Advanced Robotics, Vol. 17, No. 3, pp. 199–217 (2003)

Also available online - www.vsppub.com

Full paper

Telexistence cockpit for humanoid robot control

SUSUMU TACHI [1,*], KIYOSHI KOMORIYA [2], KAZUYA SAWADA [3], TAKASHI NISHIYAMA [3], TOSHIYUKI ITOKO [4], MASAMI KOBAYASHI [4] and KOZO INOUE [5]

[1] *University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[2] *AIST, MITI, 1-2 Namiki, Tsukuba Science City 305-8564, Japan*
[3] *Matsushita Electric Works, Ltd., 1048 Kadoma, Osaka 571-8686, Japan*
[4] *Kawasaki Heavy Industries, Ltd., 118 Futatsuzuka, Noda, Chiba 278-8585, Japan*
[5] *Fanuc Ltd, Oshino-mura, Yamanashi 401-0597, Japan*

Received 20 June 2001; accepted 4 April 2002

Abstract—In the fiscal year of 1998, The Ministry of Economy Trade and Industry (METI) of Japan launched a national 5-year project called the Humanoid Robotics Project. As a part of this project, we are developing a novel humanoid robot telexistence (tel-existence) system to assist and cooperate with people. This paper describes a newly developed telexistence cockpit for humanoid robot control, and shows a technical demonstration to evaluate the developed cockpit and the robot. A human operator controls the robot within the remote cockpit as if he or she were inside the robot itself. The telexistence cockpit consists of three subsystems: a three-dimensional (3D) audio/visual display subsystem, a telexistence master subsystem, and a communication subsystem between the cockpit and the robot. A series of real images are captured by cameras mounted on the robot and presented on the visual display, and the human operator in the cockpit observes them with a sensation of real-time presence. He or she can intuitively control the arms and hands of the slave robot through the telexistence master subsystem with force feedback.

Keywords: telexistence; telepresence; master–slave system; humanoid robotics project; augmented reality.

1. INTRODUCTION

A teleoperated robot system is useful in various situations such as maintenance of plants or power stations, operation of construction work, supply of aid in the case of an emergency or disaster and care for elderly or handicapped people. A humanoid robot is most desirable as a remote teleoperated robot because of its functionality,

*To whom correspondence should be addressed. E-mail: tachi@star.t.u-tokyo.ac.jp

size an shape to realize the required tasks by substituting human activities in the remote site.

In order to easily control the remote humanoid robot from a local site, it is important to provide a natural sensation of presence to an operator, such as visual, auditory, tactile and force sensations, as if the operator felt them directly in the remote site. The concept of the system that makes it possible for an operator at the control to perform remote manipulation tasks dexterously using a remote robot by intuitively providing the natural sensation of presence to the operator is called telexistence (tel-existence) [1] in Japan and telepresence [2] in the USA.

Before the concept of telexistence was proposed, there were several systems which aimed at a similar goal. In Italy, Mancini *et al.* developed a mobile teleoperated robot system, Mascot [3], as early as in 1960s. In France, Vertut *et al.* developed a teleoperation system which controlled a submarine for deep submergence technology [4] in 1977. Although these remote robots were not humanoid types and no sensation of presence was provided in a strict sense, the systems were very close to telexistence in a sense. Hightower *et al.* in the US developed a humanoid (upper body)-type telexistence system, called Greenman [5], during 1983 to 1988. TOPS (TeleOperator/telePresence System) [6] was made in the post project of Greenman.

In Japan, a telexistence system called TELESAR (Telexistence Surrogate Anthropomorphic Robot) has been developed as a part of the Advanced Robotics Project in Hazardous Environments (1983–1990) of METI (Japanese Ministry of Economy, Trade and Industry) to realize the advanced teleoperated robot control system in hostile environments [7, 8]. It was extended to the development of robots in human coexistence environments [9–11]. Through these studies the telexistece design procedure has been established.

After a 2-year feasibility study called Human Friendly Network Robotics (FNR), which was conducted from April 1996 till March 1998, METI launched a National Applied Science & Technology Project, 'Humanoid and Human Friendly Robotics (HRP)', in 1998. It is a 5-year project toward the realization of a safe and reliable human-friendly robot system capable of carrying out complicated tasks and supporting humans within the sphere of human lives and activities by providing humanoids, control cockpits and virtual robots for simulation.

Within HRP, as shown in Fig. 1, we have applied our telexistence technology to a new type of cockpit system for controlling a humanoid biped robot.

Visual feedback with a sensation of presence and force feedback not only to upper limbs but also to a hip for mobility sensation of the humanoid robot are the vital key parts as well as other supporting systems such as the communication system and the hand system. In this paper, we describe our design concept and method of a newly developed telexistence cockpit for humanoid robot control, and demonstrate the effectiveness of the cockpit designed for the humanoid robot. This was the world premier experiment of controlling a humanoid biped robot using telexistence, i.e. teleoperation with a real-time sensation of presence.

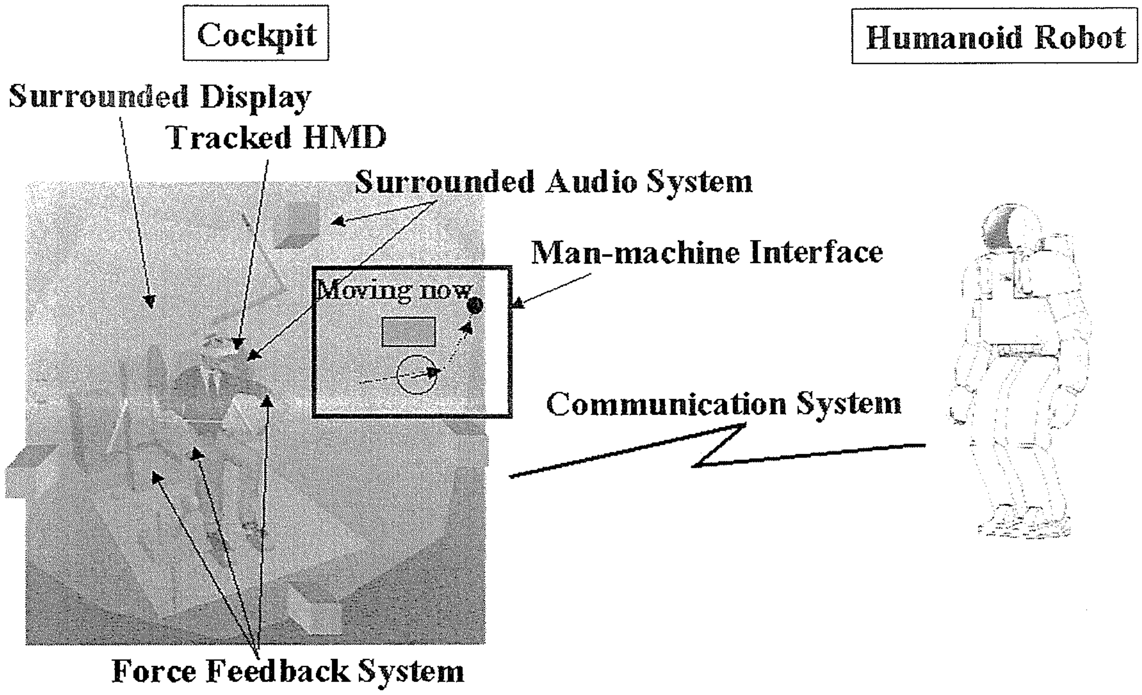


Figure 1. Concept of the telexistence cockpit system.

2. TELEXISTENCE COCKPIT

2.1. Total system architecture

The telexistence cockpit that has been developed in this project (Fig. 2) consists of three main subsystems: a audio/visual display subsystem, a teleoperation master subsystem, and a communication subsystem between the cockpit and the humanoid robot. Figure 3 shows the total system architecture of the cockpit and the robot.

2.2. Audio/visual display subsystem [12, 13]

In order to address the problem of narrow fields of view associated with head-mounted displays (HMDs), we have recently developed a surround visual display, using immersive projection technology (as adopted in the CAVE [14]). The surround visual display panoramically presents real images captured by a stereo multi-camera system for a wide field of view mounted on the robot, which allows the operator to have the feeling of onboard motion when he or she uses the robot to walk around. (When people walk around, a wide field of view has an important effect on their sense of movement, particularly the outward-directing vectors in the peripheral view.)

In addition, when the human operator uses the robot to manipulate an object at a robot site, he or she needs an image precisely coordinated with his or her head motion. An HMD system with a head-tracking function has been developed to meet these needs. Since a binocular camera platform is originally installed, (we utilized the binocular camera platform that was previously installed on the robot by Honda,

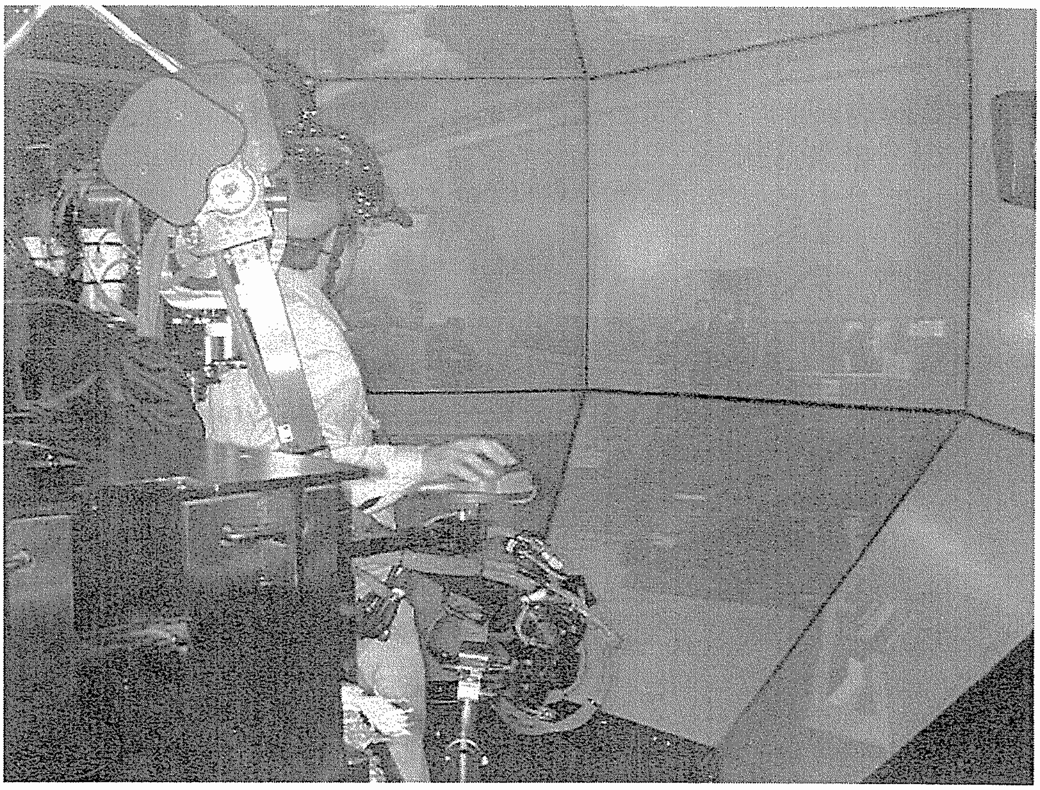


Figure 2. General view of the telexistence cockpit.

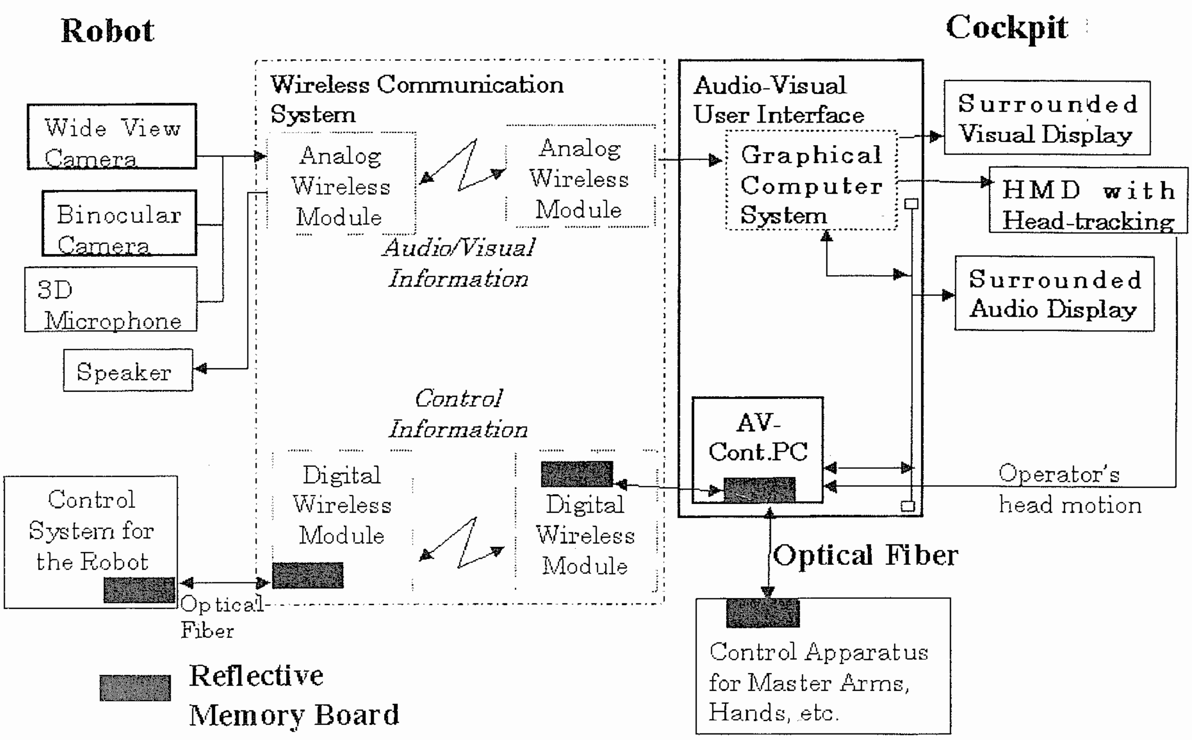


Figure 3. Total architecture of the cockpit and the robot.

Ltd.) the real right and left images captured by the binocular camera are presented on the HMD as the camera precisely follows the operator's head motion in real time.

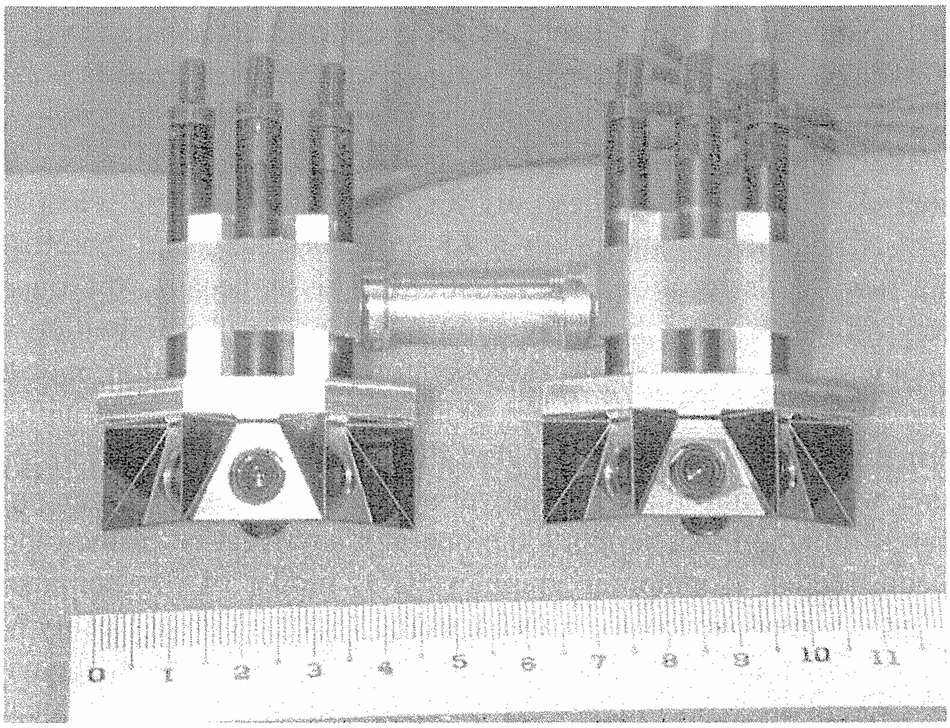


Figure 4. Stereo multi-camera system for a wide field of view (scale in cm).

Also, an augmented reality technique [15] is utilized to support the manipulation of the operator and a virtual environment is supplemented to the real environment images captured by the robot camera. A surround audio display system consists of eight speakers mounted on the robot and headphones worn by the human operator. A three-dimensional (3D) microphone system mounted on the robot detects sound signals around the robot, which are displayed on the eight speakers and the headphones.

The surround visual display, shown in Fig. 2, is composed of nine screens, each 152.4 cm (60 in) along the diagonal. Two projectors are located on the back of each screen to display polarized right-eye and left-eye images. The operator wears polarizing glasses to assemble a stereo image.

The stereo multi-camera system for the wide field of view mounted on the robot is shown in Fig. 4. There are two sets of four small cameras: one set for each eye, separated by a distance of 65 mm. Each camera corresponds to one screen. The real images captured by the multi-camera system are presented on the four screens of the surround visual display: left, right, center and bottom. Thus, the field of vision is set at 150° in the horizontal, 19° in the upper vertical and 58° in the lower vertical directions.

When the human operator manipulates an object through the robot hands, he looks at the real images presented on the HMD. The HMD system with head-tracking function has a counter-balancing mechanism so that the operator is not bothered by the weight of the HMD he or she is wearing. Three axes are installed on the top portion of a head, the left and right portions of the ears, and the top portion of the head, respectively. These axes enable the operator to move his head in thepan, tilt and roll directions. The measurement cycle of the head tracking is 300 Hz (maximum) and the time delay is lower than 2 ms. The field of view of the HMD is 48° horizontally and 36° vertically.

If a visual user interface provides only a camera image during teleoperation of the robot, it is possible for the operator to get disoriented, and therefore unable to navigate the robot's location or orientation. This is because the operator has to perceive and assess the robot's situation based on local information provided from the camera. In order to help the operator assess a situation and decide an appropriate control action for the robot, (s)he needs to be provided with not only local information from the camera but also global information.

Therefore, we have introduced the novel system of augmenting camera images with global information that supports the operator's navigation of the robot. Here, we have constructed a computer graphics (CG) model of the humanoid robot operating in the virtual environment (VE), using VRML (Virtual Reality Modeling Language), as shown in Fig. 5. The VE is constructed to show the real environment where the real robot is operating. As described in Section 4, the location and orientation of the real robot is shown as the CG robot in the VE. We have both the CG model in the VE and camera images presented on the surrounded visual display, as shown in Fig. 2.

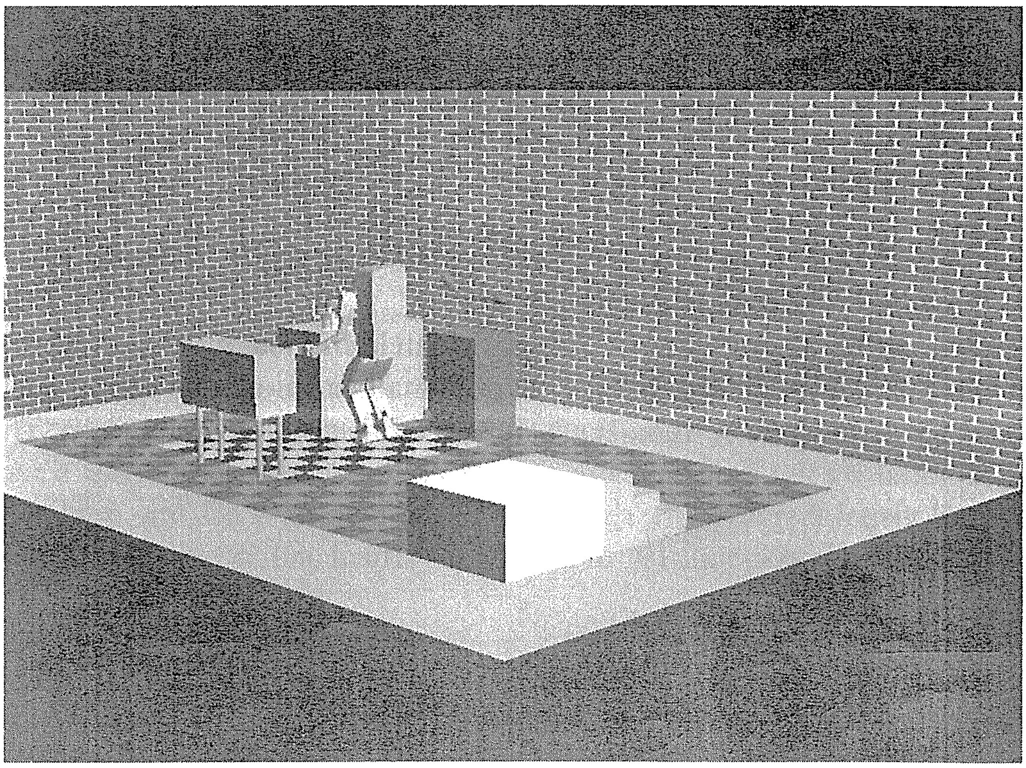


Figure 5. Graphical model of the humanoid robot in a virtual environment.

2.3. Teleoperation-master subsystem [16, 17]

The telexistence teleoperation master system, shown in Fig. 6, consists of left and right master arms, each with a gripping operation device, a motion-base and a 3D mouse.

When using the teleoperation master system, a human operator leans on a seat on the motion base, attaches the gripping operation device and grips the master arm. Through the master arm and the gripping operation device, the operator can remotely manipulate the robot arms with their hands. The motion base can display vibration, shock and acceleration acting on the robot, as well as the relative displacement of the robot's upper body from a reference position based on the inclination of the operator.

Each master arm is designed as an exoskeleton type and has 7 d.o.f. This redundancy in the d.o.f. allows the operator to execute multiple postures of a slave arm directly using an elbow posture, the motion of which is tracked by a joint motor on each master arm and measured by optical sensors located on the lower links. The other joint motors generate appropriate force (up to 10 N) based on the feedback force from the slave arm, which allows the operator to feel force and moment naturally.

Each master arm has a recently developed gripping device, with which an operator can easily operate open–close motion by feeling the gripping force of the slave robot.

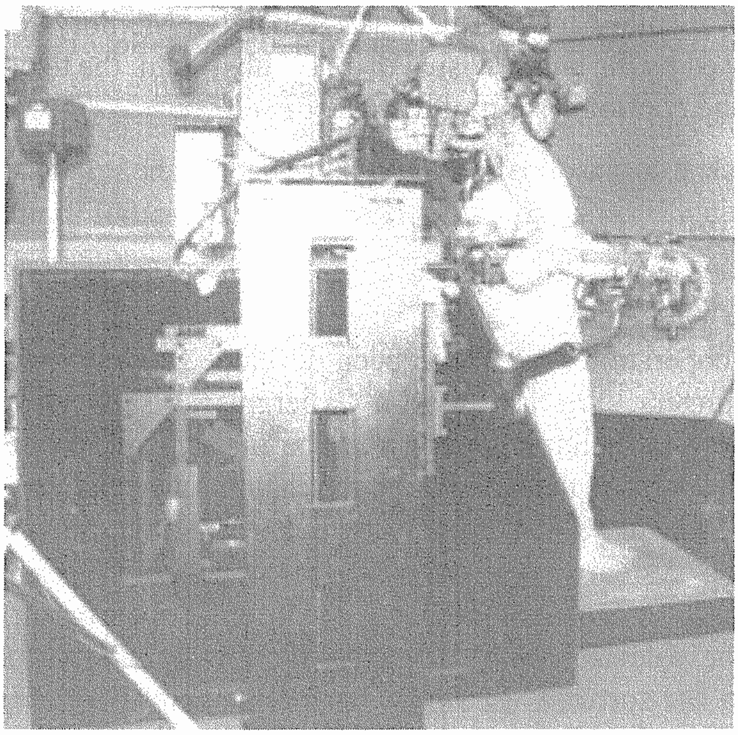


Figure 6. General view of the teleoperation master system.

In order to realize small and lightweight mechanisms as well as a wide operation space for the thumb and the index finger, a wire tension mechanism with a passive d.o.f. is used to facilitate the thumb's radial abduction and ulnar adduction.

The developed motion base system allows the operator to experience locomotion of a humanoid robot with a sensation of reality by representing its acceleration, posture and motion. The motion base provides the operator with a sensation of walking, displacement and upper body inclination by driving the seat position under the operator's standing posture. In order to minimize the displacement of an operator's focal point, the motion base system limits locomotive motion to a 3 d.o.f. translation: back and forth (surge), left and right (sway), and up and down (heave).

The teleoperation master system has a 3D mouse for the operator to input commands to the main control program, such as control mode change. The computation time for controlling these subsystems is within 5 ms and the teleoperation master system communicates with the robot periodically. We carried out various teleoperation tests by using the developed teleoperation master system, and the results reveal that kinesthetic presentation by using the master system with visual image greatly improves both the operator's sensation of walking and dexterity at manipulating objects.

2.4. Communication subsystem

The communication system between the cockpit and the robot consists of two main subsystems: one for communicating audio/visual information and the other for control information. The audio and visual information is transmitted through an analog communication module. The control information is exchanged and shared through a shared memory module called a Reflective Memory Module, which is shared and accessed by the audio/visual display subsystem, the teleoperation master subsystem, and the control system of the robot itself.

3. HAND TELEOPERATION SYSTEM

3.1. System

A robot hand teleoperation system has been developed to teleoperate a slave robot hand with four fingers. We have used a Cybergrasp system as a master hand to control the slave robot hand in real-time. The master hand system consists of a Cyberglove, which senses the orientation of each of the operator's fingers, and a Cybergrasp, which displays information of the slave hand to the operator. Attached to the Cybergrasp system is a Polhemus tracker, which can sense position and rotation in 3D space by measuring the operator's wrist position, in order to control the robot arm. These devices are connected to the Engineering Work Station (EWS) shown in Fig. 7. The software on the EWS translates information from the master hand into control commands for the slave hand and likewise translates information from the slave hand into control commands for the master hand.

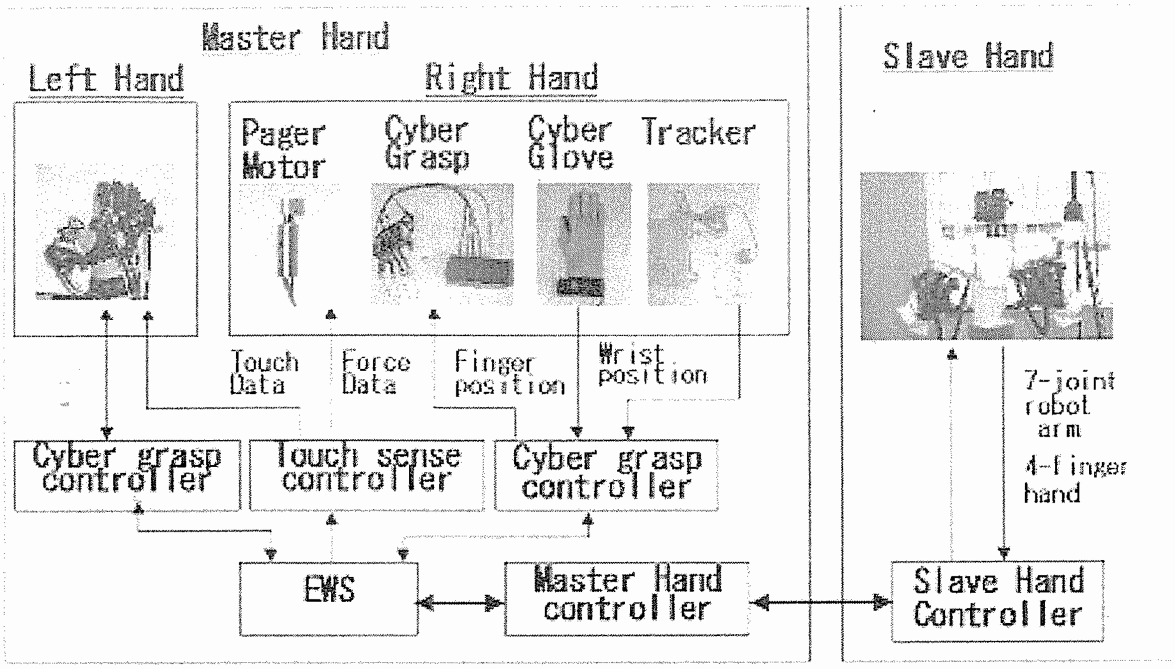


Figure 7. Hand teleoperation system.

3.2. Function

We have developed two function modules to meet the demand of the use for translating interactive information of master and slave hand systems.

3.2.1. Translation using five to four correspondence. Data from the five fingers of the master hand is translated into data for the four fingers of the slave hand. This was developed for grasping objects (Fig. 8a). The placement and force feedback of the finger's tip of a slave hand is calculated as follows. A line that is shaped from the finger's tips of a master hand is approximated to a curve and the finger's tips of a slave hand is placed along the curve. The force feedback of a slave hand is made from a distribution of force of a master hand. However, it is difficult to grasp a small object for this translation.

3.2.2. Translation using four to four correspondence. Data from the first four fingers of the master hand is translated into data for the corresponding fingers of the slave hand. This was developed for picking small objects (Fig. 8b).

4. EVALUATION OF THE DEVELOPED COCKPIT

4.1. Evaluation of the telexistence cockpit

In order to evaluate the usability of the cockpit for HRP robots, we carried out an experiment that had an operator walk around and manipulate objects by utilizing a humanoid robot as his surrogate. To demonstrate the possibility of using the

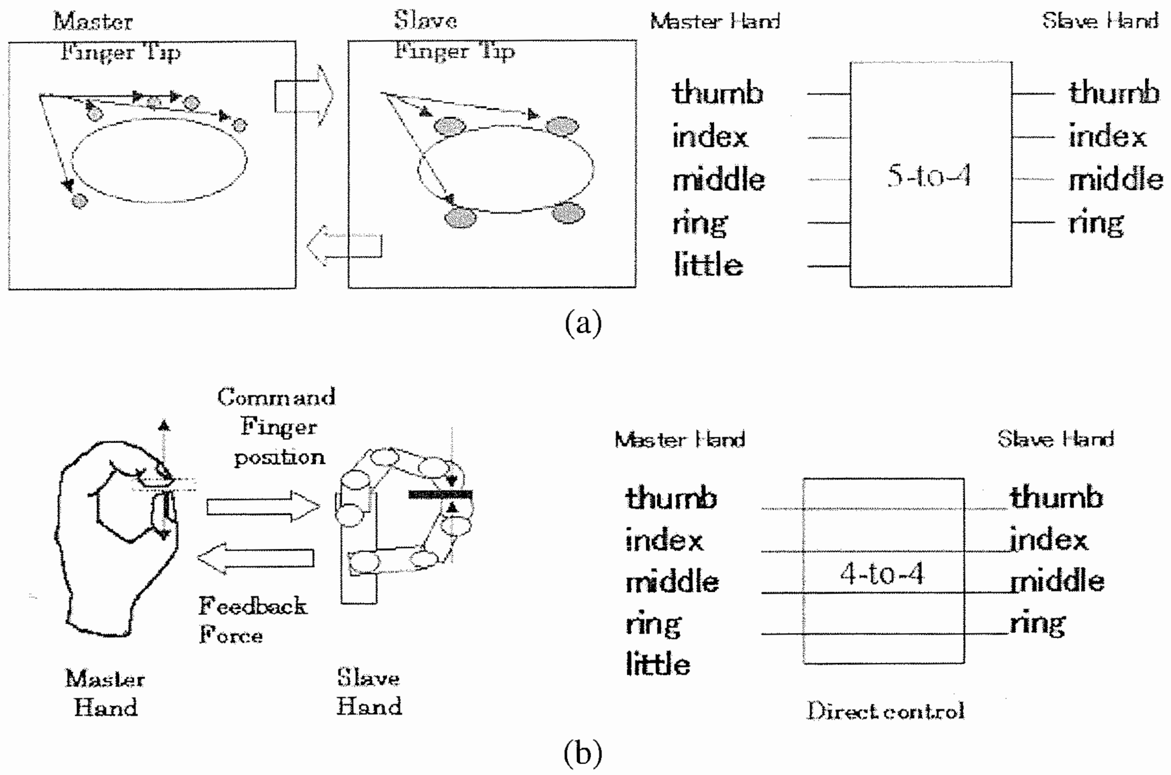


Figure 8. (a) Five to four translation. (b) four to four translation.

developed system in the field of service robots, we built a mock-up shopping zone in a real environment 3.5 × 6.0 m in size. We set a humanoid robot inside the mock-up and a human operator in the telexistence cockpit in the remote site to control the robot with a sensation of presence. The operator navigated the robot as if he were inside the robot, and manipulated the robot's arms and hands to handle a stuffed animal, stack blocks, open and close a glass window, pick up a can from the inside, place the can into a basket, etc.

When the operator controlled the robot to walk around, he wore polarizing glasses and leaned on the sheet of the motion base. On the bottom-left screen of the surrounding visual display, an operational menu appeared as shown in Fig. 9. The menu included a 2D map of the environment and a series of operational commands to the robot. The operator uses the 3D mouse to indicate on the map an objective location and orientation for the robot to reach, and the menu system automatically generated a path to reach the goal. If the operator issued a command to move the robot, the robot actually walked to the goal.

While the robot walked around, the real images captured by the multi-camera system for the wide field of view were displayed on four screens of the surrounding visual display shown in Fig. 10. This made the operator feel as if he were inside the robot, walking around the robot site. A CG model of the robot in the virtual environment was represented and updated according to the current location and orientation received from the real robot. It was displayed on the bottom-right screen of the surround visual display (Fig. 5) and when augmented to the real images captured by the camera system, it supported the operator's navigation of the robot.

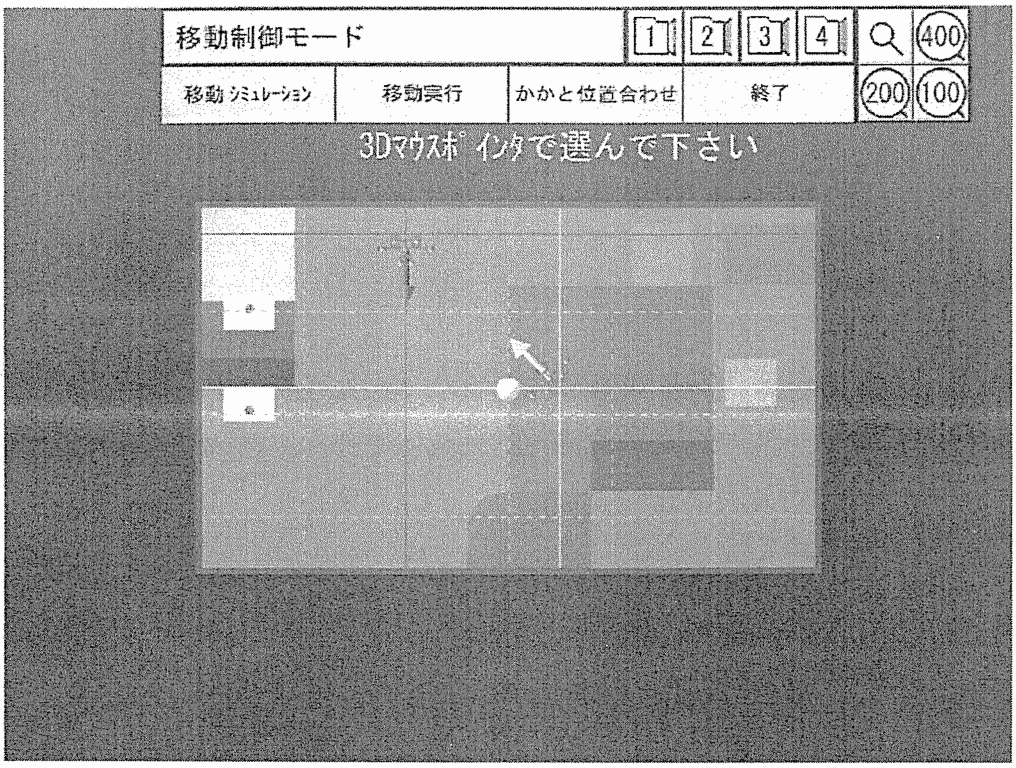


Figure 9. An example of the operational menu.

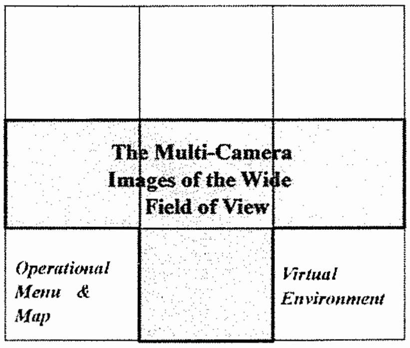


Figure 10. Location of image on the surround visual display.

Figure 11 illustrates the way in which the robot steps down stairs. Since the series of real images presented on the visual display are integrated with the movement of the motion base, the operator feels the real-time sensation of walking or stepping up and down.

If no motion is presented to the operator, an operator easily get sick because of the up and down motion of the images presented to the operator as the robot moves. However, thanks to the motion base system that moves synchronized with the presented images, the observed images becomes stabilized, so the operator is prevented from getting dizzy.

In order to change the control mode from walking to manipulation, the operator selected from the menu, wore the HMD, and used the left and right master arms and

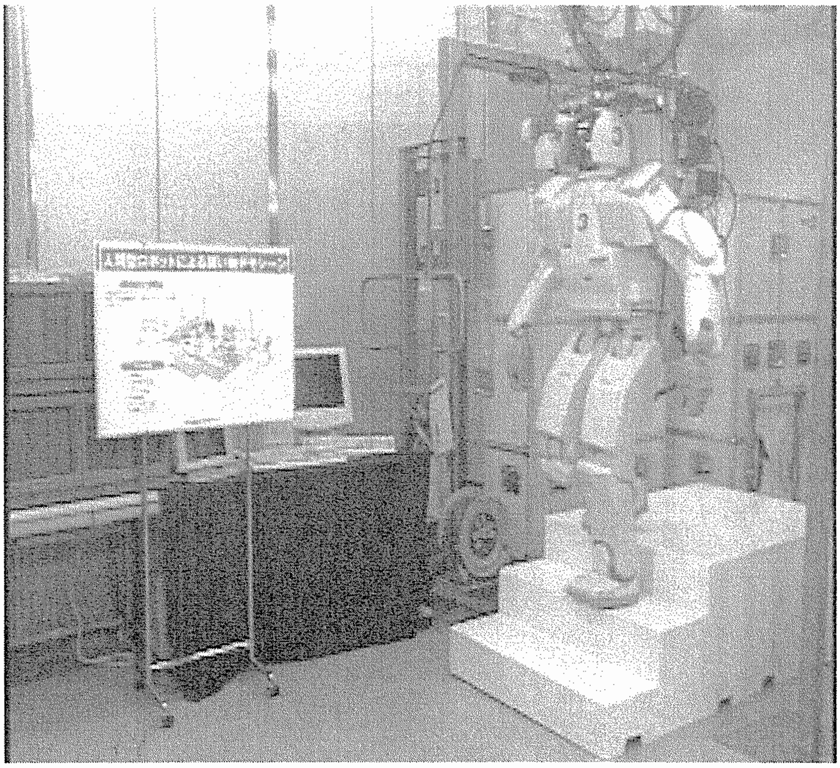


Figure 11. Robot stepping down stairs.

Figure 12. Image displayed on the HMD.

hands to control the arms and hands of the slave robot. Real images were presented on the HMD as shown in Fig. 12.

Figure 13 shows a photograph of picking up a can as an example. The operator observed the binocular camera images on the HMD, and captured a can with the

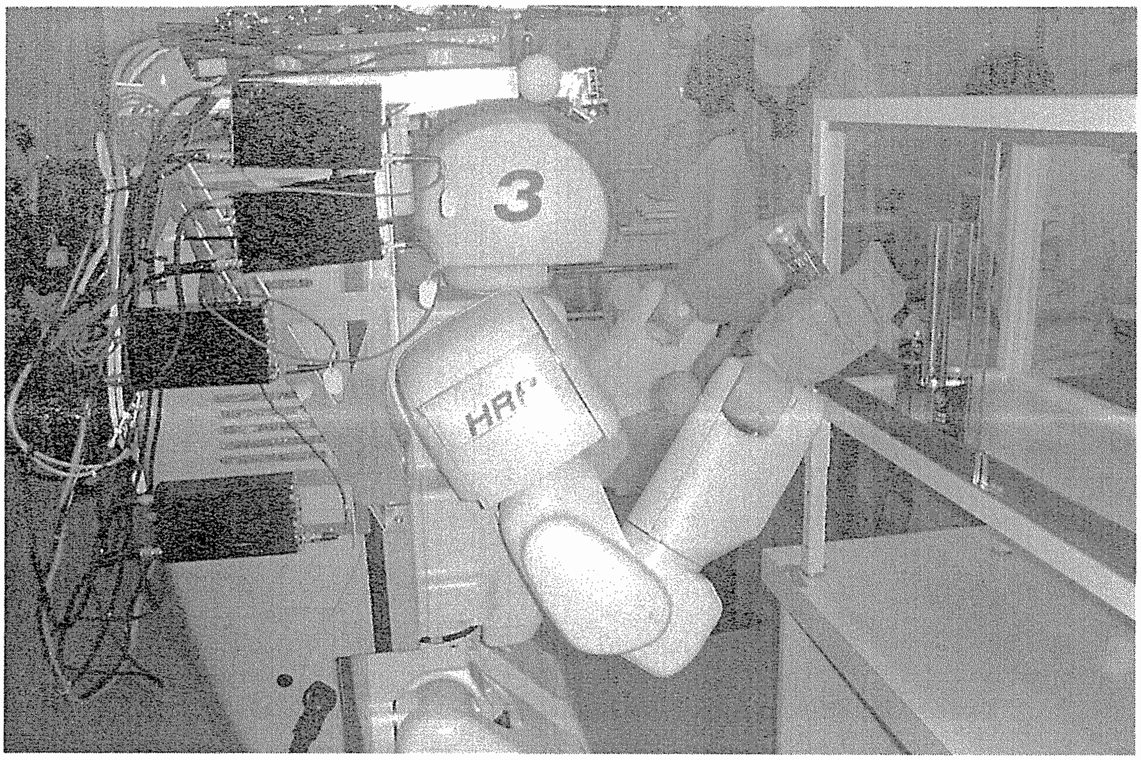


Figure 13. Picking up a can.

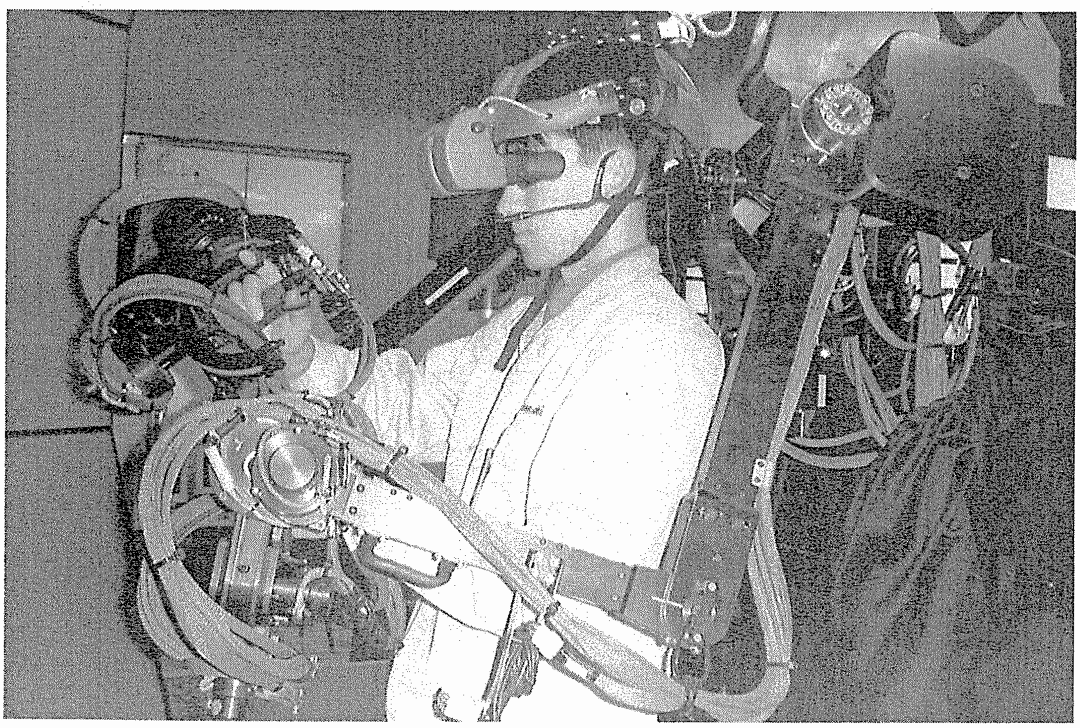


Figure 14. Operator in the cockpit.

arms and hands of the robot by operating the master arms and hands, while he felt a force feedback received from the robot hands shown in Fig. 14. Figure 15 illustrates the robot handing over the can to a child.

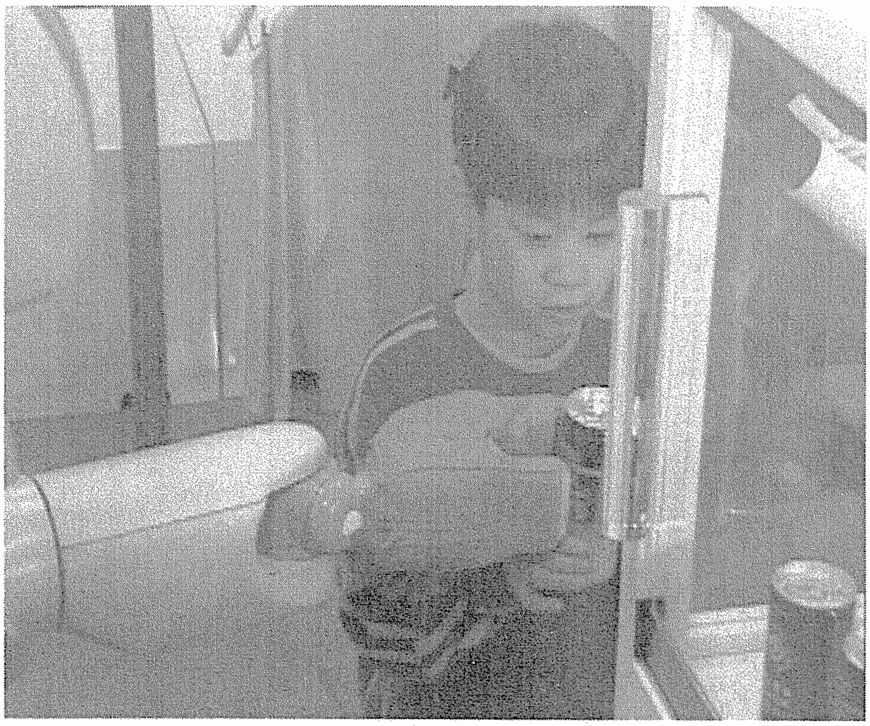


Figure 15. Robot handing over a can to a child.

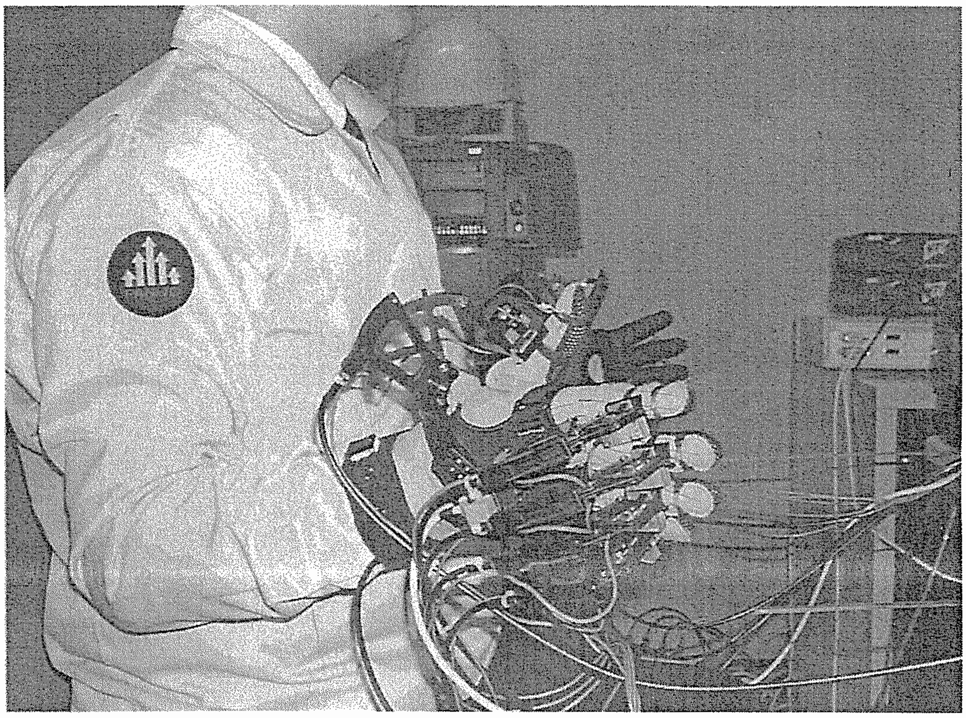


Figure 16. Initial position of the operator.

4.2. Evaluation of teleoperation of a robot hand

As an operator operates the attached master hand, he sees the 3D picture received from the camera mounted on the head of the fixed slave robot and receives a sensation of grasping an object, as shown in Fig. 16. As an evaluation task, we tried

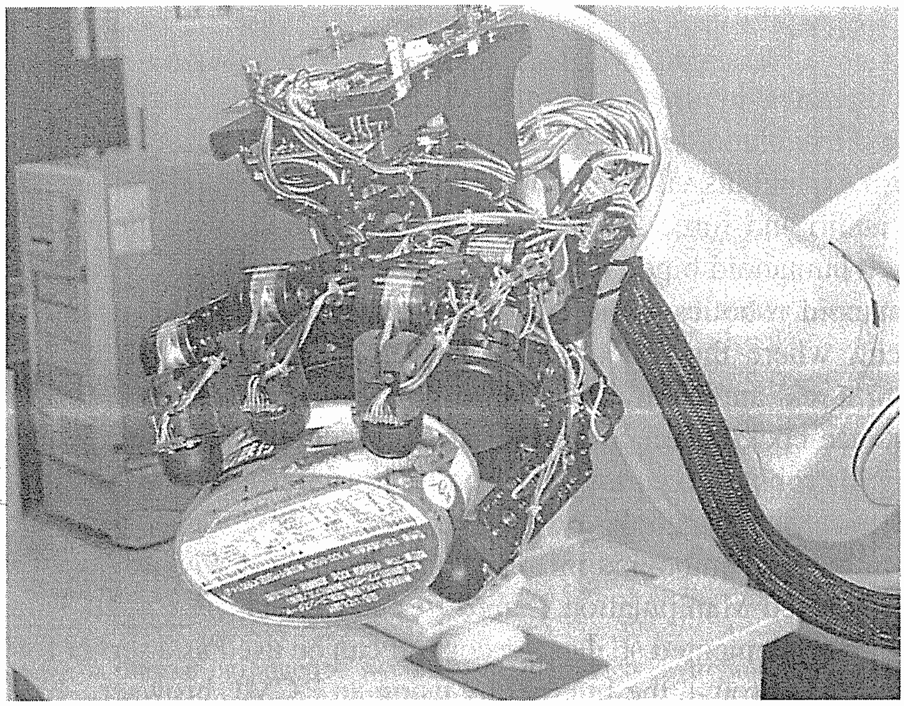


Figure 17. Grasping a can.

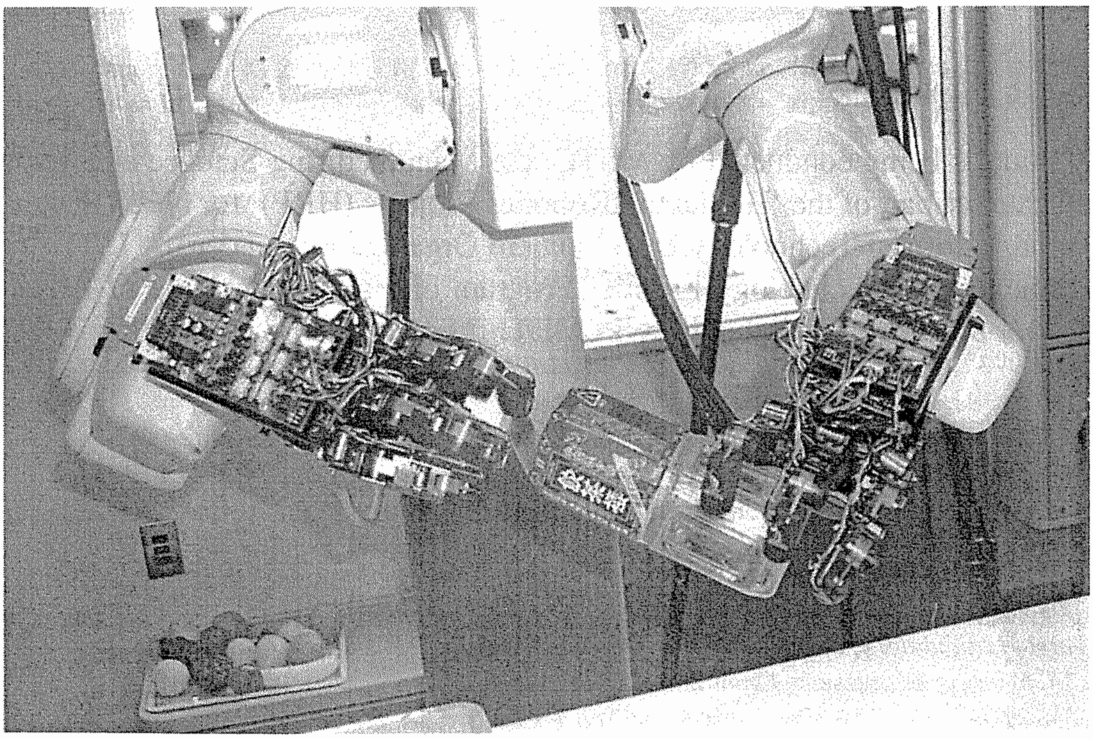


Figure 18. Exchanging an object from hand to hand.

to grasp a variety of objects (varying in shape, size and consistency) and to pack the objects into a box. Figure 17 shows that the grasping operation is made possible by the function of the translation modules. Figure 18 shows the robot exchanging an object from hand to hand by robot arm control.

5. CONCLUSION

A human operator in the telexistence cockpit we developed can navigate and manipulate the humanoid robot as his surrogate as if he were inside the robot itself, and can also expand his visual, audio and tactile abilities through the augmentation of visual, audio and force feedback. This is the first experiment and success of controlling a humanoid biped robot using telexistence.

The humanoid robotics project is now stepping up to the second phase of its development, where the robot and the developed cockpit will be practiced and evaluated in a real application field mentioned in Section 1. A human operator in the telexistence cockpit can communicate with people around the humanoid robot by utilizing the robot as a communication tool or interface, i.e. those in the cockpit can communicate with people around the robot by sharing not only audio/visual information, but also embodied information, as shown in Fig. 15.

RCML (R-Cubed Manipulation Language) and RCTP (R-Cubed Transfer Protocol) [11] were implemented so that the cockpit can be used as a server for the control of the HRP robot through the Internet by using an RCML browser.

Thus, we conclude that the telexistence cockpit will be used as a human tool for the augmentation of human ability, especially in expanding the limits of space and time.

Acknowledgements

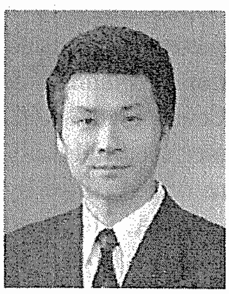
This study is being conducted by MSTC, the Manufacturing Science and Technology Center as part of the 'Humanoid Robotics Projects (HRP)' for NEDO, New Energy and Industrial Technology Development Organization, under the ISTF, Industrial Science and Technology Frontier Program of National Institute of Advanced Industrial Science and Technology in METI, Ministry of Economy, Trade and Industry.

REFERENCES

1. S. Tachi, K. Tanie, K. Komoriya and M. Kaneto, Tele-existence (I): design and evaluation of a visual display with sensation of presence, in: *Proc. 5th Symp. on Theory and Practice of Robots and Manipulators*, Udine, Italy, pp. 245–254 (1984).
2. M. Minsky, Telepresenc, *Omni* **2** (9), 44–52 (1980).
3. H. A. Ballinger, Machines with Arms, *Sci. J.* October, 58–65 (1968).
4. J. Charles and J. Vertut, Cable controlled deep submergence teleoperator system, *Mechanism Machine Theory* **12**, 481–492 (1977).
5. J. D. Hightower, E. H. Spain and R. W. Bowles, Telepresence: A hybrid approach to high-performance robots, in: *Proc. Int. Conf. on Advanced Robotics*, Versailles, France, pp. 563–573 (1987).
6. M. S. Shimamoto, TeleOperator/telePresence System (TOPS) Concept Verification Model (CVM) depelopment, in: *Recent Advances in Marine Science and Technology*, N. K. Saxena (Ed.), pp. 97–104 (1992).

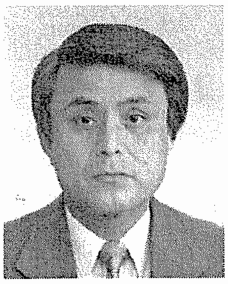
7. S. Tachi, H. Arai and T. Maeda, Development of an anthropomorphic tele-existence slave robot, in: *Proc. Int. Conf. on Advanced Mechatronics*, pp. 385–390, Tokyo (1989).
8. S. Tachi, H. Arai and T. Maeda, Tele-existence master slave system for remote manipulation, in: *Proc. IEEE Int. Workshop on Intelligent Robots and Systems*, pp. 343–348 (1990).
9. E. Oyama, N. Tsunemoto, Y. Inoue and S. Tachi, Experimental study on remote manipulation using virtual reality, *Presence* **2** (2), 112–124 (1993).
10. S. Tachi and K. Yasuda, Evaluation experiments of a teleexistence manipulation system, *Presence* **3** (1), 35–44 (1994).
11. S. Tachi, Real-time remote robotics toward networked telexistence, *IEEE Comp. Graphics Appl.* **18** (6), 6–9 (1998).
12. T. Nishiyama, H. Hoshino, K. Suzuki, R. Nakajima, K. Sawada and S. Tachi, Development of surrounded audio-visual display system for humanoid robot control, in: *Proc. 9th Int. Conf. of Artificial Reality and Tele-existence*, Tokyo, pp. 60–67 (1999).
13. T. Nishiyama, H. Hoshino, K. Suzuki, K. Sawada and S. Tachi, Development of visual user interface embedded in tele-existence cockpit for humanoid robot control, in: *Proc. IMEKO 2000*, Vol. XI (Topic 17 & ISMCR2000), Vienna, pp. 171–176 (2000).
14. C. Cruz-Neira, T. DeFanti and D. Sandin, Surrounded-screen projection-based virtual reality, in: *Proc. SIGGRAPH '93*, pp. 135–142 (1993).
15. J. Rekimoto, A tutorial introduction to computer augmented environments, *Comp. Software* **13** (3), 4–18 (1996) (in Japanese).
16. H. Hasunuma, H. Kagaya, M. Takatori, J. Fujimori, F. Mifune, S. Shikoda, M. Kobayashi, T. Itoko and S. Tachi, Development of teleoperation master system with a kinesthetic sensation of presence, in: *Proc. 9th Int. Conf. on Artificial Reality and Tele-existence*, Tokyo, pp. 53–59 (1999).
17. H. Hasunuma, H. Kagaya, M. Koyama, J. Fujimori, F. Mifune, H. Moriyama, M. Kobayashi, T. Itoko and S. Tachil, Teleoperation master arm system with gripping operation devices, in: *Proc. Int. Conf. on Machine Automation*, pp. 567–572 (2000).

ABOUT THE AUTHORS

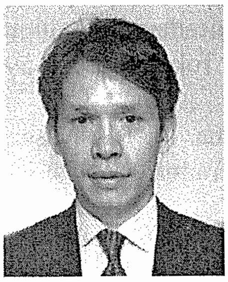


Susumu Tachi received the BE, MS and PhD degrees in Mathematical Engineering and Information Physics from the University of Tokyo in 1968, 1970 and 1973, respectively. He joined the Faculty of Engineering of the University of Tokyo in 1973, and in 1975 moved to the Mechanical Engineering Laboratory, Ministry of International Trade and Industry, Tsukuba Science City, Japan, where he served as Director of the Biorobotics Division. In 1989 he rejoined the University of Tokyo and is currently Professor at the Department of Information Physics & Computing. From 1979 to 1980, he was a Japanese Government Award Senior Visiting Scientist at the Massachusetts Institute of Technology, Cambridge, MA. His scientific achievements include intelligent mobile robot systems for the blind dubbed MELDOG, the Guide Dog Robot (1976–1983) and National Large Scale Project on Advanced Robot Technology in Hazardous Environments, especially advanced human robot systems with a real-time sensation of presence known as Telexistence (Tel-Existence) (1983–1990). He served as Project Leader of the Monbusho Priority Research Area Project called Fundamental Study on Virtual Reality (1995–1999). His present research covers telexistence, real-time remote robotics (R-Cubed) and virtual reality, and he serves as Project Leader of the Tachi CREST Project on Telexistence Communication Systems. He is a Founding Director of the RSJ, a Fellow of the SICE and the Founding President of the Virtual Reality Society of Japan (VRSJ). From 1988 he served as Chairman of the IMEKO (International Measurement Confederation) Technical Committee 17 on Measurement in Robotics.

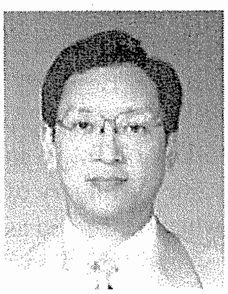
Kiyoshi Komoriya received the BE and ME degrees in Mechanical Engineering from the University of Tokyo in 1974 and 1976, respectively. He joined the Mechanical Engineering Laboratory of MITI in 1976. He has been engaged in research and development mainly in the field of mobile robotics. From August 1986 he stayed at the Robotics Institute of Stanford University for 1 year as a Visiting Scholar. He received DE from the University of Tokyo in 1993. He has been one of the Group Leaders of the Intelligent Systems Institute, National Institute of Advanced Industrial Science and Technology (AIST) from 2001. His current research interests include mobile robots, mobile manipulators, human friendly robotics, etc. He is a member of RSJ, JSME, SICE, SOBIM and IEEE.



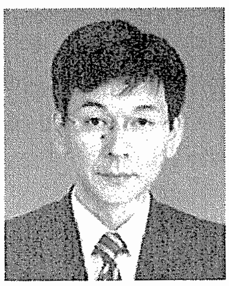
Kazuya Sawada received the BE and ME degrees in Systems Engineering in 1976 and 1978, respectively, from Kobe University, and the DE degree in Systems Engineering in 1995, from Hiroshima University, Japan. He has been with Matsushita Electric Works, Ltd., Osaka, Japan, since 1978. Currently, he is working as a Senior Staff Researcher at the Human Media Research Group, Soft Technology Laboratory, and engaged in research and development on a range of projects and applications related to virtual reality and human interface technologies. He has also been serving as a part-time Lecturer at Osaka Institute of Technology, Osaka, Japan, since 2000.



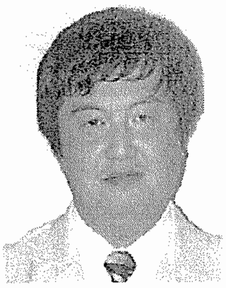
Takashi Nishiyama received the BE, ME and DE degrees in Precision Mechanical Engineering from Kyoto University, Japan in 1986, 1988 and 1994, respectively. He joined Matsushita Electric Works, Ltd., Osaka, Japan, in 1991, and is presently working as a Senior Researcher at the Human Media Research Group, Soft Technology Laboratory. His current research interests include virtual reality, artificial intelligence, spoken dialogue systems and human interfaces.



Toshiyuki Itoko received the BS, MS and PhD degrees in Aeronautics in 1974, 1976 and 1998, respectively, all from the University of Tokyo, Japan. Since 1976 he has been involved in research and development on control systems in Kawasaki Heavy Industries, Ltd. (KHI). He is currently a Senior Manager of the Planning & Control Department of the System Technology Development Center of the KHI. His research interests include vehicle control, man–machine interfaces and robot programming. He is a professional engineer of software engineering certified by the Science and Technology Agency of Japan, a member of the AIAA, SICE and JSME.



Masami Kobayashi received the BE and ME degrees in Mechanical Engineering in 1988 and 1990, respectively, from Meiji Uniersity, Japan, and the PhD degree in Information Sciences in 1996 from Okayama University, Japan. Since 1990 he has been involved in research and development on control systems in Kawasaki Heavy Industries, Ltd. (KHI). He is currently an Assistant Manager of the Research Department of the System Technology Development Center of the KHI. His research focus is the area of robotics, particularly man–machine interface and robot programming. He is a member of the JSME and RSJ. He received the Technical Innovations Award from the RSJ in 2001.



Kouzou Inoue received the BE and ME degrees in Mechanical Engineering from the University of Akita in 1986 and 1988. He joined Fanuc Ltd in 1988 and he joined HRP in 1998. His research interests are in the control of the electrical injection machines and robot offline teaching systems.