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MUTUAL TELEXISTENCE SYSTEM USING RETRO-REFLECTIVE PROJECTION TECHNOLOGY

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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 is, 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. Although conventional telexistence systems 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 paper proposes a method of mutual telexistence using projection technology with retro-reflective objects, and describes experimental hardware constructed to demonstrate the feasibility of the proposed method.

Keywords: Telexistence; tele-existence; telepresence; mutual telexistence; retro-reflective projection technology (RPT); head-mounted projector (HMP).

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 to achieve a similar goal. In the US, Sutherland[1] proposed the first head-mounted display system, which led to the birth of virtual reality in the late 1980s. In Italy, Mancini *et al.*[2] developed a mobile teleoperated robot system, Mascot, as early as the 1960s. In France, Vertut *et al.*[3] developed a teleoperation system that controlled a submarine for deep submergence technology in 1977. Although these remote robots were not of 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 US, Europe and Japan,[7–23] it has nearly become possible for humans to use a humanoid robot in a remote environment as if it were an other self, i.e. we are able to have the sensation of being 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 present, 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 reviews the original telexistence technology, and introduces a method of mutual telexistence based on the projection of real-time images of the operator on the surrogate robot, based on newly developed technology dubbed RPT (Retro-reflective Projection Technology). Following the proposed design principle using RPT, an experimental system was constructed, which demonstrated the feasibility of the concept of mutual telexistence.

2. Short 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.

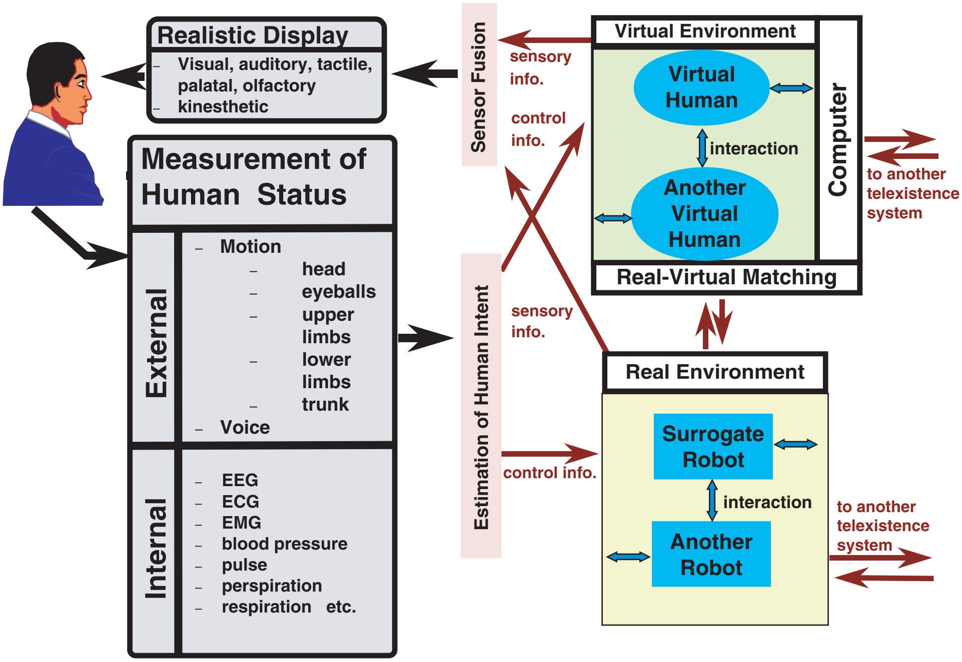

Fig. 1. Concept of telexistence.

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

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.[13–15]

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

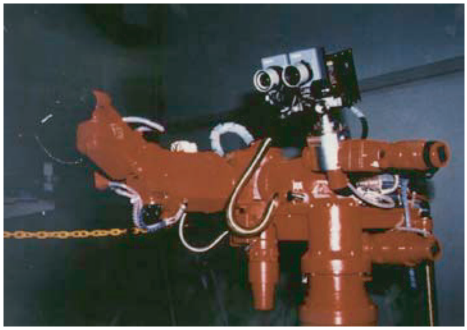

Fig. 2. Telexistence surrogate anthropomorphic robot (TELESAR) at work (1988).

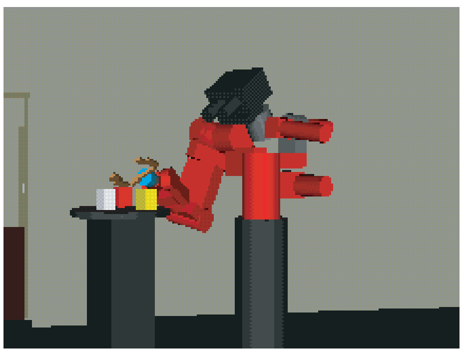

Fig. 3. Virtual TELESAR at work (1993).

Fig. 4. Telexistence master (1989).

and Fig. 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]

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 Fig. 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.[20–23]

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.

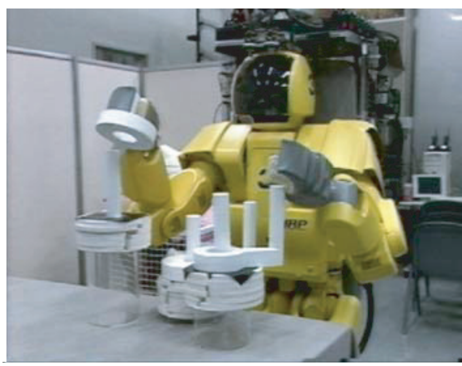

Fig. 5. HRP humanoid robot at work (2000).

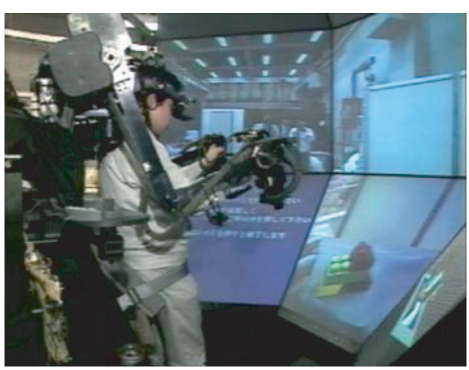

Fig. 6. Telexistence cockpit for humanoid control (2000).

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 surrounding visual display. This made the operator feel as if he or she was inside the robot, walking around the robot site.

A CG model of the robot in the virtual environment was represented and updated according to the current location and orientation received from 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 behavior 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).[24–26]

3. Retro-reflective Projection Technology (RPT)

Two classic virtual reality visual display types are the Head Mounted Display (HMD) and IPT (Immersive Projection Technology), which although quite useful, are not without their shortcomings, as shown in Fig. 7(c) and (d), respectively. The former has a trade-off of high resolution and wide field of view, and the latter has problems concerning the user's body casting shadows on a virtual environment, and the interaction between the user's real body and the virtual interface. In addition, both displays have problems concerning occlusion when in use under the augmented reality condition, i.e. virtual objects and real objects are mixed.

Figure 7(a) shows a virtual vase and a virtual ashtray on a virtual desk. When a real hand is placed between two virtual objects, an ideal occlusion should be depicted as in Fig. 7(b), i.e. the real hand occludes the virtual vase and is occluded by the virtual ashtray. However, a real hand cannot occlude the virtual vase nor be occluded by the virtual ashtray when an optical see-through HMD is used to display virtual objects, and the hand and the ashtray look as if they are transparent. This is simply due to the fact that the physical display position of an HMD is always just in front of the eyes of the user.

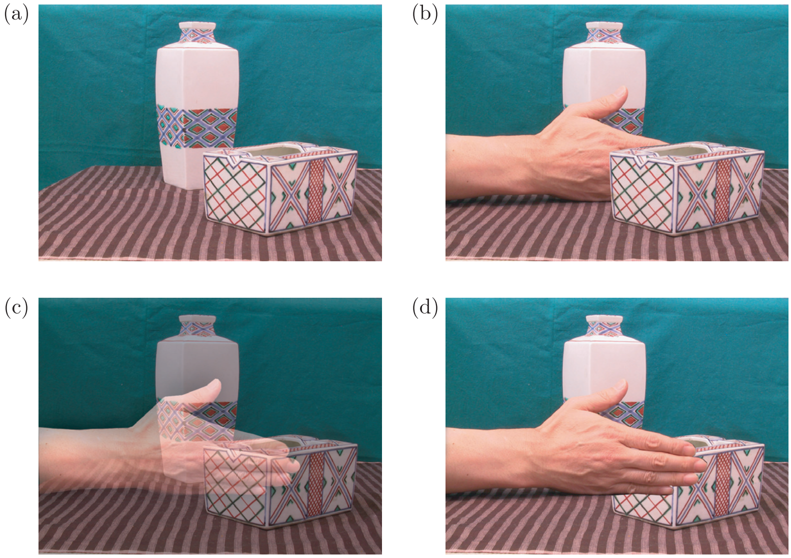

Fig. 7. (a) A virtual vase and a virtual ashtray on a virtual desk; (b) an ideal occlusion when a real hand is placed between two virtual objects; (c) unfavorable results when optical see-through HMD is used; and (d) unfavorable results when IPT (Immersive Projection Technology) like CAVE is used.

Conversely, the virtual ashtray cannot occlude a real hand when IPT like the CAVE (CAVE Automatic Virtual Environment) is used, as shown in Fig. 7(d). This is due to the fact that the display position of virtual objects is always on the screen surface, which is one to two meters away from the human user when IPT displays are used.

In our laboratory at the University of Tokyo, a new type of visual display is being developed called X'tal (pronounced crystal) vision,[27–30] which uses retro-reflective material as its projection surface. We call this type of display technology RPT (Retro-reflective Projection Technology).

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 Fig. 8. Images are projected onto a screen that is constructed, painted, or covered with retro-reflective material.[27]

A retro-reflective surface reflects back the projected light only in the direction of projection, while conventional screens normally used for IPT scatter projected light in all directions ideally as a Lambertian surface (Fig. 9). Figure 10 shows how a retro-reflective surface behaves. It is covered with microscopic beads of about 50 μm in diameter, which reflect the incident light back in the incident direction. It can also be realized with a microstructure of prism-shaped retro-reflectors densely placed on a surface.

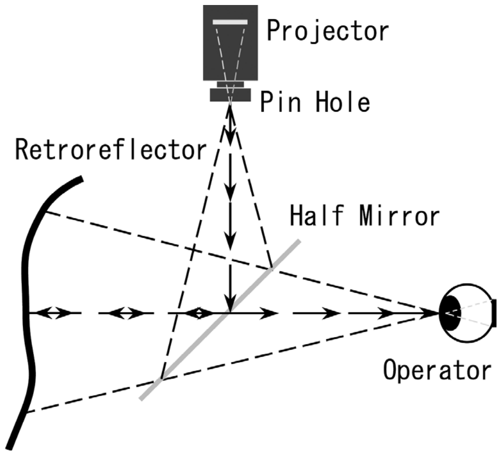

Fig. 8. The principle of RPT system.

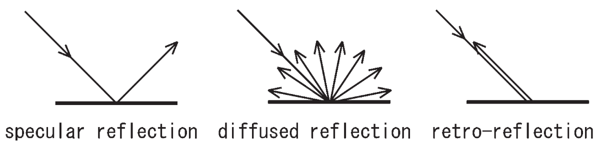

Fig. 9. Three typical reflections.

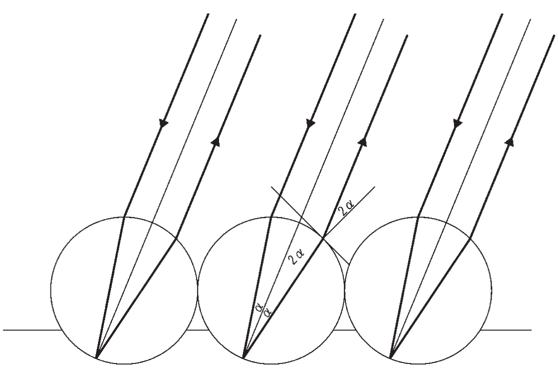

Fig. 10. Retro-reflective surface densely covered with microscopic beads of about 50 μm diameter. Ideally, the refractive index should be 2.

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.

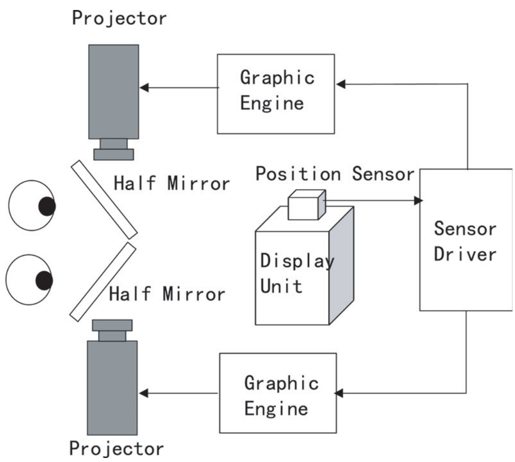

Fig. 11. Principle of stereo display using RPT.

By using the same characteristics of an RPT system, binocular stereo vision becomes possible using only one screen with an arbitrary shape. Figure 11 shows how stereo vision can be realized using RTP. In the figure, the display unit is an arbitrarily shaped object covered or painted with retro-reflective material. 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 also retro-reflected by the same display surface and can be observed by the left eye.

By using the same display surface, the right eye observes the image projected by the right projector and the left eye observes the image projected by the left projector. Thus by generating CG images with appropriate disparity, the human observer perceives the stereo view of an object at the position of the display unit. By using measurements of the position sensor on the display unit, it is possible to display a three-dimensional object image, which changes its appearance according to the position and orientation indicated by the motion of the display. This enables the user to have the sensation that he or she is handling a real object.

The projector can be mounted on the head of a user, which we call an HMP (Head Mounted Projector) system. Figure 12 shows a general view of a prototype HMP.

Figure 13 shows an example of an image projected on a sphere painted with retro-reflective material. As apparent in the figure, the projected image looks like a real object, and is partly hindered naturally by human fingers.

Figure 14 shows an example of projecting a virtual cylinder onto a Shape Approximation Device (SAD),[31] which is a haptic device that enables the user to touch geometrical shapes as if they were real. The use of the SAD as the retro-reflective screen enables us to feel just as we see by observing through a HMP. In the figure, 14(a) illustrates the principle of SAD, 14(b) shows an image to be displayed,

Fig. 12. General view of a head mounted projector.

Fig. 13. Projected image on a spherical retro-reflective screen.

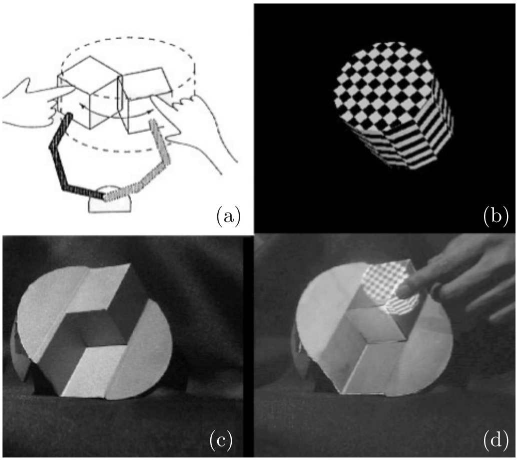

Fig. 14. Projected image on a shape approximation device. (a) Principle of SAD; (b) image; (c) actual SAD; (d) image projected on SAD.

14(c) is an actual SAD, and 14(d) indicates the image projected onto SAD, which can be touched as it is seen.

Thus, RPT can provide a way to change any physical object into a virtual object simply by covering its surface with retro-reflective material.

4. Mutual Telexistence Using RPT

More than twenty years have passed since we initially proposed the concept of telexistence, and it is now possible to telexist in the remote and/or virtual environment with a sensation of presence. We can work and act with the feeling that we are present in several real places at once. However, in the location where the user telexists, people see only the robot but cannot feel that the person is actually present. Simply placing a TV display on board the robot to show the face of the user is not very satisfying, since it appears mostly comical and far from reality.

By using RPT, the problem can be solved as shown in Fig. 15:[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. 3D 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

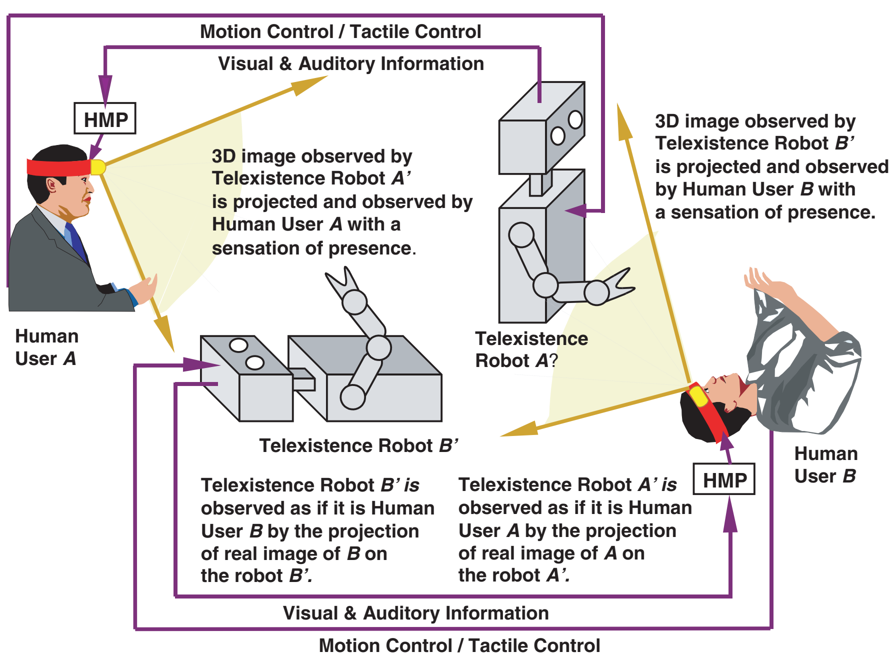

Fig. 15. Concept of robotic mutual telexistence (adapted from Ref. 24).

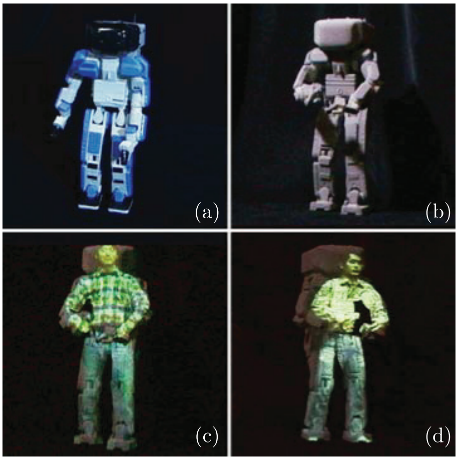

Fig. 16. (a) Miniature of the HONDA humanoid robot; (b) painted with retro-reflective material; (c) example of projecting a human onto it; (d) another example (adapted from Ref. 24).

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.

Figure 16 presents an example of how mutual telexistence can be achieved through the use of RPT. Figure 16(a) shows a miniature of the HONDA Humanoid Robot, while Fig. 16(b) shows the robot painted with retro-reflective material. Figures 16(c) and (d) show how they appear to a human wearing an HMP. The telexisting 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.

5. Experimental Hardware System

In order to verify the feasibility of the proposed method, an experimental hardware system was constructed. Figure 17 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.

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

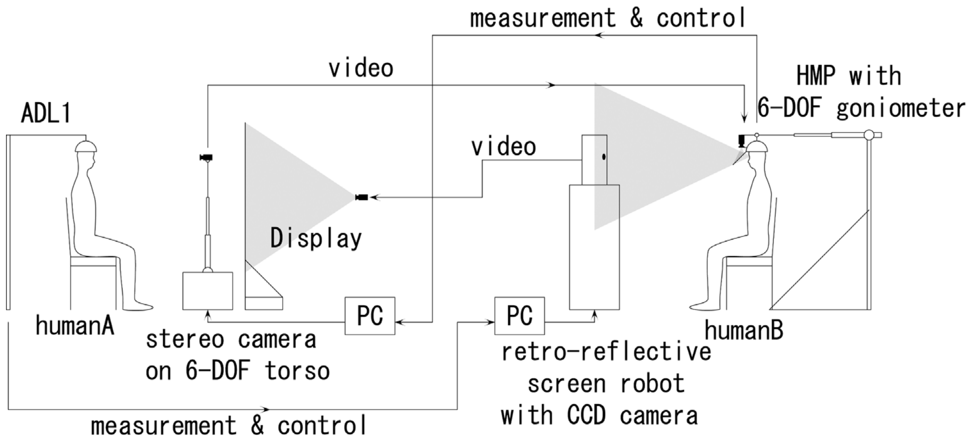

Fig. 17. Schematic diagram of the experimentally constructed robotic mutual telexistence system.

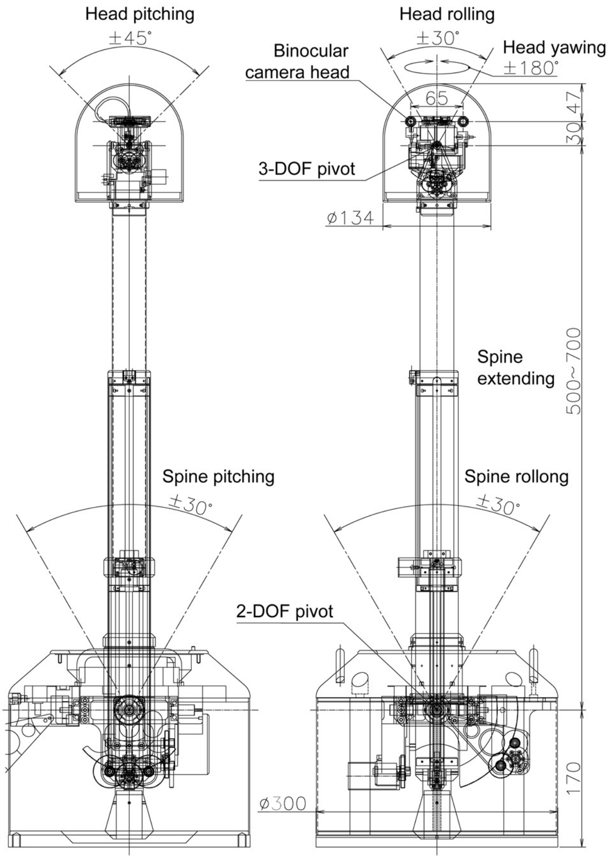

Fig. 18. Design of stereo camera mounted on torso mechanism with 6-DOF.

Fig. 19. General view of stereo camera mounted on torso mechanism with 6-DOF.

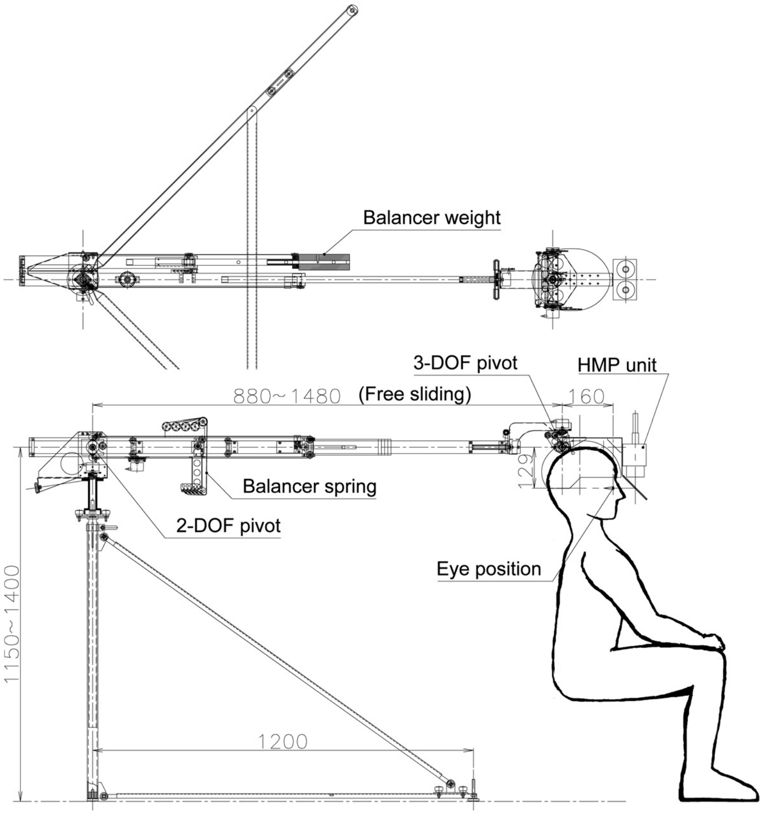

Fig. 20. Design of head-mounted projector suspended by counter-balanced goniometer with 6-DOF.

Fig. 21. General view of head-mounted projector suspended by counter-balanced goniometer with 6-DOF.

Fig. 22. General view of head-mounted projector used in this configuration.

B sees the screen robot using HMP (Head-Mounted Projector). His head movement is measured by a recently designed and constructed 6-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*.

Figures 18 and 19 show the stereo torso camera mechanism. It has six degrees of freedom and is designed to track seated human motion at frequencies up to 1.3 Hz. Two parallel cameras are placed 65 mm apart from each other, each with a horizontal field of view of 45 degrees.

Figure 20 shows the mechanism of the 6-DOF goniometer for HMP, and Fig. 21 shows a general view. The HMP's weight (1.65 kg) is fully counterbalanced by a weight and spring, while six degrees of head motion (up/down, left/right,

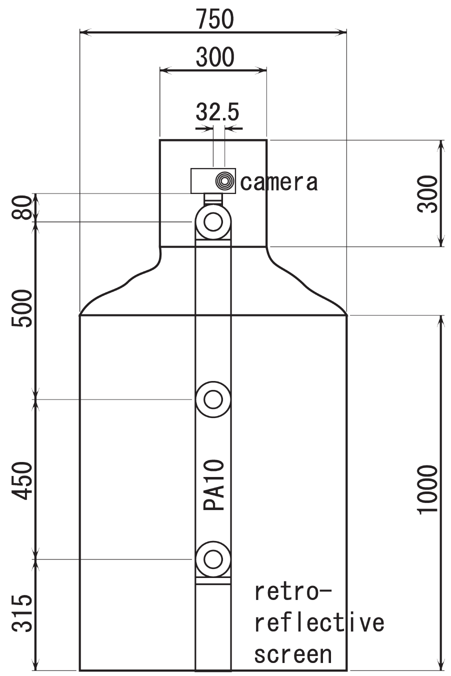

Fig. 23. Configuration of retro-reflective screen robot.

back/forth, pitch, roll and yaw) are fully unrestricted. For the positioning, spherical coordinates are used with translational motion of 980∼1,580 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.

Figure 22 indicates a general view of the constructed HMP. It consists of two 0.7-inch full-colour LCD projectors with a resolution of 832×624, two pinholes, and an acrylic half mirror. The horizontal field of view of the projector is 60 degrees.

Figure 23 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.

A video camera is mounted on top of the mechanism 32.5 mm shifted from the center, where a hole with 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 Fig. 24. In Figure 24(a) and (b) human user A is at the local cockpit (A), and his motion is measured by ADL1. He moves to the left in Fig. 24(b).

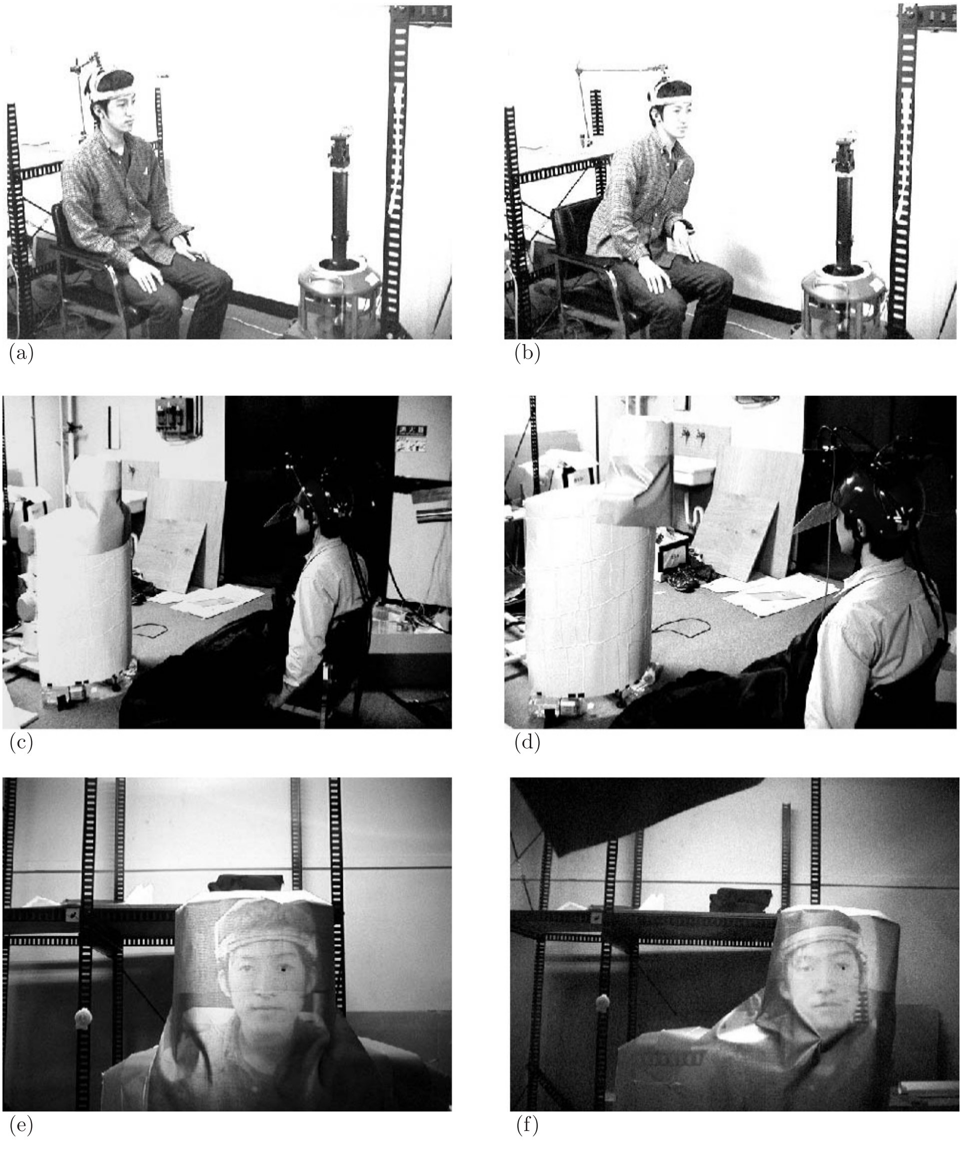

Fig. 24. Experimental results: (a) and (b) Human user A at local cockpit (A); (c) and (d) human user B and telexistece robot A' in environment (B); and (e) and (f) the image of the human user A on the robot A'. A black dot is where the camera is located.

In Figure 24(c) and (d), 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 24(e) and (f) 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.

6. Conclusions

Projection technology on retro-reflective surfaces is called Retro-reflective Projection Technology (RPT), which is a new approach to augmented reality (AR). The first demonstration of RPT together with a Head Mounted Projector (HMP) was made at SIGGRAPH98, followed by demonstrations at SIGGRAPH99 and SIGGRAPH2000.

Mutual telexistence is one of the most important technologies for the realization of networked telexistence, because users "telexisting" in a robot must know whom they are working with over the network. A method using RPT, especially an HMP and a robot with retro-reflective covering was proposed and proved to be a promising approach toward the realization of mutual telexistence.

In this paper, a short history of telexistence is reviewed, and mutual telexistence the principle of RPT is explained, and the design of an experimental mutual telexistence system using RPT is described to demonstrate its feasibility and efficacy.

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