テレイグジスタンス
− 過去、現在、未来 −
Telexistence
--- Past, Present, and Future

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Abstract: The telexistence technology enables a highly realistic sensation of existence in a remote place without any actual travel. The concept was proposed by the author in 1980, and its feasibility has been demonstrated through the construction of alter-ego robot systems such as TELESAR that was developed under the national large scale project on “Robots in Hazardous Environments” as well as the HRP super-cockpit biped robot system developed under the “Humanoid Robotics Project.” A mutual telexistence system TELESAR II, which can generate the effect of existing in a remote place in local space using a combination of an alter-ego robot and the 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 the telexistence technology has been discussed.

Keywords: telexistence, mutual telexistence, telepresence, teleoperation, master-slave system, virtual reality, augmented reality, TELESAR, TWISTER, RPT

1. Introduction

Telexistence is fundamentally a concept that refers to the general technology that allows a human being to have a real-time sensation of existing in a place other than where he/she actually exists and to interact with the remote environment, which may be real, virtual, or a combination of both. It also refers to an advanced type of teleoperation system that enables an operator at the controls to perform remote tasks dexterously with the feeling of existing in a surrogate robot working in a remote environment. Telexistence in the real environment through a virtual environment is also possible.

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

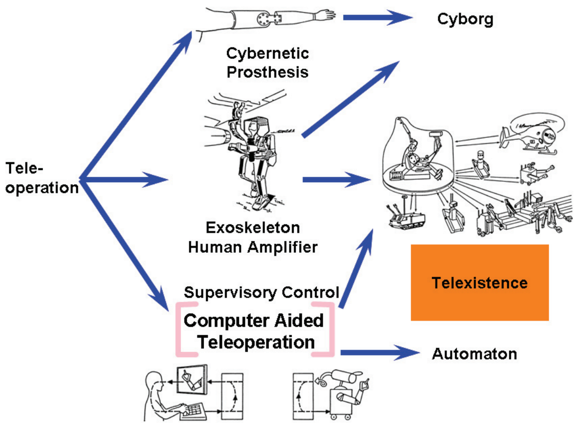

Figure 1: Emergence and Evolution of telexistence.

2. Short History and Present Status of Telexistence

2.1. How Telexistence was Conceptualized and Developed

It has long been a desire of human beings to project themselves in a remote environment, i.e., to have the sensation of existing in a place other than the one they really exist in, at the same time. Another dream has been to amplify the human muscle power and sensing capability by using machines while maintaining human dexterity with a sensation of actually performing the task.

In the late 1960s, a research and development program was planned to develop a powered exoskeleton that an operator would wear in the same manner as a garment. The concept of 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 will multiply his/her strength by a factor of 25,

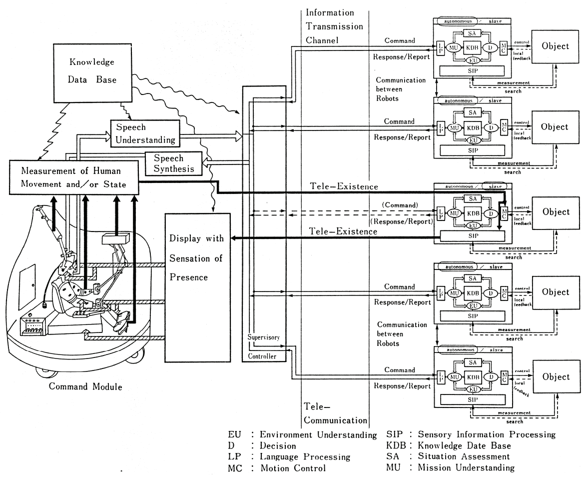

Figure 2: Telexistence System Architecture.

yet, in this union of man and machine, he/she would feel the object and forces almost as if he/she were in direct contact with it.

However, the program was unsuccessful because of the following reasons: (1) Wearing the powered exoskeleton was potentially quite dangerous in the event of the malfunctioning of the machine. (2) Autonomous mode was difficult to be achieved and everything must be done by a human operator. Thus, the design proved impractical in its original form.

With the advent of science and technology, however, it has become possible to realize this dream with a different concept. The concept of projecting ourselves by using robots, computers, and a cybernetic human interface is referred to as telexistence (tel-existence). This concept extends to include projection in a computer-generated virtual environment. Figure 1 illustrates the emergence and evolution of the concept of telexistence.

The concept of telexistence was proposed by the author in 1980 [1], and it was the fundamental principle of the eight-year Japanese national large scale project of "Advanced Robot Technology in Hazardous Environment," which started in 1983 together with the concept of the Third Generation Robotics.

Telexistence enables a human operator at the controls to perform remote manipulation tasks dexterously with the feeling that he/she exists in an anthropomorphic robot in a remote environment [2-8].

Fundamental studies for the realization of telexistence systems were conducted under the national large scale project "Advanced Robot Technology in Hazardous Environment," which was a research and development program launched for developing a system that avoids the need for humans to work in potentially hazardous working environments such as nuclear power plants, under water, and disaster areas.

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

Our first report [3,5] proposed the principle of a telexistence sensory display and explicitly defined its design procedure. The feasibility of a visual display providing a sensation of existence was demonstrated through psychophysical measurements performed using an experimental visual telexistence apparatus. Figure 3 illustrates the first prototype telexistence visual display developed.

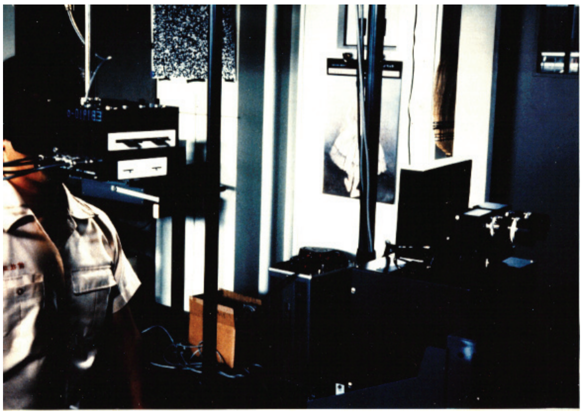

Figure 3: First Prototype Telexistence Visual Display.

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 existence. A prototype mobile televehicle system was constructed, and the feasibility of the method was evaluated [9]. Figure 4 presents a prototype telexistence mobile robot, and Fig. 5 illustrates the head-linked display with a sensation of existence used in the system.

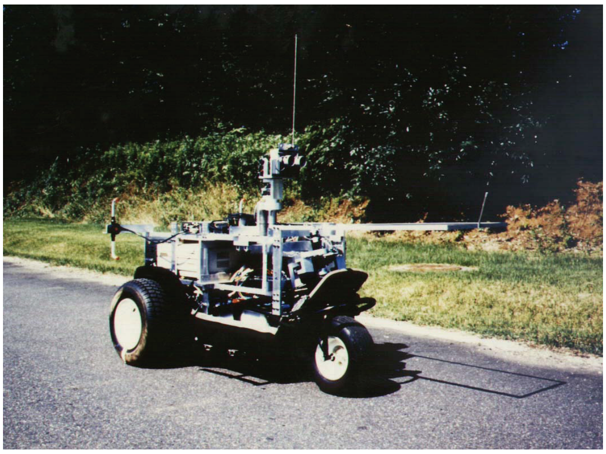

Figure 4: Prototype Mobile Telexistence Vehicle (Televehicle) .

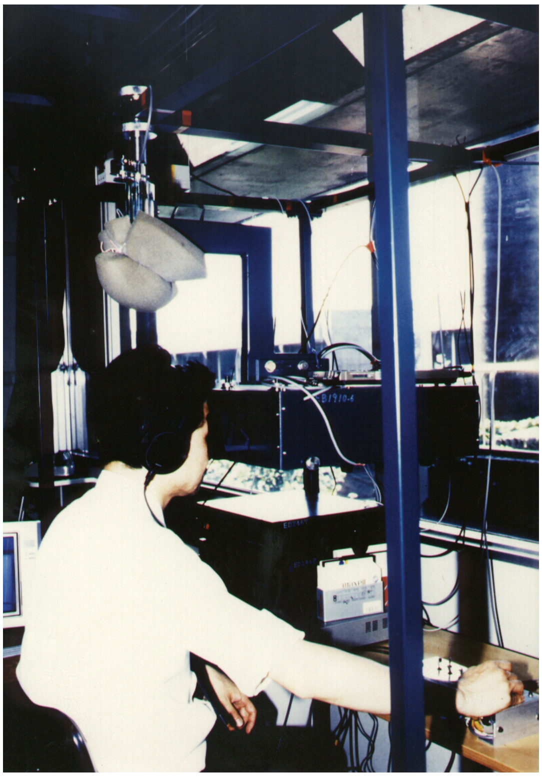

Figure 5: Head-linked Stereo Display with a Sensation of Existence.

2.2. 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 performing calibration. An experimental operation of block-building was successfully conducted by using a humanoid robot called TELESAR (TELExistence Surrogate Anthropomorphic Robot) (Fig. 6). Experimental studies of the tracking tasks quantitatively demonstrated that a human being can telexist in a remote environment by using a dedicated telexistence master-slave system [12]. Figure 7 illustrates a telexistence master system.

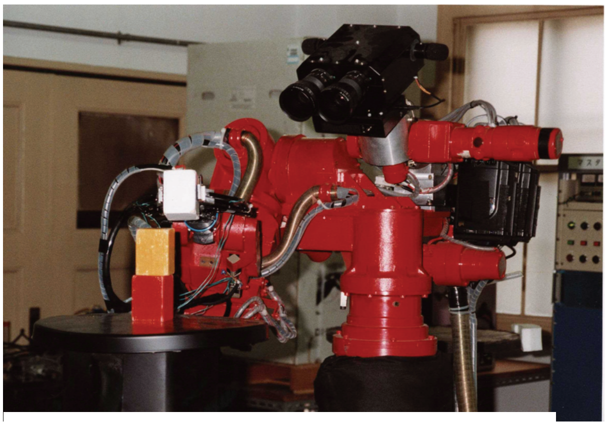

Figure 6: TELESAR (Telexistence Surrogate Anthropomorphic Robot) at work.

Figure 7: Telexisitence Master Manipulation System.

2.3. 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.

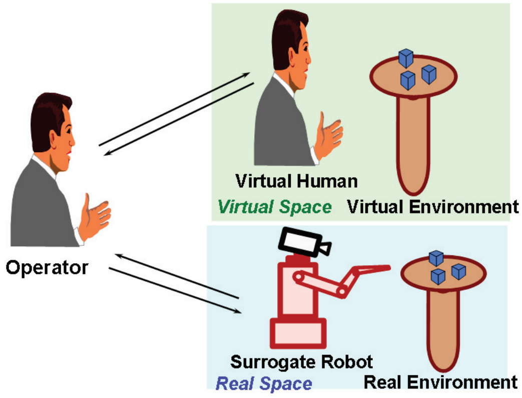

Figure 8: Telexistence in Real and Virtual Environment.

The former can be referred to as "transmitted reality;" the latter, "synthesized reality."(Fig. 8)

Synthesized reality can be classified as follows: a virtual environment representing a real world and that representing an imaginary world. Combining transmitted reality and synthesized reality, which is referred to as mixed reality, is also possible, and it has a great significance in 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 for controlling a slave robot, the modelling 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 by using Telesar (Fig. 6) and the virtual dual. Figure 9 illustrates the virtual telexistence anthropomorphic robot used in the experiment [13, 14].

A quantitative evaluation of the telexistence manipulation system was conducted through tracking tasks by using the telexistence master-slave system. Through these experimental studies, it was demonstrated that a

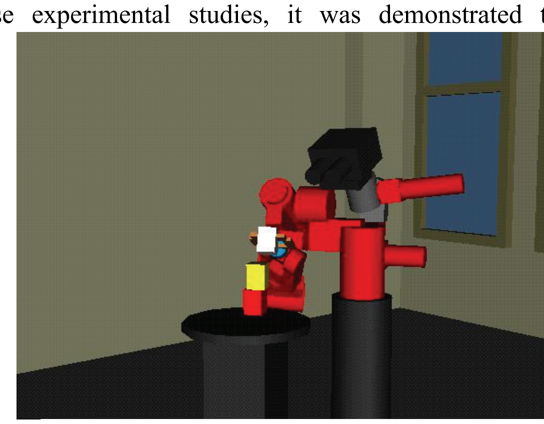

Figure 9: Virtual TELESAR at Work.

human being can telexist in a remote environment and/or a computer-generated environment by 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.

2.4. 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, which was dubbed R-Cubed (R3) in 1995. R3 stands for real-time remote robotics. The concept of this program was the research and development of the technologies that enable human operators to telexist freely by integrating robots, virtual reality, and network technology [15].

Figures 10 and 11 present examples of a conceptual networked telexistence application using R3 robots.

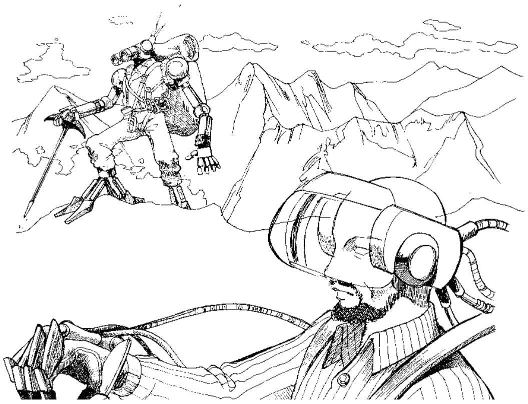

Figure 10: Conceptual Image of Mountain Climbing using R-Cubed Robot.

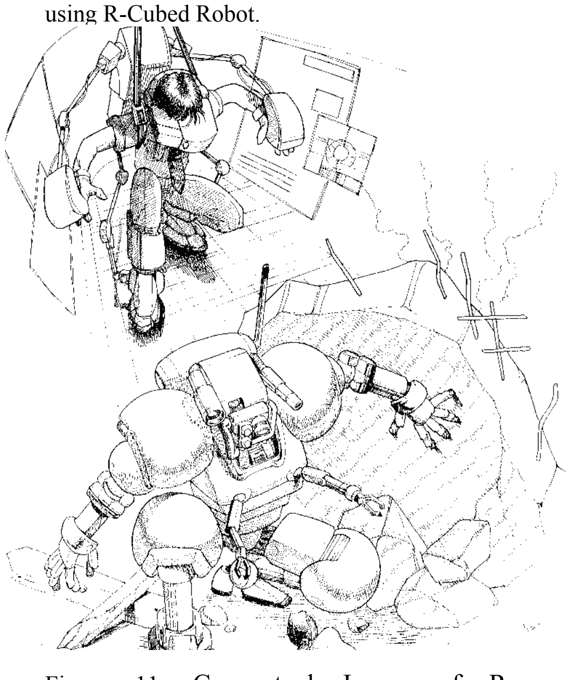

Figure 11: Conceptual Image of Rescue Operation using R-Cubed Robot

Figure 12 illustrates an example of an R3 robot system. Each robot site has a server for 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.

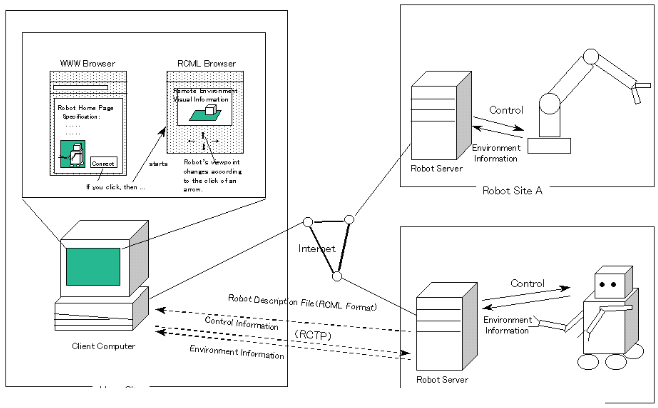

Figure 12: R-Cubed Robot system.

Each client has its teleoperation system. It 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, RCML/RCTP (R-Cubed Manipulation Language/R-Cubed Transfer Protocol) is now under development.

An operator accesses the web site describing the information of a robot in the form of hypertext and icon graphics using a WWW browser. Clicking on an icon downloads a description file, which is written in 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 the arrangement of the degrees of freedom of the robot, controllable parameters, available motion ranges, sensor information, and other pertinent information.

The browser decides the type and number of devices required to control the remote robot. It then generates a graphical user interface (GUI) panel to control the robot, plus a video window that displays the images as "seen" by the robot and a monitor window that lets the operators observe the robot's status from outside the robot. The operator can employ a device such as a 6-degree-of-freedom (DOF) position/orientation sensor instead of the conventional GUI panel to indicate the robot-manipulator's endpoint.

2.5. HRP (Humanoid Robotics Project)

On the basis of the R3 program and after conducting a two-year feasibility study called Friendly Network Robotics (FNR) from April 1996 till March 1998, a National Applied Science & Technology Project "Humanoid and Human Friendly Robotics," or "Humanoid Robotics Project (HRP)" in short, was launched in 1998. It was a five-year project toward the realization of a so-called R3 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, supply of aid in case of emergencies or disasters, and care of elderly people. If we consider such systems from both technical and safety points of view, however, it is clearly intractable to develop a completely autonomous robot system for these objectives.

Robot systems should therefore 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 itself [16].

Thus, in phase 1 of the project, a telexistence cockpit for humanoid control was developed (Fig. 13), and the telexistence system was constructed using the developed humanoid platform.

Figure 13: Telexistence Super Cockpit.

In order to address the problem of narrow fields of view associated with conventional HMDs, a surround visual display using an immersive projection technology, as that adopted in the CAVE (CAVE Automatic Virtual Environment), was developed. The surround visual display panoramically presents the real images captured by a stereo multi-camera system mounted on the robot for a wide field of view, which allows the operator to have the feeling of on-board motion when he/she uses the robot to walk around.

Various teleoperation experiments performed using the developed telexistence master system confirmed that kinesthetic presentation by the master system through visual imagery greatly improves both the operator's sensation of walking and the dexterity at manipulating objects.

If the operator issues a command to move the robot, the robot actually walks toward the goal. As the robot walks around, real images captured by the multi-camera system with a wide field of view are displayed on the four screens of the surround visual display. This makes the operator feel as if he or she is inside the robot, walking around at the robot site (Fig. 14).

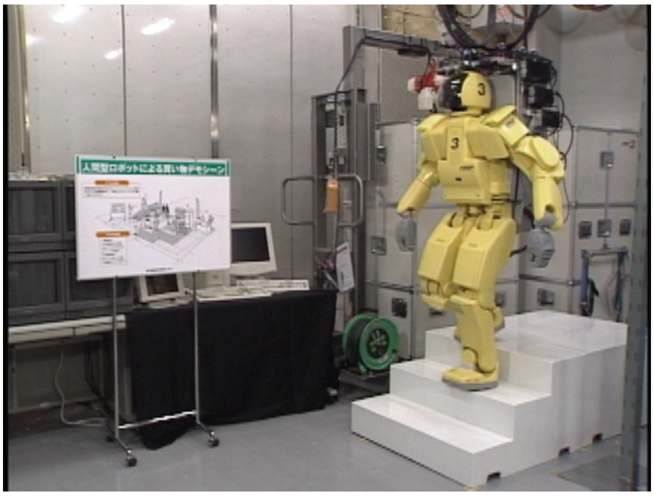

Figure 14: Telexistence in Humanoid Biped Robot.

A CG (Computer Graphics) 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, it assists the operator with the 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 a real-time sensation of stepping up and down.

This was the world-first experiment and success of controlling a humanoid biped robot using telexistence [16].

2.6. Mutual Telexistence: TELESAR II

A new prototype of a mutual telexistence master-slave system was designed and developed [17-24]. The mutual telexistence master-slave system is based on the RTP and is composed of three subsystems - slave robot TELESAR II, master cockpit, and viewer system - as shown in Fig.15.

The robot constructed for this communication system is called "TELESAR II (Telexistence Surrogate Anthropomorphic Robot 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 a stereoscopic vision. It also has four pairs of stereo cameras located on top of its head for a 3D surround display for the benefit of the operator. A microphone array and a speaker are also employed for an 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 that the operator can move smoothly, each master arm has a 6-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 7-DOF motions for each corresponding slave arm, while the force is fed back from each slave arm to each corresponding master arm with six DOFs.

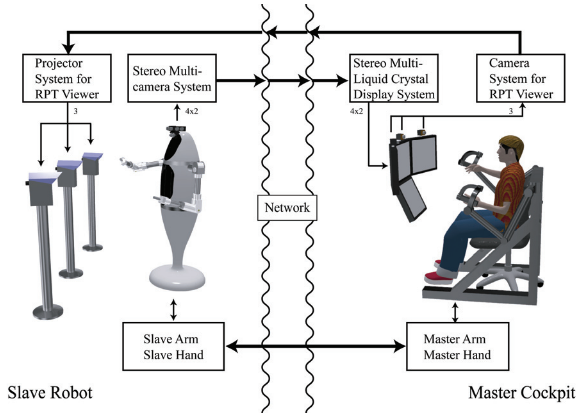

Figure 15: TELESAR II Master-Slave System.

The master arm is lightweight, and its impedance is controlled so that the operator feels as if he/she is inside the slave robot. It is important that the master should transmit the exact amount of force to the operator and the slave robot should maintain a safe contact with humans in a remote environment. The impedance-control-type master-slave system adopted by us can achieve the force presentation. Moreover, a safe 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 by using a head tracker in the master cockpit.

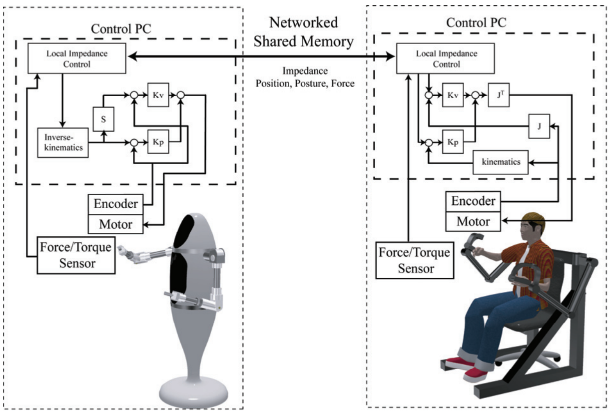

Figure 16: Impedance Control of TELESAR II.

The operator can easily control the hands of TELESAR II because the motions of the operator's hands are measured by the master cockpit manipulators and controlled by master-slave methods. In the case of an autonomous robot system, a precise computation of motions is required to be performed to prevent the collisions of the arms, hands, or torso of the robot. In the case of the telexistence system, however, collision detection is not required to be performed. The operator calculates it subconsciously. This is a remarkable feature of the telexistence system. Despite this, we calculated the collision limit, and collision can be prevented even if the operator fails to avoid collision (fail-safe mechanism or safety intelligence system). Figure 16 presents a general outline of the impedance-control-type master-slave teleoperation system used in this study.

Figure 17 illustrates a general view of TELESAR II (left) and the structure of its arm (right).

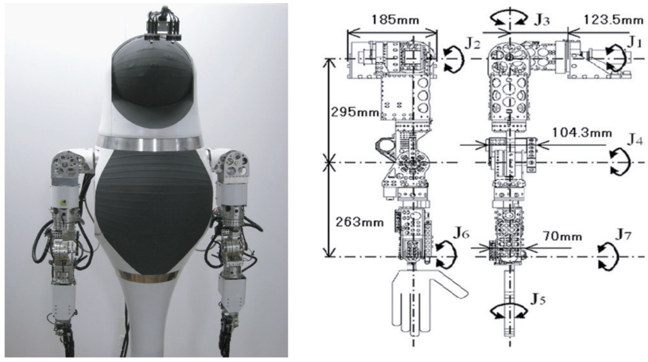

Figure 17: General View of TELESAR II (left) and structure of its arm (right).

Figure 18 presents a general view of the master cockpit of TELESAR II. The most distinctive feature of the TELESAR II system is the use of an RPT viewer system. Both the motion and the visual image of the operator are important factors to be determined for the operator to feel the 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 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. TELLESAR II acts as a screen, and a person seeing through the RPT viewer system observes the robot as if it is the operator because of the projection of the real image of the operator onto the robot.

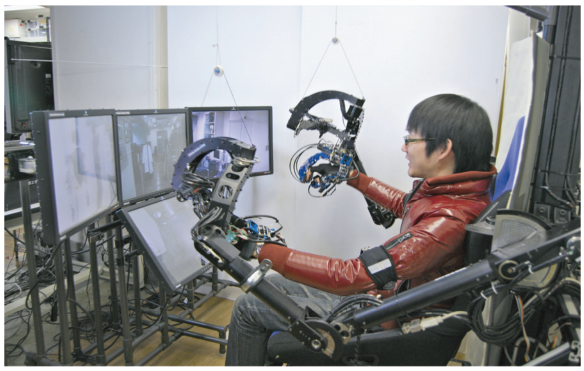

Figure 18: TELESAR II Master Cockpit.

In our laboratory at the University of Tokyo, a new type of visual display termed an RPT display is being developed, which uses a retro-reflective material as its projection surface. The retro-reflective surface functions as a special screen. In the RPT configuration, a projector is arranged at the axial symmetric position of the operator's eyes with reference to a half mirror, with a pinhole placed in front of the projector to ensure an adequate depth of focus.

The face and chest of TELESAR II are covered by a retro-reflective material. A ray incident from a particular direction is reflected in the same direction from the surface of the retro-reflective material. Because of this characteristic of the retro-reflective material, an image is projected onto the surface of TELESAR II without distortion. Since many RPT projectors have been used in different directions and different images are projected corresponding to the cameras placed around the operator, the corresponding images of the operator can be viewed.

Figure 19 illustrates an example of the projected images of an operator onto its surrogate robot.

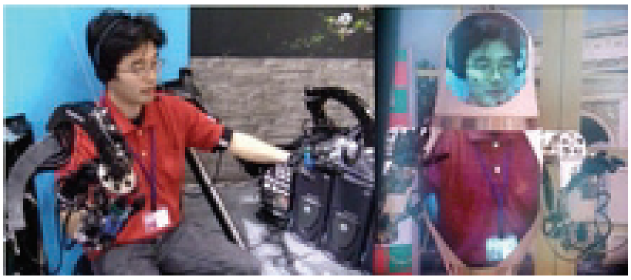

Figure 19: Projection of an Operator to the Robot.

Figure 20 indicates a slave hand (left) and a master hand (right) of the telexistence system. 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.

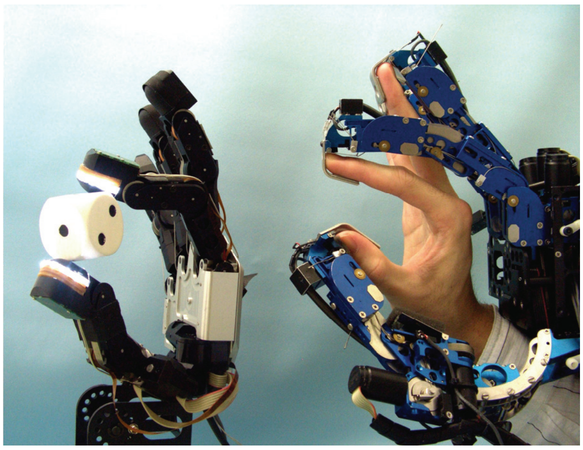

Figure 20: Haptic Telexistence.

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 sensation and enables unconstrained motion of the operator's fingers. Each finger tip has an electrocutaneous display unit attached to it in order to present the tactile sensation to each finger of the operator to realize haptic telexistence.

3. Future Prospect of Telexistence

Figure 21 shows examples of applications of telexistence systems in our society. Researches conducted on virtual reality and telexistence are attempts on releasing human beings from spatial restrictions and time constraints.

Figure 21: Examples of Future Usage of Telexistence.

Based on this perspective, the applications of telexistence may be given as follows:

(1) To provide substitutes for manual labor in potentially dangerous working environments such as nuclear facilities, ocean engineering, disaster prevention, and space activities and to apply to construction work and mining;

(2) To apply to secondary industries, i.e. manufacturing industries, using a telemachining system as a new production support tool;

(3) To apply to primary industries such as agriculture (telefarmers) and fishing (telefishermen);

(4) To apply to tertiary industries including cleaning, maintenance, and other services;

(5) To apply to leisure, amusement, and game industries in the form of telexistence travel;

(6)To apply to medical fields such as in micro-surgery and telesurgery;

(7) To apply to communication industries such as communication with a sensation of existence;

(8) To apply to the education industry, for example, using experience simulators;

(9) To apply to support tools (CAD, IMS) for designing virtual products;

(10) To apply to the design field, including interior designing, for developing virtual environments;

(11) To apply to scientific-engineering researches using virtual scientific visualization as a tool;

(12) To apply to researches conducted on the behavior of humans and other living creatures using displays providing a sensation of existence;

(13) To provide a new medium of communication that, by embracing linguistic and pictorial expressions and going beyond them, may be used to express ideas and sensibility.

4. Conclusion

The telexistence technology was historically reviewed, current advancements in telexistence, including mutual telexistence and haptic telexistence, were studied, and future prospects 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.

It will provide human beings with a tool for communication, control, creation, entertainment, experience/education, or elucidation (human tools for 3C's and 3E's).

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