Telexistence

Past, Present, and Future

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Abstract. Telexistence technology allows for highly realistic sensation of existence in remote places without actual travel. The concept was originally proposed by the author in 1980, and its feasibility has been demonstrated through the construction of alter-ego robot systems such as the TELExistence Surrogate Anthropomorphic Robot (TELESAR) and TELESAR V, which were developed under national large-scale projects on "Robots in Hazardous Environments" and "CREST Haptic Telexistence Project," respectively, as well as the HRP super-cockpit biped robot system developed under the "Humanoid Robotics Project." Mutual telexistence systems, such as TELESAR II & IV, capable of generating the sensation of being in a remote place in local space using the combination of an alter-ego robot and retro-reflective projection technology (RPT) has been developed, and the feasibility of mutual telexistence has been demonstrated. In this paper, the past, present, and future of telexistence technology is discussed.

Keywords: Telexistence · Mutual telexistence · Telepresence · Teleoperation · Master-slave system · Virtual reality · Augmented reality · Retro-reflective projection technology (RPT) · TELESAR · TWISTER

1 Introduction

Telexistence is a fundamental concept that refers to the general technology that allows human beings to experience real-time sensation of being in a place different from their actual location and interact with such remote environment, which can be real, virtual, or a combination of both [1]. It also refers to an advanced type of teleoperation system that allows control operators to perform remote tasks dexterously with the perception of being in a surrogate robot working in a remote environment. Telexistence in the real environment through a virtual environment is also possible.

Sutherland [2] proposed the first head-mounted display system that led to the birth of virtual reality in the late 1980s. This was the same concept as telexistence in computer-generated virtual environments. However, Sutherland's system did not include the concept of telexistence in real remote environments. The concept of providing an operator with a natural sensation of existence in order to facilitate dexterous remote robotic manipulation tasks was called "telepresence" by Minsky [3] and "telexistence" by Tachi [4]. Telepresence and telexistence are very similar concepts proposed independently in the USA and in Japan, respectively. However, telepresence

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does not include telexistence in virtual environments or telexistence in a real environment through a virtual environment.

The concept of telexistence was proposed by the author in 1980 [4], and it was the fundamental principle of the eight-year Japanese national large scale "Advanced Robot Technology in Hazardous Environment" project, which began in 1983, together with the concept of "Third Generation Robotics." Theoretical considerations and the systematic design procedure of telexistence were established through the project. An experimental hardware telexistence system was developed and the feasibility of the concept was demonstrated.

In this paper, the development of telexistence technology and telexistence systems is historically reviewed; its present status is summarized, and future prospective is discussed.

2 Telexistence

2.1 What Is Telexistence?

In telexistence, the requirements to create an environment where a person effectively exists are as follows: (1) it must be composed of a natural three-dimensional space; (2) the person must be able to act freely in it, and interaction with the environment must occur naturally in real time; and (3) self-projection into the environment must occur. These are analogous to the three elements of virtual reality (VR): life-size spatiality, real-time interaction, and self-projection.

To control a robot utilized for telexistence, the movements and internal status of the person controlling the robot are measured in real time and intent is estimated. Such estimated intent is transmitted to the robot and its motion control system is driven directly. In particular, the artificial eyes, neck, hands, and feet of the robot are controlled to faithfully reproduce the movements of the person. Concurrently, information from the artificial sensory organs of the robot is transmitted directly to the corresponding sensory organs of the person.

For example, if the person turns in a certain direction to see, the robot faces the same direction; moreover, the image of the scene in that direction, where there might be people present, is formed as an actual image on the person's retina. If the person brings their hand before their eyes, the hand of the robot appears in the person's visual field in place of their own hand, with exactly the same positional relationship. In this manner, it is possible for the person to perform tasks by capturing the relationship between their hand and the object or with the surrounding space based on similar scenarios from the person's past experience. The robot transmits its sense of contact with the object as tactile stimulation to the person's hand, and the person might experience a sensation similar to having touched the object directly.

Thus, telexistence refers to the technology of working or communicating from a remote location while providing a highly realistic sense of being present in another environment. The practical use of this technology is being promoted in the fields of medical care, space exploration, and deep-sea investigation; furthermore, the use of a robot as a person's alter ego is being studied.

Telexistence liberates humans from conventional space-time constraints and allows them to exist effectively in an environment that is beyond space, time, or both. It is a technique that can make humans ubiquitous by using a robot. Incidentally, the term ubiquitous means "being or seeming to be everywhere at the same time: omnipresent". The term "ubiquitous computing" was created by Mark Weiser of Xerox Palo Alto Research Center (PARC) in 1993, and it refers to the concept of being able to use a computer anywhere at any time. In contrast, telexistence is the concept of making humans, rather than computers, ubiquitous.

Using telexistence, it is possible to manipulate a robot in a remote location as one's other self, experience the working environment of the robot with a realistic sensation through its sight, sound, and touch sensory receptors, and act freely in that environment. Furthermore, it is possible to enter the artificial environment generated by a computer and act in it with the perception of actually being present at that location.

In addition to creating the perception of being in a remote location, telexistence helps to enhance the capability of the person. For example, humans are not capable of seeing objects obscured by darkness or smoke; however, by using the robot's infrared or ultrasonic sensors, the obscured objects can be perceived. If the robot's sensor information obtained by remote presence is presented in actual space utilizing the augmented reality method, it is possible to act even in darkness or smoke by controlling the robot in actual space. This is referred to as augmented telexistence.

Figure 1 displays the structure of an actual environment, a virtual environment, and telexistence in the actual environment via the virtual environment. The human side of the system remains exactly the same, irrespective of whether telexistence is in the actual environment or in the virtual environment. The current status of the person and his/her intent are estimated; accordingly, the alter ego robot in the actual environment or the virtual human in the virtual environment is controlled at will. As the alter ego robot or the virtual human acts in the actual or virtual environment, interaction with the respective environment proceeds, and the results received through the sensory organs of the alter ego robot or the virtual human are integrated and realistically presented to the corresponding human sensory organs. Other telexistence users can also participate in the environment; accordingly, their interactions are also transmitted.

2.2 Design Concept of Telexistence

Figure 2 gives the configuration of a basic telexistence system and a concrete method for the configuration of a visual display that provides a sense of self-presence. Figure 2(I) shows the principle of the recording and reproduction of light wave fronts in a holographic manner, as conceived in the past. In other words, a closed surface is created so as to surround the remote place, and the wave fronts entering that area are recorded at multiple points on the enclosure surface.

These wave fronts are then transmitted to the location of the local observer and are subsequently reconstructed using a reproduction device on a similar enclosure surface surrounding the observer. However, this method alone makes it difficult to realize telexistence for the following reasons [5, 6]:

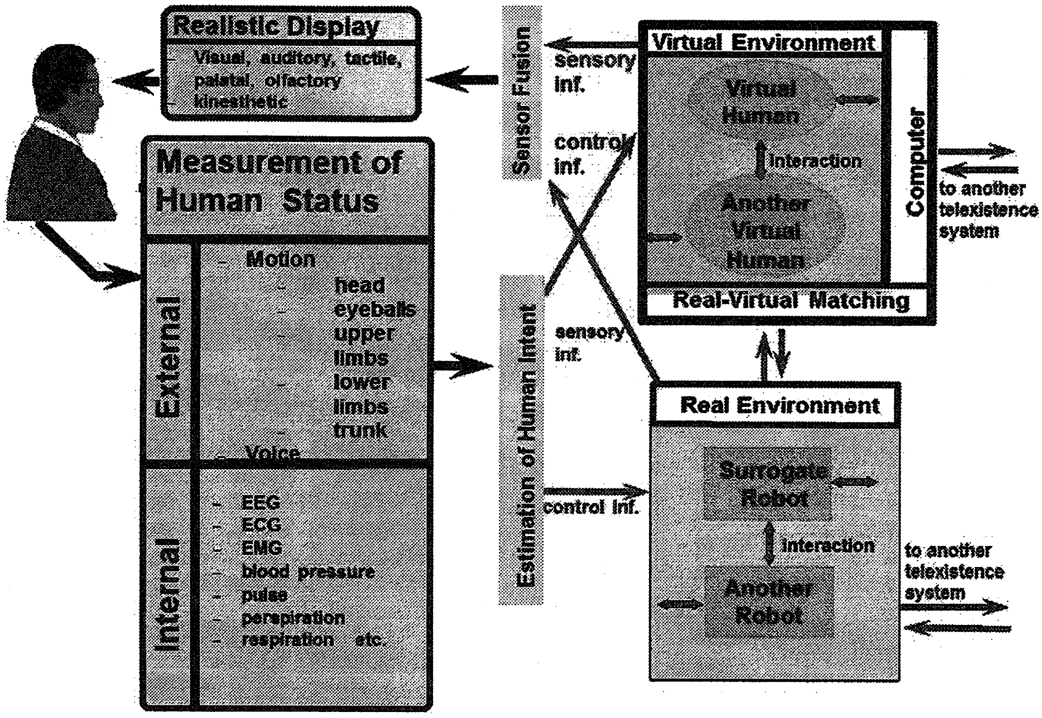

Fig. 1. Telexistence in a real environment, a virtual environment, and a real environment via the virtual environment. (I) Estimation of the user's state (including the external state represented by user movements and tone of voice, as well as the internal state represented by electroencephalograms and electrocardiograms) and evaluation of the human decision making process; (II) interaction between the robot and the natural environment and/or interaction between the virtual human and the virtual environment; and (III) presentation to the user of the process described in (II) and results with a sense of presence in real time.

(1) If the recording and reproduction device were designed to reconstruct the actual environment, they would be too large to be practical. In addition, in holography, the recording and reproduction of real-time information cannot be achieved with the technology that is presently available
(2) Although the display of a distant background scene can be approximated by a large two-dimensional screen, technically, it is extremely difficult to achieve a three-dimensional reproduction of nearby objects in actual size and in real time without such objects being occluded by real objects
(3) In particular, the actual sense of presence cannot be achieved if the hands of the operator are located at a place different from those of the robot. In telexistence, the hands of the robot must be visible at the place where those of the human operator ought to appear. However, the realization of such a state is generally difficult when using the abovementioned holographic method

As a consequence, it is not possible to utilize this conventional method to acquire a true sense of presence, i.e., the sense of being inside the robot or at the place where the robot is located, which would be produced by the realization of the appropriate relationship between the background scene, the task at hand, and the hands of the robot.

Figure 2(II) shows the proposed method for configuring telexistence on the basis of robot technology and human sensory structure. According to the method described

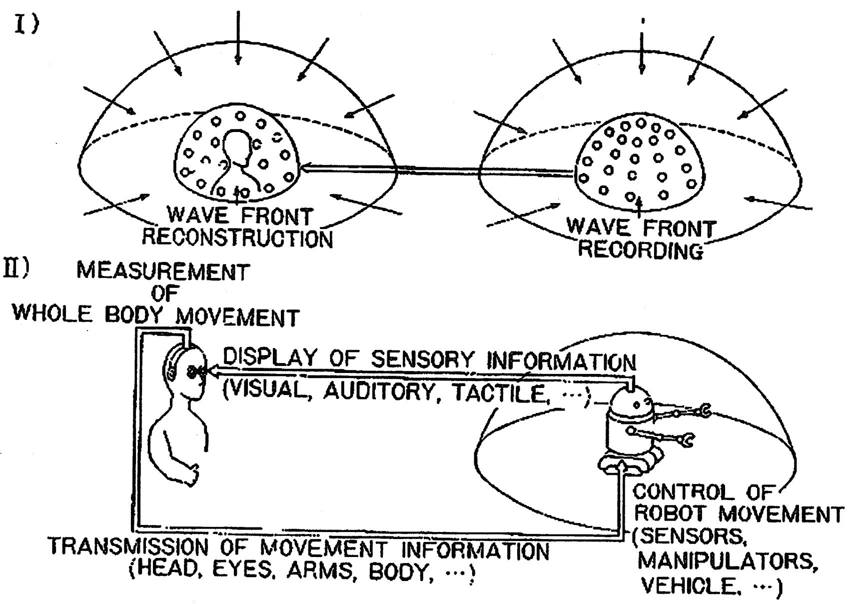

Fig. 2. Principle of telexistence: (I) principle for the recording and reproduction of light wave fronts in a holographic manner; (II) principle for configuring telexistence on the basis of robot technology and human sensory structure [5, 6].

in (I), an attempt is made to reproduce all wave fronts simultaneously. However, this is unnecessary in view of the working mechanism of the human visual perception system. The basis of human visual perception is a pair of images focused on the retinas, and the wave fronts perceived by a person as retinal images at any given instant of time constitute only part of the total wave fronts. These wave fronts change in real time with the movements of the person's head and eyes. The person then creates, inside his/her brain, a three-dimensional world based on two images that change with time, and projects it back to the place where the objects really exist.

As a result, if it is possible to measure a person's head and eye movements faithfully and in real time, to move the head and the eyes of the robot in line with those movements, to transmit to the human side the pair of images created in the visual input device of the robot at that time, and to recreate these images on the person's retinas accurately and without a time delay using a suitable display device, that person can then receive retinal images equivalent to those seen directly by the robot. In other words, by using these images, the person can create inside his/her brain a three-dimensional world equivalent to the one seen directly from the place where the robot is located, and then project it again into the real world.

Thus, by scanning partial wave fronts continuously using a human motion measurement device and a system that consists of a display device and a slave robot, a recording and reproduction device can be produced that is small enough to be realistically configured; therefore, problem (1) presented above can be solved.

In addition, this method creates a state in which visual information obtained from direct observation on the human side is shielded, and instead, visual information from the remote robot is displayed as though the human operator were at the same place where the robot is located. Moreover, because the movement of human hands, arms, and torso is measured faithfully, and because this information is used to move the manipulators and body of the robot, when the human operator moves his/her hands and arms in front of his/her eyes, a configuration becomes possible in which the robot manipulators appear in front of its eyes at the same position where the operator hands and arms are supposed to be.

As a result, problems (2) and (3), which are relevant in the case of conventional display systems, such as the one in (I), can also be solved.

Maximum transmission rate necessary for full transmission of information from robot to human is an order of 0.5–6 Gbps without using data compression. When we compress the data, we must always be careful of the latency caused by coding and decoding. The latency or time delay allowed for the direct bilateral control of a robot is a maximum of to 200 ms [7]. This includes time delays caused by data acquisition, transmission, and display.

2.3 "Sense of Self-Presence" vs. "Sense of Their Presence"

The perception of actually positioning oneself in a certain place is referred to as the "sense of self-presence," or "sense of self-existence." This is the "sense of realism." The audio stereo system that creates a listening effect similar to being in a concert hall might be referred to as a system filled with realism. This is auditory realism. Virtual reality and telexistence provide the system user with a realistic sensation visiting the environment generated by the computer and/or an actual remote environment. In realism, the senses of vision, hearing, touch, smell, taste, and body balance are all ideally aligned, and studies are being conducted to facilitate ultimate realism in virtual reality and telexistence.

Thus, realism is a word frequently used to describe the capabilities of sound reproduction equipment such as the stereo or the telephone, and visual reproduction technology such as film, television, and the videophone. In these cases, realism denotes the sensation perceived by the system user.

There is also a sensation referred to as the "sense of their presence," or simply the "sense of presence." The sense of their presence is the perception of the definite existence of people or objects. This term existed before the invention of telephones, stereos, or movies. There are innumerable examples of phrases such as "he has no sense of presence" used in the real world. In particular, regardless of a person being present as an entity, the people around the person might not notice his/her presence, and there might be occasions when his/her presence is ignored. In contrast, when the person is more than a mere physical entity and his/her presence is noticeable, he/she is said to have a strong presence, or that they are "larger than life."

The "sense of self-presence," i.e., the perception of being present in the place experienced by the user and the "sense of their presence," i.e., the presence of the user perceived by people nearby are illustrated in Fig. 3.

With the widespread use of videoconferencing, the lack of sense of presence of a person on the screen was perceived as a limitation, similar to the real world. The lack of sense of presence is considered natural, given the absence of a physical entity. However, the reasons that a sense of presence cannot be created using only pictures and sounds remain unsolved. Researchers are attempting to integrate a sense of self-presence and

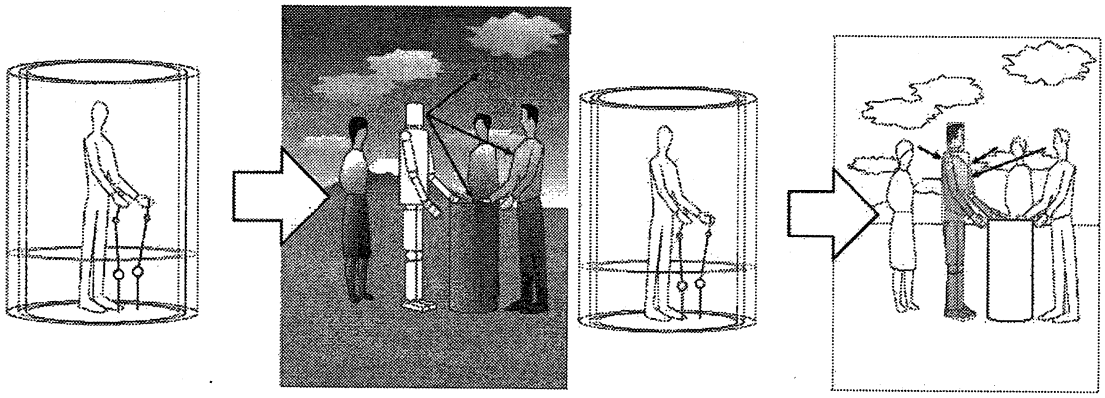

Fig. 3. Sense of self-presence: system user has a sensation of being present in a place (left), and Sense of their presence: people nearby perceive the presence of the system user (right).

sense of their presence, currently missing in typical teleconference systems, into virtual reality and telexistence systems, and to achieve the ultimate sense of presence, along with a sense of realism.

Sense of self-presence and sense of their presence are described below utilizing a videoconferencing system as an example. Suppose that there is a large screen in the conference room and one person is participating in the conference from a distant place. The person participating from the distant place sees the image of the camera installed in the conference room on the monitor placed in his room. Because the present system is usually two-dimensional, the sense of self-presence is obtained to some extent, and it is not exactly similar to being at the remote location. This is what is perceived by the system user from the distant place.

At the other location, the people gathered in the meeting room look at the screen and welcome the participant from the distant place, and at that time, everybody notices him. A certain type of a sense of his presence is created at that time. However, the person on the screen might be forgotten when the discussion among the people who are actually gathered in the conference room becomes impassioned. In this situation, the sense of his presence becomes extremely weak.

To summarize, the sense of self-presence or self-existence is perceived by the system user, and it is a sensation of being present in a generated or remote environment. In contrast, the sense of their presence or sense of their existence is not what is perceived by the system user, but by the people around the system user with regard to the user's presence.

In this case, what is it that conveys a sense of presence or sense of existence? If the sense of presence in the real world is analyzed as an example, a higher possibility of having an impact on the people who are nearby generally results in a higher sense of presence. The sense of presence is as high as the degree or effectiveness of the potential for interaction. Between a stone that is stable on the floor and one that might fall at any moment, the latter has a higher sense of presence. If a wasp, a poisonous snake, or a lion is in one's immediate vicinity, its sense of presence is high. In a similar way, objects that make a loud noise, are colorful, or move have a high sense of presence. People who are quiet and yet convey a sense of presence also have a dignity and an aura about them. When all the people in an environment perceive, for some reason, a sense of danger, fear, or enjoyment because of the presence of an object or a person, an interaction occurs and the possibility of being affected heightens the sense of presence.

The reason that the sense of presence is greater in a live performance or in a play than in television or in films originates from the feeling that it is possible to touch the viewer at any moment. The difference in the sense of presence between watching a game of sumo from a gallery where a giant sumo wrestler can fall, and watching it on a big screen TV, is quite evident.

In order to create the sense of their existence in media, it is obviously important to convey that which is not present in the existing images, such as a complete three-dimensional feeling with multi-view support, the sense of smell, and other stimuli. In addition, it is necessary to provide a structure to allow the possibility of direct interaction with the generated object or person, and in particular, one that can detect danger.

In this context, among insufficient sensations, the sense of touch is, at present, more likely to contribute to the creation of the sense of presence. However, the sense of presence can be conveyed even if contact does not actually occur. In other words, there is a high sense of presence of something frightening that could cause harm.

If telexistence is achieved, operators will perceive the distant environment as the actual environment; they will be able to talk, hear, and act similar to the actual environment and relate with the people at the distant environment as a real person, without any sense of incongruity. However, this is not the case with individuals who are in the environment where the person appears by telexistence. If a robot in a person's vicinity moved as a human being and generated a human-like voice, it would be incongruous.

Accordingly, it is not desirable to establish a setting where people would interact or work together. Thus, it becomes important for the person appearing through telexistence to be depicted pictorially and clearly. Moreover, if this image is fitted onto the body or head of a robot and projected on a TV screen, the image remains unchanged on the viewing side, and it is unlikely to create the feeling of the person being present.

The user of a telexistence device can act with a sense of self-presence or self-existence, with the perception of having entered into a robot and integrated into the remote environment. This is achievable because the user senses that the surrounding environment and the people in it have an awareness of his/her physical existence in the environment. More succinctly, there is a sense of realism. However, the people looking at the robot perceive the presence of the robot, not the presence of the user. Accordingly, the sense of their presence is lacking.

For example, consider a caregiving situation utilizing a telexistence system. Similar to the previous case, in reality, a human being is providing care, not the automatic robot. However, because the person receiving care only sees the robot, he/she does not feel the presence of the human caregiver. In this case, if the caregiver appears to the person receiving care as being within the robot, it is possible to persuade the latter to believe that he/she is actually being cared for by the human caregiver. If a three-dimensional image of the operator is projected on the robot, the person receiving care would see the robot not as a mere mechanical device, but as the actual caregiving person, who is the operator.

This is the concept of the next generation telexistence that has both the sense of self-existence and the sense of their existence, or "mutual telexistence."

Mutual telexistence also enables a number of people to gather through telexistence in an actual location using plural alter-ego robots through a network. Furthermore, dispensing with the robot, a virtual environment can be created in which each person will enter using a telexistence booth near his/her home. In this booth, the virtual environment is observed through his/her avatar with the sense of self-existence in the virtual environment. At the same time, each person's image is captured in real time and projected on his/her corresponding avatar in the virtual environment, thus creating the sense of their presence. It will then be possible for people to converse with each other while watching facial expressions, similar to having a face-to-face conversation. This system will become a highly evolved videophone.

3 Short History of Telexistence

3.1 How Telexistence Was Conceptualized and Developed

Human beings have long desired to project themselves in remote environments, i.e., to experience the sensation of existing in a place different from the one they really exist in, at the same time. Another goal has been to amplify human muscle power and sensing capability using machines while maintaining human dexterity with a sensation of actually performing a given task.

In the late 1960s, a research and development program was planned to develop a powered exoskeleton that an operator could wear similar to a garment. The concept for the Hardiman exoskeleton was proposed by General Electric Co.; an operator wearing the Hardiman exoskeleton would be able to command a set of mechanical muscles that would multiply his/her strength by a factor of 25, yet, in this union of man and machine, he/she would feel the object and forces almost as though he/she were in direct contact with it.

However, the program was unsuccessful because: (1) wearing the powered exoskeleton was potentially quite dangerous in the event of machine malfunction; and (2) autonomous mode was difficult to achieve and everything had to be performed by a human operator. Thus, the design proved impractical in its original form.

However, with the advance of science and technology, it has become possible to realize this dream with a different concept. The concept of projecting ourselves using robots, computers, and a cybernetic human interface is referred to as telexistence. This concept allows human operators to perform remote manipulation tasks dexterously with the perception that he/she exists in an anthropomorphic robot in a remote environment. Telexistence realizes a virtual exoskeleton human amplifier, i.e., a human can work with his/her power multiplied without actually being inside the exoskeleton. Because a human operator is not inside the robot, he/she is safe even in the event of malfunction. An exoskeleton robot can be replaced by an intelligent robot so that the robot is used autonomously when the operator is not telexisting into it. Thus, telexistence solves the aforementioned two problems of an exoskeleton human amplifier.

Figure 4 illustrates the emergence and evolution of the concept of telexistence. Teleoperation emerged in Argonne National Laboratory soon after World War II to manipulate radioactive materials. In order to work directly in the environment rather than remotely, an exoskeleton human amplifier was invented in the 1960s as described previously, whereas the concept of supervisory control was proposed by T. B. Sheridan in the 1970s to add autonomy to human operations. In the 1980s, the exoskeleton human amplifier evolved to telexistence, i.e., into the virtual exoskeleton human amplifier. This virtual system also integrated supervisory control in order to include the concept of a telexistence human-intelligent robot system. Fundamental studies for the realization of telexistence systems were conducted under the national large scale project "Advanced Robot Technology in Hazardous Environment," which was an eight-year research and development program launched in 1983 for the development of a system that avoids the need for humans to work in potentially hazardous working environments, such as nuclear power plants, underwater, and disaster areas. Figure 5 shows a human-intelligent robot system that performs essential work in hazardous working environments.

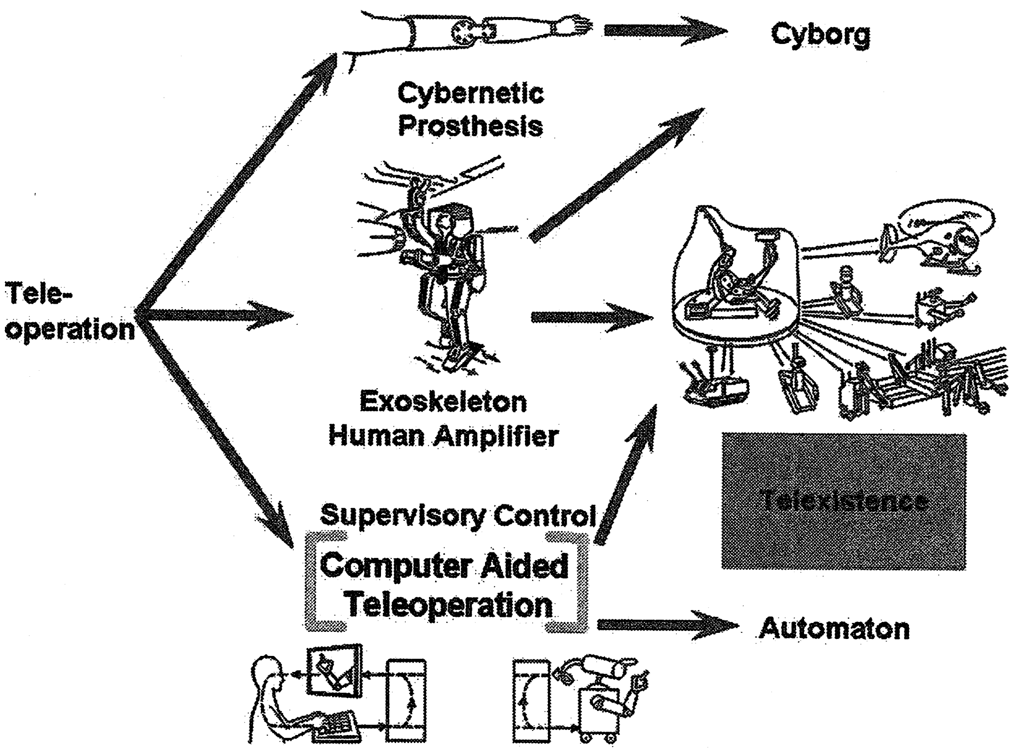

Fig. 4. Emergence and evolution of telexistence. Cyborg, telexistence, and automaton originated form teleoperation, which emerged soon after World War II.

Each independent, mobile, intelligent robot assumes part of the overall work and operates in conjunction with other robots in severe environments. Instructions are provided to these robots by a human operator stationed in a control module. A supervisory controller is responsible for the allocation of work, as well as for planning and scheduling, and the intelligent mobile robots send it reports concerning work progress. Such information is organized by the supervisory controller, and it is then transmitted to the operator by voice or by visual or tactile information. If the operator instructs in a language similar to natural language, these instructions are transmitted to the respective robots through speech recognition equipment and the supervisory controller.

The respective robots recognize the task description and perform using their own intelligence and knowledge.

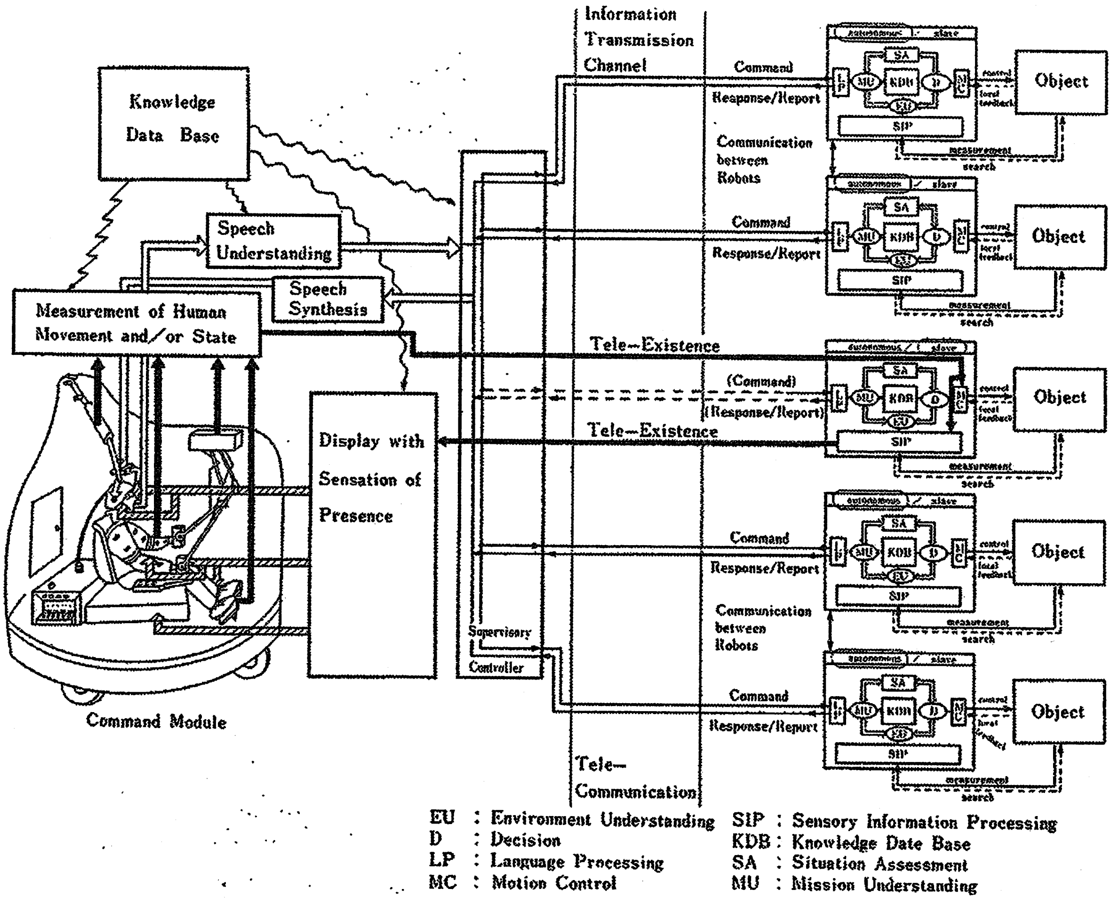

Fig. 5. Telexistence system architecture. The system consists of intelligent mobile robots, their supervisory controller, a command module to control robots with a sensation of self-presence and a sensory augmentation system that allows an operator to use the robot's ultrasonic, infrared, and additional, otherwise invisible, sensory information with the computer-generated pseudo-realistic sensation of presence. In the command module, realistic visual, auditory, tactile, kinesthetic, and vibratory displays are provided [8].

Information in the robots' intelligence system is an important source of operation and can be monitored by the operator at any time. Moreover, safety is checked at three levels: by the intelligent robot, by the supervisory controller, and by the operator; thus, safety is greatly improved.

When an intelligent robot encounters difficult work that it cannot manage, the operation mode of the robot is switched to remote control mode either at the robot's own request or at the judgment of the operator. At that time, instead of a conventional remote control system, an advanced type of teleoperation system, called telexistence, is used. This enables the operator to control the robot as though he/she were inside the robot. In this case, each subsystem of the intelligent robot works similar to a slave-type robot that is directly and accurately controlled by the operator.

The operator can also utilize the robot's sensor information about radiation, ultraviolet rays, infrared rays, microwaves, ultrasonic, and extremely low frequency waves. The operator can effectively use this information to expand human ability. The knowledge base inside the control module can be utilized so that the operator's command can be performed more accurately.

Through this project, theoretical consideration and systematic design procedure of telexistence is established. An experimental hardware telexistence system is developed, and the feasibility of the concept is demonstrated.

Our first report [5, 6] proposed the principle of a telexistence sensory display and explicitly defined its design procedure. The feasibility of a visual display that provided a sensation of self-existence was demonstrated through psychophysical measurements performed using an experimental visual telexistence apparatus.

In 1985, a method was also proposed to develop a mobile telexistence system that can be driven remotely with both an auditory and a visual sensation of self-existence. A prototype mobile televehicle system was constructed, and the feasibility of the method was evaluated [9].

3.2 TELExistence Master-Slave Manipulation System: TELESAR

The first prototype telexistence master-slave system for performing remote manipulation experiments was designed and developed, and a preliminary evaluation experiment of telexistence was conducted [10–12].

The slave robot employs an impedance control mechanism for contact tasks and for compensating for errors that remain even after calibration. An experimental operation of block building was successfully conducted using a humanoid robot called TELExistence Surrogate Anthropomorphic Robot (TELESAR). Experimental studies of the tracking tasks quantitatively demonstrated that a human being can telexist in a remote environment using a dedicated telexistence master-slave system [12]. Because measurements are performed using goniometers and potentiometers and all programs are written in C, the system is operated at an extremely high speed cycle time of 3 ms, even when the operation is conducted as impedance control mode. Virtually, no delay is observed. Human operators perceive as though they were inside the robots. Figure 6 illustrates a telexistence master-slave manipulation system.

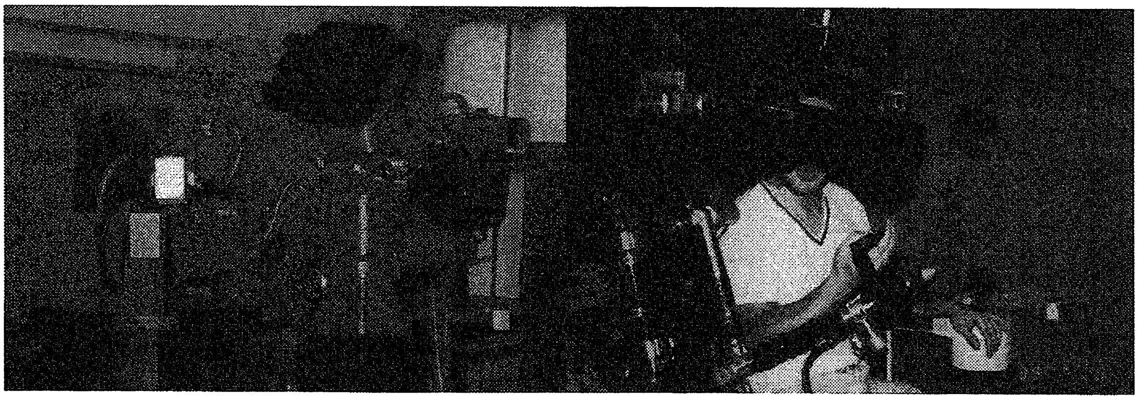

Fig. 6. TELESAR (left) and telexistence master system (right).

3.3 Augmented Telexistence

Telexistence can be divided into two categories: telexistence in a real environment that actually exists at a distance and is connected via a robot to the place where the operator is located, and telexistence in a virtual environment that does not actually exist, but is created by a computer.

The former can be referred to as "transmitted reality;" the latter as "synthesized reality." Synthesized reality can be classified as a virtual environment that represents the real world, and that which represents an imaginary world. Combining transmitted reality and synthesized reality, which is referred to as mixed reality, is also possible, and it has great significance for real applications. This is referred to as augmented telexistence to clarify the importance of a harmonic combination of real and virtual worlds.

Augmented telexistence can be used in several situations, for instance, controlling a slave robot in an environment with poor visibility. An experimental augmented telexistence system was constructed using mixed reality. An environment model was also constructed from the design data of the real environment. When augmented reality is used to control a slave robot, modeling errors of the environment model must be calibrated. A model-based calibration system using image measurements was proposed for matching the real environment with a virtual environment.

An experimental operation in an environment with poor visibility was successfully conducted using TELESAR and its virtual dual. Figure 7 illustrates the virtual telexistence anthropomorphic robot used in the experiment [13, 14].

A quantitative evaluation of the telexistence manipulation system was conducted by tracking tasks using the telexistence master-slave system. Through these experimental studies, it was demonstrated that a human being can telexist in a remote environment and/or a computer-generated environment using a dedicated telexistence system.

Through these research and development programs, it has become possible to telexist between places with dedicated transmission links, such as optical fiber communication links, as has been demonstrated by the above experiments. However, it is still difficult for everyone to telexist freely through commercial networks, such as the Internet or the next generation worldwide networks, and more efforts are anticipated.

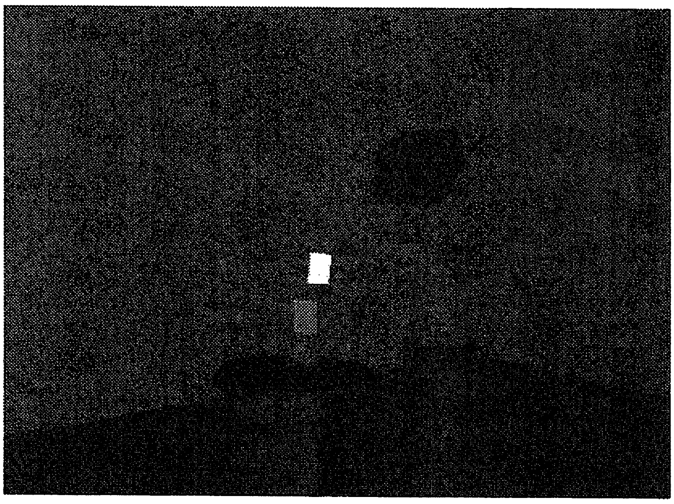

Fig. 7. Operational virtual TELESAR.

3.4 R-Cubed

In order to realize a society wherein everyone can freely telexist anywhere through a network, the Japanese Ministry of International Trade and Industry (MITI) and the University of Tokyo proposed a long-range national research and development program that was dubbed R-Cubed (R^3) in 1995. R^3 means real-time remote robotics. The concept of this program is the research and development of technologies that allow human operators to telexist freely by integrating robots, virtual reality, and network technology.

Figure 8 illustrates an example of an R^3 robot system. Each robot site has a server as its local robot. The type of robot varies from a humanoid (high end) to a movable camera (low end). A virtual robot can also be a local controlled system.

Each client has a teleoperation system. The system can be a control cockpit with master manipulators and a head-mounted display (HMD) or a CAVE Automatic Virtual Environment (CAVE) at the high end. It is also possible to use an ordinary personal computer system as a control system at the low end. In order to assist low-end operators with controlling remote robots through networks, R-Cubed Manipulation Language/R-Cubed Transfer Protocol (RCML/RCTP) was developed.

An operator accesses the web site that describes robot information in the form of hypertext and icon graphics using a WWW browser. Clicking an icon downloads a description file that is written in the RCML format, onto the operator's computer and launches the RCML browser. The RCML browser parses the downloaded file to process the geometrical information, including arrangement of the degrees of freedom of the robot, controllable parameters, available motion ranges, sensor information, and other pertinent information.

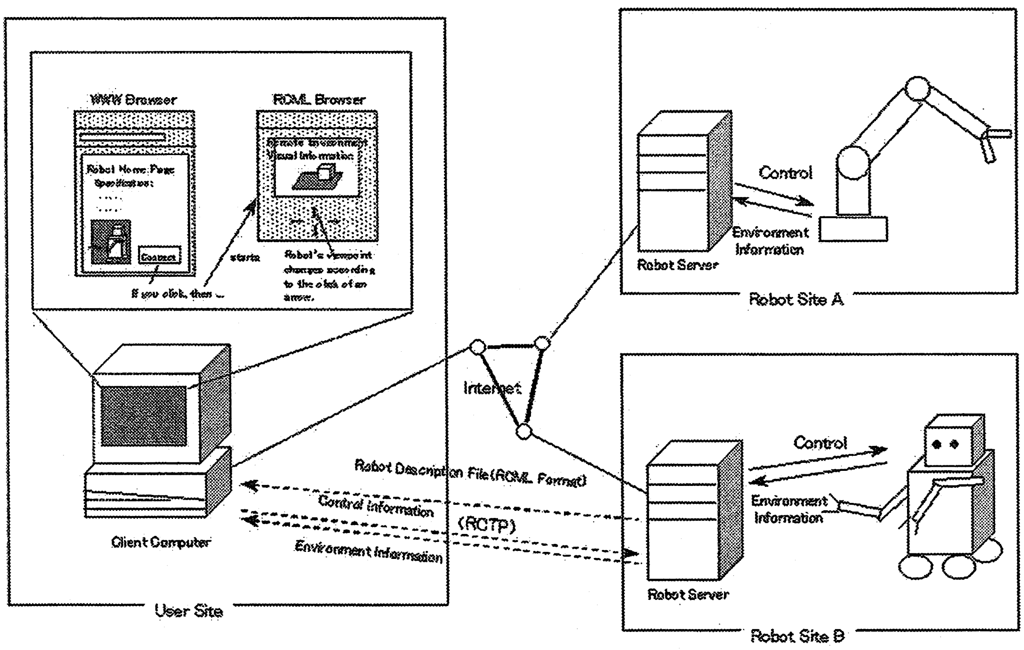

Fig. 8. Diagram for RCML and RCTP processes. Robots and control devices are placed virtually everywhere in the world and connected by Internet. Any user can use any robot when the robot is in use.

The browser decides the type and number of devices required to control the remote robot. Then, it generates a graphical user interface (GUI) panel to control the robot, in addition to a video window that displays the images "as seen" by the robot and a monitor window that allows operators to observe the robot's status from outside the robot. The operator can employ a device such as a six-degree-of-freedom (DOF) position/orientation sensor instead of the conventional GUI panel to indicate the robot-manipulator's endpoint [15].

3.5 Humanoid Robotics Project (HRP)

On the basis of the R^3 program and after conducting a two-year feasibility study called Friendly Network Robotics (FNR) from April 1996 until March 1998, a National Applied Science & Technology Project called "Humanoid and Human Friendly Robotics," or "Humanoid Robotics Project (HRP)" was launched in 1998. This was a five-year project toward the realization of an R^3 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 nuclear plants or power stations, construction work, aid supply in the case of emergencies or disasters, and care of elderly people. However, if we consider such systems from both technical and safety perspectives, it is clearly impossible to develop a completely autonomous robot system for these objectives.

Therefore, robot systems should be realized using a 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 environment in the form of natural audio, visual, and force feedback, thus invoking a feeling of existence inside the robot [13].

Thus, in phase 1 of the project, a telexistence cockpit for humanoid control was developed (Fig. 9), and the telexistence system was constructed using the developed humanoid platform.

A Computer Graphics (CG) model of the robot in the virtual environment is depicted and updated according to the current location and orientation received from the sensors located on the real robot. The model is displayed on the bottom-right screen of the surround visual display, and by augmenting the real images captured by the camera system; this assists the operator with robot navigation of the robot. Because the series of real images presented on the visual display are integrated with the movement of the motion base, the operator perceives a real-time sensation of stepping up and down.

To the best of our knowledge, this was the world's first successful experiment of controlling a humanoid biped robot using telexistence [16].

3.6 Mutual Telexistence: TELESAR II

A new prototype of a mutual telexistence master-slave system was designed and developed [17, 18]. The mutual telexistence master-slave system is based on RTP and

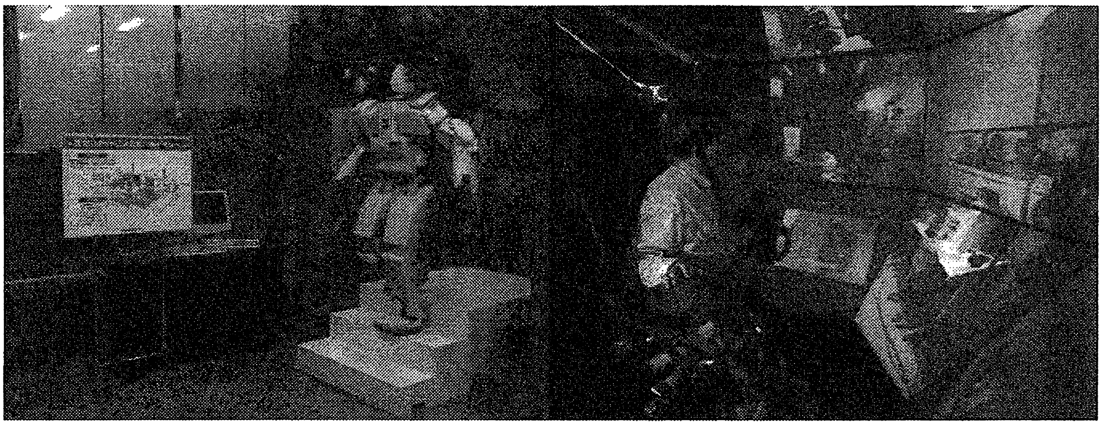

Fig. 9. HRP humanoid biped robot (left) and telexistence cockpit (right).

is composed of three subsystems: slave robot TELESAR II, master cockpit, and viewer system, as shown in Fig. 10.

The robot constructed for this communication system is called "TELESAR II." In order to use this system for telecommunication, we designed the robot by focusing on reproducing human-like realistic movements. TELESAR II has two human-sized arms and hands, a torso, and a head. Its neck has two DOFs, which can rotate around its pitch and roll axes. Two CCD cameras are placed inside its head for stereoscopic vision. The robot also has four pairs of stereo cameras located on top of its head for a three-dimensional surround display to benefit the operator. A microphone array and a speaker are also employed for auditory sensation and verbal communication. Each arm has seven DOFs, and each hand has five fingers with a total of eight DOFs.

To control the slave robot, we developed a master cockpit for TELESAR II. The cockpit consists of two master arms, two master hands, a multi-stereo display system, speakers and a microphone, and cameras for capturing the images of the operator in real time. In order for the operator to move smoothly, each master arm has a six-DOF structure so that the operator's elbow is free of constraints. To control the redundant seven DOFs of the anthropomorphic slave arm, a small orientation sensor is placed on the operator's elbow. Therefore, each master arm can measure seven-DOF motions for each corresponding slave arm, whereas force is transmitted back from each slave arm to each corresponding master arm with six DOFs.

The master arm is lightweight, and its impedance is controlled so that the operator perceives to be inside the slave robot. It is important for the master to transmit the exact amount of force to the operator, and for the slave robot to maintain safe contact with humans in remote environments. The impedance-control-type master-slave system adopted by us can achieve this force presentation. Moreover, safety compliant contact can be maintained with humans because the slave is subjected to impedance control. The motion of the robot's head is synchronized with the motion of the operator's head; these motions are measured using a head tracker in the master cockpit.

The most distinctive feature of the TELESAR II system is the use of an RPT viewer system. Both the motion and visual image of the operator are important factors to determine in order for the operator to perceive existence at the place where the robot is working. In order to view the image of the operator on the slave robot such that the

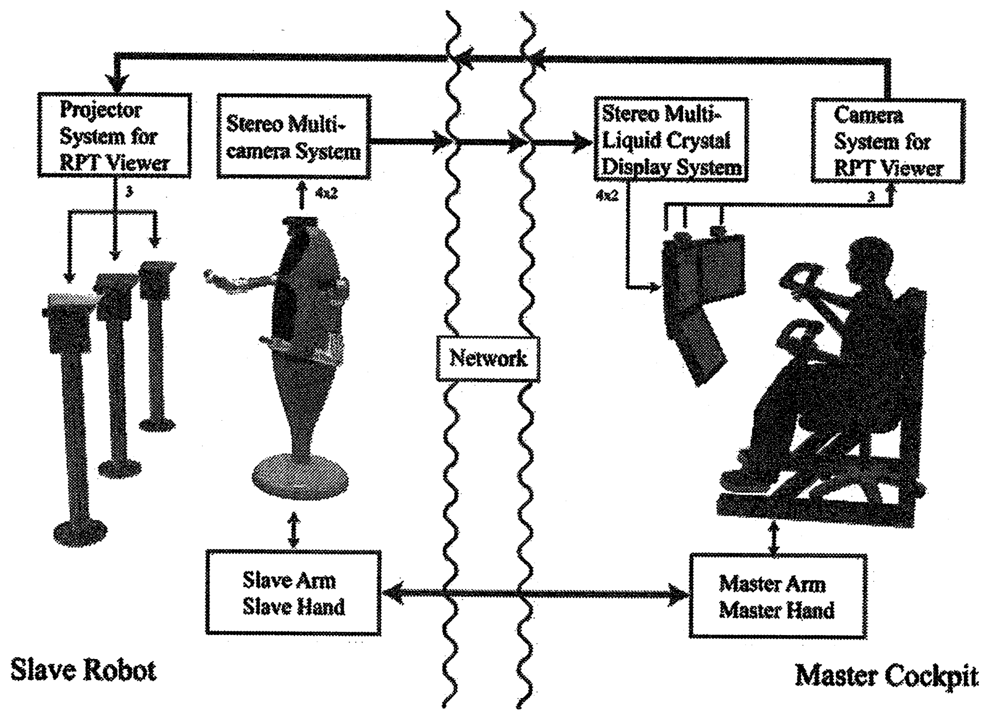

Fig. 10. Schematic diagram of TELESAR II master-slave manipulation system.

operator is inside the robot, the robot is covered with a retro-reflective material, and the image captured by the camera in the master cockpit is projected on the TELESAR II. TELESAR II acts as a screen, and a person seeing through the RPT viewer system observes the robot as though it were the operator because of the projection of the real image of the operator on the robot.

The face and chest of TELESAR II are covered with a retro-reflective material. A ray incident from a particular direction is reflected in the same direction as the surface of the retro-reflective material. Because of the characteristics of retro-reflective materials, an image is projected on the surface of TELESAR II without distortion. Because many RPT projectors are used in different directions, and different images are projected corresponding to the cameras located around the operator, the corresponding images of the operator can be viewed.

Figure 11 (left) illustrates an example of the projected images of an operator on its surrogate robot TELESAR II, and Fig. 11 (right) shows the operator who is telexisting in the TELESAR II robot.

The slave hand consists of five fingers with five finger-shaped haptic sensors. Each haptic sensor comprises a transparent elastic body, two layers of blue and red markers, and a CCD camera; it can measure the distribution of both the magnitude and direction of force. The master hand follows a compact exoskeleton mechanism called "circuitous joint," which covers the large workspace of the operator's finger. It can provide an encounter-type force feedback to the operator. The encounter-type force feedback avoids unnecessary contact sensations and allows unconstrained motion of the operator's fingers. Each fingertip has an electrocutaneous display unit attached to it in order to present tactile sensation to each finger of the operator in order to realize haptic telexistence.

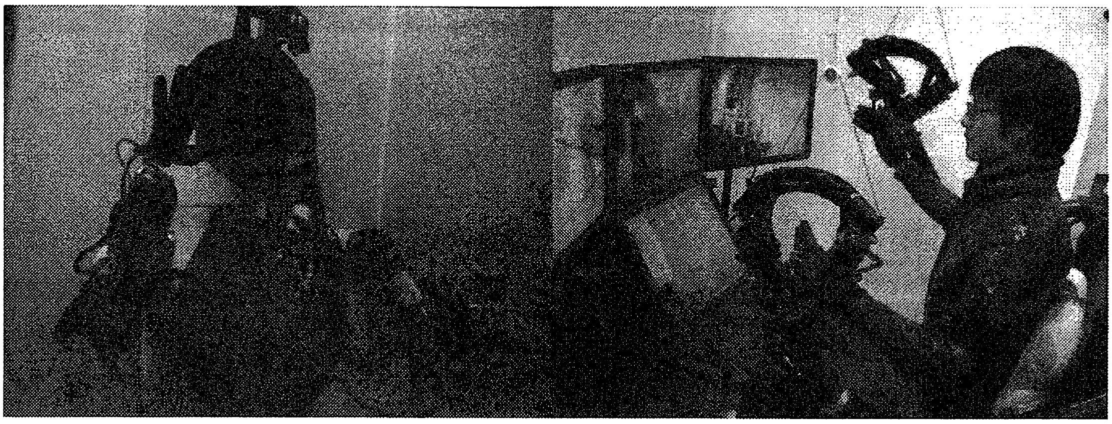

Fig. 11. TELESAR II robot with the projection of an operator (left), and the operator at the telexistence controls (right).

4 Present Status of Telexistence

There have been several commercial products with the name of telepresence, such as Teliris telepresence videoconferencing system, Cisco telepresence, Polycom telepresence, Anybots QB telepresence robot, Texai remote presence system, Double telepresence robot, Suitable Beam remote presence system and VGo robotic telepresence. Current commercial telepresence robots controlled from laptops could provide an increased sense of presence on the side of the robot, but the remote user might have a poor sense of self-presence.

An android that quite resembles its master is called a Geminoid [19]. Although it has a strong sense of the master's presence, it can only be used by the one whose face is used to make the robot. When the robot is used remotely, it is necessary to send the robot in advance. Because one of the merits of telexistence is to exist remotely without traveling, telexistence robots should be designed to be capable of being used by anyone so that it is not necessary to send the robot in advance. Study on automatic face replacement for an android has been conducted to solve this problem with some success [20]. However, three seconds are required to display the face, and real-time face expression cannot be transmitted. Research toward ideal telexistence is being conducted, such as research for transmitting the sense of presence of an operator through projections of the operator's facial image on the model of a human head in real time [21].

However, all these efforts have not achieved both a sense of self-presence and a sense of their presence as described in Sect. 2.2 in order to be mutual telexistence systems. Although ideal telexistence should provide haptic sensations, conventional telepresence systems provide mostly visual and auditory sensations with, at most, only incomplete haptic sensations. In this section, recent research aimed at mutual telexistence and haptic telexistence by the author and his team is introduced.

4.1 Face-to-Face Telexistence Communication Using TWISTER Booths

Telexistence Wide-angle Immersive STEReoscope (TWISTER) is designed as a telecommunication system that uses a virtual environment as a place for communication, thereby allowing highly realistic telecommunication between multiple persons. The system is designed to fulfill three conditions: (1) the virtual environment should have highly realistic audiovisual properties; (2) face-to-face communication should allow eye contact; and (3) participants in the virtual environment should possess a body, and should feel that the body belongs to them. We designed and built such a system and verified its utility.

In particular, to TWISTER's omnidirectional, three-dimensional naked eye display, we added a three-dimensional facial image acquisition system that captures expressions and line of sight, and a user motion acquisition system that captures information about arm and hand position and orientation; moreover, we constructed an integrated system whereby communication occurs via an avatar in a virtual environment. We then evaluated the system to verify that it fulfilled the established conditions. Furthermore, the results of having two participants engage in TWISTER-to-TWISTER telecommunication verified that participants can engage in telecommunication in the shared virtual environment under mutually equivalent conditions [22].

We used TWISTER V as a display to present audiovisual images of the virtual environment. As with TWISTER IV, TWISTER V displays binocular images using 36 LED display units, each with separate LED arrays for the left and right eyes. These are equally spaced along a circle with 1 m radius centered on the user, and rotated at high speed (1.7 rps) around the user. Persistence of vision creates a three-dimensional effect regardless of the viewing angle, and given that parallax images are presented by a rotating parallax barrier mechanism, glasses and other paraphernalia are not necessary to experience the three-dimensional effect.

TWISTER V has a 3162 × 600 pixel display resolution, and a 60 fps refresh rate. Users can move their upper body freely within the rotating part. Figure 12 (left) shows TWISTER V's exterior, and Fig. 12 (center) shows the full circumference of the interior as seen from below. Because images are displayed using persistence of vision during rapid rotation, the cylindrical surface upon which the LED units are affixed can be made transparent, allowing a clear view of the user within (Fig. 12 (right)).

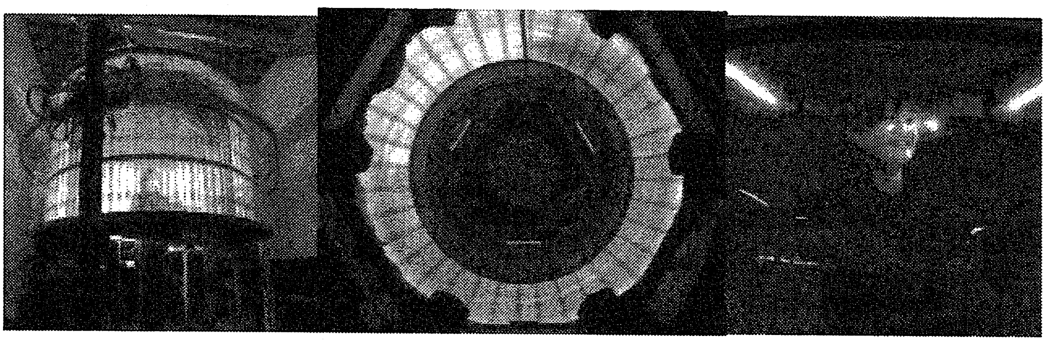

Fig. 12. TWISTER V: (left) general view, (center) view from inside, and (right) user seen from outside.

TWISTER V is equipped with speakers that allow presentation of fully inclusive sound from the bottom of the rotating part. Six speakers are located at a 60° interval along the periphery, allowing for sound directionality. This allows environmental sounds within the virtual environment and user utterances to be adjusted and presented as sounds within the space along the full periphery.

Figure 13 shows the conceptual diagram of mutual telexistence using TWISTER. This omnidirectional three-dimensional audiovisual system uses TWISTER and peripheral speakers to share virtual environment information. The movement acquisition system uses optical motion capture, a data glove, and a joystick, and information about the user hand and arm positioning and orientation is used to calculate avatar movements that are sent to the system. Information other than user facial images and utterances are collected, and differential information between the virtual environments is mutually transmitted using the User Datagram Protocol (UDP) to reflect changes in the virtual environment.

The three-dimensional facial imaging system has a mobile camera unit and a headset microphone. The mobile camera unit uses avatar positional relationships from the virtual environment to determine required camera movements, and controls self-propelled stereo cameras so that they are appropriately positioned. Captured user facial images are sent directly via a network to the virtual environment of other users. User utterances acquired by the headset microphone are sent via the network to the peripheral speakers of the user and others in the virtual environment, where they are presented along with environmental sounds.

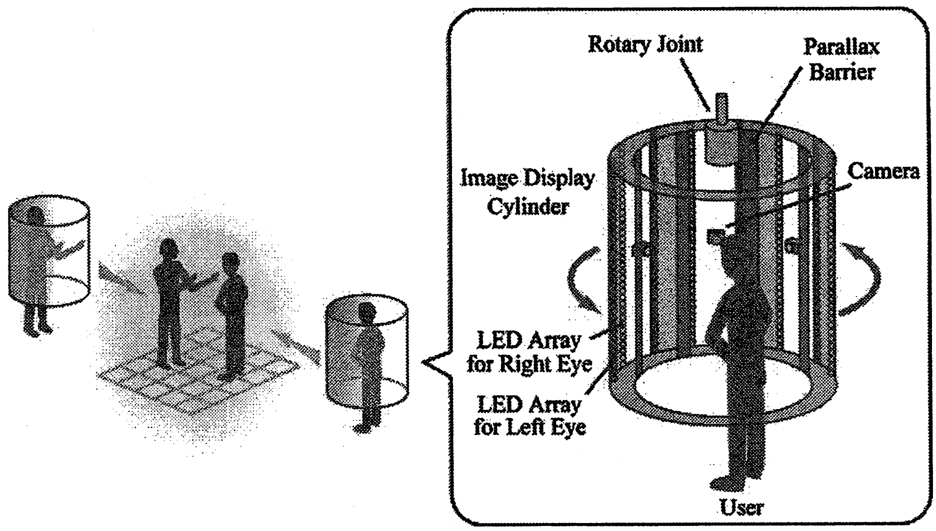

Fig. 13. Conceptual image of mutual telexistence using TWISTER.

We performed a communications experiment to test the telecommunication system, ensuring that the established requirements were sufficiently fulfilled to allow smooth communications in a shared virtual environment. The experiment was performed between two remote users engaged in one-on-one communications using TWISTER. The users were located at the University of Tokyo Hongo Campus (Hongo, Tokyo) and the Keio University Hiyoshi Campus (Hiyoshi, Yokohama). The network between the two TWISTER systems was over a dedicated 10 GB Ethernet line. Six participants were involved (three at each location), all ranging in age from 20 to 29. Two pairs of participants between the locations used the system in turn for approximately 30 min each, and one pair used it for approximately 2 h.

Figure 14 (left) shows the display of a facial image onto an avatar face area, as seen from the front. Figure 14 (center) shows the projection as seen from the side, which is presented as an appropriate three-dimensional profile image (cf. Fig. 14 (left)). Figure 14 (right) shows the position of the stereo camera and the facial image on the avatar with TWISTER external illumination adjusted so that both the stereo camera and the facial image can be seen. The stereo camera overlaps with the avatar's eye position so that line of sight naturally aligns. We verified that an avatar with physicality similar to a human can be used in a virtual environment for free movement, gestures, and transport of virtual objects such as glasses.

Fig. 14. Facial image on avatar in telexistence communication: (left) front view of the face image, (center) side view of the face image, (right) stereo camera overlapping with the eyes on the facial image, which assures eye contact of the two users.

Figure 15 shows the results of telecommunication in the integrated system. Figure 15 (left) is an image of the TWISTER booth located at Keio University and Fig. 15 (right) shows the booth at the University of Tokyo. We confirmed that the basic flow of the experiment can be conducted without significant problems.

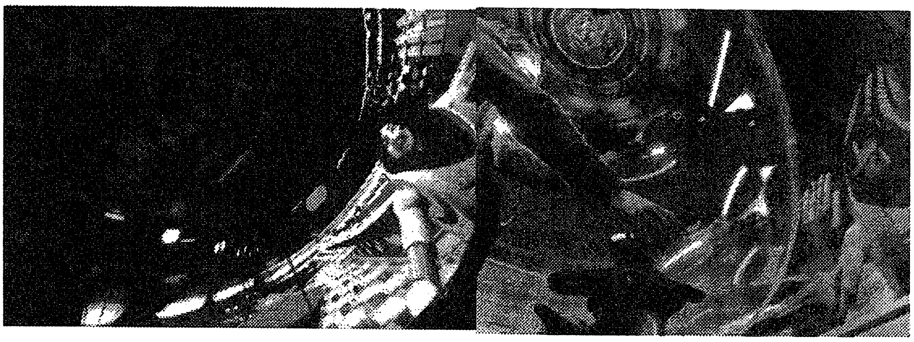

Fig. 15. TWISTER to TWISTER communication: (left) a view from TWISTER V at Keio University, (right) a view from TWISTER IV at the University of Tokyo.

Subjective evaluation of the system from experiment participants was unanimous in reporting that interactions in the virtual environment invoked sensations similar to performing interactions in the real world. One participant reported the experience as being not so similar to having one's body transported to a virtual environment, but rather as though the TWISTER booth itself had been transported. We interpret this as meaning that entering the virtual environment in clothing similar to a space suit invoked a sensation of near immersion. Demonstrative pronouns frequently used in the real world such as "there" and "this" were naturally understood, leading to opinions that communication is easily performed. Such qualitative results are further indications that telecommunication that includes physicality and transmission of intent was realized.

4.2 Mobile Mutual Telexistence Communication System: TELESAR IV

Figure 16 shows a conceptual sketch of mobile mutual telexistence using TWISTER and a surrogate robot. User A can observe remote environment [B] using an omnistereo camera mounted on surrogate robot A'. This provides user A with a panoramic stereo view of the remote environment displayed inside the TWISTER booth. User A controls robot A' by using the telexistence master-slave control method. Cameras B' and C' mounted on the booth are controlled by the position and orientation of users B and C relative to robot A', respectively. Users B and C can observe different images of user A projected on robot A' by wearing their own Head Mounted Projector (HMP) to provide the correct perspective. Since robot A' is covered with retroreflective material, it is possible to project images from both cameras B' and C' onto the same robot while having both images viewed separately by users B and C.

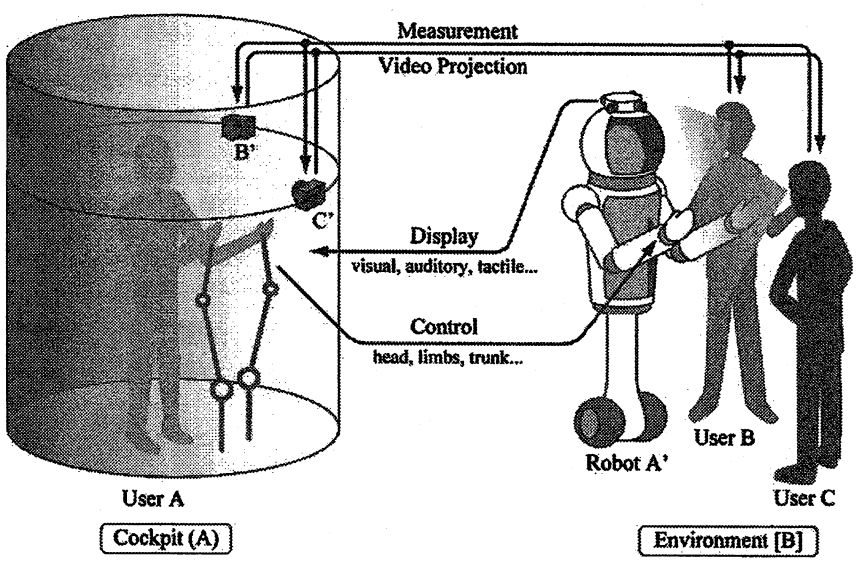

Fig. 16. Conceptual sketch of mobile mutual telexistence system using TWISTER as a cockpit.

The mobile mutual telexistence system, TELESAR IV, which is equipped with master-slave manipulation capability and an immersive omnidirectional autostereoscopic three-dimensional display with a 360° field of view known as TWISTER, was developed in 2010 [23]. It projects the remote participant's image onto the robot using RPT. Face-to-face communication was also confirmed, as local participants at the event were able to see the remote participant's face and expressions in real time. It was further confirmed that the system allowed the remote participant to not only move freely about the venue by means of the surrogate robot but also perform some manipulation tasks such as a handshake and other gestures. Figure 17 shows a general view of the system.

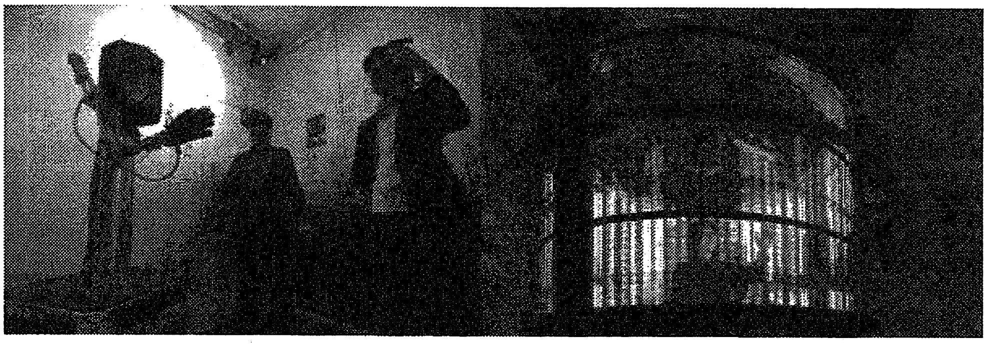

Fig. 17. General view of TELESAR IV system.

The TELESAR IV system consists of a telexistence remote cockpit system, telexistence surrogate robot system, and RPT viewer system. The telexistence remote cockpit system consists of the immersive 360° full-color autostereoscopic display known as TWISTER, a rail camera system installed outside TWISTER, an omnidirectional speaker system, an OptiTrack motion capture system, a 5DT Data Glove 5 Ultra, a joystick, and a microphone.

The telexistence surrogate robot system consists of an omnidirectionally mobile system, the 360° stereo camera system known as VORTEX, a retroreflective screen, an omnidirectional microphone system, a robot arm with a hand, and a speaker. The RPT viewer system consists of a handheld RPT projector, head-mounted RPT projector, and OptiTrack position and posture measurement system.

Stereo images captured by the 360° stereo camera system VORTEX are fed to a computer (PC1) mounted on the mobile robot. Real-time compensation and combination of the images are performed to transform these into 360° images for TWISTER. The processed images are sent to TWISTER and unprocessed sound from the omnidirectional microphone system is sent directly to the corresponding speaker system in TWISTER.

Cameras are controlled to move along the circular rail and to imitate the relative positions of the surrogate robot and the local participants at the venue. The images of the remote participant taken by these cameras outside TWISTER are fed to a computer (PC3) and sent to another computer (PC2) mounted on the mobile surrogate robot. These images are sent to the handheld and head-mounted projectors once they are adjusted using the posture information acquired by the position and posture measurement system (OptiTrack), which consists of seven infrared cameras installed on the ceiling of the venue. These processed images are in turn projected onto the retroreflective screen atop the mobile robot. The voice of the remote participant is also sent directly to the speaker of the mobile surrogate robot.

The joystick is located inside TWISTER and is controlled by the left hand of the remote participant. The data of the joystick are fed to PC3 and sent to PC1 via the network. Based on the information received, PC1 generates and executes a motion instruction to have the mobile surrogate robot move in any direction or turn freely on the spot; i.e., omnidirectional locomotion is possible. Using the motion capture system (OptiTrack) installed on the ceiling of TWISTER, the position and posture of the right arm of the remote participant are obtained. The position and posture data are also fed to PC3 and sent to PC2 via the network. Based on the received data, PC2 controls the robot arm to imitate the arm motion of the remote participant. In addition, hand motion data acquired by the 5DT Data Glove 5 Ultra are sent to the hand of the surrogate robot to imitate the hand motion of the remote participant.

A remote participant inside TWISTER joined a gathering by means of his surrogate robot and moved freely in a room with two local participants, who were able not only to see his face in real time through handheld and head-mounted RPT projectors but also to communicate with him naturally. The local participant in front of the robot saw the full face of the remote participant, while the local participant on the right side of the robot saw his right profile at the same time. The remote participant was able not only to see and hear the environment as though he were there but also to communicate face-to-face with each local participant. Moreover, he was able to shake hands and express his feelings with gestures, as shown in Fig. 18. Total latency of the visual-auditory system was less than 100 ms including data acquisition, transmission, and rendering. The total control cycle time of the robot was around 60 ms including measurement of the human operator, transmission, and control of the robot's arm and hand.

Fig. 18. Demonstration of TELESAR IV system at work.

4.3 Telexistence Avatar Robot System: TELESAR V

TELESAR V (TELExistence Surrogate Anthropomorphic Robot) is a telexistence master–slave robot system that was developed to realize the concept of telexistence. TELESAR V was designed and implemented with the development of a high-speed, robust, full upper body, mechanically unconstrained master cockpit, and 53 degrees-of-freedom (DOF) anthropomorphic slave robot. The system provides an experience of our extended "body schema," which allows a human to maintain an up-to-date representation in space of the positions of his/her various body parts. Body schema can be used to understand the posture of the remote body and to perform actions with the belief that the remote body is the user's own body. With this experience, users can perform tasks dexterously and perceive the robot's body as their own body through visual, auditory, and haptic sensations, which provide the most simple and fundamental experience of telexistence. The TELESAR V master–slave system can also transmit fine haptic sensations such as the texture and temperature of a material from an avatar robot's fingers to a human user's fingers [24, 25].

As shown in Figs. 19 and 20, the TELESAR V system consists of a master (local) and a slave (remote). A 53-DOF dexterous robot was developed with a 6-DOF torso, a 3-DOF head, 7-DOF arms, and 15-DOF hands. The robot also has Full HD (1920 × 1080 pixels) cameras for capturing wide-angle stereovision, and stereo microphones are situated on the robot's ears for capturing audio from the remote site. The operator's voice is transferred to the remote site and output through a small speaker installed in the robot's mouth area for conventional verbal bidirectional communication. On the master side, the operator's movements are captured with a motion-capturing system (OptiTrack) and sent to the kinematic generator PC. Finger bending is captured to an accuracy of 14 DOF with the "5DT Data Glove 14."

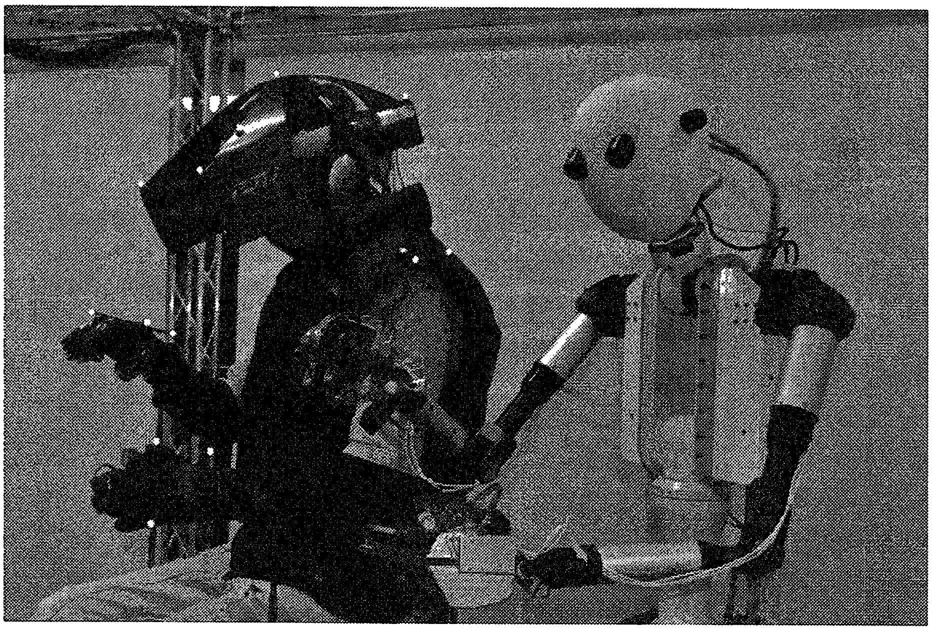

Fig. 19. General view of TELESAR V master (left) and slave robot (right).

The haptic transmission system consists of three parts: a haptic scanner, a haptic display, and a processing block. When the haptic scanner touches an object, it obtains haptic information such as contact force, vibration, and temperature. The haptic display provides haptic stimuli on the user's finger to reproduce the haptic information obtained by the haptic scanner. The processing block connects the haptic scanner with the haptic display and converts the obtained physical data into data that include the physiological haptic perception for reproduction by the haptic display. The details of the scanning and displaying mechanisms are described below [26–29].

First, a force sensor inside the haptic scanner measures the vector force when the haptic scanner touches an object. Then, two motor-belt mechanisms in the haptic display reproduce the vector force on the operator's fingertips. The processing block

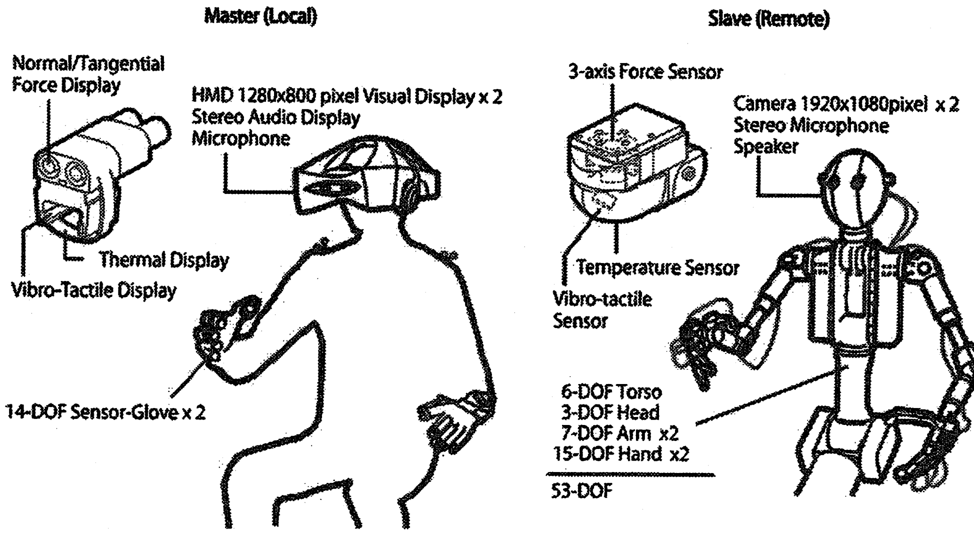

Fig. 20. TELESAR V system configuration.

controls the electrical current of each motor to provide the target torques based on the measured force. As a result, the mechanism reproduces the force sensation when the haptic scanner touches the object.

Second, a microphone in the haptic scanner records the sound generated on its surface when the haptic scanner is in contact with an object. Then, a force reactor in the haptic display plays the transmitted sound as a vibration. This vibration provides a high-frequency haptic sensation. Therefore, the information should be transmitted without delay. For this purpose, the processing block transfers the sound signals by using circuits with no transformation.

Third, a thermistor sensor in the haptic scanner measures the surface temperature of the object. The measured temperature is reproduced by a Peltier actuator placed on the operator's fingertips. The processing block generates a control signal for the Peltier actuator. The signal is generated based on a PID control loop with feedback from a thermistor located on the Peltier actuator. Figures 21 and 22 show the structures of the haptic scanner and the haptic display, respectively.

Figure 23 shows the left hand of the TELESAR V robot with the haptic scanners, and the haptic displays set in the modified 5DT Data Glove 14.

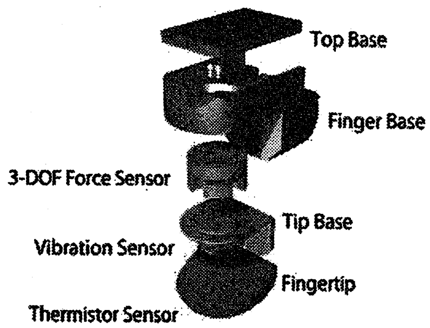

Fig. 21. Structure of haptic scanner.

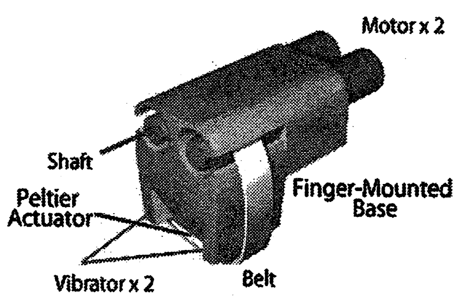

Fig. 22. Structure of haptic display.

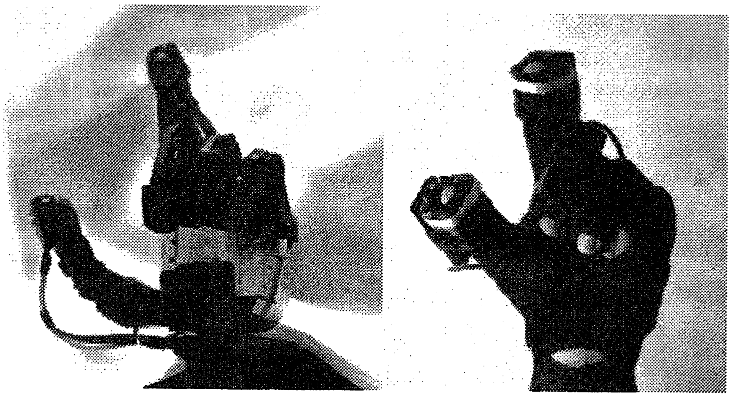

Fig. 23. Slave hand with haptic scanners (left) and master hand with haptic displays (right).

Figure 24 shows TELESAR V conducting several tasks such as picking up sticks, transferring small balls from one cup to another cup, producing Japanese calligraphy, playing Japanese chess (shogi), and feeling the texture of a cloth.

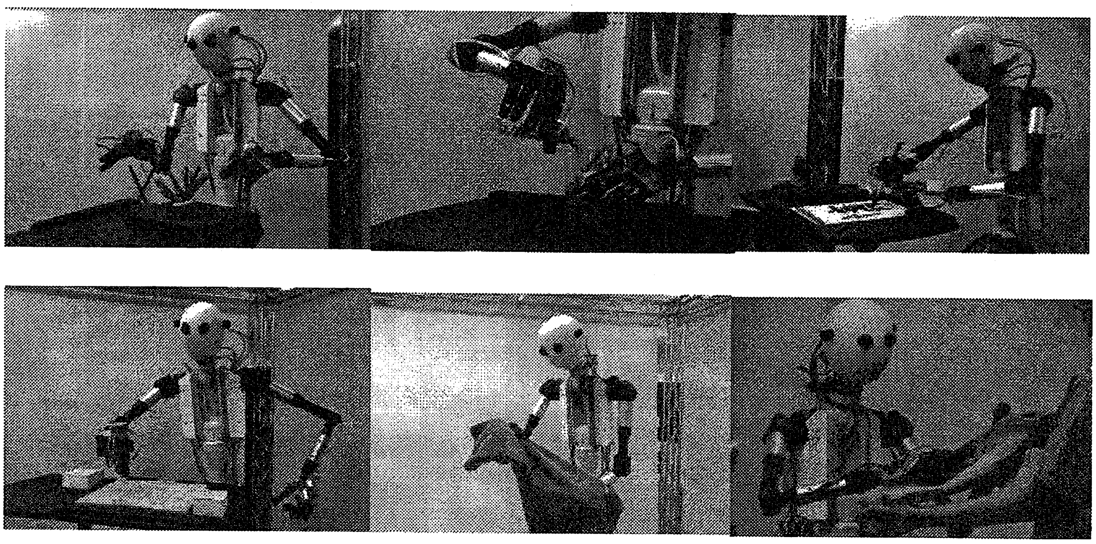

Fig. 24. TELESAR V conducting several tasks transmitting haptic sensation to the user.

5 Future Perspective of Telexistence

Telexistence technology has a broad range of applications such as operations in dangerous or poor working conditions within factories, plants, or industrial complexes; maintenance inspections and repairs at atomic power plants; search, repair, and assembly operations in space or the sea; and search and rescue operations in the event of a disaster as well as repair and reconstruction efforts in the aftermath of such a disaster. It also has applications in areas of everyday life, such as garbage collection and scavenging, civil engineering, agriculture, forestry, and fisheries industries; medicine and welfare; policing; exploration; leisure; and substitutes for test pilots and test drivers. These applications of telexistence are inclined toward the concept of conducting operations as a human-machine system, whereby a human compensates for features that are lacking in a robot or machine.

Further, there is a contrasting perspective on telexistence, according to which it is used to supplement and extend human abilities. This approach involves the personal utilization of telexistence, that is, liberating humans from the bonds of time and space by using telexistence technology.

We propose future applications as follows:

- If telexistence booths substitute telephone booths on streets or in offices, many people could meet each other using these booths, as if they were seeing each other face-to-face. Such technology could support not only conferences but also situations wherein many people walk around freely, such as cocktail parties.
- For the purpose of easy management, companies whose production sites are distributed overseas could link their branch offices and factories and treat them as though they were virtually located at one place.
- Advanced medical care could be provided worldwide by employing such a transmission system in operating rooms.
- The virtual presence of doctors would facilitate the provision of emergency medical services at early stages of an illness.
- In the event of a disaster, search and rescue operations would be possible without any concerns for ensuing disasters.
- One could immediately return from a remote location to one's office or home with a real-time sensation of existence.
- One could meet with family, relatives, and friends at remote places in a manner similar to a face-to-face meeting.
- One could have special experiences such as being in the midst of a flock of birds by using a small robot bird as his/her surrogate.
- Life-altering experiences such as looking at the earth from outer space, which is now physically possible only for astronauts, could be offered to everyone.
- One could enjoy real shopping at a remote shop as if he or she were physically present at the shop.
- One could travel to seldom-visited places with the sense of existence at those places.
- Life-sized space designs and evaluation tools would be available to architects.

6 Conclusion

Telexistence technology was historically reviewed, current advancements in telexistence, including mutual telexistence and haptic telexistence, were studied, and future perspective of telexistence were outlined.

Telexistence is a concept that allows humans to be emancipated from the restrictions of time and space and that allows them to exist at a "location" defined by inconsistent time and space, or a virtual space. Telexistence is the concept of making humans, rather than computers, ubiquitous. It differs from telepresence: the former also includes telexistence within or through virtual environments.

It is important to distinguish two key elements for telexistence: the "sense of self-presence" and the "sense of their presence". This paper described technologies that improve both of these elements towards the next generation of "mutual telexistence".

In particular, the TELESAR surrogate anthropomorphic robot was controlled from a cockpit that provides a sensory immersive (audiovisual and haptic) interface via gloves and tactile actuators. Many generations of the system have been constructed, including TWISTER, the improved version of the cockpit. One distinguishing feature of TELESAR is Retroreflective Projection Technology (RPT) system. Under this concept, a robot is covered with a retroreflective material, and viewers on the robot's side use head-mounted projectors to display the correct image of the interacting user, according to their perspective.

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