Recent Advances in Telexistence

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Abstract. Telexistence is fundamentally a concept named for the technology that enables a human being to have a real-time sensation of being at a place other than where he or 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 which enables an operator at the control to perform remote tasks dexterously with the feeling of existing in a surrogate robot. Although conventional telexistence systems the author proposed back in 1980 provide an operator the real-time sensation of being in a remote environment, persons in the remote environment have only the sensation that a surrogate robot is present, not the operator. Mutual telexistence aims to solve this problem so that the existence of the operator is apparent to persons in the remote environment by providing mutual sensations of presence. This enables humans to be seemingly everywhere at the same time, i.e., to be virtually ubiquitous. In this paper, recent advances in telexistence technology is reviewed with special focus on mutual telexistence using RPT (Retro-reflective Projection Technology) and telexistence communication using immersive booth dubbed TWISTER (Telexistence Wide-angle Immersive STERoscope).

Keywords: telexistence, tele-existence, telepresence, mutual telexistence, Retro-reflective Projection Technology (RPT), Head-Mounted Projector (HMP), TWISTER (Telexistence Wide-angle Immersive STERoscope), TELESAR (TELExistence Surrogate Anthropomorphic Robot)

1. Introduction

Telexistence (tele-existence) is a technology that enables us to control remote objects and communicate with others in a remote environment with a real-time sensation of presence by using surrogate robots, remote/local computers, and cybernetic human interfaces. This concept has been expanded to include the projection of ourselves into computer-generated virtual environments, and also the use of a virtual environment for the augmentation of the real environment.

Before the concept of telexistence was proposed, there were several systems that aimed for a similar goal. In the U.S., Sutherland [1] proposed the first head-mounted display system, which led to the birth of virtual reality in the late 1980s. In Italy, C. Mancini et al. [2] developed a mobile teleoperated robot system, Mascot, as early as the 1960s. In France, J. Vertut et al. [3] developed a teleoperation system that controlled a submarine for deep submergence technology in 1977. Although these remote robots were not a humanoid type and no sensation of presence was provided in a strict sense, the systems were closely related to the concept of telexistence, and can be regarded as its forerunner.

In order to intuitively control a remote humanoid robot, it is important to locally provide the operator a natural sensation of presence as if the operator felt directly in the remote site, by means of visual, auditory, tactile, and force sensations. The concept of providing an operator with a natural sensation of presence to facilitate dexterous remote robotic manipulation tasks was called "telepresence" by Minsky [4] in USA and "telexistence" by Tachi et al. [5] in Japan.

The concept of telexistence was proposed and patented in Japan in 1980 [6], and became the fundamental guiding principle of the eight year Japanese National Large Scale Project of "Advanced Robot Technology in Hazardous Environments," which was initiated in 1983 together with the concept of Third Generation Robotics. Through this project, we made theoretical considerations, established systematic design procedures, developed experimental hardware telexistence systems, and demonstrated the feasibility of the concept.

Through the efforts of twenty years of research and development in the U.S., Europe and Japan [7-23], it has nearly become possible for humans to use a humanoid robot in a remote environment as if it was an other self, i.e. they are able to have the sensation of being just inside the robot in the remote environment.

Although existing telexistence systems succeeded in providing an operator a real-time sensation of being in a remote environment, human observers in the remote environment did not have the sensation that the human operator is presented, but only a surrogate robot. Mutual telexistence addresses this problem so that the existence of the operator is apparent by persons in the remote environment by providing mutual sensations of presence [24-26].

This paper describes recent advances in telexistence, which fuses robotics, virtual reality and network technology. A telexistence system using RPT (Retro-reflective Projection Technology) and a humanoid robot with retro-reflective covering has been proposed and proved to be a promising approach toward the realization of mutual telexistence. Another approach is the development of TWISTER (Telexsistence Wide-Angle Immersive STEReoscope), a 360-degree immersive full-color cylindrical display with stereoscopic vision without requiring specialized eyewear, designed for face-to-face telecommunication as if users exist in the same virtual 3D space.

Technology based on the concept of networked telexistence enables users to meet and talk as if they share the same space and time, even if they are far apart from each other, as a natural progression from the telephone to the telexistence-videophone.

2. History of Telexistence

Figure 1 shows the concept of telexistence in real environments, virtual environments, and the real environment through a virtual environment (augmented telexistence). The following describes the research and development conducted in order to realize the concept.

Our first report [5, 8] proposed the principle of the telexistence sensory display, and explicitly defined its design procedure. The feasibility of a visual display with a sensation of presence was demonstrated through psychophysical measurements using experimental visual telexistence apparatus.

A method was also proposed to develop a mobile telexistence system that can be driven remotely with both an auditory and visual sensation of presence. A prototype mobile televehicle system was constructed and the feasibility of the method was evaluated [12].

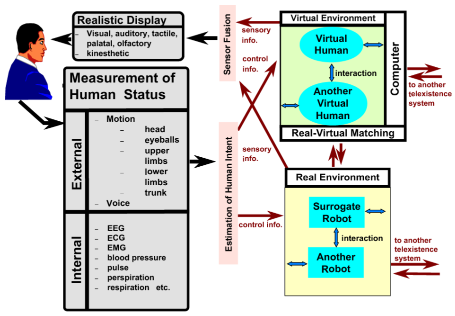

Fig.1 Concept of Telexistence.

In 1989, a preliminary evaluation experiment of telexistence was conducted with the first prototype telexistence master slave system for remote manipulation. An experimental telexistence system for real and/or virtual environments was designed and developed, and the efficacy and superiority of the telexistence master-slave system over conventional master-slave systems was demonstrated experimentally [13, 14, 15].

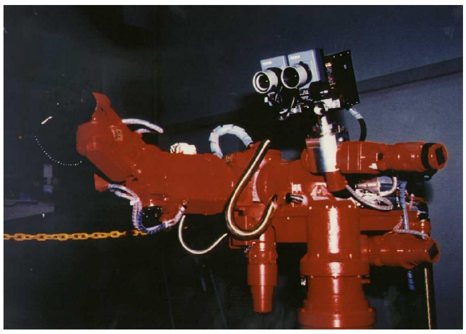

Fig. 2 Telexistence Surrogate Anthropomorphic Robot (TELESAR) at Work (1988).

Augmented telexistence can be effectively used in numerous situations. For instance, to control a slave robot in a poor visibility environment, an experimental augmented telexistence system was developed that uses a virtual environment model constructed from design data of the real environment. To use augmented reality in the control of a slave robot, a calibration system using image measurements was proposed for matching the real environment and the environment model [16, 17].

The slave robot has an impedance control mechanism for contact tasks and to compensate for errors that remain even after calibration. An experimental operation in a poor visibility environment was successfully conducted by using a humanoid robot called TELESAR (TELExistence Surrogate Anthropomorphic Robot) (Fig.2) and its virtual dual. Figure 3 shows the virtual TELESAR used in the experiment and Figure 4 shows the master system for the control of both real TELESAR and virtual TELESAR.

Experimental studies of tracking tasks demonstrated quantitatively that a human being can telexist in a remote and/or a computer-generated environment by using the dedicated telexistence master slave system [15].

A networked telexistence paradigm called R-cubed (Real-time Remote Robotics) was proposed in 1985, and several pertinent ongoing research efforts are being conducted, including a real-time remote robot manipulation language dubbed RCML [18, 19].

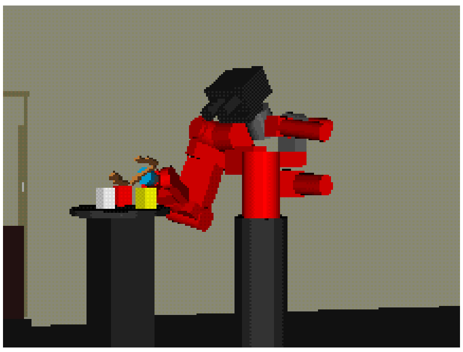

Fig. 3 Virtual TELESAR at Work (1993).

Fig. 4 Telexistence Master (1989).

Telexistence technology was adapted in the national five-year Humanoid Robotics Project (HRP) sponsored by the Ministry of Economy, Trade and Industry (METI) to develop a new type of cockpit system to control a humanoid bipedal robot, as shown in Figure 5. The telexistence cockpit was completed for this project in March 2000 (Fig 6). It consists of three main subsystems: an audio/visual display subsystem, a teleoperation master subsystem, and a communication subsystem between the cockpit and the humanoid robot [20, 21, 22, 23].

Fig.5 HRP Humanoid Robot at Work (2000).

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

If the operator issued a command to move the robot, the robot actually walked to the goal. As the robot walked around, real images captured by a wide field of view multi-camera system were displayed on four screens of the surrounded visual display. This made the operator feel as if he or she was inside the robot, walking around the robot site.

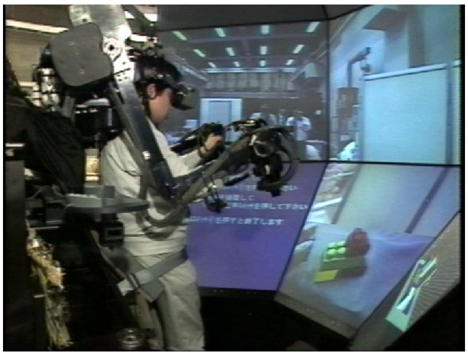

Fig.6 Telexistence Cockpit for Humanoid Control (2000).

A CG model of the robot in the virtual environment was represented and updated according to the current location and orientation received from sensors on the real robot. The model was displayed on the bottom-right screen of the surround visual display, and by augmenting real images captured by the camera system, it supported the operator's navigation of the robot. Since the series of real images presented on the visual display are integrated with the movement of the motion base, the operator feels the real-time sensation of stepping up and down.

Persons can control the robot by just moving their bodies naturally, without using verbal commands. The robot conforms to the person’s motion, and through sensors on board the robot the human can see, hear and feel as if they sensed the remote environment directly. Persons can virtually exist in the remote environment without actually being there.

For observers in the remote environment, however, the situation is quite different: they see only the robot moving and speaking. Although they can hear the voice and witness the behaviour of the human operator through the robot, it does not actually look like him or her. This means that the telexistence is not yet mutual. In order to realize mutual telexistence, we have been pursuing the use of projection technology with retro-reflective material as a surface, which we call RPT (Retro-reflective Projection Technology) [24, 25, 26].

By using RPT, the problem can be solved as shown in Figure 7 [24]: suppose a human user A uses his telexistence robot A' at the remote site where another human user B is present. The user B in turn uses another telexistence robot B', which exists in the site where the user A works. 3-D images of the remote scenery are captured by cameras on board both robots A' and B', and are sent to the HMP’s of human users A and B respectively, both with a sensation of presence. Both telexistence robots A' and B' are seen as if they were their respective human users by projecting the real image of the users onto their respective robots.

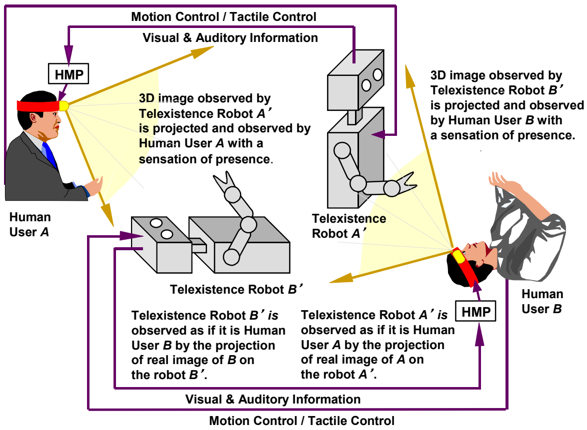

Fig. 7 Concept of Robotic Mutual Telexistence (adopted from [24]).

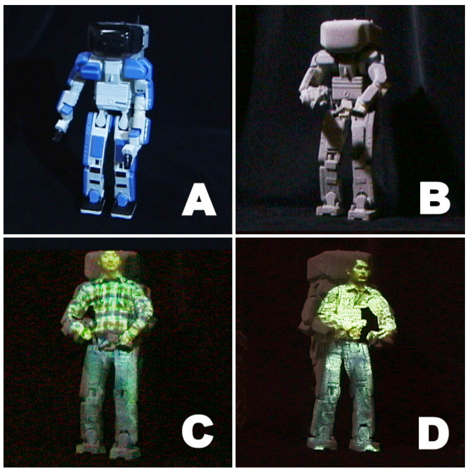

Fig. 8 (A) Miniature of the HONDA Humanoid Robot,
(B) Painted with Retro-reflective Material,
(C) Example of Projecting a Human onto it,
(D) Another Example (adopted from [24]).

Figure 8 presents an example of how mutual telexistence can be achieved through the use of RPT. Figure 8(A) shows a miniature of the HONDA Humanoid Robot, while Figure 8(B) shows the robot painted with retro-reflective material. Figures 8 (C) and (D) show how they appear to a human wearing an HMP. The telexisted robot looks just like the human operator of the robot, and telexistence can be naturally performed [24]. However, this preliminary experiment was conducted off-line, and real-time experiments are yet to be conducted by constructing and using a mutual telexistence hardware system [25,26].

In order to verify the feasibility of the proposed method, an experimental hardware system was constructed [27]. Figure 9 shows its schematic diagram. In the figure, human user A tries to telexist in a remote environment [B] from a local cockpit (A) using a robot A'. Human A is in the local cockpit (A), where his head motion is measured by ADL1 (Shooting Star Technology, Inc.), a mechanical goniometer with six-DOF (Degrees of Freedom). He observes the remote environment [B] through a back projection display in the cockpit, while his figure is captured by a stereo-camera mounted on a newly designed and constructed six-DOF torso servomechanism.

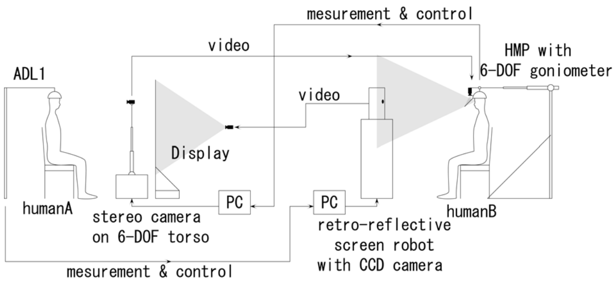

Fig. 9 Schematic Diagram of the Robotic Mutual Telexistence system Experimentally Constructed [27].

In a remote environment [B], a robot built using PA-10 (Mitsubishi Heavy Industry Co.) as a head motion mechanism, is covered with a screen with retro-reflective material. Images captured by a camera inside the screen robot's head are sent to the rear projection display in the local cockpit. A human observer B sees the screen robot using HMP (Head-Mounted Projector). His head movement is measured by a recently designed and constructed six-DOF counter-balanced position/orientation measurement system. The human observer B's head motion is sent to the local cockpit, where a torso stereo camera is controlled according to the tracked motion of human B.

The stereo torso camera mechanism has six degrees of freedom and is designed to track seated human motion at frequencies up to 1.3Hz. Two parallel cameras are placed 65 mm apart from each other, each with a horizontal field of view of 45 degrees.

Figure 10 shows a general view of the 6-DOF goniometer with HRP. The HRP's weight (1.65kg) is fully counterbalanced by a weight and spring, while six degrees of head motion (up/down, left/right, back/forth, pitch, roll and yaw) are fully unrestricted. For the positioning, spherical coordinates are used with translational motion of 980~1580 mm, base pitch of –15~15 degrees, and base yaw of –180~180 degrees, while orientation is realized using a three-axis pivot with pitch of -60~60 degrees, roll of -90~90 degrees, and yaw of -30~30 degrees.

Fig. 10 General View of Head-Mounted Projector (HMP) suspended by Counter-balanced Goniometer with 6-DOF. [27]

Figure 11 indicates a general view of the constructed HMP. It consists of two 0.7-inch full-colour LCD projectors with a resolution of 832x624, two pinholes, and an acrylic half mirror. The horizontal field of view of the projector is 60 degrees.

Figure 12 shows the dimensions and mechanism of the constructed telexistence screen robot. The torso of the robot is fixed and does not move, while using a robot manipulator PA10 its head can move up and down, left and right, back and forth, and rotate pitch, roll and yaw. The robot is covered with retro-reflective material, including the bellows connecting its head and torso.

Fig. 11 General View of Head-Mounted Projector (HMP) used in this configuration.

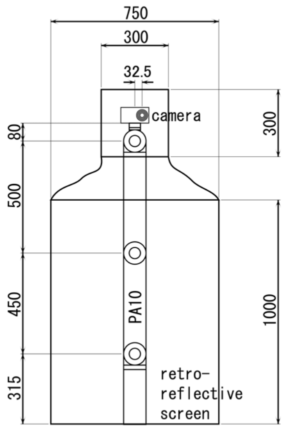

Fig.12 Configuration of Retro-reflective Screen Robot.

A video camera is mounted on top of the mechanism 32.5 mm shifted from the center, where a hole with a diameter of 7 mm is open on the surface of the head. The captured image is sent to the human user A. The motion of the screen robot is controlled to follow the motion of the human user A.

An example of the experimental results is shown in Figure 13. In Figure 13 (1a, 1b) Human User A is at the Local Cockpit(A), and his motion is measured by ADL1. He moves to the left in (1b). In Figure 13 (2a, 2b) Human User B and Telexistence Robot A' are facing each other in Environment [B]. The robot moves to the left according to the motion of Human User A.

Figure 13 (3a, 3b) shows the image of the human user A on the robot A'. The image is still on the surface of the robot head when it is moved to the left. The black dot on the surface of the head of the robot indicates the location of the camera. The head is controlled so that the point always coincides with the location of the left eye of the human user A.

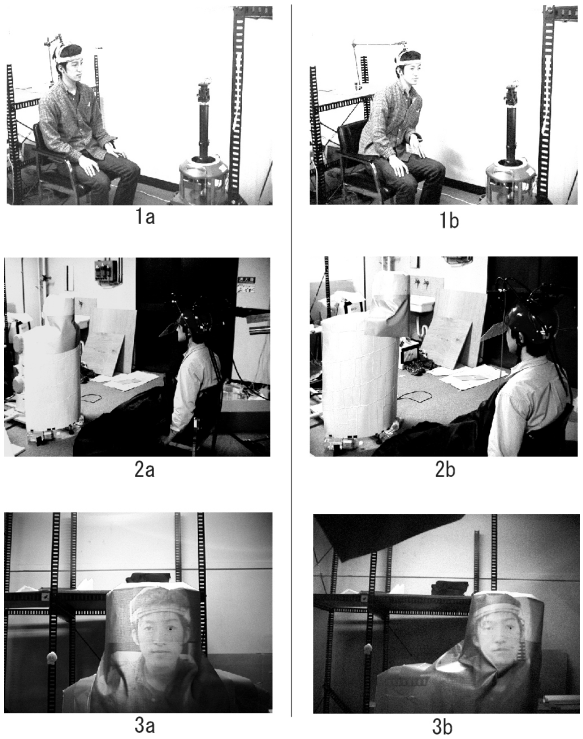

Fig. 13 Experimental Results: (1a, 1b) Human User A at Local Cockpit(A), (2a, 2b) Human User B and Telexistece Robot A' in Environment[B], and (3a, 3b) the image of the human user A on the robot A'. A black dot is where the camera is located.

3. RPT: Retro-reflective Projection Technology

In our laboratory at the University of Tokyo, a new type of visual display is being developed called X'tal (pronounced crystal) vision [28,29,30,31], which uses retro-reflective material as its projection surface. We call this type of display technology RPT (Retro-reflective Projection Technology) as is explained in the previous section, which is a new approach to augmented reality (AR).

The idea was patented in 2001 and 2002, while first demonstration of RPT together with HMP was made at SIGGRAPH98, followed by demonstrations at SIGGRAPH99 and SIGGRAPH2000.

Under the RPT configuration, a projector is arranged at the axial symmetric position of a user's eye with reference to a half-mirror, with a pinhole placed in front of the projector to ensure adequate depth of focus, as shown in Figure 14. Images are projected onto a screen that is constructed, painted, or covered with retro-reflective material [28].

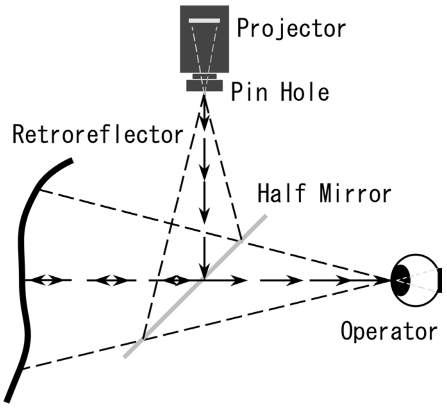

Fig.14 The principle of RPT system.

A retro-reflective surface reflects back the projected light only in the direction of projection, while conventional screens normally used for IPT scatter projected lights in all directions ideally as a Lambertian surface. Figure 15 shows how a retro-reflective surface behaves. It is covered with microscopic beads of about 50 micrometers in diameter, which reflect the incident light back to the incident direction. It can also be realized with a microstructure of prism-shaped retro-reflectors densely placed on a surface.

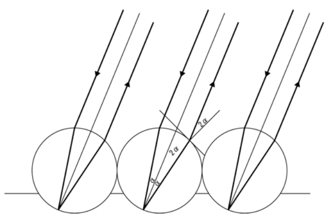

Fig. 15 Retro-reflective surface densely covered with microscopic beads with about 50 micrometer diameter. Ideally, the refractive index should be 2.

The retro-reflector screen, together with the pinhole, ensures that the user always sees images with accurate occlusion relations. In the construction of an RPT system, screen shapes are arbitrary, i.e., any shape is possible. This is due to the characteristics of the retro-reflector, and the pinhole in the conjugate optical system.

By using the same characteristics of an RPT system, binocular stereovision becomes possible using only one screen with an arbitrary shape. An object is covered or painted with retro-reflective material to be used as the screen. The light projected by the right projector is retro-reflected on the surface of the display unit and is observed by the right eye, while the light projected by the left projector is retro-reflected also by the same display surface and can be observed by the left eye.

RPT can provide a way to change any physical object into a virtual object simply by covering its surface with retro-reflective material. Figure 16 shows, for example, how optical camouflage can be achieved using real-time video information. The coat is made of retro-reflective material so that the coming light is reflected back to the same direction that it comes from. Microscopic beads on the surface of the coat have the function of retro-reflection.

A half mirror as is shown in Fig.14 makes it possible for a spectator to see virtually from the position of the projector. An HMP projects an image of the background scenery captured by the video camera behind the camouflaged subject. A computer calculates the appropriate perspective and transforms the captured image to the image to be projected on the subject using image-based rendering techniques.

Thus, an observer looking through a half mirror sees a very bright image of the scenery so that he is virtually transparent.

Fig.16 Optical camouflage using RTP..

4. TELESAR 2 (TElLExistence Surrogate Anthropomorphic Robot Mark 2)

The principle of mutual telexistence using RTP has been proposed [24] and its feasibility has been demonstrated [27] as is described in Section 2. However, in order to realize a practical mutual telexistence system using RTP, it is necessary to construct a hardware robot system which is capable of working as both a retro-reflective screen and telexsitence surrogate robot.

At Tachi Laboratory of the University of Tokyo an anthropomorphic robot called TELESAR 2 (TELExistence Surrogate Anthropomorphic Robot Mark 2) and a master cockpit for the control of the robot are being constructed.

The robot consist of two 7-DOF arms, two 5-fingered hands, a 3-DOF neck mechanism, torso, and a head with stereo cameras, microphones and a speaker. Fig.17 shows a conceptual system and real hardware so far constructed. The robot will be covered with retro-reflective material to be projected an image of a user of the robot.

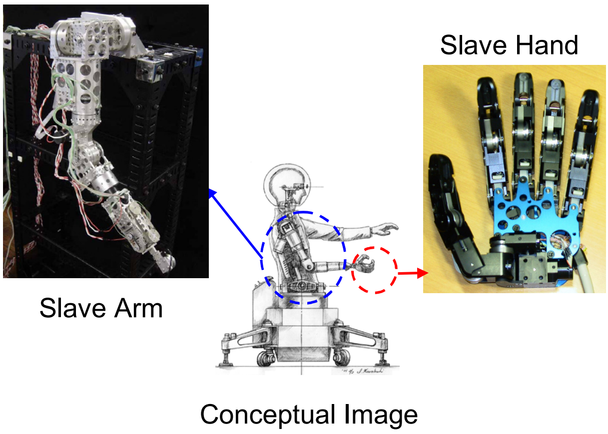

Fig. 17 TELESAR2 Slave system.

Figure 18 shows the master system for TELESAR2. It consists of two master arms with 6 DOF force feedback mechanism and 7 DOF measurement system, two 4 fingered master hand, and an HMP mounted on a 6 DOF goniometer.

The master slave system is controlled by using impedance based bilateral control [32].

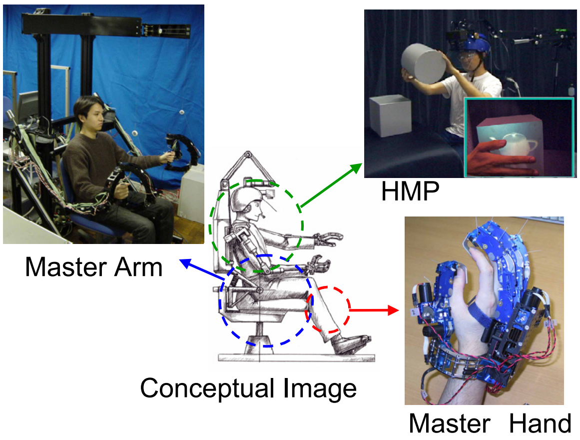

Fig.18 TELESAR2 Master System.

5. Mutual Telexistence using TWISTER: Telexistence Wide-angle Immersive STEReoscope

Another approach to mutual telexistence without the use of robotics can be taken if we restrict our purposes only to communication. The basic idea [18] is shown in Fig. 19. Each human user stands inside of a booth with a rotating cylindrical mechanism that plays the role of both a display device and an input camera device to capture moving pictures of the user inside the booth. Each user can see the three dimensional figures of other users working in real-time in the mutual virtual environment.

This concept was first proposed in 1996, and a preliminary experiment successfully demonstrated the feasibility of the idea [33].

In general, in order to display three-dimensional objects for an arbitrary viewpoint outside a closed surface, ray information is required from a sufficient variation of directions inward, and at points of sufficient density over a closed surface separating the observer and the object. However, it is difficult to capture images from continuous viewpoints simultaneously because each camera occupies physical space. To increase the number of viewpoints, we considered two approaches: to reduce the camera size, and to exploit the camera's motion.

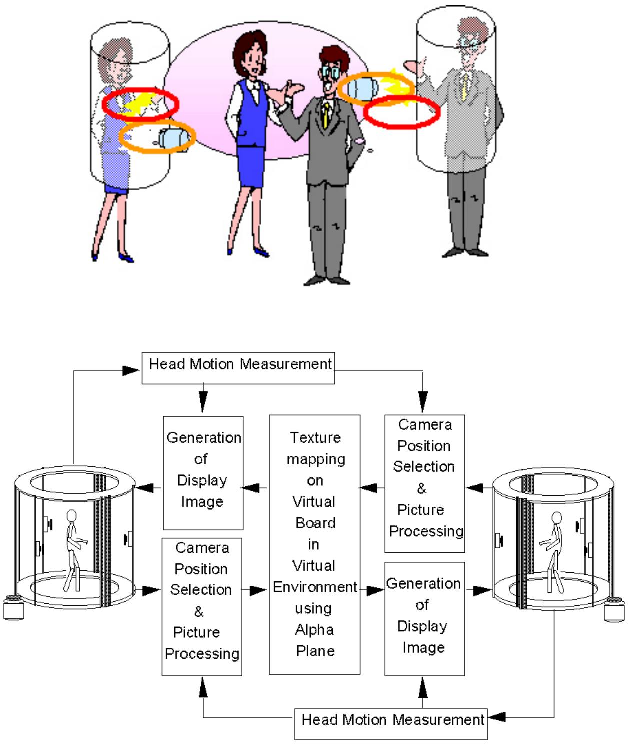

Fig. 19 Basic Idea of Mutual Telexistence Booth (Adpoted from [18]).

For capturing a human figure in real-time and displaying it in a virtual environment with a virtual viewpoint given by a user, the rendering PC calculates the regions of each camera image used for multi-texture-mapping. The information of the region is sent to the control PC and used as an indication of the video switch. The switch timing is synchronized with the camera scanning, and the camera scanning direction is vertical. In this way, the rendering PC can selectively capture the necessary column image from the cameras.

Then, the captured images are texture-mapped onto a plane at a corresponding focal distance in the virtual three-dimensional space. This process is equivalent to the simple memory copy. Finally, the rendering PC renders the scene with 3D graphics. One cycle of all these processes completes within video rate (1/30[sec]), so the system realizes real-time rendering.

The basic idea of this form of mutual telexistence is the projection of human beings into a mutual virtual environment in real-time. With multiple booths, each user can see the three dimensional figures of other users working in real-time in the mutual virtual environment [18,34].

We implemented the display partially as a series of apparatus dubbed TWISTER (Telexistence Wide-angle Immersive STERoscope) from model I through Model IV, and confirmed its performance as a stereoscopic display of full-color images [35-37].

TWISTER has a rotating display and camera units surrounding the observer. One unit consists of two LED (Light-Emitting Diode) arrays, a parallax barrier, and a camera. Each LED array consists of pairs of red, green, and blue LEDs, and displays time-varying patterns so that the observer can perceive an image. Due to the use of LEDs, TWISTER can be used as a display of high intensity full-color images, even in a bright room.

The rotation of the display unit makes it a wide-angle display. In fact, the angle of view as a normal display is 360 degrees. In addition, since the horizontal and temporal resolutions of this display are determined by the period of LED emission, the spatio-temporal resolution can be adaptive and optimized to the subject (Fig.20).

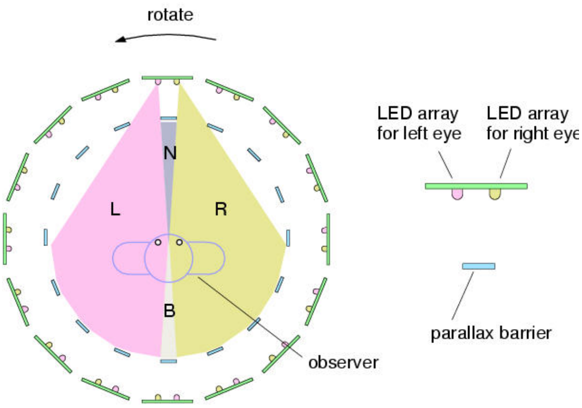

Fig.20 Principle of autosteropsis using moving parallax barrier.

The key device for autostereopsis is the parallax barrier. One of the LED arrays is for the left eye, and the other is for the right eye. Because the parallax barrier obscures LED emission from the opposite side, different images are shown to the left and right eyes. The angle of view as a stereoscopic display depends on the direction and the position of the observer. If the head of the observer is fixed, it exceeds 120 degrees in an ideal condition. On the other hand, if the observer always faces the center of the image region of interest, it can be 360 degrees.

With the moving parallax barriers, the crosstalk between the left eye image and the right eye image is reduced to almost zero, which gives it a powerful advantage over other stereoscopic vision systems. Since the rotating unit has cameras on it, you can capture the image of the observer simultaneously. With this system, the face of the observer is clearly captured, and natural non-verbal communication between multiple booths is achieved when the image data is transferred in real-time.

The rotator of TWISTER rotates counterclockwise (viewed from the top) at a constant speed of about one revolution per second. The sync signal is generated when a photo detector attached to the rotator senses the light from a photo diode attached to the framework.

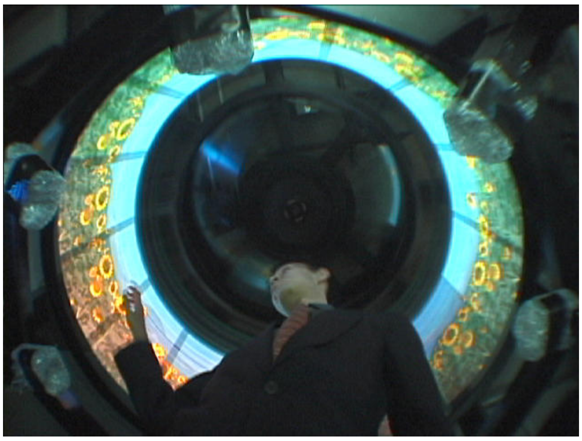

Fig.21General view of TWISTER II (2001).

We have already achieved full-color presentation of 3D images. With LEDs, it can easily be seen in a well-lit room. The capabilities for autostereopsis without eyewear, and panoramic (360degree) presentation of normal three-dimensional images have been also confirmed. The result was demonstrated at SIGGRAPH 2001 (Fig.21, Fig.22).

Figure 23 indicates a general view of a newly developed TWISTER IV with both 360-degree display and camera capabilities.

Fig.22 Preliminary Experimental Telexistence Communication using TWISTER II (2001).

Communication experiments exemplified in Fig. 19 are being conducted connecting TWISTER III and IV.

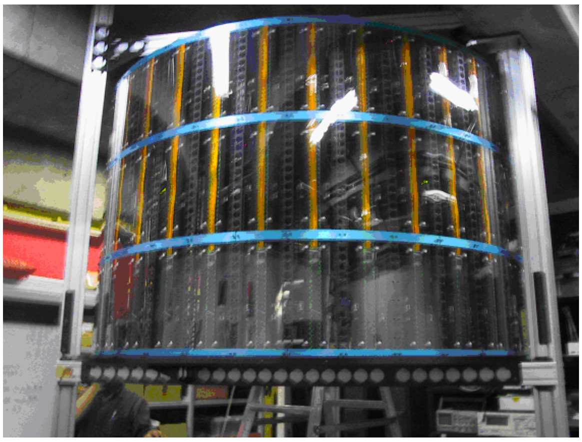

Fig.23 General view of TWISTER II (2001).

It is also possible to use TWISTER as a cockpit of mutual telexistence using robots, as is show in Fig.24. In the figure pictures of a user A is captured by TWISTER and sent to a robot, which sends the image to humans wearing HMP. The HMP projects the image on the robot to show the figure of the user A.

Human positions and orientation measured by the robot are sent to TWISTER to determine the images that should be transmitted.

Human A can control the robot as if he is presented by utilizing visual, auditory and tactile information with a sensation of presence.

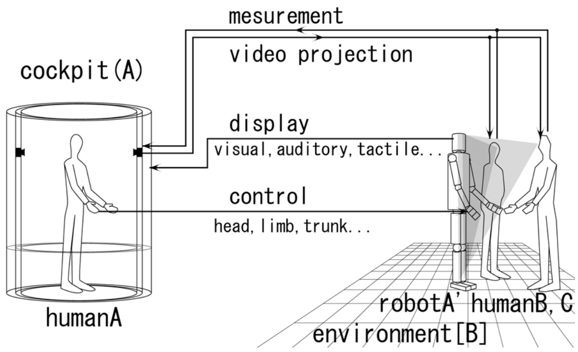

Fig.24 Schematic diagram of TWISTER used as a cockpit for robotic mutual t elexistence.

6. Conclusions

In this keynote paper, a history of telexistence was reviewed, the principle of RPT was explained, and an experimental mutual telexistence system using RPT, which was designed and constructed to demonstrate its feasibility and efficacy, was introduced. It was also demonstrated that an immersive auto stereoscopic booth called TWISTER can be used as a promising device not only for the presentation of three-dimensional images but also for the device of the future telecommunication as telexistence videophone by capturing three dimensional images of the user in real-time.

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