Advanced Robotics, Vol. 15, No. 1, pp. 1 – 16 (2001)

Full paper

Mobile robot teleoperation system utilizing a virtual world

KUNIAKI KAWABATA [1,*], TAKESHI SEKINE [2], TSUYOSHI SUZUKI [1], TERUO FUJII [3], HAJIME ASAMA [1] and ISAO ENDO [4]

[1] *Advanced Engineering Center, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[2] *Ajinomoto Co., Inc., 1-1, Suzuki-cho, Kawasaki-ku, Kawasaki-shi, 210-8681, Japan*
[3] *Institute of Industrial Science, University of Tokyo, 7-22-1, Roppongi Minato-ku, Tokyo, 106-8558, Japan*
[4] *Biochemical Systems Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

Received 20 January 2000; accepted 26 June 2000

Abstract—This paper discusses the problems in teleoperation systems for a mobile robot and the utilization of a virtual world in such systems. In order to achieve smooth operation of the mobile robot through a communication link, we should consider time delays in data transfer. To compensate for the incomplete data sets, the virtual images can be generated by computer graphics when the information on the working environment can be acquired beforehand. In this paper, we construct a teleoperation system with a virtual world. The performance of the system is examined through experiments with actual mobile robots which show that the virtual robot can be operated by an operator in almost the same manner as the teleoperated real robot. In an experimental environment with a second moving robot, we can keep the status of the second robot under perfect control and operate the first robot with no interference.

Keywords: Teleoperation; virtual world; Internet; mobile robot.

1. INTRODUCTION

The role of mobile robots has become increasingly important to our lives. However, to date, robots are not yet able to carry out all the tasks autonomously. A human operator should somehow take over the operation of the robotic system according to the task requirements. We (Suzuki *et al.*) have already proposed a teleoperation system for mobile robots and established the command levels for operating multiple mobile robots [1, 2]. Also, Kawabata *et al.* have tried direct teleoperation through a real network under limited feedback information [3, 4], and Ishikawa *et al.* proposed a GUI (Graphical User Interface) for direct teleoperation [5]. Sekimoto *et al.* have reported a design of a driving device for a mobile robot. They used the real feedback

*E-mail: kuniakik@riken.go.jp

image with a touch panel. However, this design would have problems in the case of long-distance operation [6].

In recent years, the Internet has been extended throughout the world and realizes access to any site very easily. Hirukawa *et al.* proposed WWR (World-Wide Robotics) and constructed a prototype of a standard teleoperation system using VRML (Virtual Reality Modeling Language) [7]. Mituishi *et al.* proposed 'Action Media' as a sort of user interface [8]. Moreover, teleoperation systems that can be used by non-specialists from any Internet site are discussed [8–11]. However, it is difficult for these teleoperation systems to have a communication infrastructure with stable rates of data transfer. There are always unexpected time delays on a public network such as the Internet.

In this paper, we discuss the problems of the teleoperation systems of a mobile robot and the utilization of a virtual world in which the human–robot collaboration is based on such systems that provide as comfortable a human interface as possible. Even if the communication link shows unstable performance, we could compensate for the control or monitoring signals by computed virtual ones. The performance of the developed system is examined through experiments with an actual mobile robot in a real network. We also report the performance of the system in a real environment with a second moving robot.

2. TELEOPERATION SYSTEM WITH A VIRTUAL WORLD

2.1. *Time delays*

When a human operator operates a robot from a remote site, it is inevitable that time delays will occur and these need to be considered. The reasons for the time delays can be summarized as follows:

- A large amount of information flow and heavy traffic in the network.
- A shortage of capacity of the robot to obtain image data, save it and send it to the operator.
- A shortage of capacity of the computer to receive the image data from the robot, process it and display the images.

Therefore the image data taken by the real robot cannot be smoothly displayed, e.g. at video rate, on the screen at the operation site. In the research field of networked robotics and space robotics [12], the time delay problem is mainly discussed because teleoperation or communication is a key technique on such system. Naturally, the operationability and working efficiency depend on the delay. In this paper, we consider to improve operationability of teleoperation system under the public network environment.

2.2. *Advantage of a virtual world*

Figure 1 shows an example of the information flow in such a teleoperation system. By using a virtual world with real robot operation, many advantages will appear in

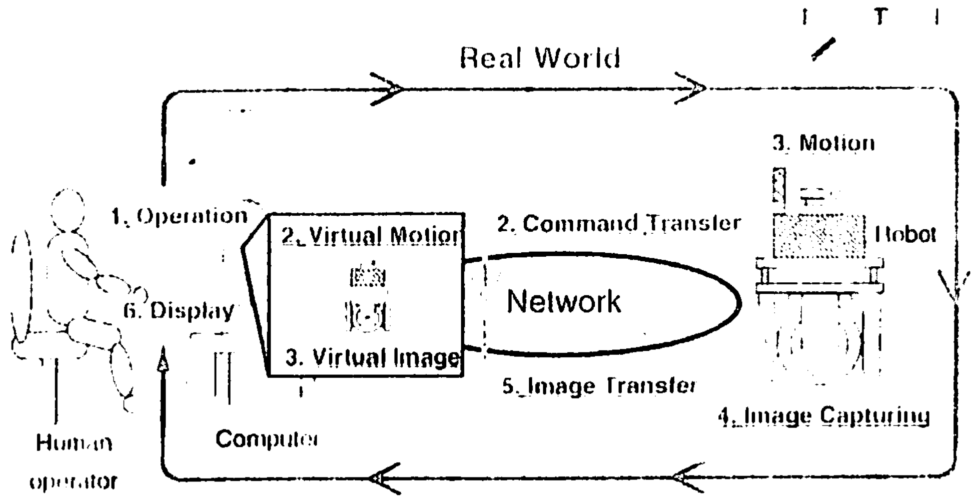


Figure 1. Example of the information flow in a teleoperation system.

the system. Mitsuishi *et al.* [13] proposed a tele-guiding system through the network using three-dimensional (3D) computer graphics. Their basic idea is similar to ours of introducing 3D virtual reality techniques for helping the operator work. However, the role of their interface in the tele-guiding system is to realize easy recognition of task error between two working sites. In this paper, we try to maneuver the robot smoothly under time delay conditions using a virtual reality interface.

Here, we describe the outline of our teleoperation system. In the real world, the operator gives some commands to the robot through the network. Then, the robot starts a motion according to the commands whilst sending back the images captured from its own camera to the operator. However, the operator cannot execute smooth operation in this cycle, because there are large random time delays, which depend on the state of the network at that time and are therefore not constant. However, the commands from the operator could directly communicate to a virtual robot in a virtual world. In this case, the virtual images could be communicated to the operator with little time delay. Therefore, the operator does not have to account for the delay of communicating the information and operates the robot more smoothly. Thus, the virtual world plays a role as an agent for interpolating time delay and the lack of data on the network. Actually, the information error between the real robot and the virtual robot is revised when the operator stops to send the command. Therefore the operator does not feel any time delay during maneuvering the robots. In later sections, we describe technical characteristics of our proposed system in detail. Then, the operator often uses the real images that are sent from the camera on the mobile robot or in the environment through the network for fine operation. Moreover, by using the images taken from the virtual robot moving in the virtual world, the intervals between the image data from the real world can be filled in by virtual images. These images give the operator a realistic and smooth visual display for a comfortable operation of the mobile robots. In addition, by using the virtual world, the human operator can watch the object from various views, such as a bird's-eye view, from which the human operator is not able to watch the image in the real case. Its function is useful to recognize the robot's situation in the environment and maneuver the robot easily. In next section, we discuss actual equipment and devices which make up our system.

3. OVERALL STRUCTURE OF THE TELEOPERATION SYSTEM

We have developed a prototype teleoperation system for mobile robots utilizing a virtual world for better image display for human operators. Figure 2 shows the overall structure of the developed system. The system consists of human interface devices, operation targets and a computer. This system uses TCP/IP (Internet protocol) and each part is connected to the network. In particular, the robot and the computer are linked via the Internet through a radio LAN.

3.1. Human interface and devices

Figure 3 shows the input and output devices. A joystick is used as an input device for easy maneuvering of the robot, whereas the pan and tilt motions of the camera are controlled by the output from a FASTRAK motion tracking system attached to an HMD (Head Mounted Display). The real image captured by the real camera and the virtual image captured by the virtual camera on the virtual robot are displayed on the HMD. The joystick has 2 d.o.f. for forward–backward and left–right, and a button which is pushed when the operator wants to rotate the robot. The human operator inputs the motion commands using the joystick [3]. When the FASTRAK motion tracking system detects a change of magnetic field, it converts this to a

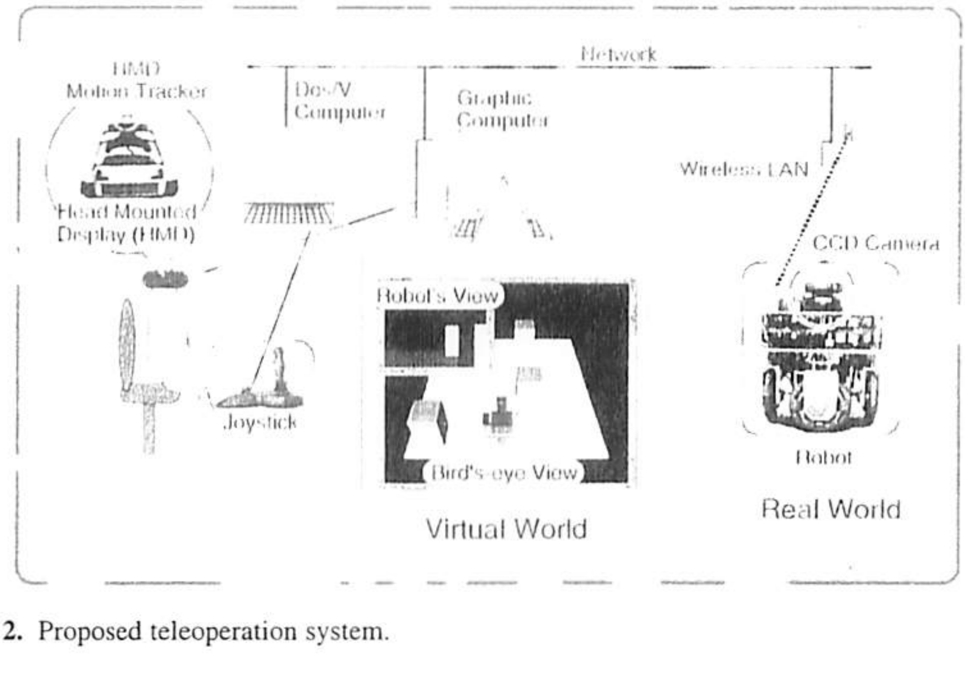


Figure 2. Proposed teleoperation system.

numerical value of an angle. The motions of the camera on the real robot and the virtual robot are managed by the value of the angle.

3.2. Operation targets

3.2.1. In the real world. The real world consists of a mobile robot, a single onboard CCD camera and an environment in which the mobile robot moves around. Figure 4 shows an omni-directional mobile robot. The mobile robot has a specially designed driving mechanism and wheels with free rollers. This machinery realizes omni-directional motion and decoupled control of 3-d.o.f. movement in a horizontal plane [14]. The omni-directional mobility is suitable for teleoperation systems because an operator can maneuver the robot intuitively. The dimensions of the omni-directional mobile robot are: width = 0.45 m, depth = 0.45 m and height = 0.53 m. The robot has its own IP address and is connected with the computer though a radio LAN device and TCP/IP. It is a kind of physical agent on the Internet. The robot carries a CCD camera with pan (from +40° to −40°), tilt (from +20° to −20°) and zoom functions.

Figure 3. Input and output devices.

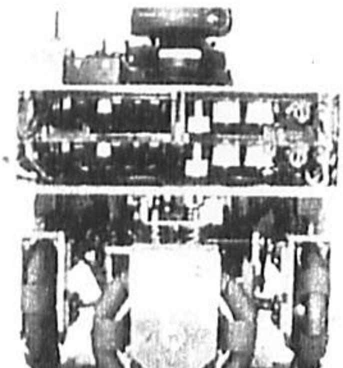


Figure 4. Real omni-directional mobile robot.

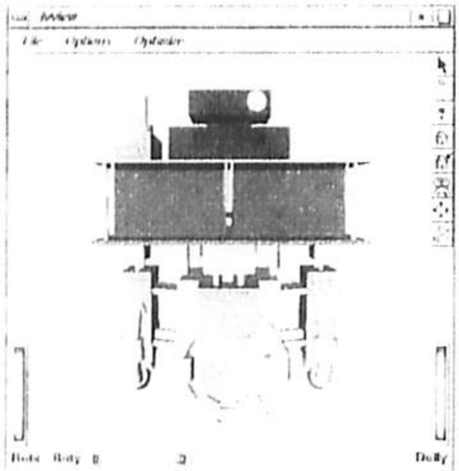


Figure 5. Virtual robot.

3.2.2. In the virtual world. The virtual world consists of an environment model, a mobile robot model and a process for the virtual robot. The environment model is created using computer graphics based on the real environment where the real mobile robot exists. It is a very difficult problem to automatically model the environment using sensor information, but our target in this paper is to improve the network time-delay problem. Here, we assume that the environment model is given or known. The modeling of an unknown environment using sensor information is a separate and difficult problem. Similarly, the mobile robot model is also created using computer graphics based on the real mobile robot (Fig. 5). Figure 6 shows the structure of the overall processes for generation of the virtual world. The roles of the processes for the virtual robot are data acquisition and data processing for operation of the robot in the virtual world. On a graphical workstation, the process which displays the animation is the parent process and the other processes, which receive the angle of the camera and calculate the coordinates of the robot positions, are child processes.

The data flow of the process for the virtual robot is as follows:

(a) The camera control commands, which are calculated on the basis of the head attitude and direction detected by the head motion tracking sensor (FASTRAK), are sent to the graphical workstation through socket communications.

(b) Similarly, the motion commands that are calculated on the basis of the joystick position are sent.

(c) Camera and position data are sent to the parent process for animation.

(d) The parent process calls animated images for 3D models.

(e) The position of the real robot is not always controlled precisely. Therefore we have to correct for the deviation of the position between the real robot and the virtual robot. For that purpose the position of the real robot detected by the onboard rotary encoder and the gyroscope is sent to the child process for robot motion.

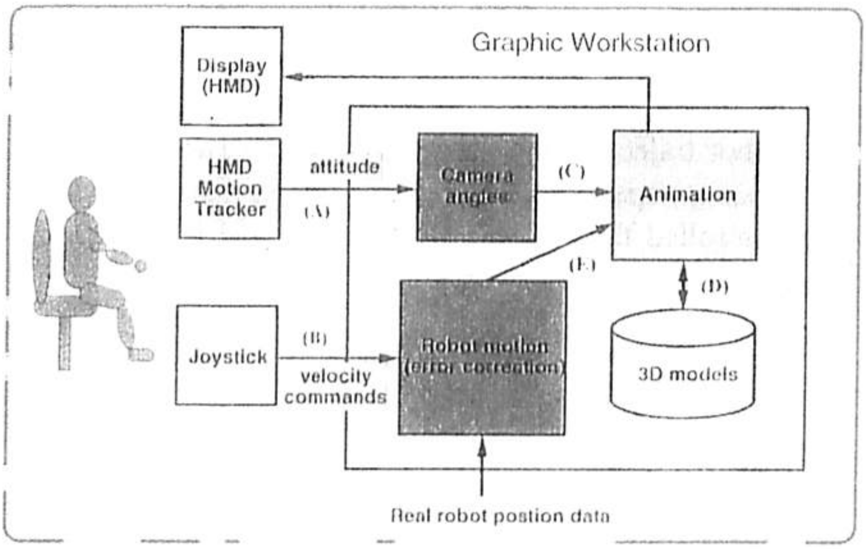


Figure 6. Process for the virtual world.

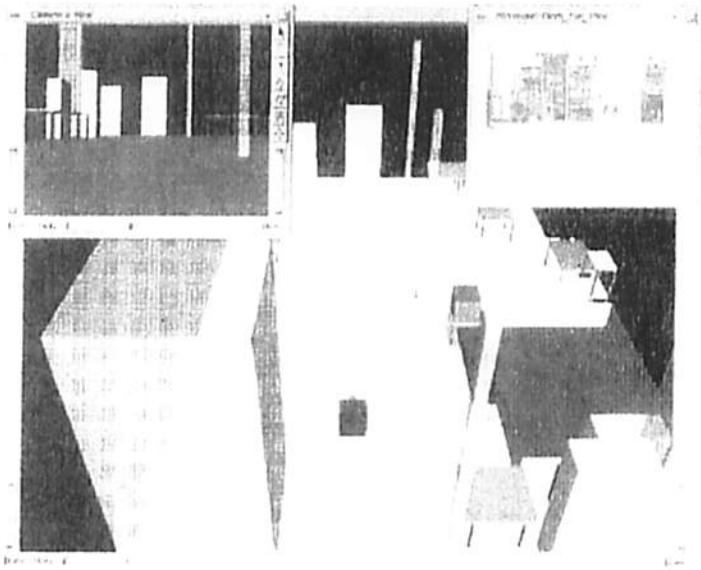


Figure 7. The interface to the virtual world.

Figure 7 shows an example of the interface image of the virtual world from a bird's-eye view, the image from the virtual robot's view and the real image from the CCD camera on the real robot. The operator can operate the robot easily whilst watching these virtual images.

4. EXPERIMENTAL RESULTS

We examined the validity and the performance of the developed teleoperation system to see whether or not similar motions of the robots can be displayed to the operator compensating for the deviation of the position between the real robot and the virtual robot. Also, using the developed system, we operated the robot in an experimental environment with a second moving robot. Figure 8 shows a real working environment of our experiment. The experimental environment and the operated robot trajectory are shown in Fig. 9. The task of the robot is to move within the narrow space. In Figure 9, the dotted lines indicate the target route. The operator controlled the real robot and the virtual robot simultaneously using the joystick and the head motion-tracking sensor (FASTRAK).

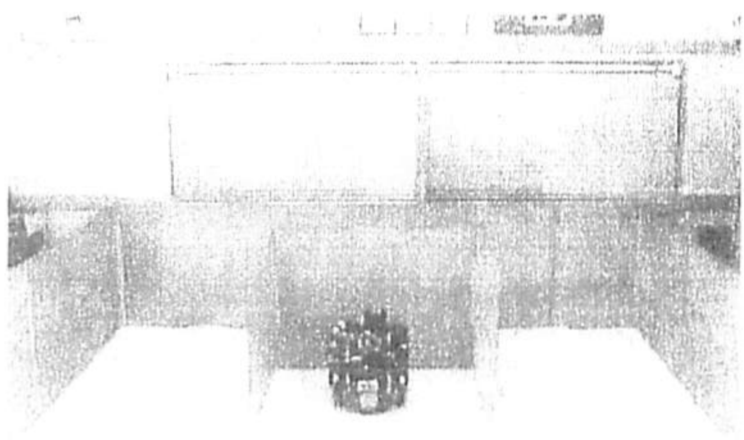


Figure 8. Real environment for the experiment.

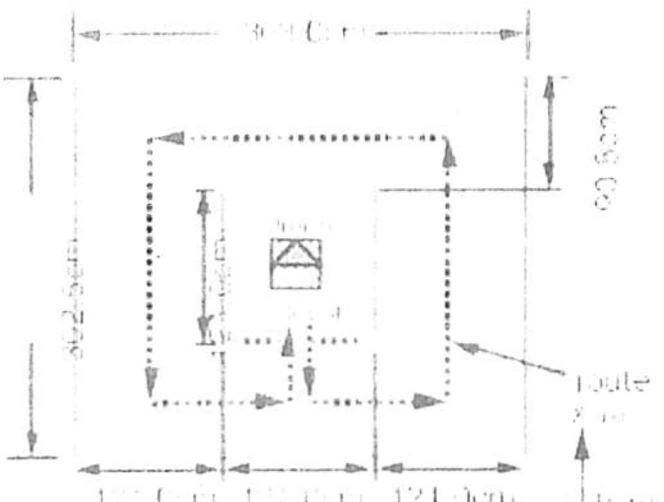


Figure 9. Environment and the robot's route.

4.1. Characteristic estimation for the teleoperation system

To confirm the performance of the developed system, we compared the speed and the accuracy of the operation between the case of using a virtual world and the case of using only direct information. When we operated the robot without using a virtual world, we use the images from the CCD camera on the real robot and from the real birds-eye view camera.

4.1.1. Comparison of speed of teleoperation. To compare the speed of the teleoperation between the case of using a virtual world and the case of using only direct information, we have performed teleoperation of the robot five times in each case. We examined all of the experiments in this paper using the usual computer network. Therefore, there were random time delays and these changed dynamically. The maximum time delay was 473 ms and average value was 8.67 ms in an experiment lasting 9 min. Also, there was 2% data lack on average.

Table 1 shows the results of this experiment. When the average time for each case is compared, the speed of teleoperation for the case of using a virtual world is approximately 20% faster than the speed of teleoperation for the case without a virtual world. Figure 10a and b shows the trajectories of the real robot, operated using a virtual world and using only direct information. In Fig. 10, the tip of the triangle indicates the forward direction of the robot. When we use the virtual world to operate the robot, we do not have to adjust the direction of the real robot. We can also change the angle of the virtual world, so we do not have to do that. However, when we operate the real robot using only direct information, i.e. the bird's-eye view, it is difficult to grasp the correct position of the real robot, especially when the robot is behind the central walled region. Therefore we have to rely on information from the CCD camera on the real robot and change the direction of the robot from the images from the CCD camera. As a result, this method is slower than when using a virtual world.

Table 1.
Comparison of working speed

Repeated time	Time (s)	
	Virtual world	Real world
1	71.4	109.8
2	65.8	77.8
3	65.6	80.4
4	63.4	76.4
5	74.4	79
Total time	340.6	423.2
Average time	68.12	84.64

4.1.2. Comparison of accuracy of teleoperation. In order to examine the accuracy of the teleoperation between the case of using a virtual world and the case of using only direct information, we have compared the information for teleoperation between the two cases whilst using the joystick. Figure 11a and b shows the inputs from the joystick [x-axis, y-axis: 0.4 (m/s)/100 value, r-axis: 12.5 (deg/s)/100

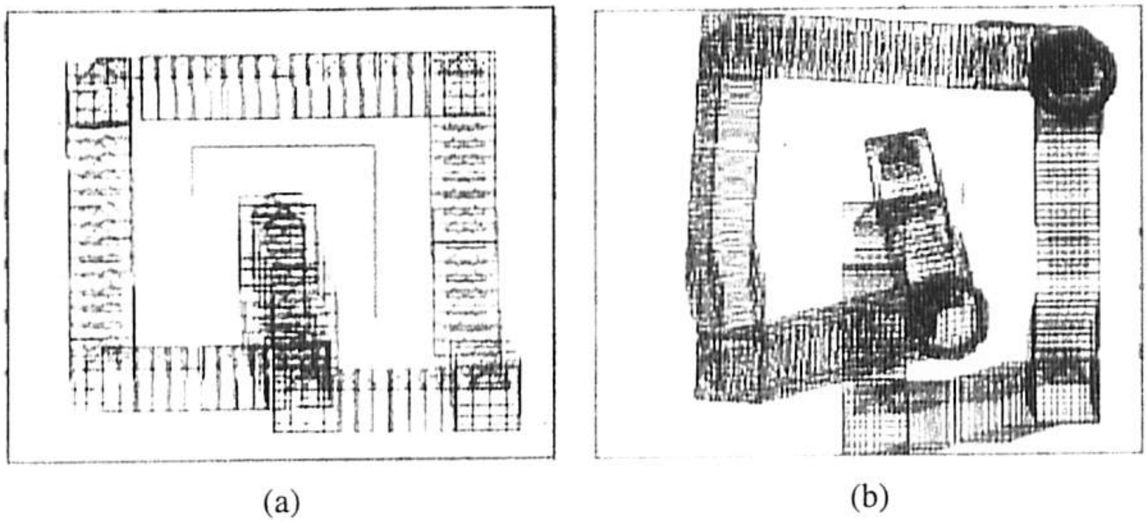


Figure 10. The real robot's trajectory during the experiment. (a) By using the virtual world. (b) Without using the virtual world.

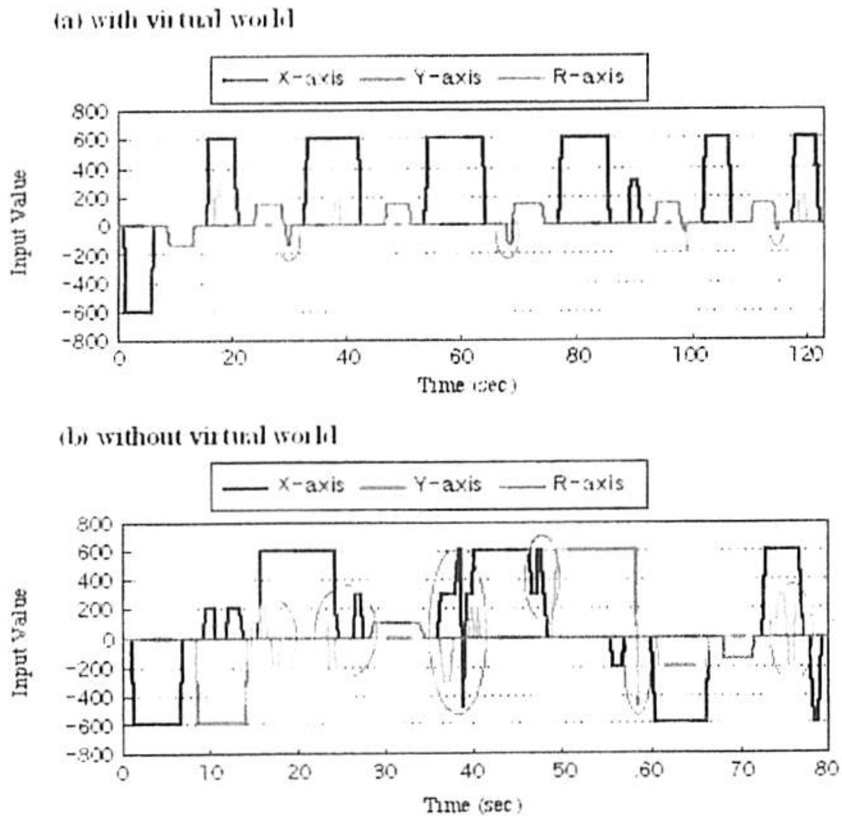


Figure 11. Operator's commands during the experiments.

value] when performing the task. In Fig. 11, erroneous joystick motions are indicated by the circled regions. As a result, we can confirm that teleoperation using a virtual world is more accurate than when using only direct information.

4.2. Revision of the robot position

When we operate the robot utilizing a virtual world, there are some deviations of position between the real robot and the virtual robot. In this system, we have developed and confirmed the performance of a revision system. Figure 12 shows the position of the real and virtual robots whilst following orders from an operator. In Fig. 12, the x-axis, y-axis and r-axis indicate the x direction, y direction and rotation on the world coordinate system, respectively. In this experiment, the system continues to control the position of the robot even when the operator does not control the robot by means of the joystick. The position of the robot in the virtual world is different from the real position while the operator maneuvers the robot. When the operation is paused, the position of the virtual robot is corrected using the position and the posture data that are sent from the real robot. Figure 13a–c

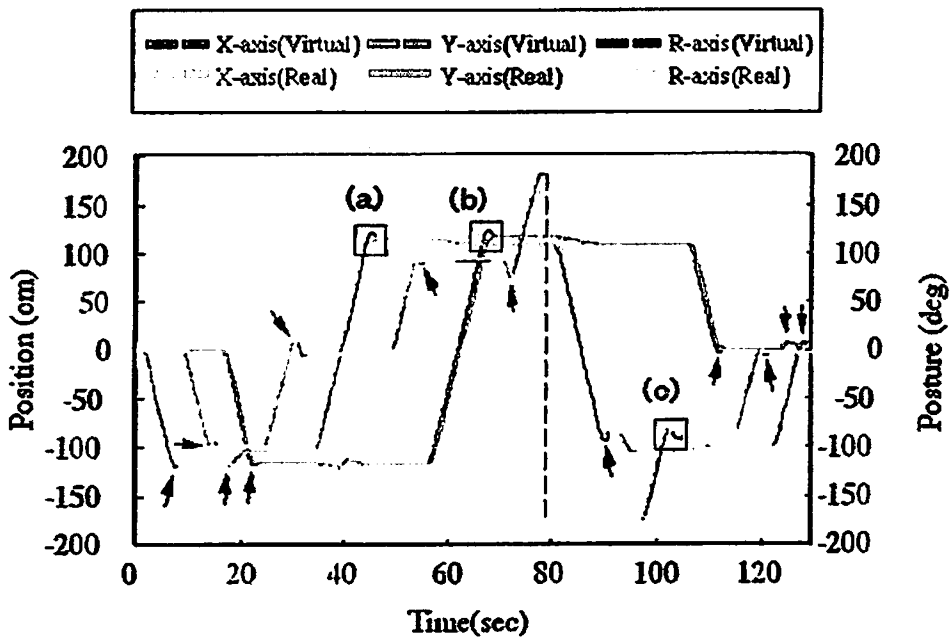


Figure 12. Experimental result with the revision process.

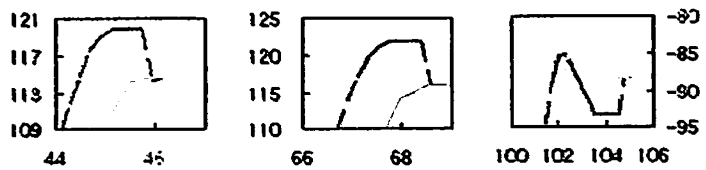
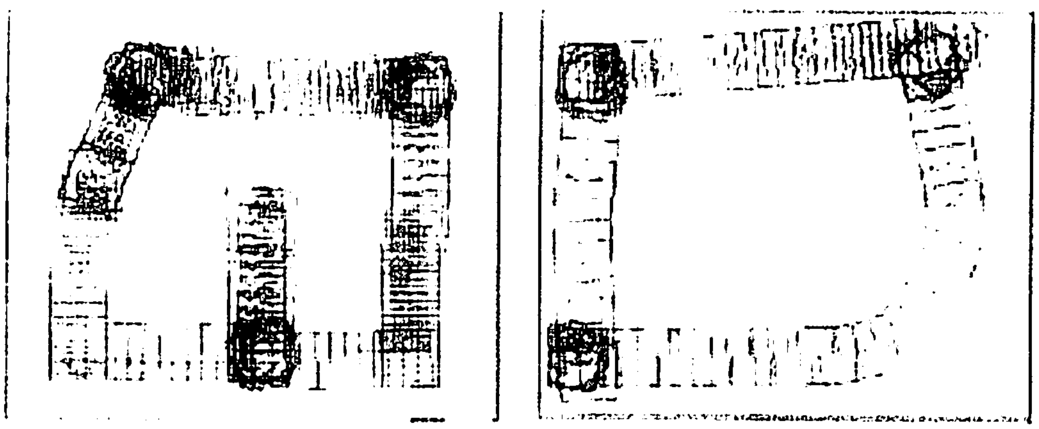


Figure 13. Enlargement of regions (a), (b) and (c) in Fig. 12.

shows an enlargement of Fig. 12a–c. Figure 13 shows the deviation of the position between the real robot and the virtual robot, and that the position of the virtual robot is corrected according to the position data from the real robot. We can confirm that compensation between the position of the real robot and the virtual robot has been also realized at each arrow in Fig. 12.

4.3. Teleoperation experiment using a network

Using the developed system, we also examined teleoperation of a mobile robot in the experimental environment in the presence of a second robot. Both robots were operated by a human operator, the first robot being operated using a virtual world and the second robot being operated only by direct information. The position data of the second robot was communicated via the Internet. The data was received by the developed system and displayed in the virtual world. The human operator can operate the first robot without paying attention to the second robot. The trajectories of each robot are shown in Fig. 14a and b. In Fig. 14a, the starting point of the first robot, which is operated with a virtual world, is the center of the environment. The starting point of the direct-operated robot is the lower-left corner (Fig. 14b). In this experiment, the direct-controlled robot (without a virtual world) collided with the upper wall. However, the robot using a virtual world did not collide with anything. This indicates the validity of the proposed system on a real network. Figure 15 shows the combined trajectories of Fig. 14a and b, showing that the experiment was done without collision between the two robots. Under the experimental conditions, we confirmed the teleoperation of the robots successfully without any interruption of either robot system.



(a) (b)

Figure 14. Trajectory of real robots in the same environment. (a) Robot operated with a virtual world. (b) Directly operated robot.

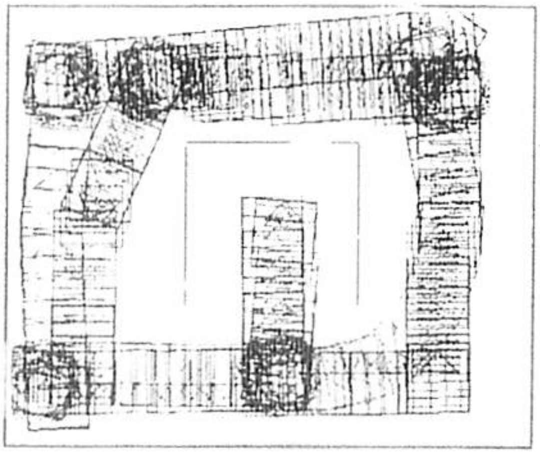


Figure 15. Combined trajectories of Fig. 14a and b.

5. CONCLUSION

In this paper we have proposed the framework of a human interface system for teleoperation of a mobile robot. The prototype of the teleoperation system was constructed utilizing a virtual world as an operation interface. A human operator could simultaneously operate a robot in the real world as well as in a virtual world that could compensate for the incomplete data transfer to the real robot. We have confirmed that teleoperation utilizing a virtual world is much better than teleoperation without a virtual world, and we have experimentally confirmed the correction of the deviation of the position between the real robot and the virtual robot. Moreover, under the experimental conditions, we have confirmed the successful teleoperation of two robots without any interruption of each robot system.

For our future work we will not consider operating in an unknown environment. Next, we are going to integrate an autonomous system and our developed system. Finally, we will operate plural robots in an unknown environment.

REFERENCES

1. T. Suzuki, T. Fujii, H. Asama, K. Yokota, H. Kaetsu, N. Mitomo and I. Endo, Cooperation between a human operator and multiple robots for maintenance tasks at a distance, in: *Distributed Autonomous Robotic Systems 2*, pp. 50–59. Springer, Berlin (1996).
2. T. Suzuki, T. Fujii, H. Asama, K. Yokota, H. Kaetsu and I. Endo, A multi-robot teleoperation system utilizing the Internet, *Advanced Robotics* **11** (8), 781–797 (1998).
3. K. Kawabata, T. Ishikawa, T. Fujii, T. Noguchi, H. Asama and I. Endo, Teleoperation of autonomous mobile robot under limited feedback information, in: *Proc. Int. Conf. on Field and Service Robotics*, pp. 158–164 (1997).
4. K. Kawabata, T. Ishikawa, H. Asama and I. Endo, Mobile robot teleoperation with local storages, in: *Proc. IEEE Int. Conf. on Control Applications*, pp. 1141–1145 (1999).
5. T. Ishikawa, K. Kawabata, Y. Ueda, H. Asama and I. Endo, Graphical user interface for collaborative system of human and mobile robots with sensors, in: *Distributed Autonomous Robotic Systems 3*, pp. 319–328. Springer, Berlin (1998).

6. T. Sekimoto, T. Tsubouchi and S. Yuta, A simple driving device for a vehicle — Implementation and evaluation, in: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 147–154 (1997).
7. H. Hirukawa, T. Matsui and S. Hirai, A prototype of standard teleoperation systems on an enhanced VRML, in: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 1801–1806 (1997).
8. M. Mitsuishi, K. Tanaka, Y. Yokokohji and T. Nagao, Remote rapid manufacturing with 'Action Media' as an advanced user interface, in: *Proc. Int. Conf. on Robotics and Automation*, pp. 1782–1787 (1999).
9. Y. Inagaki, H. Sugie, H. Aisu, S. Ono and T. Unemi, Behavior-based Intention Inference for Intelligent Robots Cooperating with Human, in: *Proc. Int. Joint Conf. 4th IEEE Int. Conf. on Fuzzy Systems and 2nd Int. Fuzzy Engineering Symp.*, pp. 1695–1700 (1995).
10. Y. Masson and R. Fournier, EVEREST: a virtual reality interface to program a teleoperated mission, in: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 1813–1817 (1997).
11. J. A. Adams, R. Bajcsy, J. Kosecka, V. Kumar, R. Mandelbaum, M. Mintz, R. Paul, C. Wang, Y. Yamamoto and X. Yun, Cooperative material handling by human and robotic agents: module development and system synthesis, in: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 200–205 (1995).
12. T. B. Sheridan, Space teleoperation through time delay: review and progress, *IEEE Trans. Robotics Automat.* **9** (5), 592–606 (1993).
13. M. Mitsuishi, Y. Chotoku and T. Nagao, Tele-guidance system using 3D-CG and real-time tracking vision, in: *Proc. 5th IEEE Int. Workshop on Robot and Human Communication*, pp. 172–175 (1997).
14. H. Asama, M. Sato, L. Bogoni, H. Kaetsu and I. Endo, Development of an omni-directional mobile robot with 3DOF decoupling drive mechanism, in: *Proc. Int. Conf. on Robotics and Automation*, Vol. 2, pp. 1925–1930 (1995).
15. K. Kawabata, T. Sekine, T. Ishikawa, H. Asama and I. Endo, Direct mobile robot teleoperation via Internet, *J. Robotics Mechatron.* **11** (1), 54–59 (1999).
16. T. Sekine, T. Suzuki, T. Oura, K. Kawabata, T. Fujii, H. Asama, K. Sato and I. Endo, Mobile robot teleoperation system with virtual environment, in: *Proc. 7th IEEE Int. Workshop on Robot and Human Communication*, Vol. 2, pp. 613–618 (1998).
17. T. Sekine, T. Suzuki, K. Kawabata, T. Fujii, H. Asama and I. Endo, Mobile robot teleoperation system utilizing virtual world, in: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Vol. 3, pp. 1727–1732 (1999).

ABOUT THE AUTHORS

Kuniaki Kawabata received the BE, ME and PhD degrees in Electrical Engineering from Hosei University in 1992, 1994 and 1997, respectively. He joined the Biochemical Systems Laboratory at RIKEN (The Institute of Physical and Chemical Research) as a Special Postdoctral Researcher from 1997 to 2000. In 2000, he joined the Advanced Engineering Center at RIKEN as a Research Scientist. His research interests cover robotic teleoperation, distributed autonomous robotic systems (DARS), emergent systems and adaptive mechanisms. He is a member of RSJ, SICE, IEEJ, JSAI and IEEE.

Takeshi Sekine received the BE and ME degrees in Industrial Chemistry from the Science University of Tokyo in 1997 and 1999, respectively. He joined Ajinomoto Co. in 1999. His research interests cover mobile robot teleoperation systems and human interfaces.

Tsuyoshi Suzuki graduated from Tokyo University in 1992 and received the Doctor degree of Engineering from Saitama University in 1998. He joined the Institute of Physical and Chemical Research (RIKEN) as a Junior Research Associate from 1996 to 1998, and as a Contract Researcher from 1998 to 1999. He is currently a Postdoctoral Researcher in RIKEN. His main interests are distributed autonomous robotic systems and human–robot interaction. He is a member of RSJ, JSME and JSPE.

Teruo Fujii received the BE, ME and PhD degrees in Naval Architecture and Ocean Engineering from the University of Tokyo in 1988, 1990 and 1993, respectively. He served as an Associate Professor of Globe Engineering at the Institute of Industrial Science (IIS), University of Tokyo from 1993 to 1995, and he was with the Biochemical Systems Laboratory at the Institute of Physical and Chemical Research (RIKEN) from 1995 to 1999. In 1999, he joined the IIS again where he is currently an Associate Professor at the newly founded Underwater Technology Research Center. His research interests cover distributed autonomous robotic systems and microbiochemical systems. He is a member of AAAS, ACS and IEEE.

Hajime Asama received the BE, ME and PhD from the University of Tokyo in 1982, 1984 and 1989, respectively. He joined the Chemical Engineering Laboratory of the Institute of Physical and Chemical Research (RIKEN) in 1986, and is currently a Senior Scientist of the Department of Research Fundamentals Technology and Biochemical Systems Laboratory, and the Leader of the Extreme Conditions Mechatronics Team of RIKEN. He was also a Visiting Professor at the Cooperative Research Center of Saitama University in 1998. He received the Promotion of Advance Automation Technology Award in 1992, JSME Robomec Award in 1995, JSME Best Poster Award in 1996, RoboCup97 Engineering Challenge Award and RoboCup98 Japan Open JSAI award as a member of UTTORI United Team. He played an editorship of *Distributed Autonomous Robotics Systems*, Vols 1 and 2, which were published by Springer-Verlag in 1994 and 1996, respectively. His main interests are distributed autonomous robotic systems, cooperation of multiple autonomous mobile robots, maintenance robots and intelligent bioprocess systems. He is a member of RSJ, JSME, IEEE, New York Academy of Science, etc.

Isao Endo graduated from the University of Tokyo in 1965 and received a Doctor of Engineering degree from the University of Tokyo in 1970. He joined RIKEN (The Institute of Physical and Chemical Research) in 1970 and is currently a Chief Scientist of the Biochemical Systems Laboratory. Since 1989 he has been co-appointed as a Visiting Professor of Saitama University. In 1994 he received a Honorary Doctor of Engineering from Helsinki University of Technology. His main interests are bioprocess engineering and distributed autonomous robotic systems. He is a member of the New York Academy of Science, AIChE, ACS, Engineering Academy of Japan, etc.