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TELEsarPHONE: Mutual Telexistence Master-Slave Communication System based on Retroreflective Projection Technology

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Abstract : TELEsarPHONE is a conceptual prototype of a mutual telexistence system, designed for face-to-face telecommunication via robots. Because of the development of telexistence technology, we can acquire a feeling that we are present in several actual remote places using remote robots as our surrogates and can work and act freely there. However, people in the place where someone telexists using a robot see only the robot, and they cannot feel the existence of the telexisting person. Mutual telexistence aims to solve this problem so that the existence of a telexisting person (visitor) is apparent to the people in the remote environment by providing mutual sensations of presence. On the basis of the concept of mutual telexistence, we have designed and developed a prototype of a telexistence master-slave system for remote communication by applying retroreflective projection technology. In the TELEsarPHONE system, the face and chest of the slave robot TELESAR II are covered by retroreflective material. To provide the feeling of existence, the real-time image of the visitor is projected onto the robot so that people can see the visitor in real time.

Key Words : telecommunication, teleoperation, telexistence, virtual reality, augmented reality, retroreflective projection, human robot systems, system integration

1. Introduction

Telexistence (tele-existence) is a fundamental concept 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 being able to interact with a 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 to perform remote tasks dexterously with the feeling of existing in a surrogate robot working in a remote environment.

Before the concept of telexistence was proposed, there were several systems that aimed for 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. This concept was the same as telexistence in computer-generated virtual environments. However, it did not include the concept of telexistence in real remote environments. In Italy, Mancini et al.[2] developed a mobile teleoperated robot system, Mascot, as early as in the 1960s. In France, Vertut et al.[3] developed a teleoperation system for use in deep submergence technology in 1977; this system controlled submarines. Although these remote robots were not humanoid-type robots and no sensation of presence was provided in a strict sense, the systems were closely related to the concept of telexistence in real remote environments, and they could be regarded as the forerunners of telexistence.

In order to intuitively control a remote humanoid robot, it is important to locally provide the operator with a natural sensation of presence as if the operator were actually present at the remote site, by means of visual, auditory, and haptic sensations. The concept of providing an operator with a natural sensation of presence to facilitate dexterous remote robotic manipulation tasks was termed “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 “Advanced Robot Technology in Hazardous Environments,” which was initiated in 1983 together with the concept of third generation robotics. Through this project, theoretical considerations of telexistence were made, systematic design procedures were established for it, experimental hardware telexistence systems were developed, and the feasibility of the concept of telexistence was demonstrated.

Through the efforts of twenty-five years of research and development in the US, Europe, and Japan [7]–[23], it has almost become possible for humans to use humanoid robots in a remote environment as if they were their other persons, i.e., humans are able to have the sensation of being inside the robots in the remote environment.

Although conventional telexistence systems succeeded in providing an operator with a real-time sensation of being in a remote environment, human observers in the remote environment did not have the sensation of the presence of the human operator; rather, the observers saw only a surrogate robot. Mutual telexistence addresses this problem so that the existence of the operator is apparent to people in the remote environment by providing mutual sensations of presence [24]–[26].

A method for mutual telexistence based on the projection of real-time images of the operator onto a surrogate robot, which in turn is based on RPT (retroreflective projection technology), was first proposed in 1999 [20], and the feasibility of the concept was demonstrated by constructing an experimental mutual telexistence system using RPT in 2003 [24] and 2004 [25]. However, the demonstrated system had only a 6-DOF (degree of freedom) head mechanism and no manipulation mechanism.

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In this study, we have developed a master-slave manipulation system with the function of mutual telexistence. We also propose the concept of using a mutual telexistence system as a new communication tool as an extension of the telephone and videophone and employ the system to demonstrate the feasibility of the proposed concept.

2. Concept of TELEsarPHONE System

The history of communication shows that communication methods have evolved over the past few decades. The telephone is a communication device that uses sound for communication and a videophone uses both sight and sound for communication. The next generation of communication devices will carry out communication by haptics along with sight and sound.

"Body presence" is an element that is necessary to convey the feeling that a remote participant is present at a site. Many audio-visual systems that attempt to convey this feeling have been proposed and implemented, such as remote meeting systems using videophones. However, such systems do not affect any physical action in the remote environment; that is, they are only eyes and ears located at the remote location. To achieve a realistic sensation, it is necessary that the person "telexists" at the remote location.

For this purpose, it is necessary to set up a surrogate body of a person and an artificial system that (1) performs physical actions in the remote environment on the basis of the person's motion through the surrogate body and (2) lets the person feel sensations felt by the surrogate body in the remote environment. We propose to let a surrogate robot participate at a site, and we establish a system in which a remote participant feels the robot as his or her representative and acts via the surrogate robot as if it were a part of his or her body.

We have been conducting research on telexistence and a technology for operating surrogate robots in a remote environment, and have found that a robot can be used as a communication tool. Traditionally, robots are classified into Astro-Boy-type robots with self-directed intelligence and Gundam-type robots with human operation. However, we have confirmed the existence of a third type of robot, an alterego robot, which acts and communicates on behalf of its operator.

"Mutual existence" refers to participants at a site being aware of the existence of a remote participant when they encounter a surrogate robot that is operated by the remote participant. Our earlier studies on telexistence focused on a remote participant acquiring a realistic sensation, and we developed a demonstration system that was successful in transferring the realistic sensation to the remote participant. However, the participants at the site felt as if they were talking with a robot, and the existence of the remote participant was surprisingly weak. While the voice, sound, and action of the remote operator were transferred to the site, essential visual information was not conveyed. The most important elements of nonverbal communication, such as facial expression, were not transferred, and as a result, the "existence" became weak. To strengthen existence, the face of the remote participant should be projected onto the head of the representing robot in the correct direction. Furthermore, assuming that several people are standing around the robot, displaying a single image on the head by using LCD monitor [26] is insufficient. Rather, multiple images should be projected in different directions.

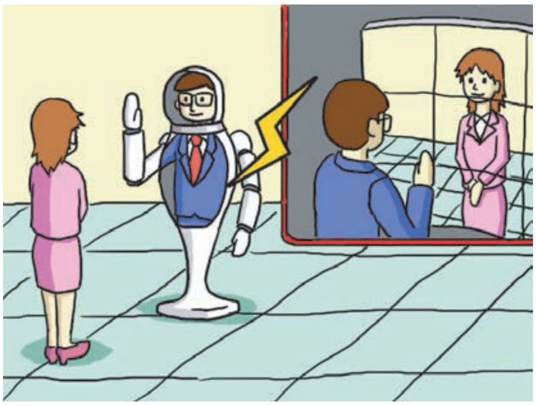

Fig. 1 Conceptual image of TELEsarPHONE.

TELEsarPHONE is a conceptual prototype of a mutual telexistence system, designed for face-to-face telecommunication via robots (Fig. 1). TELEsarPHONE is composed of three elements: a humanoid robot, a cockpit for operating the robot, and a viewer system. Both the robot and the cockpit are located at different sites and connected by a high-speed communication network. The video, audio, and tactile information of what the robot sees and feels is sent to the cockpit, where the information is reconstituted three-dimensionally. Conversely, the robot reflects the actions of the operator sitting in the cockpit, and the operator feels as if he or she is actually at the place where the robot is and is also able to behave as he or she wants.

The viewer system is intended for those who are communicating with the operator through the robot. The body of the robot contains a screen onto which images of the operator that are captured in the cockpit are projected. The use of the RPT, which enables observers to individually observe a proper image from their own perspective, enables observers in the area surrounding the robot to feel and communicate as if the operator is actually there.

3. Mutual Telexistence Master-Slave System for Telecommunication

To implement the concept of TELEsarPHONE, a new prototype of a mutual telexistence master-slave system for communication has been designed and developed. The mutual telexistence master-slave system is based on the RTP and composed of 3 subsystems - slave robot TELESAR II, master cockpit, and viewer system - as is shown in Fig. 2.

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 have designed the robot by focusing on reproducing human-like realistic movement. TELESAR II has two human-sized arms and hands, a torso, and a head. Its neck mechanism has 2 DOFs, which can rotate around pitch and roll axes. There are 2 CCD cameras located in its head for stereoscopic vision. It also has 4 pairs of stereo cameras on top of the head for a 3D surround display for the benefit of an operator. A microphone array and a speaker are also employed for auditory sensation and verbal communication. Each arm has 7 DOFs, and each hand has 5 fingers with a total of 8 DOFs.

To control the slave robot, we have developed a master cockpit for TELESAR II. The cockpit consists of two master arms, two master hands, multi-stereo display system, speakers and a microphone, and cameras for capturing the images of an operator in real time. In order that an operator can gesture smoothly, each master arm has 6-DOF structures so that the operator's elbow is free from constraints. To control the redundant 7 DOF of the anthropomorphic slave arm, we place a small orientation sensor on the operator's elbow. Therefore, each master arm can measure 7-DOF motion for each corresponding slave arm, while force is fed back from each slave arm to each corresponding master arm with 6 DOFs.

The master arm is lightweight and impedance control is carried out so that the operator feels as if he or she is inside the slave robot. It is important that the master can apply an exact force to an operator and the slave robot maintain safe contact with humans in a remote environment. The impedance-control-type master-slave system adopted by us can achieve the force presentation. Moreover, by using the slave, we can maintain safe compliant contact with humans because the slave is subjected to impedance control. The motion of the head on the robot is synchronized with the motion of the operator's head; these motions are measured by a head tracker in the master cockpit. The operator can easily control the hands of TELESAR II because the motion of the operator's hands is measured by the master cockpit and controlled by master-slave methods. In the case of autonomous robot system, such a system should perform precise computation to prevent the collision of the arm, hand or torso of the robot. In the case of telexistence, however, the system does not require collision detection. The operator calculates it subconsciously. This is a remarkable feature of the telexistence system. Despite this, we calculate the collision limit, and collision can be prevented even if the operator fails to avoid collision (fail-safe or safety intelligence). Figure 3 shows the general outline of the master-slave impedance-controlled teleoperation system used in this study.

The most distinctive feature of the TELEsarPHONE system is the use of the RPT viewer system. Both the motion and the visual image of the operator are important factors for feeling the existence of the operator 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 retroreflective material and the image captured by a camera at 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.

4. Telexistence Surrogate Anthropomorphic Robot: TELESAR II

4.1 Slave Robot Arm

TELESAR II has two 7-DOF arms, as shown in Fig. 4. Each arm is designed such that its weight is minimum in order that it can move rapidly and is safe for human use. By uniting the housing parts of a harmonic drive gear system with other parts, such as the rotational axes of joints, we have ensured that the entire mechanism of the arm is very lightweight. The weight of the arm is 7.3 kg and its payload is 0.5 kg. The maximum velocity of the arm is 1.2 m/s. The slave arm supports sufficient payload and speed for mutual telexistence by using gestures, and since it is considerably lighter than existing arms [27], the potential danger of injury due to malfunction is also greatly reduced. At the same time, our slave arm has a larger range of mobility in the joints above the elbow. Three shoulder joints J1, J2, and J3 have a mobility range of -180 degree to 180 degree, 0 degree to180 degree, and -180 degree to 180 degree, respectively. The reduction ratio of the harmonic drive of each joint of the slave arm is set to 50 to maintain back-drivability. The maximum force at the tip of the slave arm is 164 N.

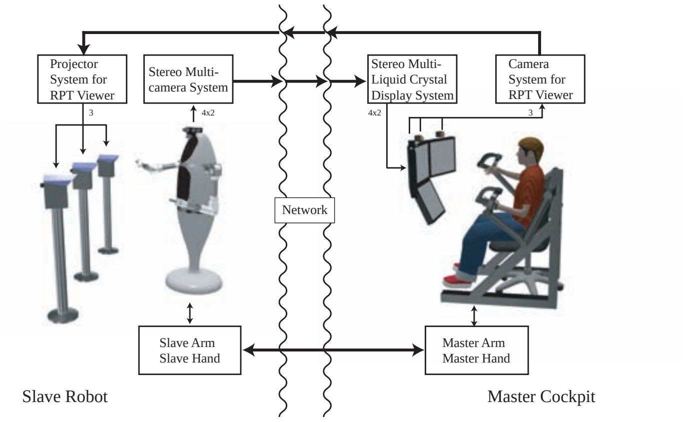

Fig. 2 Schematic diagram of TELESAR II master-slave manipulation system.

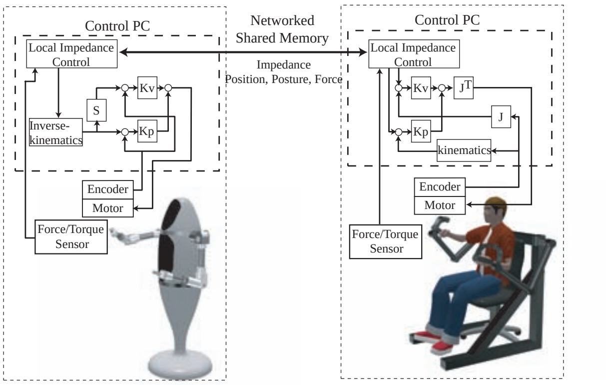

Fig. 3 Schematic diagram of impedance-controlled teleoperation.

The motor driver controls the DC motors in the joints by means of a torque control mode, according to commands received from a DA board. The angular velocity and posture of each joint are measured using an encoder attached to the motor. The neutral point of each joint is defined by photo-interrupters, whose signals are read by the AD board. The slave arm's control system is connected to the master arm system through shared memory. The control system for the master arm is the same as that for the slave arm.

The distribution of the joints of the arm replicates the structure of the human arm in order to facilitate operation by telexistence using kinesthetic sensation. This human-mimicked structure is also useful for interaction with people because the operator can fully use the sensation of congruity.

4.2 Slave Robot Hand

Each slave hand has 5 fingers. Its thumb has 3 DOFs while the remaining 4 fingers have 1 DOF. The hand has also abduction DOF, and altogether 8 DOFs. The hand weighs 0.5 kg. The size of the hand is similar to that of a typical human, i.e., a length of 185 mm, width of 100 mm, and thickness of 35 mm. All parts such as motors, gears, and encoders are packed in-

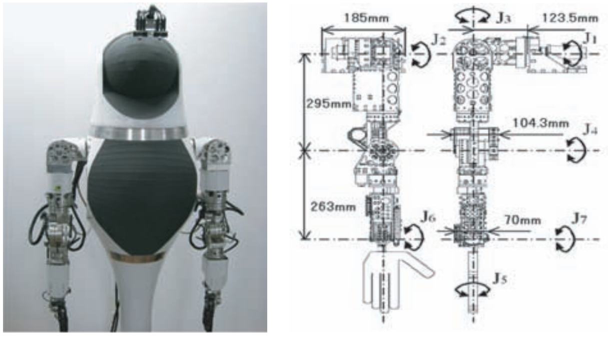

Fig. 4 Slave arm (left: overview; right: structure of right arm).

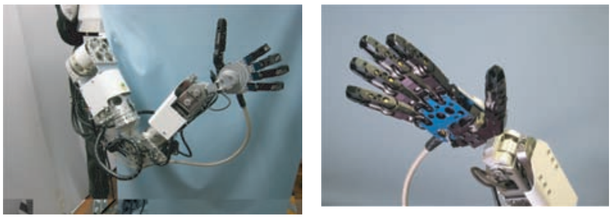

Fig. 5 Slave hand (left: right hand with right arm; right: right-hand palm).

side the hand mechanism. The hand is connected to the control system, i.e., a servo amplifier and control computers, with only one cable.

Figure 5 shows the general view of the slave hand used in our study.

5. Telexistence Cockpit

5.1 Master Arm

The salve arm of TELESAR II and a general anthropomorphic slave arm are built as 7-DOF mechanisms; these arms have the same structure as a human arm. The master arm used as the teleoperation system is also usually built a 7-DOF structure. However, it is normally difficult to achieve the free motion of the operator if the master arm has active 7 DOFs because it tends to restrain the operator's elbow mechanically. When we think of force to be applied to the operator's hand, it is along a maximum of six axes, i.e., 6 DOFs, even the motion of the human arm has 7 DOF. Thus, we have designed the master arm such that it effectively performs the function of force presentation in these six axes; we have also built the master arm as a 6-DOF mechanism.

While the force feedback mechanism is sufficient for 6 DOFs, it is necessary to have 7 DOFs for the measurement of human arm motion. The master arm has a cantilever beam structure as serial links; therefore, if the DOF of the master arm increases, the length of the cantilever beam and the total weight of the actuators also increase, thereby decreasing the rigidity and stability of the master arm. Since the measurable movement of the master arm that follows the operator's hand has 6 DOFs, we use a new lightweight posture sensor composed of an acceleration sensor [28] to measure the final DOF, which is critical to identifying the posture of the operator's entire arm. Altogether, the master arm serves as a master system with 7 DOFs for measurement of the arm's posture and 6 DOFs for force presentation. Since the posture sensor is very lightweight compared to the mechanical restraints on the operator's elbow, the sensor enables considerably high movement of the opeartor's arm without any undesirable load on it.

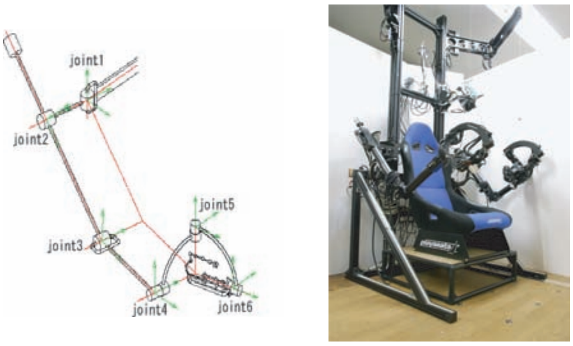

Fig. 6 Master arm (left: structure; right: overview).

An exoskeleton structure is widely used because it can be adopted for the movement of an operator with minimal size requirements, which is an essential requirement for correspondence to various everyday actions of humans. Structure and general view of the master arm are shown in Fig. 6.

A potentiometer and an encoder are installed in each joint, and the operator's initial posture is computed from the output signals of the potentiometers. During movement, the joint angles and angular velocities of the operator's arms are computed from the output signals of the encoders. The three axes of the joints in the master arm's wrist cross at one point and a 6-axis force sensor (MINI 4/20, BL AUTOTEC) is attached to that point. Output signals of this sensor are used to measure the force acting between the wrists of the master arm and operator in the direction of the rotating axis and the torque that acts around the axis. The exoskeleton-type multifingered master hand is attached to the tip of the master arm and a bilateral system including fingers is realized.

A gravity compensation system is realized by suspending a wire at the tip of the master arm, which enables the manipulator to yield the maximum performance. The tension of the wire is 20.6 N. Because of this gravity compensation system, the actuators of the joints of the master arms do not have to compensate for the gravitational torque applied to the master arm. Therefore, the master arm is able to present forces to the operator's hand with a small output torque and high accuracy. A passive link that has two joints is attached above the master arm. A constant force spring runs through the link. Constant tension acts on the wire by passing it through a pulley at the tip of the spring. The wire is attached to the tip of the master arm. Since the joints of this link are parallel to the direction of gravity, the link can follow the master arm smoothly by means of the wire that runs through the master arm, while maintaining a horizontal posture. The maximum force at the tip of the master arm is 239 N.

As our master arm has 6 DOFs and the slave arm has 7 DOFs, a simple symmetric servo cannot be employed between corresponding joints. Our two requirements are precise hand movement: and communication by gestures. For satisfying the first requirement, the position and orientation of the slave arm's wrist must coincide with those of the master. 6DOFs are used for this purpose. For satisfying the second requirement, the slave's posture must be as similar as possible to that of the operator. The remaining 1 DOF is used for this purpose. It should be noted that the conventional method based on the pseudo inverse of the Jacobian matrix is not appropriate because it does not satisfy the second requirement.

Fig. 7 Acceleration sensor attached to operator's upper arm along swivel axis.

There are some possible techniques for measuring an operator's posture, such as the use of markers and cameras, which are adopted in general motion capture systems. However, the optical method has two problems: time delay and occlusion. Therefore, we consider another simpler method mentioned below to avoid these problems. By this measurement, the master side has 7 DOFs for position and orientation and 6 DOFs for force feedback.

As the operator's arm can be regarded as a redundant manipulator, conventional methods to solve the inverse kinematics of a redundant arm can be applied to measure the operator's posture. One of the popular methods is to define the swivel angle of an arc of a circle, which the elbow traces; this angle lies on a plane whose normal is parallel to the wrist-to-shoulder axis. Given the wrist position, orientation, and elbow swivel angle, an algorithm can compute the joint angles analytically. It should be noted that the wrist position and orientation of the operator are identical to those of the master manipulator. In order to acquire the remaining information (swivel angle), we use an acceleration sensor (ADXL202E, Analog Devices, Inc.) attached to the operator's upper arm. The sensor has a suitable high-frequency response (1 kHz), while its small size and low weight permit the operator to move his or her arm freely. We use an axis of the sensor corresponding to the change in the swivel angle, as shown in Fig. 7.

5.2 Master Hand

We have developed a new type of master hand, as shown in Fig. 8. It has the following two features. One is the compact exoskeleton mechanism of the master hand's finger contrived to cover wide workspace of an operator. The exoskeleton mechanism can be placed either over (parallel joint) or beside (coaxial joint) an operator's finger. The former placement has a disadvantage that the master arm's finger obstructs the motion of the operator's finger when the operator's finger is bent. However, the latter placement is difficult because there is little space to place the exoskeleton mechanism. To solve this problem, we have proposed a "circuitous joint" that coincides the joint axis of the master hand with that of the operator by extending the link length in proportion to the joint angular displacement, as shown in Fig. 9 [29].

The other feature of the master hand is the encounter-type force feedback [30]. An encounter-type device remains at the location of the object in the remote envirunment and waits for an operator to encounter it. As shown in Fig. 10, our encounter-type master hand's finger usually follows the operator's finger without physical contact. It enables the operator to touch nothing when the slave hand does not touch anything. When the slave hand touches an object, the master finger stops its movement so that the operator's finger touches a plate of the master hand. The plate provides both the feeling of contact and an appropriate resistive force. Therefore, our master hand is able to provide both perfect unconstrained motion and natural touch sensation.

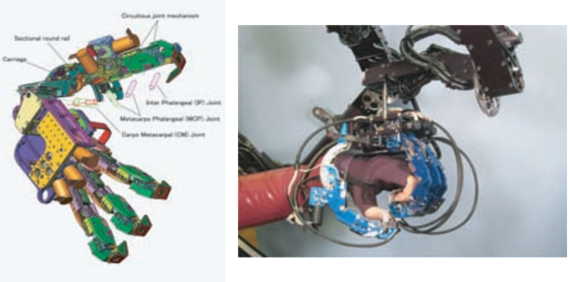

Fig. 8 Master hand (left: structure; right: overview).

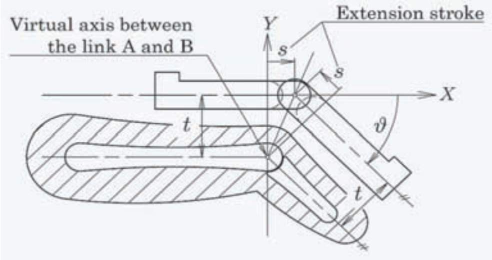

Fig. 9 Basic scheme of circuitous joint.

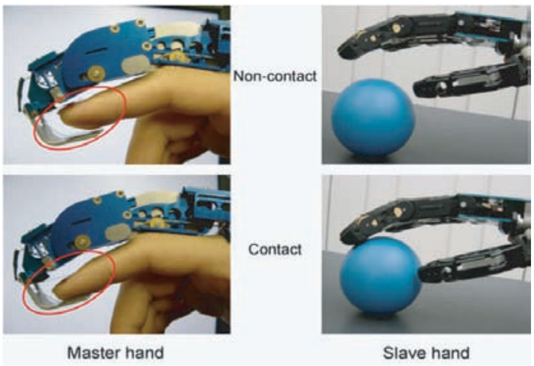

Fig. 10 Encounter-type master-slave hand system.

5.3 3D Display System

If we use a head-mounted display (HMD) for displaying the 3D (three-dimensional) scenery of the place where a surrogate robot is working, people at that place inevitably see an operator with a HMD, which is not preferable from the viewpoint of the desired face-to-face communication.

Therefore, we have constructed a 3D display system consisting of four 3D displays (SynthaGram 204: 20 inch lenticular-type LCD display) arranged in front and on the left, right, and bottom, thereby forming a T-shape. Because of lenticular lenses placed on the display surface of the LCD display, the operator can view a stereoscopic image without wearing any special glasses such as shutter glasses or polarized glasses.

3D camera system is located on top of the robot. Since the display system is fixed, the camera system should also be fixed. The 3D camera system consists of four pairs of CCDs (8

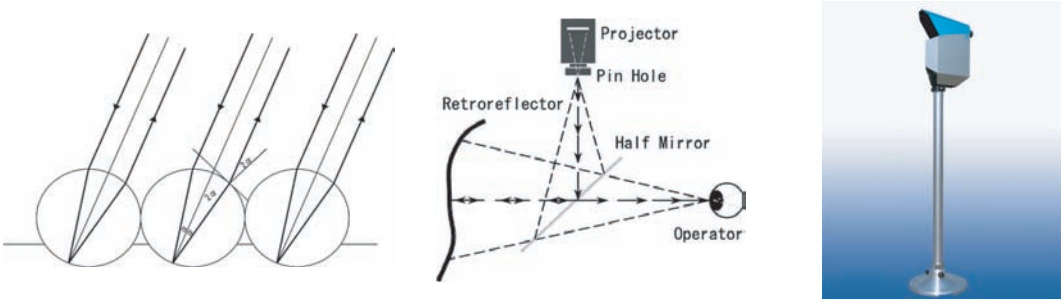

Fig. 11 RPT (left: retroreflection; center: principle of RPT; right: overview of RPT system).

Fig. 12 Example of RPT view (left: TELESAR II without projection; center: with projection of an operator; right: operator at the control).

CCDs). The pairs of cameras are for front, right, left, and bottom views. Each image captured by these cameras is transferred to its respective display. The system provides an approximated egocentric view of the operator.

6. RPT Viewer System

In our laboratory at the University of Tokyo, a new type of visual display termed an RPT display is being developed, which uses retroreflective material as its projection surface [31]–[34]. The retroreflective surface functions as a special screen. In the RPT configuration, a projector is arranged at the axial symmetric position of a user's eye with reference to a halfmirror, with a pinhole placed in front of the projector to ensure an adequate depth of focus. Figure 11 shows the principle of the RPT system and a general view of the system.

The face and chest of TELESAR II are covered by retroreflective material. A ray coming from a particular direction is reflected in the same direction on the surface of the retroreflective material. Because of this characteristic of the retroreflective material, an image is projected onto the surface of TELESAR II without distortion. Since we use many RPT projectors in different directions and project different images corresponding to the cameras placed around an operator, observers can view the corresponding images of the operator.

Figure 12 shows an example of projecting images of an operator to its surrogate robot.

7. Feasibility Experiments

In order to demonstrate the feasibility of the concept of the TELEsarPhone system, we constructed a hardware system and exhibited it at Expo 2005 Aichi Japan as one of the prototype robots at the Morizo and Kiccoro Exhibition Center from June 9 through June 16 [35].

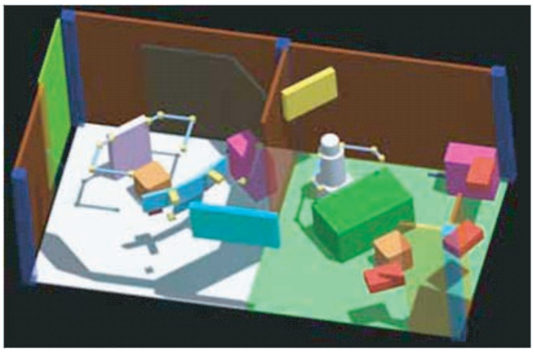

Fig. 13 Booth layout (left: cockpit booth; right: robot booth).

Two booths were constructed. One was a cockpit booth and the other was a robot booth (Fig. 13). We assumed that the cockpit booth was located in Tokyo and the robot booth was located in Paris. The robot booth was assumed to be a store specializing in stuffed animals, and the store had a telexistence communication robot in order to greet a foreign customer without actually having to travel. A person in the robot booth, which was supposed to be located on a street in Tokyo as a future extension of a telephone booth on the street, could visit the store in Paris without actual travel using the telexistence communication system (Fig. 14).

The person (operator) would sit down and wear master arms and hands and log into the surrogate robot in Paris through a dedicated network. Then, the robot would move its arms and hands corresponding to the operator's motion. The operator could obtain a 3D view of the shop by using the autostereoscopic display in front of him or her. The operator could communicate with the clerk in the shop using a headset comprising a microphone and speaker. Using the master-slave communication system, the operator could communicate with the clerk by gestures or shake hands with the clerk. The operator could

Fig. 14 General view of the booths (left: cockpit booth; center: robot booth; right: human robot communication).

Fig. 15 Mutual telexistence using RPT (left: without RPT viewer; center: through RPT viewer; right: observer viewing through RPT).

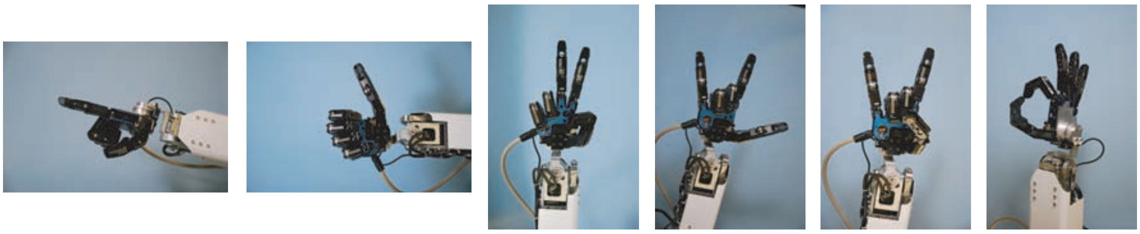

Fig. 16 Hand gestures.

not only select the stuffed animal of his or her choice but also handle the selected stuffed animal using the master-slave manipulation system.

Thus, the person in Tokyo could acquire the feeling of visiting the store in Paris and select the merchandise he or she desired to buy. The clerk in Paris could also see the visitor at the shop by using the RPT viewer system. Figure 15 shows an example of such views. In the Aichi Expo, we set up 3 RPT viewers in front and on the right side and center of the booth. Observers could simultaneously see the front view, right-hand side view, and left-hand side view of the face of the operator.

Three cameras were arranged corresponding to the RTP viewers. Three persons were able to see the operator's images simultaneously. One person was facing the front side of the operator's face, while the remaining two people were diagonally facing the left- and right-hand sides of the operator's face. They could see the corresponding images of the operator, i.e., frontal, diagonally left, and diagonally right, respectively. As the operator turned his or her face, he or she could communicate with one of the three people face to face.

The main features of the proposed system are as follows:(1) nonverbal communication is possible in addition to the conventional verbal communication and (2) face-to-face communication is possible under the condition that several people are present.

In order to evaluate the above mentioned features of the proposed system, the following additional experiments were conducted.

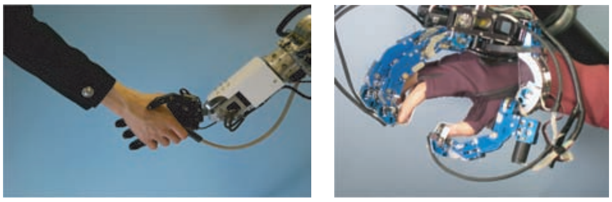

Fig. 17 Handshaking experiment (left: handshaking with slave hand; right: operator with master hand).

(1) Nonverbal communication using hand gestures and handshakes was carried out. Several hand gestures such as the pointing gesture, iconic gestures, and emblematic gestures such as pointing, thumbs up, ok, etc., were easily made using the developed master-slave system. Figure 16 shows some examples of the realization of such gestures.

A handshake action was performed, and the positions and forces of the slave arm and the master arm were measured. Figure 17 shows an example of a handshake with a surrogate robot.

Figures 18 and 19 show examples of the measured position and force in the upward and downward directions respectively, during a handshake. As indicated by this figure, motion is initiated by the slave because the action of a handshake with a surrogate robot requires initiative on the part of a person shaking hands with the slave. The graph shows that the position of the master follows the position of the slave without any delay and the force of the master is delayed compared to the force of

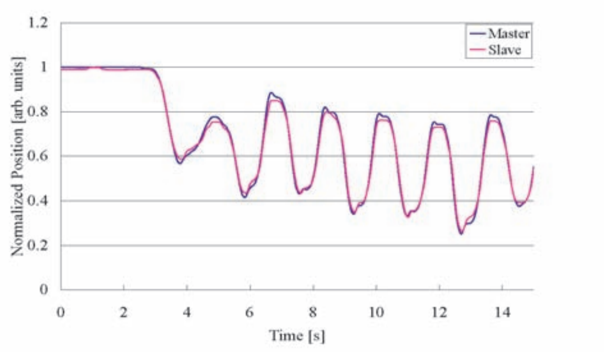

Fig. 18 Normalized positions of slave and master during a handshake.

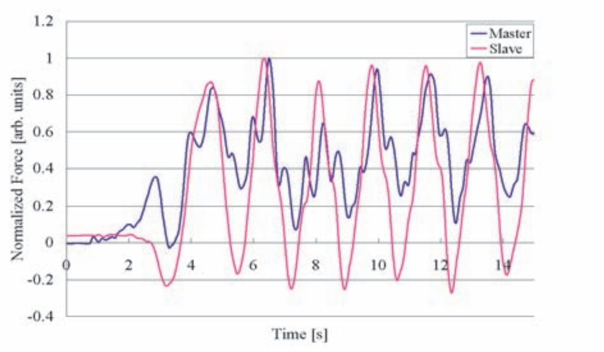

Fig. 19 Normalized forces of slave and master during a handshake.

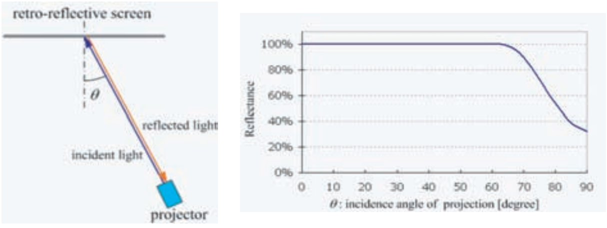

Fig. 20 Reflectance of Retroreflective Material as a Function of Incident Angle of Projection.

the slave by around 0.2s. At the beginning of the handshake action, antagonistic force is produced on the master side and no movement occurs for approximately 3s; then, the person on the master side follows the motion of the person on the slave side. These movements have been clearly recorded in Fig.17.

(2) Figure 20 shows the characteristics of the retroreflective material used to cover the surface of the robot. A reflectance of 100% with reference to normal incidence is obtained for an incident angle of more than 60 degrees, which is sufficient for a human-sized robot.

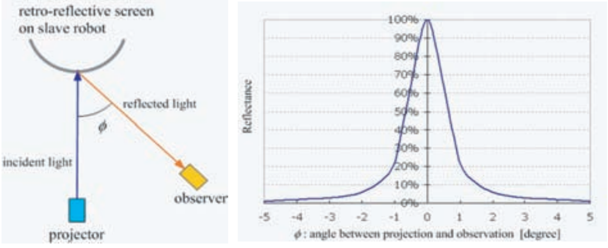

Fig. 22 Reflectance of retroreflective material as a function of the angle between projection and observation.

Figure 21 shows an example of a projected image observed from several positions around the robot. Clear images of the person at the control are obtained from any angle because of the reflectance characteristics shown in Fig. **??**.

In order to estimate the maximum number of people who could view the person's image simultaneously, the following measurement was performed. White uniform image was projected onto the retroreflective surface of the robot, and reflectance was measured as a function of the angle between the projector and an observer, as shown on the left-hand side of Fig. **??**. The result is shown on the right-hand side of Fig. 22. This indicates that virtually the entire reflected light is within an angle of 3 degrees. This implies that when we separate two observation points at an angle of 3 degrees, no interference occurs. If we simply divide the view of 360 degrees by 3 degrees, 120 simultaneous viewing points are obtained.

8. Conclusion

The concept of using a robotic mutual telexistence system for natural face-to-face communication was proposed, and its feasibility was demonstrated by constructing a mutual telexistence master-slave system using the RPT.

In order to carry out face-to-face communication between two people who are located in different places, person "A" must be able to see another person "B" face to face, and vice versa. We proposed a system in which person "A" used a surrogate robot, which was located at the place where person "B" was present, and the surrogate robot was covered with retroreflective material so that a real-time image of "A" could be projected onto it. It was demonstrated that not only was "A" able to see "B" face to face but also "B" was able to see "A" face to face

Fig. 21 Projected images observed from various angles.

by using the proposed RTP-based mutual telexistence method.

It was also proved that nonverbal communication actions such as gestures and handshakes could be performed in addition to conventional verbal communication because of the use of a master-slave manipulation robot as the surrogate of a human.

It was also shown that person "A," who visited a place where a surrogate robot was located, could be seen naturally and simultaneously by several people standing around the surrogate robot.

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