Toward the Telexistence Next Generation

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Abstract

Twenty years have passed since the first proposal of telexistence (tele-existence). Telexistence enables a human being to have a sensation of existence in a remote environment where a surrogate robot exists, while being augmented by a virtual environment synthesized by a computer, whose structure is based on the sensor information on board the robot. The concept of telexistence, i.e., virtual existence in a remote and/or computer-generated environment, has developed into a national R&D scheme of R-Cubed (Real-time Remote Robotics) for the advanced and comfortable life of the 21st century human society. Based on the scheme of R-Cubed, in the fiscal year of 1998, Ministry of Economy, Trade and Industry (METI) of Japan launched a national five-year project called Humanoid Robotics Project (HRP). This is an effort to integrate telerobotics, network technology and virtual reality into networked telexistence. This paper reviews how telexistence technology has been developed, and describes a newly developed telexistence cockpit for humanoid robot control, and shows a technical demonstration to evaluate the developed cockpit and the robot. The next generation of telexistence technology using HMP (Head Mounted Projector) and retro-reflective screen is also proposed, and the conducted feasibility experiments are described.

Key words: telexistence, tele-existence, telepresence, virtual reality, master-slave manipulation, humanoid robots, TNG (Telexistence Next Generation), HMP (Head Mounted Projector), retro-reflective screen

1. Introduction

It has long been a desire of human beings to project themselves to a remote environment, i.e., to have a sensation of existence in a different place while actually remaining where they are. Another dream has been to amplify human muscle power and sensory capabilities with machines, while preserving human dexterity through a sensation of direct operation.

In the late 1960s, General Electric proposed a research and development program to develop a powered exoskeleton that a person would wear like a garment, called Hardiman. The concept was that a man wearing the Hardiman exoskeleton would be able to command a set of mechanical muscles that multiply his strength by a factor of 25, yet in this union of man and machine he would feel object and forces almost as if he were in direct contact.

However, the project was unsuccessful for a couple of reasons. First was the potentially dangerous effect of wearing a powered exoskeleton should it malfunction. Second, space inside the machine was needed to store computers, controllers, actuators and energy source, which eliminated the space for a human operator. Thus, the design proved impractical in its original form. With the advent of new science and technology, however, the realization of these dreams again becomes possible with a different concept.

The concept of projecting ourselves by using robots, computers and cybernetic human interface is called telexistence (tel-existence). This concept expands to include projection in a remote real world, or existing in a computer-generated virtual environment. Figure 1 illustrates the original idea of telexistence using the original figure published in 1982 in Japanese [1] and in 1984 in English [2].

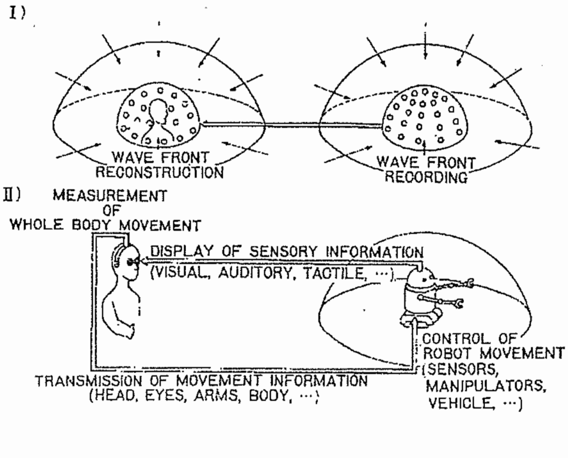

Fig. 1 Principle of Telexistence. (Adopted from [1,2])

The concept of the telexistence was proposed by the author in 1980 and it played the principal role in the eight year Japanese National Large Scale Project "Advanced Robot Technology in Hazardous Environment." The project started in 1983, along with the concept of the third generation robotics. Through this project, theoretical consideration has been done and a systematic design procedure for telexistence systems has been established.

As part of the project, experimental hardware telexistence systems have been developed and the feasibility of the concept has been demonstrated.

In our first reports [1,2], the principle of the telexistence sensory display was proposed, and its design procedure was explicitly defined. Experimental visual display hardware was built, and the feasibility of the visual display with the sensation of presence was demonstrated by psychophysical experiments using a test apparatus (Fig.2).

Fig. 2 First Experimental Apparatus Constructed.

A method was also proposed to develop a mobile telexistence system, which can be remotely driven with the auditory and visual sensation of presence. A prototype mobile tele-vehicle system was constructed and the feasibility of the method was evaluated [3]. Figure 3 shows the tele-vehicle during an experiment.

The first prototype telexistence master slave system called TELESAR (TELExistence Surogate Anthropomorphic Robot) for remote manipulation experiments was designed and developed, and preliminary evaluation experiments of telexistence were conducted by using TELESAR. Quantitative evaluation of the telexistence manipulation system was conducted by using this telexistence master slave system for tracking tasks. By comparing the telexistence master-slave system with conventional master-slave systems, efficacy of the telexistence master-slave system and the superiority of the telexistence method were demonstrated experimentally (Fig.4) [4, 5, 6].

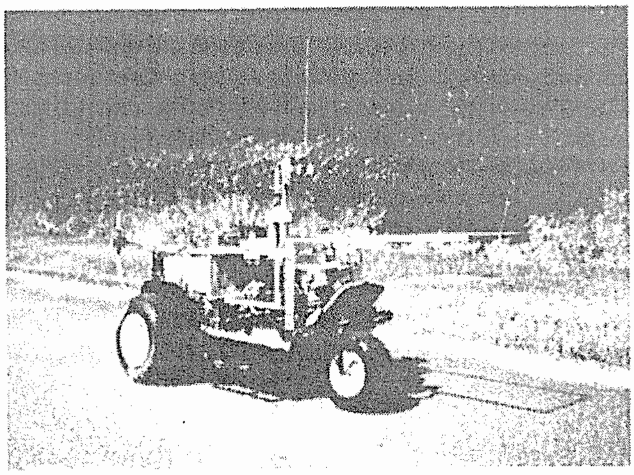

Fig. 3 Mobile Telexistence System (Tele-Viechle).

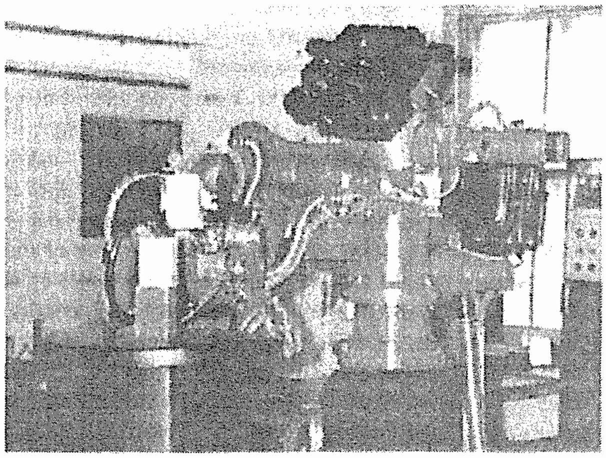

Fig. 4 Telexistence Surrogate Anthropomorphic Robot (TELESAR) at Work.

2. Augmented Telexistence

Telexistence can be divided into two categories: telexistence in the real world, which actually exists at a distance and is connected via a robot to the user's location, and telexistence in a virtual environment, which does not actually exist but is created by a computer. The former can be called "transmitted reality," while the latter is "synthesized reality." The synthesized reality can be classified into two, i.e., a virtual environment as a model of the real world and a virtual environment of an imaginary world. Combination of transmitted reality and synthesized reality, which is called mixed reality, is also possible and has great importance in real applications. This we call augmented telexistence to clarify the importance of harmonic combination of real and virtual environments.

Augmented telexistence can be used in several situations. Taking, for instance, the control of a slave robot in a poor visibility environment, we constructed an experimental augmented telexistence system using a virtual environment [7, 8]. The model environment was constructed from the design data of the real environment.

A model-based calibration system using image measurements was proposed for matching the real environment and a virtual environment. The slave robot had an impedance control mechanism for contact tasks and compensating for errors that remain even after the calibration. An experimental operation in a poor visibility environment was successfully conducted by using Telesar and the Virtual Telesar. Figure 5 shows the virtual telexistence anthropomorphic robot (Virtual Telesar used in the experiment and Fig. 6 shows how the real environment is augmented by the computer model [7, 8].

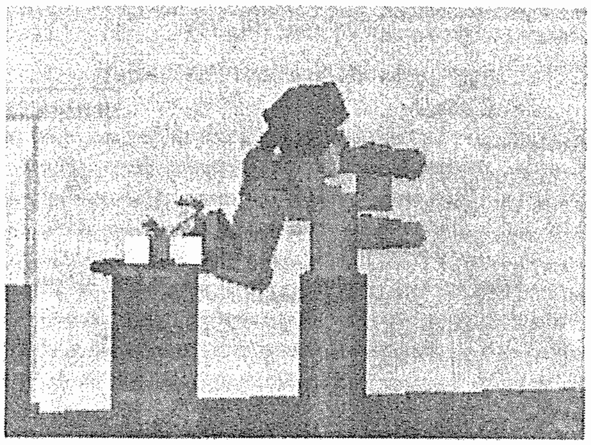

Fig. 5 Virtual TELESAR at Work.

Through these experimental studies, it has been demonstrated that a human being can telexist in a remote environment and/or a computer-generated environment by using the dedicated telexistence system.

However, it is difficult for everyone to telexist freely through commercial networks like the Internet, or the next generation of worldwide networks.

3. R-Cubed (Real-time Remote Robotics) Scheme

In order to realize a society where everyone can freely telexist anywhere through a network, Japanese Ministry of Economy, Trade and Industry (METI) together with the University of Tokyo, proposed a long-range national research and development scheme in 1995, which is dubbed R-Cubed (Real-time Remote Robotics) [9].

Figure 7 shows an example of an artist's image of a future use of R-Cubed System. In this example, a handicapped person climbs a mountain with his friends using networked telexistence system.

In an R-Cubed system, each robot site includes its local robot's server. The robot type varies from a mobile camera (low end) to a humanoid (high end). A virtual robot can also be a controlled system to be telexisted.

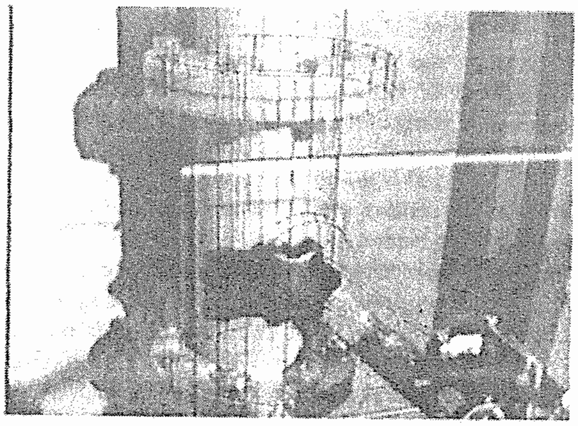

Fig. 6 An Experimental Augmented Reality.

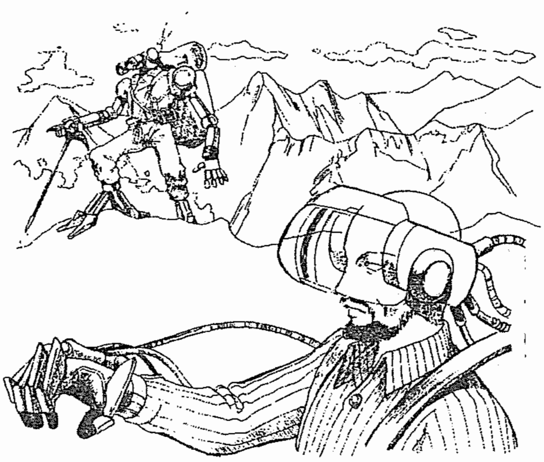

Fig. 7 Mountain Climbing using R-Cubed.

Each client has a teleoperation system, ranging from an ordinary personal computer system on the low end to a control cockpit with master manipulators and a head mounted display (HMD), or a CAVE Automatic Virtual Environment (CAVE) on the high end. RCML/RCTP (R-Cubed Manipulation Language / R-Cubed Transfer Protocol) is now under development to support the lower end user's ability to control remote robots through a network [9,10].

To standardize the following control scheme, a language dubbed RCML (http://www.rcml.org/), which describes a remote robot's features and its working environment, has been proposed. A communication protocol RCTP, which is designed to exchange control commands, status data, and sensory information between the robot and the user, has also been developed.

With a Web browser, a user accesses a Web site describing information of a robot in the form of hypertext and icon graphics, shown in Fig. 8. Clicking on an icon downloads the description file, which is written in RCML format, to the user's computer and launches the RCML browser. The RCML browser parses the downloaded file to process the geometry information, including the arrangement of the degrees of freedom of the robot, controllable parameters, available motion ranges, sensor information, and other pertinent information.

The browser decides what kind and how many devices are required to control the remote robot. It then generates a graphical user interface (GUI) panel to control the robot, plus an *egocentric* video window that displays the images "seen" by the robot and an *exocentric* monitor window that lets users observe the robot's status from outside the robot. If the user has a device such as a 6-degrees-of-freedom (DOF) position /orientation sensor to indicate the robot-manipulator's endpoint, the user can employ that instead of the conventional GUI panel.

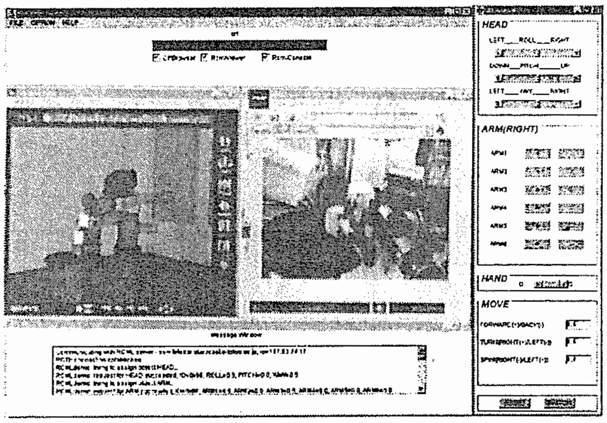

Fig. 8 An Example of an RCML Browser.

4. Humanoid Robotics Project (HRP)

After a two-year feasibility study called the Human Friendly Network Robot (FNR), which was conducted from April 1996 till March 1998 based on the R-Cubed Scheme, The National Applied Science & Technology Project, "Humanoid and Human Friendly Robotics (HRP)," was launched in 1998. It is a five-year project toward the realization of a so-called R-Cubed Society by providing humanoids, control cockpits and remote control protocols.

A novel robot system capable of assisting and cooperating with people is necessary for any human-centered system to be used for activities such as the maintenance of plants or power stations, the operation of construction work, the supply of aid in case of emergency or disaster, and the care for elderly people. If we consider such systems from both a technical and a safety point of view, however, it is clearly intractable to develop a completely autonomous robot system for these objectives.

The robot system should therefore be realized with the combination of autonomous control and teleoperated control. By introducing telexistence techniques through an advanced type of teleoperated robot system, a human operator can be provided with information about the robot's remote site in the form of natural audio, visual, and force feedback, thus making him or her feel that he or she exists inside the robot itself [11, 12, 13].

For METI's national five year HRP, telexistence technology has been adapted to a new type of cockpit system for controlling a humanoid biped robot, as shown in Fig.9. The telexistence cockpit developed for this project (Fig.10) consists of three main subsystems: an audio/visual display subsystem, a teleoperation master subsystem, and a communication subsystem between the cockpit and the humanoid robot (Fig.11).

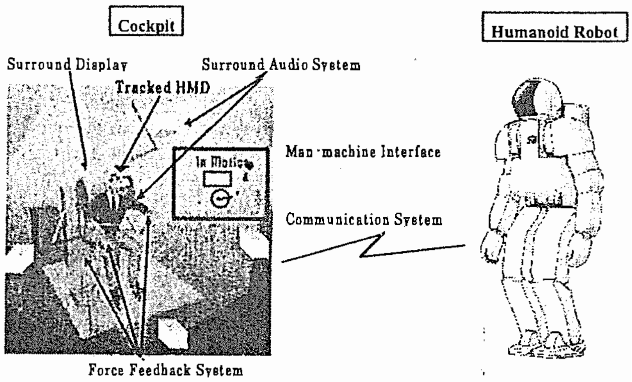

Fig.9 Telexistence Control of Humanoid Robot.

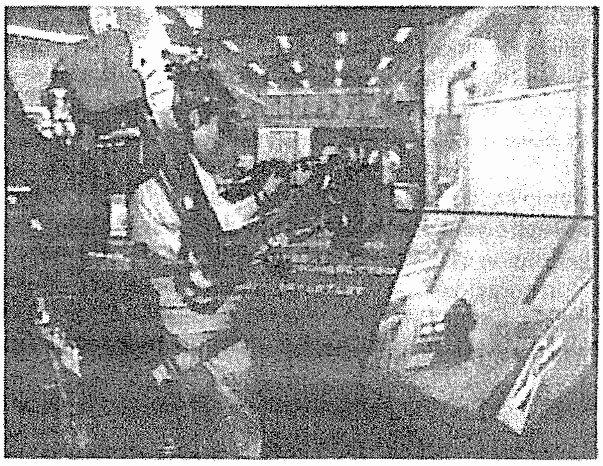

Fig.10 Telexistece Cockpit for Humanoid Control.

In order to address the problem of narrow fields of view associated with HMD's (Head Mounted Display), a surround visual display, using immersive projection technology (as adopted in the CAVE), has recently been developed. 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 on-board motion when he or she uses the robot to walk around.

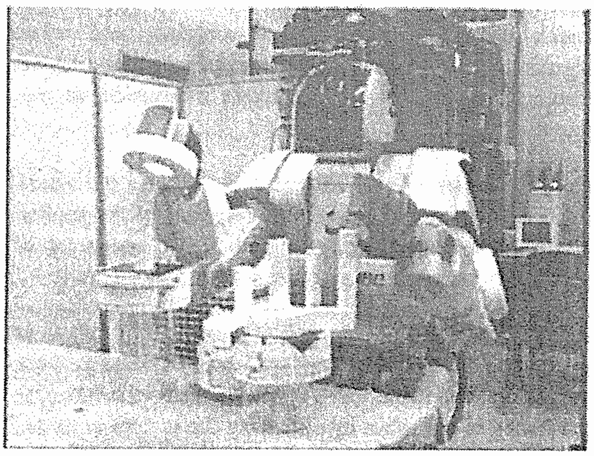

Fig.11 HRP Humanoid Robot at Work.

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/her head motion, so an HMD system with a head-tracking function has been developed to meet these needs. Since a binocular camera platform is originally installed, 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.

In addition, an augmented reality technique 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 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. 10, is composed of nine screens, each 60 inches along the diagonal. Two projectors are located on the backside 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 consists of two sets of four small cameras: one set for each eye, separated by a distance of 65mm. 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 degrees in the horizontal, 19 degrees in the upper vertical, and 58 degrees in the lower vertical directions.

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 must perceive and assess the robot's situation based on local information provided from the camera. In order to aid the operator's assessment and appropriate decision making for control, (s)he should be provided not only with local information from the camera but also global information.

Thus, 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). We have both the CG model in the VE and camera images presented on the surround visual display.

The telexistence teleoperation master system, shown in Fig.10, consists of left and right master arms each with a gripping operation device, a motion-base, and a three-dimensional 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 his or her 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 seven degrees of freedom (DOF). This redundancy in the DOF allows the operator to execute multiple postures of a slave arm directly using 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, so the operator feels 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. In order to realize small and lightweight mechanisms as well as a wide operation space for the thumb and index finger, a wire tension mechanism with a passive DOF 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 DOF translation: back and forth (surge), left and right (sway), and up and down (heave).

Various teleoperation tests by using the developed telexistence master system were carried out, and the results show 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.

The communication system between the cockpit and the robot consists of two main subsystems: one for communicating audiovisual information, and the other for control information. The audiovisual information is transmitted through an analogue 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 audiovisual display subsystem, the telexistence master subsystem, and the control system of the robot itself.

In order to evaluate the usability of the cockpit for HRP robots, an experiment that had an operator walk around and manipulate objects by utilizing a humanoid robot as the surrogate was carried out (Fig.8). To demonstrate the possibility of using the developed system in the field of service robots, we built a mockup-shopping zone in a real environment 3.5x6.0m in size.

A humanoid robot was set inside the mockup, 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 (s)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, (s)he wore polarizing glasses and leaned on the sheet of the motion base. On the bottom-left screen of the surrounded visual display, an operational menu appeared. 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 surrounded visual display. 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, and when augmented to the real images captured by the camera system, it supported the operator's navigation of the robot.

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.

Figure 12 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 arms and hands of the robot by operating the master arms and hands, while (s)he felt force feedback received from the robot hands.

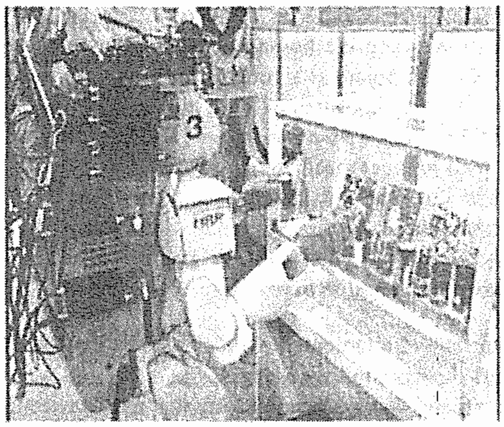

Fig.12 HRP Robot picking up a Can.

5. Telexistence Next Generation (TNG)

A Head Mounted Display (HMD) and a CAVE are two typical virtual reality visual displays. Although they are quite useful displays, it is also true that they have some demerits. The former has a problem of tradeoff of high resolution and wide field of view, and the latter has a problems of a shadow of the user's body on a virtual environment and the interaction of the user's virtual body with his or her real body.

In our laboratory at the University of Tokyo, a new type of visual display is being developed called X'tal vision [14], and it uses retro-reflective material as its screen.

A projector is arranged at the conjugate position of a user's eye, and an image is projected on a screen made of, painted with, or covered with retro-reflective material. A pinhole is placed in front of the projector to ensure adequate depth of focus (Fig.13).

The retro-reflector screen, together with the pinhole, ensures that the user always sees images with accurate occlusion relations. This means that if the user's body has a retro-reflector on it, their body becomes a part of the virtual environment and disappears, replaced by a virtual body. A body without a retro-reflector on it will occlude the virtual environment without a troublesome shadow obscuring the virtual environment.

In the construction of X'tal vision, screen shapes are arbitrary, i.e., any shape is possible. This is due to the characteristics of the retro-reflector, and the pinhole in the conjugate optical system. By using the same characteristics of X'tal vision, binocular stereo vision becomes possible using only one screen with an arbitrary shape. This can be mounted on a head of a user, which we call a HMP (Head Mounted Projector) System.

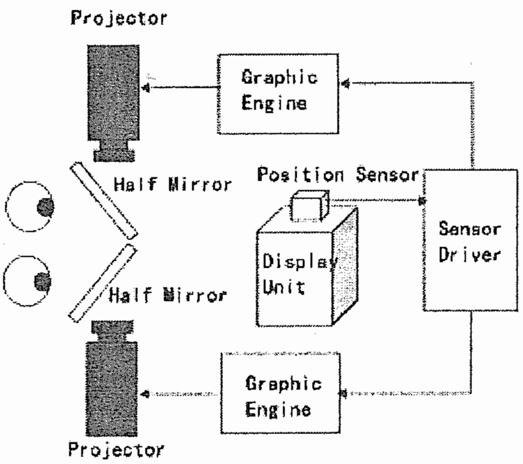

Fig. 13 Principle of X'tal Vision.

Twenty years have passed since our first idea and concept of telexistence, and it is now possible to telexist in the remote environment and/or virtual environment with a sensation of presence. We can have feelings that we are present in several real places and can work and act. However, in the location where the user telexists using a robot, people see only the robot but cannot feel that the person is actually present. It is useless to use a TV display on board the robot to show the face of the user, since it is just comical and far from reality.

Figure 14 illustrates the proposed method of mutual telexistence using X'tal vision HMP in order to solve the above problem, i.e., to make a telexisted robot look like the robot's user. This is an effort toward the next generation telexistence [15].

A human user "A" uses his telexistence robot "A" at the remote site where another human user "B" is present. The user "B" also uses another telexistence robot "B", which exists in the site where the user "A" works. Both robots are painted with retro-reflective material and can act as screens, and they are controlled by their users as conventional telexistence robots.

Remote scenery sensed by cameras on board the robots "A" and "B" are sent to the HMPs of human users "A" and "B", respectively. The 3-D image taken by the telexistence robot "A" is projected to and observed by the human user "A", while the 3-D image taken by the telexistence robot "B" is projected to and observed by the human user "B", both with a sensation of presence.

The telexistence robot "B" is seen as if it is the human user "B" by the projection of real image of "B" on the robot "B", while the telexistence robot "A" is seen as if it is the human user "A" by the projection of real image of "A" on the robot "A".

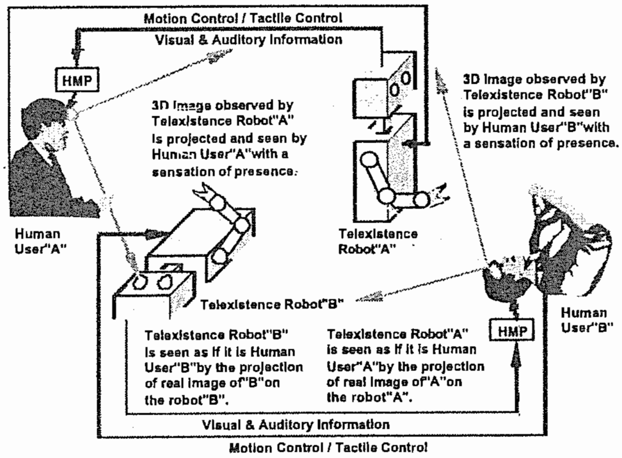

Fig. 14 Telexistence Next Generation (TNG). (Adopted from [15])

Thus mutual telexistence becomes possible by using X'tal vision method, i.e., not only does the user see other people naturally, but other people can also observe the user of the robot naturally.

We are now in the process of a feasibility study for the proposed method using Telesar.

Figure 15 shows an example of how a robot can be seen by a human being who wears a HMP. It can be seen as if the robot is a human being telexisting in the robot. Figure 15(A) shows a miniature of the HONDA Humanoid Robot, while Fig. 15(B) illustrates the robot painted with retro-reflective material. Figures 15(C) and (D) show how they are seen by a human being wearing a HMP. The telexisted robot looks just like the human operator of the robot, and telexistence can be naturally performed.

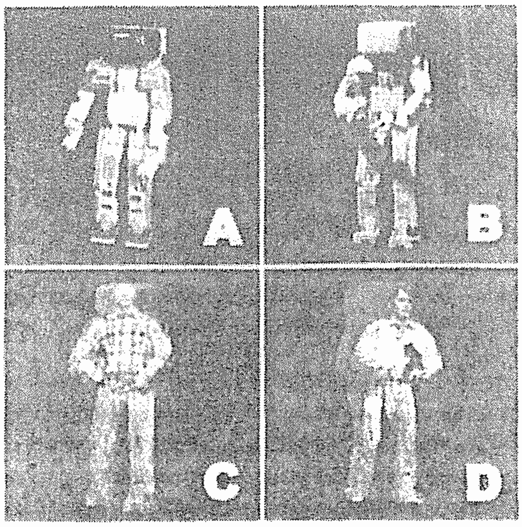

Fig. 15 (A) Miniature of the HONDA Humanoid Robot, (B) Painted with Retro-reflective Material, (C) An Example of Projecting a Human Image on it, (D) Another Example. (Adopted from [15])

6. Conclusion

According to *The American Heritage Dictionary* "virtual" means, "existing in essence or effect though not in actual fact or form." Thus virtual reality must have the essence of the reality in its computer-generated environment or a transmitted remote environment so that it is effectively the reality itself. One of the most promising technologies today is the integration of virtual realty and robotics on the network. It is called networked robotics in general, and R-Cubed (Real-time Remote Robotics) in particular. R-Cubed is a Japanese national R&D scheme toward the realization of the next generation of telexistence through various kinds of networks including the Internet. Japanese Ministry of Economy, Trade and Industry (METI) launched the 5-year Project "Humanoid and Human Friendly Robotics (HRP)" in April 1998. This is the first step toward the realization of Telexistence Next Generation, and the results are as we expected.

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