executed. The efficiency results obtained were similar to those outlined above. Therefore, a similar result is expected for other tasks. However, we did not execute experiments on tasks such as excavating the ground because that kind of work is impracticable for the system. Investigation of such tasks will be undertaken in future work.

4. Conclusion

In this research, we investigated a tele-robotic construction system developed by us. In our previous study, we developed a system that presents video images transmitted from an operation field. This image was generated by a pair of stereo CCD cameras, allowing a real

stereo video image to be observed through 3D glasses. However, this system was difficult in that the operator observed the operation field only from a back oblique angle through the screen. We considered that if, instead of the video, CG of the robot were presented to the operator, the task efficiency would be expected to increase because the operator would have a multi-angle view of the operation field.

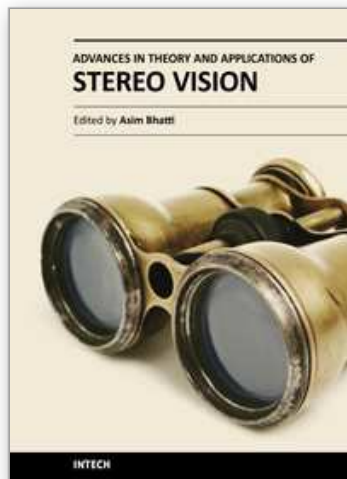
In the present study, we investigated the application of a method that allows the operator to obtain a better sense of the operation field, in order to confirm that this method allowed the operator to control the robot more effectively and stably. To this end, CG images of a virtual robot were generated. It was expected that watching a thus obtained VR robot image in addition to viewing the task object would increase the task efficiency. In the experiments, the task of carrying a concrete block was performed by 33 operators, some of whom were amateurs. The results confirmed statistically that the tasking time was shortened by introduction of the VR images. Considering that the 3D glasses are tiring to wear, the overall usefulness of the developed system remains to be assessed.

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Advances in Theory and Applications of Stereo Vision

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The book presents a wide range of innovative research ideas and current trends in stereo vision. The topics covered in this book encapsulate research trends from fundamental theoretical aspects of robust stereo correspondence estimation to the establishment of novel and robust algorithms as well as applications in a wide range of disciplines. Particularly interesting theoretical trends presented in this book involve the exploitation of the evolutionary approach, wavelets and multiwavelet theories, Markov random fields and fuzzy sets in addressing the correspondence estimation problem. Novel algorithms utilizing inspiration from biological systems (such as the silicon retina imager and fish eye) and nature (through the exploitation of the refractive index of liquids) make this book an interesting compilation of current research ideas.

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