Telexistence: Next-Generation Networked Robotics

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Abstract. Research on human-robot systems started as teleoperation and cybernetic prostheses in the 1940's. Teleoperation developed into telerobotics, networked robotics, and telexistence. 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 that enables an operator at the control 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 enables humans to be seemingly everywhere at the same time, i.e., to be virtually ubiquitous. This paper reviews the generation of robots and discusses the prospects of future networked robotics, as exemplified by telexistence.

Keywords: generations of robots, networked robotics, Real-time Remote Robotics (R-Cubed), Humanoid Robotics Project (HRP), telexistence, mutual telexistence, telepresence, virtual reality, Retro-reflective Projection Technology (RPT)

1. Introduction

One of humanity's most ancient dreams has been to have a substitute that can undertake those jobs that are dangerous, difficult or tedious. In primeval times, the dream was realized by utilizing animals, and unfortunately, by using fellowmen as slaves. In some countries, such conditions continued until nearly a hundred years ago.

With the advent of robotics and automation technology, and also the progress of computers and electronics in recent years, it has become possible to let automated machinery replace human labor. Robots are expected to replace human work as the only tolerable slave from a humanitarian point of view. The "Human Use of Human Beings" of Norbert Wiener will be truly realized only when humans make robots to replace them for adverse tasks, supporting an important end in the development and safety of our modern society.

The application fields are not limited only to ordinary manufacturing in secondary industry, but have been expanding gradually to mining, civil engineering and construction in the same secondary industry, as well as to agriculture, forestry and fisheries in primary industry. They are expanding also to retailing, wholesaling, finance, insurance, real estate, warehousing, transportation, communications, nuclear power, space, and ocean development, to social work, such as medical treatment, welfare and sanitation, and to disaster control, leisure, household, and other tertiary industry-related fields.

Another dream of human beings has been to amplify human muscle power and sensing capability by using machines while reserving human dexterity with a sensation of direct operation. Also it has long been a desire of human beings to project themselves into a remote environment, that is, to have a sensation of being present or existing at the same time in a different place other than the place they really exist, i.e., to become virtually ubiquitous. This dream is now on the way to accomplishment using robots as surrogates of ourselves over networks through technologies such as virtual reality, augmented reality, wearable systems and ubiquitous computing.

As this realization progresses our relations with the robot are becoming more and more important. These are called human-robot systems, human-robot interfaces, or human-robot communications, and are also referred to as teleoperation, telerobotics, networked robotics, r-cubed (real-time remote robotics) or telexistence when robots are remotely placed. These are some of the most undeveloped areas despite being among the most important in robot technology.

As an example of the human-robot cooperation system, which will play an increasingly important role in the highly networked society of today and the future, telexistence will be presented and intensively discussed.

2. Generations of Robots

Since the latter half of the 1960's, robots have been brought from the world of fiction to the practical world, and the development of the robot is characterized by generations, as in the case of the computer. With the rapid progress of science and technology after World War II, the robot, which had been only a dream, came to realize some human or animal functions, although it had a different shape. Versatran and Unimate were the first robots made commercially available in 1960, and were introduced to Japan in 1967. They are called industrial robots and can be said to be the First Generation of robots finding practical use.

This is considered to have resulted from a combination of two large areas of development after World War II: hardware configuration and control technology for a remote operational type mechanical hand (or manipulator), which had been under research and development for use in the hot radioactive cell of a nuclear reactor, and automation technology for automated machinery or NC machine tools. The term “industrial robot” is said to have originated under the title “Programmed Article Transfer,” which George C. Devol applied for registration in 1954 and which was registered in 1961 in the United States. It has come into wide usage since the American Mental Market, a U.S. journal, used the expression in 1960. After passing through infancy in the latter half of the 1960’s, the industrial robot reached the age of practical use in the 1970’s.

Thus the robot entered an age of prevalence in anticipation of a rapid increase in demand. That is why 1980 is called “the first year of the prevalence of the industrial robot.” From a technical point of view, however, the first generation robot that found wide use is a kind of repetition machine, which plays back repeatedly its position and posture instructed in an embedding process before commencement of operation.

In essence, it is a composite system of technology based on control techniques for various automated machines and NC machine tools, and design and control techniques of manipulators with multiple degrees of freedom. Naturally, the application area is limited. These robots can be most effectively used in manufacturing processes in secondary industry, especially in material handling, painting, spot welding, etc.

In other areas, such as arc welding and assembling, it is necessary to vary actions and to better understand human instructions by using not only knowledge from within, like for the First Generation Playback Robot, but also to acquire external information with sensors. A device that could change its actions according to the situation using a sensor is the so-called Second-Generation sensor-based adaptive robot. It came to prevail gradually in the 1970’s.

The non-manufacturing areas of primary industry (agriculture, fisheries, and forestry), secondary industry (mining and construction), and tertiary industry (security and inspection) had so far been excluded from mechanization and automatization, as the older type First and Second Generation robots could not operate in environments that were dangerous and unregulated or unstructured. However, harsh and hazardous environments such as nuclear power plants, deep oceans, and areas affected with natural disasters, are where robots are needed the most as substitutes to humans who risk their lives working there. The Third Generation Robot was proposed to answer these problems.

The key to the development of the Third Generation Robot was to figure out a way to enable the robot to work in an environment that was not maintained or structured. The First and Second Generation Robots possess the data of the maintained environment. This means that humans have a grasp of the entire scope of data concerning the environment. This is called the "structured environment." The factory where first and second generation robots work is an example of the structured environment. All the information concerning the structure of the factory, such as where passages are and how things are arranged, is clear. One can also change the environment to accommodate the robot. For example, objects can be rearranged to where the robot's sensor can recognize them easily.

However, there are structured environments that cannot be altered so easily. For example, it is not possible to change the environment in places such as the reactor of a nuclear power plant, objects in the ocean, and areas affected by disasters. Even with full knowledge about the environment, one cannot alter the environment to accommodate robots. In many cases, one cannot determine the vantage points and lighting. Furthermore, one can encounter an "unstructured environment" where humans do not possess accurate data. Nature is also full of environments where humans are totally disoriented.

In the development of the Third Generation Robot, one focused on the structuralization of the environment based on available information. Robots conduct their work automatically once the environment was structured, and worked under the direction of humans in an environment that was not structured. This system, called the supervisory controlled autonomous mobile robot system, was the major paradigm of the Third Generation Robot. Thus the Third Generation Robot was able to work in places where humans possessed basic data of the environment but were unable to alter the environment. These robots are engaged in security maintenance in such uncontrollable environments, and could deal with unpredictable events with the help of humans.

In Japan, between 1983 and 1991, the Ministry of International Trade and Industry (now Ministry of Economy, Trade and Industry) promoted the research and development of a National Large-Scale Project under this paradigm called "dvanced Robot Technology in Hazardous Environments". Telexistence played an important role in the paradigm of the Third Generation robots. In the Third Generation robots, robots are beginning to work outside the factories. However, the environments are usually restricted to humans, i.e., robots can work without conscious of human beings. Although there might be humans working together, they are professionals like operators or plant workers and have knowledge on robots and/or robotics.

The Fourth Generation robots really work outside the factories, i.e., on the streets, in the hospitals, in the offices or at home, where human beings without knowledge of robotics or robots are exiting together. Thus, a paradigm shift is essential in this generation.

From the human society point of view, Safety Intelligence, Alter Ego, Anti-Anonymity are three pillars of development of the robots coexisting with human beings. The safety intelligence requires high technology and its innovation will not be an easy task. The intelligence must be perfect, as a partially successful safety intelligence would be totally useless. The robots need to possess safety intelligence that even exceeds human intelligence. As Alan M. Turing has argued, this idea was still not relevant in the twentieth century, when autonomous robots could not have true intelligence as humans have. However, inventing the safety intelligence is the most important mission in the twenty-first century as robots are about to enter the everyday lives of humans.

On the other hand, there is an alternate approach to this problem. One could argue that the "alter- Ego-Robots: one's other-self-robots" rather than the "independent robots" should be the priority in development. The alter-ego-robots are analogous to automobiles. The robots are machines and tools to be used by humans; robots are extensions of humans both intellectually and physically.

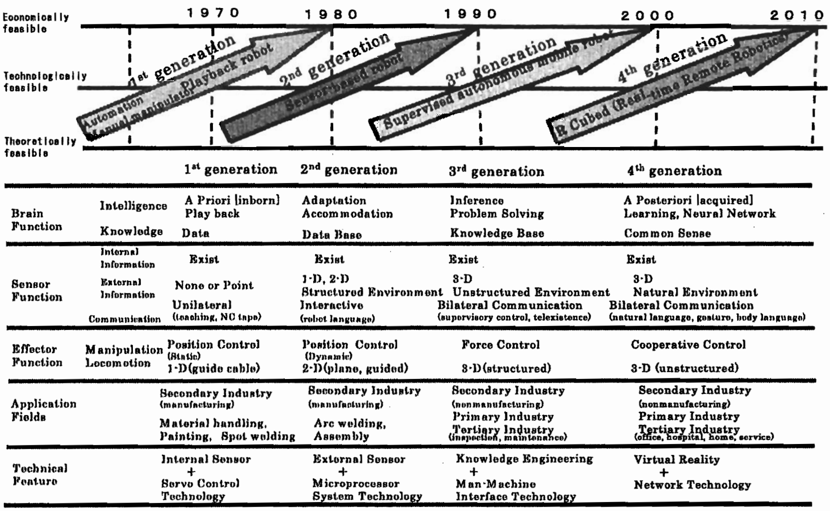
An alter-ego-robot is a promising path that humans can follow. Take nursing for example. It is not desirable for a nursing robot that takes care of you to be an independent being. We can protect the patient's privacy the most when it is the patient who is taking care of himself. Accordingly, it is more appropriate if the nursing robot is an alter-ego-robot, an extension of oneself. The alter-ego-robot can either help himself or other people.

One can nurse himself not only by using his own alter-ego-robot but also by asking family members and professional nurses to take care of him by using robots. These people, who may live far away from the patient, can use telexistence technology to personify the robot near the patient to help him. One important consideration in using this technology is that through the robot the patient needs to feel as though a person he knows, rather than an impersonal robot, is taking care of him. It is essential that the robot have a "face": a clear marker of who personifies it.

The analogy with the automobile is effective in considering the importance of clarifying who is using the robot. Just as the driver of a car, as opposed to the car itself, is responsible for the consequences of the car, so is the person using the robot is responsible for the robot's conduct. When you interact with a robot controlled by someone else, you need to know who is using the robot. The author calls this concept a robot's "anti-anonymity". To put it simple, the concept refers to the visibility of the face and figure of the robot's user.

Thus "alter ego," "anti-anonymity," and "safety intelligence" will be the three pillars of technical elements that are essential to future robots.

The robots can be applied to plenty of areas. It can be said that they can be applied to virtually any field imaginable. That ranges from home household use to space exploration. However, in the Fourth Generation of robots, we focus on the humanitarian use of robots, i.e. Humanitarian Robotics, which promote human welfare, e.g., save the life of humans. This field of humanitarian use of robots includes robotic surgery, robotic care, rehabilitation robotics, rescue robotics, and robotics for humanitarian demining.



		1st generation	2nd generation	3rd generation	4th generation
Brain Function	Intelligence	A Priori [inborn] Play back	Adaptation Accommodation	Inference Problem Solving	A Posteriori [acquired] Learning, Neural Network
	Knowledge	Data	Data Base	Knowledge Base	Common Sense
Sensor Function	Internal Information	Exist	Exist	Exist	Exist
	External Information	None or Point	1-D, 2-D Structured Environment	3-D Unstructured Environment	3-D Natural Environment
	Communication	Unilateral (teaching, NC tape)	Interactive (robot language)	Bilateral Communication (supervisory control, telexistence)	Bilateral Communication (natural language, gesture, body language)
Effector Function	Manipulation	Position Control (Static)	Position Control (Dynamic)	Force Control	Cooperative Control
	Locomotion	1-D(guide cable)	2-D(plane, guided)	3-D(structured)	3-D (unstructured)
Application Fields		Secondary Industry (manufacturing) Material handling, Painting, Spot welding	Secondary Industry (manufacturing) Arc welding, Assembly	Secondary Industry (nonmanufacturing) Primary Industry Tertiary Industry (inspection, maintenance)	Secondary Industry (nonmanufacturing) Primary Industry Tertiary Industry (office, hospital, home, service)
Technical Feature		Internal Sensor + Servo Control Technology	External Sensor + Microprocessor System Technology	Knowledge Engineering + Man-Machine Interface Technology	Virtual Reality + Network Technology

Figure 1: Generations of Robots.

Robot technology that is used in this field can be divided into three parts. They are robot mechanisms, operation cockpits including human interfaces, and communication technology. Teleoperation, telepresence and telexistence play an important role for the realization of the system adding to the technologies as nano/micro technology, virtual reality and network technology.

3. Telexistence

Telexistence (tel-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.

The concept of telexistence was proposed and patented in Japan in 1980, and became the fundamental guiding principle of the eight-year Japanese National Large Scale Project called “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 more than twenty years of research and development in the U.S., Europe and Japan [1-10], 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.

Our first report [5,7] 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.

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 [11].

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 [12].

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), shown in Figure 2. 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.

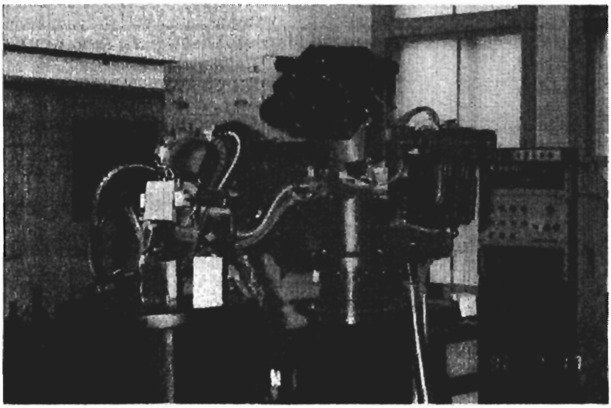


Figure 2: Telexistence Surrogate Anthropomorphic Robot (TELESAR) at Work.

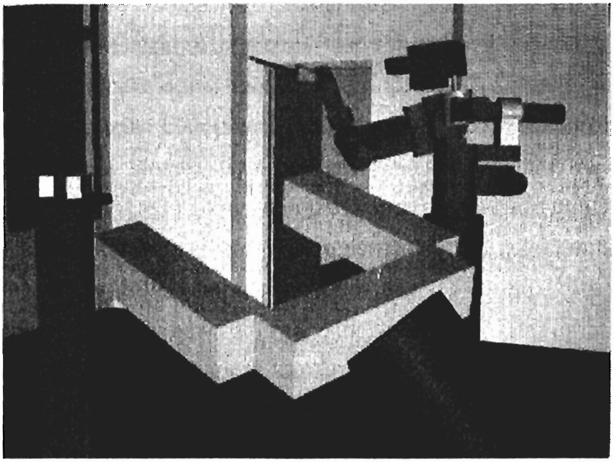


Figure 3: Virtual TELESAR at Work.

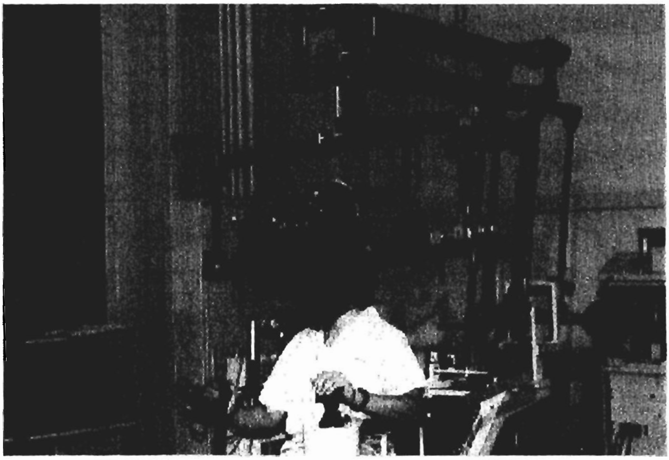


Figure 4: Telexistence Master.

Experimental studies of tracking tasks demonstrated quantitatively that a human being can telexist in a remote and/or computer-generated environment by using the dedicated telexistence master slave system [11].

4. R-Cubed

In order to realize a society where everyone can freely telexist anywhere through a network, the Japanese Ministry of Economy, Trade and Industry (METI) together with the University of Tokyo, proposed a long-range national research and development scheme in 1995 dubbed R-Cubed (Real-time Remote Robotics) [13]. Figure 5 shows an example of an artist's rendition of a future use of R-Cubed System. In this example, a handicapped person climbs a mountain with his friends using a networked telexistence system.

In an R-Cubed system, each robot site includes its local robot's server. The robot type varies from a mobile camera on the low end, to a humanoid on the high end. A virtual robot can also be a controlled system to be telexisted.

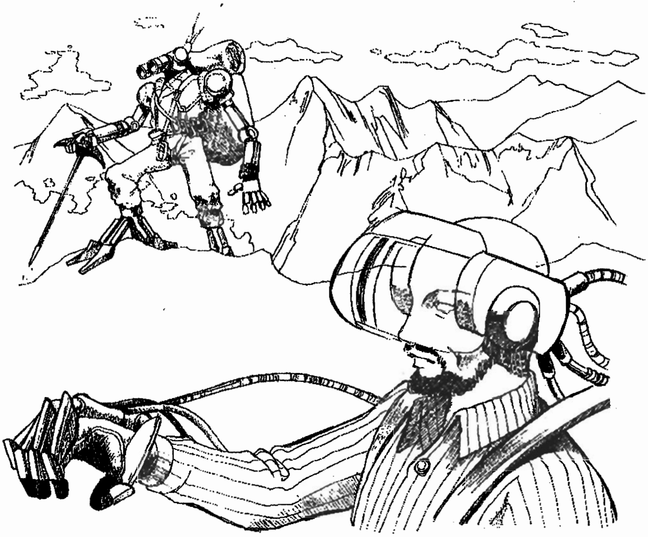


Figure 5: Mountain Climbing using R-Cubed.

Each client has a teleoperation system called a cockpit, ranging from an ordinary personal computer system on the low-end to a control cockpit with master manipulators and a Head Mounted Display (HMD), or a CAVE Automatic Virtual Environment (CAVE) on the high end. RCML/RCTP (R-Cubed Manipulation Language/R-Cubed Transfer Protocol) is now under development to support the lower end user's ability to control remote robots through a network [13].

To standardize the following control scheme, a language dubbed RCML (http://www.rcml.org), which describes a remote robot's features and its working environment, has been proposed. A communication protocol RCTP has also been designed and developed to exchange control commands, status data, and sensory information between the robot and the user.

5. Humanoid Robotics Project (HRP)

After a two-year feasibility study called the Human Friendly Network Robot

(FNR), which was conducted from April 1996 till March 1998 based on the R-Cubed Scheme, a National Applied Science & Technology Project called "Humanoid and Human Friendly Robotics (HRP)" was launched in 1998. It is a five-year project toward the realization of a so-called R-Cubed Society by providing humanoid robots, control cockpits and remote control protocols.

A novel robot system capable of assisting and cooperating with people is necessary for any human-centered system to be used for activities such as the maintenance of plants or power stations, the operation of construction work, the supply of aid in case of emergency or disaster, and the care of elderly people. If we consider such systems from both a technical and a safety point of view, however, it is clearly intractable to develop a completely autonomous robot system for these objectives.

The robot system should therefore be realized with the combination of autonomous control and teleoperated control. By introducing telexistence

Figure 6: Telexistence Cockpit for Humanoid Control.

techniques through an advanced type of teleoperated robot system, a human operator can be provided with information about the robot's remote site in the form of natural audio, visual, and force feedback, thus invoking the feeling of existing inside the robot itself [14,15].

In order to address the problem of narrow fields of view associated with HMD's, a surround visual display using immersive projection technology as adopted in the CAVE (CAVE Automatic Virtual Environment), has been developed (Figure 6). The surround visual display panoramically presents real images captured by a stereo multi-camera system for a wide field of view mounted on the robot, which allows the operator to have the feeling of on-board motion when he or she uses the robot to walk around.

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

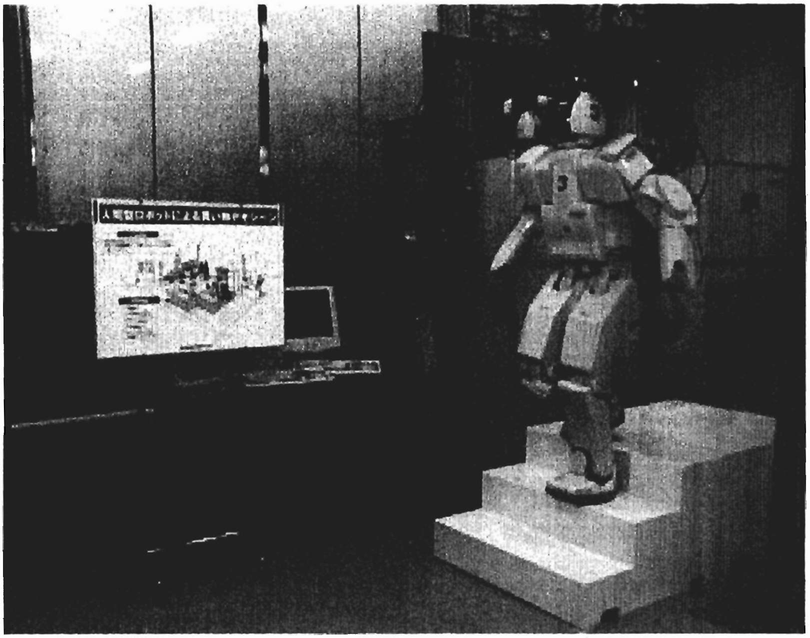


Figure 7: HRP Humanoid Robot at Work.

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 (Figure 7).

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. This was the first experiment and success of controlling a humanoid biped robot using telexistence [15].

6. 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 Figure 8 (C) and (D), respectively. The former has a tradeoff 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 8 (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 Figure 8 (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.

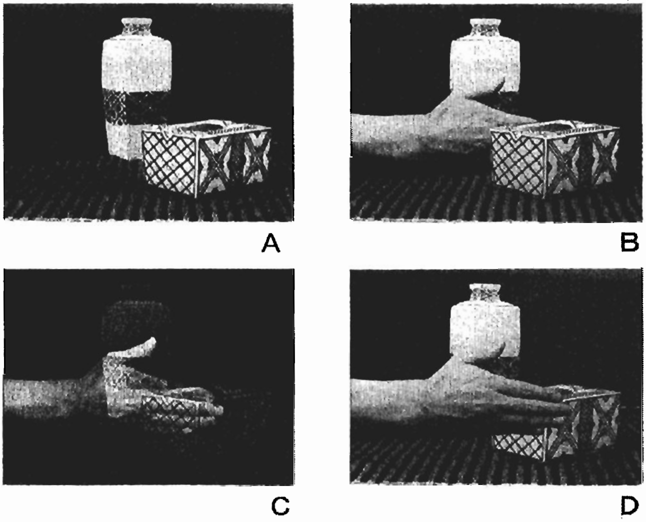


Figure 8: (A) A virtual vase and a virtual ashtray on a virtual desk; (B) An ideal occlusion when a real hand is placed between two virtual objects; (C) Unfavorable results when optical see-through HMD is used; (D) Unfavorable results when IPT (Immersive Projection Technology) like CAVE is used.

Conversely, the virtual ashtray cannot occlude a real hand when IPT like the CAVE is used, as shown in Figure 8(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 [16,17,18,19,20], 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 Figure 9. Images are projected onto a screen that is constructed, painted, or covered with retro-reflective material [16].

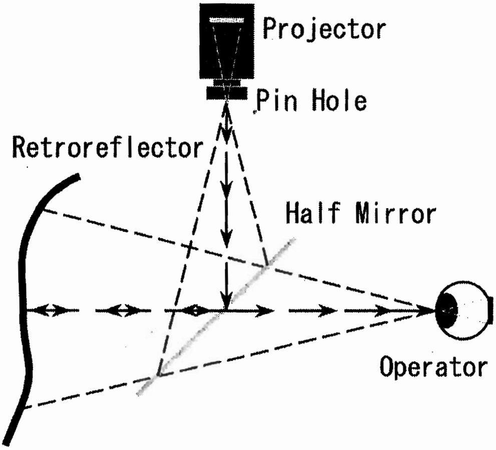


Figure 9: The principle of RPT system.

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 10). Figure 11 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.

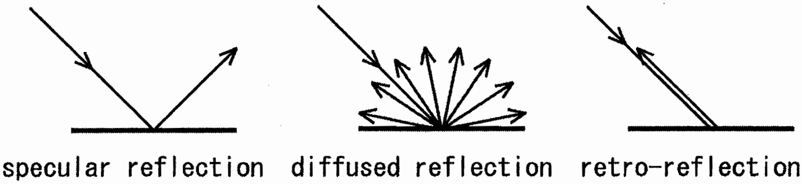


Figure 10: Three typical reflections.

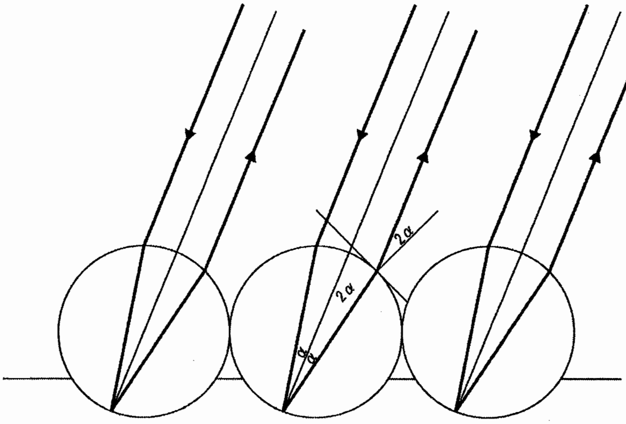


Figure 11: Retro-reflective surface densely covered with microscopic beads with about 50 micrometer diameter.
Ideally, the refractive index should be 2.

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. Figure 12 shows how stereovision 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 retro-reflected also 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 [16].

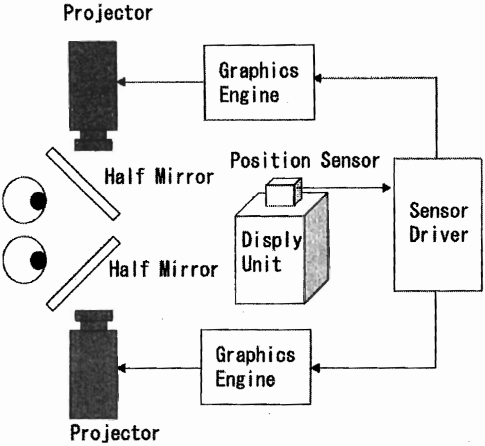


Figure 12: Principle of stereo display using RPT.

The projector can be mounted on the head of a user, which we call an HMP (Head Mounted Projector) system. Figure 13 shows a general view of a prototype HMP.

Figure 13: General view of a Head Mounted Projector (HMP).

Figure 14 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 15 shows an example of projecting a virtual cylinder onto a Shape Approximation Device (SAD) [21], which is a haptic device that enables the user to touch geometrical shapes as if they were real. The use of the SAD as

Figure 14: Projected image on a spherical retro-reflective screen.

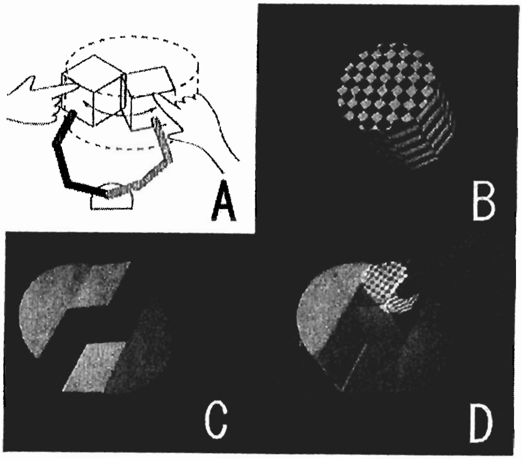


Figure 15: Projected image on a Surface Approximation Device (SAD).
A: Principle of SAD; B: Image; C: Actual SAD; D: Image projected on SAD, which can be touched as it is seen.

the retro-reflective screen enables us to feel just as we see by observing through a HMP. In the figure, (A) illustrates the principle of SAD, (B) shows an image to be displayed, (C) is an actual SAD, and (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.

Figure 16 shows an example of the use of RPT for augmented reality. Pre-captured x-ray and/or MRI data can be superimposed onto a human patient so that a surgeon can have open surgery related information even under the minimally invasive surgery environment. By superimposing ultra-sonic data, real-time presentation of inner body information is also possible through RPT. Figure 17 shows another example of applying RPT to medicine.

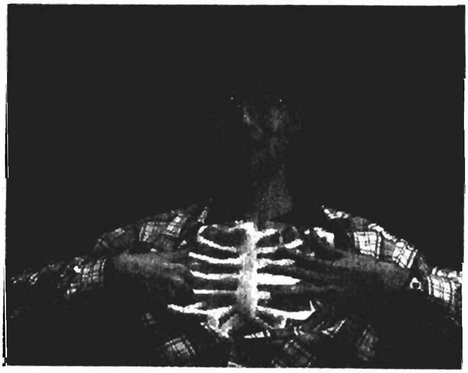


Figure 16: An Augmented Reality Application using PRT.

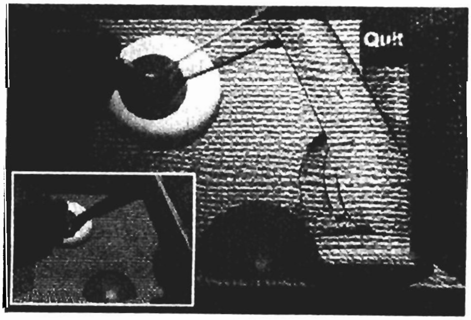


Figure 17: Another Example of the application of RPT to medicine.

Figures 18 and Figure 19 show application examples of using RPT for optical camouflage. In Figure 18, pre-captured a background image is projected so that a retro-reflective object grasped by a human appears to be transparent.

Figure 18: An optical Camouflage Application using RPT.

Figure 19 shows how optical camouflage can be achieved using real-time video information. Figure 20 shows how RPT is applied to realize the situation of Figure 19. 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 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. Since the cloak the subject is wearing is made of a special retro-reflective material, which reflects back the incident light just the same direction it comes from, an observer looking through a half mirror sees a very bright image of the scenery so that he is virtually transparent.

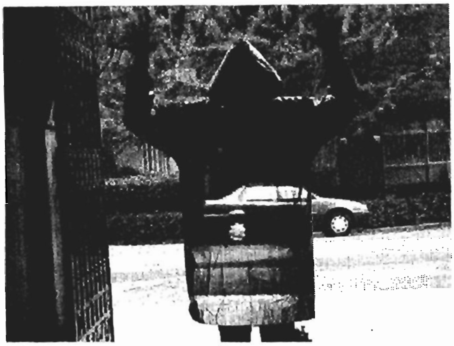


Figure 19: Another example of application of RPT to optical camouflage.

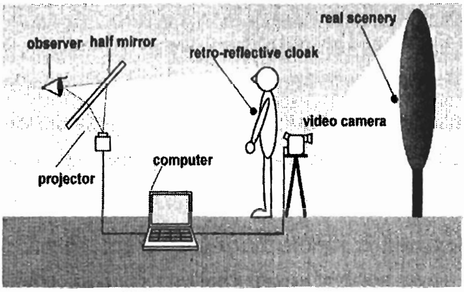


Figure 20: A schematic diagram of the RPT system used for the Figure 19.

The first demonstration of RPT together with an HMP was made at SIGGRAPH98, followed by the demonstration at SIGGRAPH99 as the optical camouflage. This technology was selected as COOLEST INVENSIONS OF 2003 by TIME Magazine in November 2003.

7. Mutual Telexistence using RPT

By using a telexistence system, persons can control the robot by simply 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 RPT, projection technology with retro-reflective material as a surface. The first idea was proposed in 1999 [22], and was demonstrated at SIGGRAPH2000.

By using RPT in conjunction with an HMP, the mutual telexistence problem can be solved as shown in Figure 21: suppose a human user A uses his telexistence robot A' at the remote site where another human users B is present. The user B in turn use 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. However, this situation is somewhat confusing because two real environments [A] and [B] are involved.

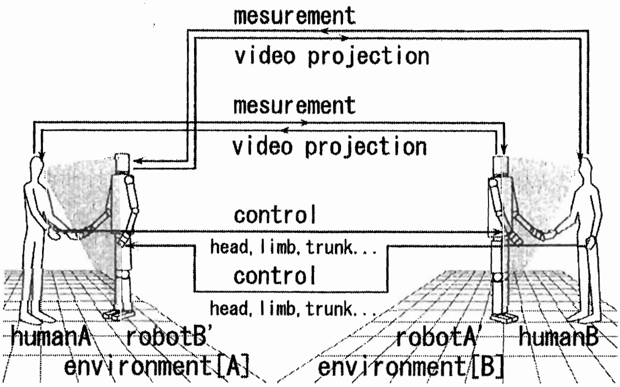


Figure 21: Concept of Robotic Mutual Telexistence with Two Real Environents.

This can be more simplified by restricting the real environment only one environment, i.e. the environment [B]. Only a human user A can telexist using his surrogate robot A', while human users B and C stay at the real environment [B] as in Figure 22. Cockpit (A) has a capability of displaying three-dimensional images of the environment [B] 360 degrees around the human user A, and he or she can enjoy the scenery of the real environment [B] without using any eyewear, i.e., auto stereoscopically. This can be realized using the technology called TEWISTER (TElexistence Wide-angle STEReoscopy) [23]. Using control devices installed in the cockpit, the user A can control the robot with a sensation of presence. This can be realized using haptic devices like the one described in [21]. Humans B and C can project images taken by cameras B' and C' on to the robot A', respectively, so that they can see the user A as if he or she exists inside the robot. The cameras are virtually controlled to see from the direction of the humans B and C relative to the human A, respectively. Position measurements of the humans B and C are made by the robot, and the appropriate directional images of the human A are sent to the humans B and C through the robot, respectively. Thus, mutual telexistence becomes possible.

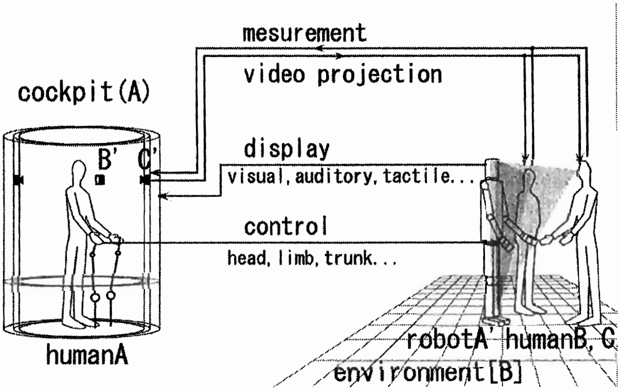


Figure 22: Concept of Robotic Mutual Telexistence with One Real Environent.

8. Experimental Hardware System [24]

In order to verify the feasibility of the proposed method, an experimental hardware system was constructed. Figure 23 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 B sees the screen robot using HMP. His head movement is measured by a 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.

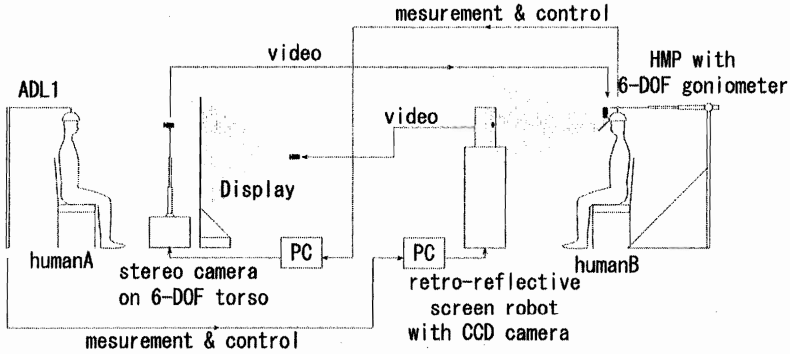


Figure 23: Schematic Diagram of the Robotic Mutual Telexistence System Experimentally Constructed.

Figure 24 and Figure 25 show the stereo torso camera mechanism. It has six degrees of freedom and is designed to track seated human motion at frequencies up to 1.3Hz. Two parallel cameras are placed 65 mm apart from each other, each with a horizontal field of view of 45 degrees.

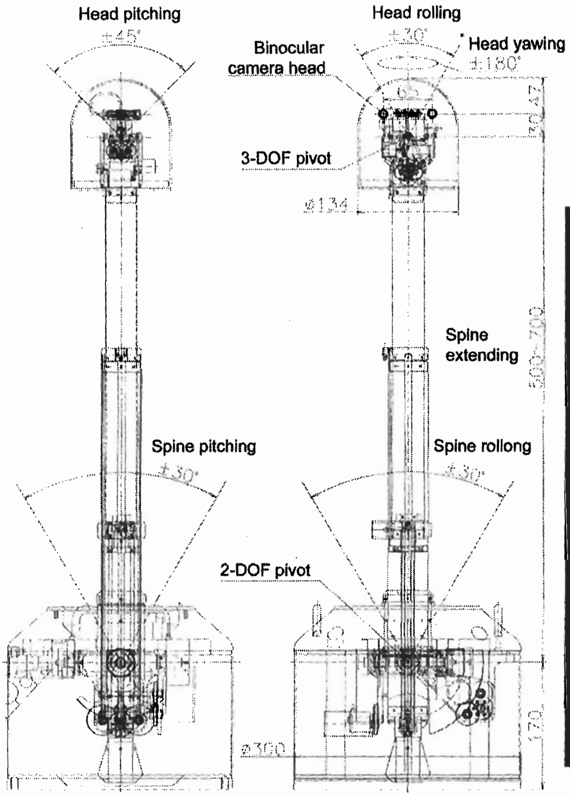


Figure 24: Design of Stereo Camera mounted on Torso Mechanism with 6-DOF.

Figure 25: General View of Stereo Camera mounted on Torso Mechanism with 6-DOF.

Figure 26 shows the mechanism of the 6-DOF goniometer for HRP, and Figure 27 shows a general view. 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.

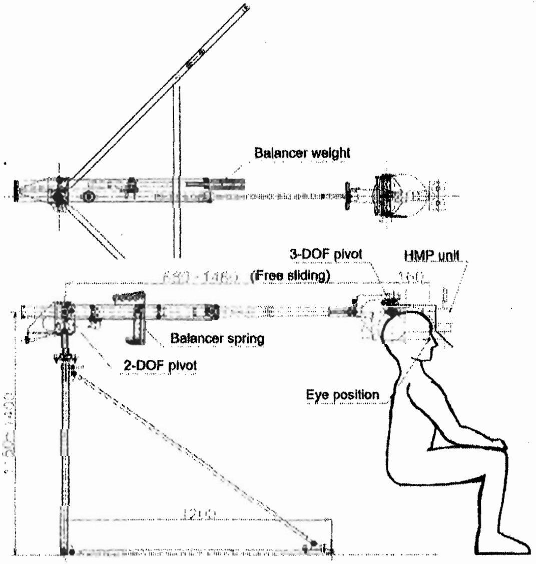


Figure 26: Design of Head-Mounted Projector (HMP) suspended by Counter-balanced Goniometer with 6-DOF.

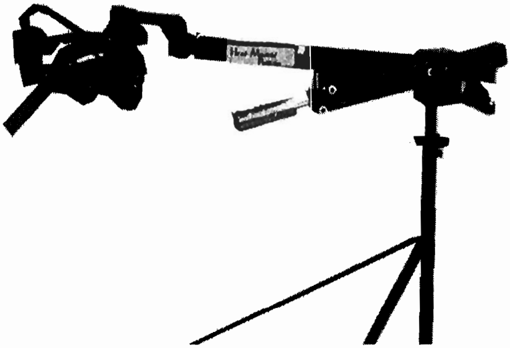


Figure 27: General View of Head-Mounted Projector (HMP) suspended by Counter-balanced Goniometer with 6-DOF.

Figure 28 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 29 shows the dimensions and mechanism of the constructed telexistence screen robot. The torso of the robot is fixed and does not move,

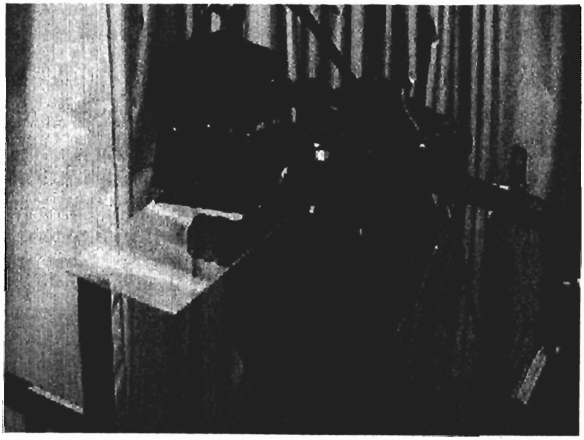


Figure 28: General View of Head-Mounted Projector (HMP) used in this configuration.

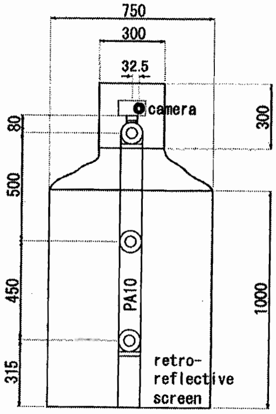


Figure 29: Configuration of Retro-reflective Screen Robot.

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.

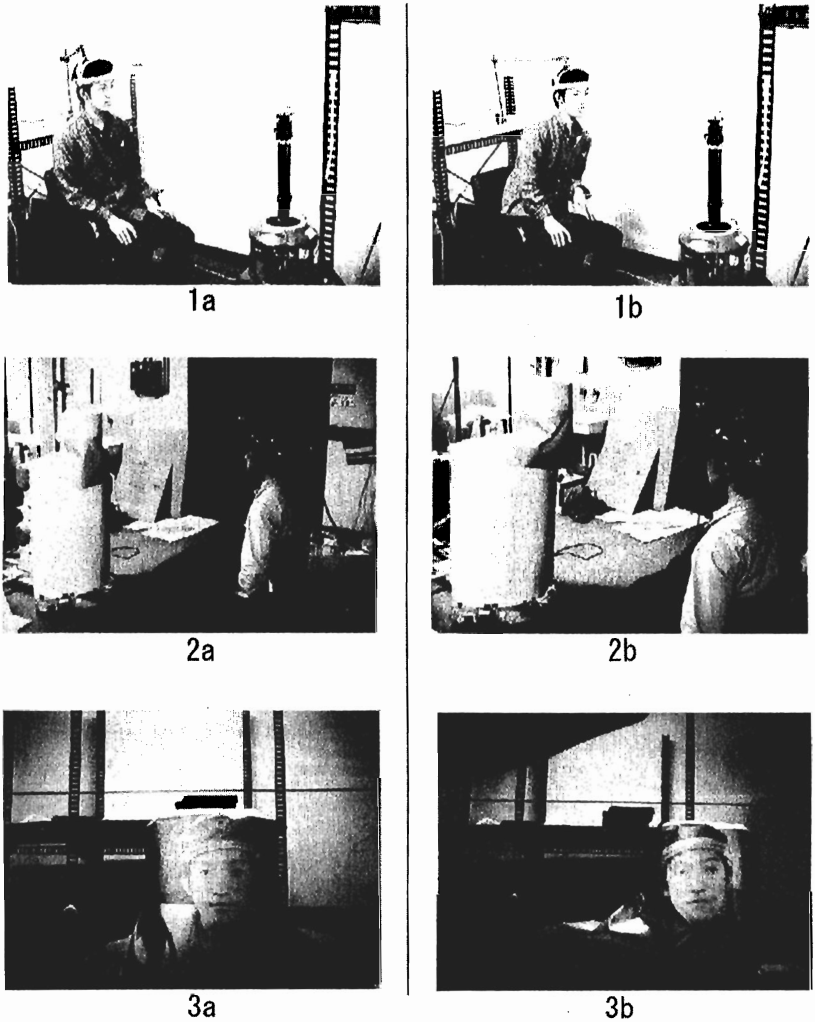


Figure 30: Experimental Results: (1a, 1b) Human User A at Local Cockpit(A), (2a, 2b) Human User B and Telexistece Robot A' in Environment[B], and (3a, 3b) the image of the human user A on the robot A'. A black dot is where the camera is located.

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 Figure 30. In Figure 30 (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 30 (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 30 (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.

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. As is shown by the preliminary experiments, the proposed method using RPT, especially an HMP and a robot with retro-reflective covering was proved to be a promising approach toward the realization of mutual telexistence.

9. Toward the Future

There are two major styles or ways of thinking in designing robots. An important point to note here is that these ways of thinking have nothing to do with the forms of robots, such as the distinction between humanoid robots or those with special forms. Other distinctions include those that perform general or specific functions, and those in the shapes of animals or those that are not. These distinctions are indeed important especially when the robots are applied to practical use, and must be considered in practical situations.

However, the distinction that is discussed here concerns the philosophy toward robot design per se. The two different ways of thinking concern the question of whether to make "robots as independent beings" or "robots as extensions of humans". Robots as independent beings will ultimately have a will of their own, although that is far off from the stage of development today. Accordingly, commands toward the robots are made through language, such as spoken words, written manuals, or computer instructions.

On the other hand, robots as extensions of humans do not have a will of their own. Robots are a part of the humans who command them, and humans are the only ones who possess will. Commands are made automatically according to human movements and internal states, and not through language. Robots move according to the human will.

A prime example of robots as extensions of humans is a prosthetic upper-limb or an artificial arm, which substitutes lost arms. Humans move artificial arms as though they moved their own arms. What if one gained an artificial arm as a third arm, in addition to the existing two arms? The artificial arm would move according to the human will and function as an extra arm extending the human ability. The artificial arm, or, a robot as an extension of human, could physically be separate from the human body; it would still move according to the human will without receiving lingual commands. The robot would not have its own will and function as part of the human, even though the robot is physically separated from the human body. This is what can be called "Alter-Ego-Robot" or "one's other-self-robot". There may be multiple alter-ego robots.

It is also possible to create an environment where humans feel as if they are inside alter-ego-robots, thereby the human cognizes the environment through the sense organs of the robot and then operates the robot using its effect organs. This technology is known as telexistence. Telexistence enables humans to transcend time and space, and allow them to be virtually ubiquitous.

Robots as independent beings must have the intelligence that pre-empts any attempt of the robots to harm humans. That is to say, "safety intelligence" is the number one priority in this type of robot. Isaac Asimov's three laws of robotics, for example, are quite relevant in designing this type of robot. It is crucial to find a solution to make sure that machines would never harm humans by any means.

On the other hand, there is an alternate approach to this problem as is discussed in Section 1. One could argue that the "alter-ego-robots" rather than the "independent robots" should be the priority in development. The alter-ego-robots are analogous to automobiles. The robots are machines and tools to be used by humans; robots are extensions of humans both intellectually and physically. This approach pre-empts the problem of robots having their own rights, as they remain extensions of humans. Humans therefore need not to be threatened by robots, as the robots remain subordinate to humans. One's alter-ego-robot therefore is a promising path that humans can follow.

In general, there are two major uses of alter-ego-robots: one is to transcend time and space by expanding one's existence, and the other is to supplement and extend human abilities by using the robot as part of oneself, as exemplified by artificial arms and seeing-eye dog robots, e.g., Guide Dog Robot know as MELDOG [25]. Furthermore, the ultimate use of the alter-ego-robot would be to make an appreciator of oneself. It is a copy of oneself, including its intelligence. The robot would memorize the intelligence and the behavioral patterns of its user by being used through telexistence. The robot becomes, so to speak, the replica of its user.

Computers can imitate language and memory; however, only robots can imitate behaviors. One's alter-ego-robot spends its daily life with its user as the other-self or a companion, thereby recording that human individual's behaviour. The robot can exist after the user's death, serving as the remnant of the deceased person, together with his photos, recorded voice, videotaped images, writings, paintings, and music compositions that the person leaves behind. The alter-ego-robot therefore has a more extended use than the robot as an independent being.

A paradigm shift is essential in this research in the sense that the research of intelligence should not be focused on finding out and replicating the working of human intelligence; the safety intelligence is a far more important and pressing topic for research. Pursuit of research concerning three elements, i.e., "alter ego," "anti-anonymity," and "safety intelligence" are essential to future technology as a whole, and will lead to the realization of twenty-first century robotics, i.e., Next-Generation Human-Robot Networked Systems.

Acknowledgments

The research presented here has been conducted in part under the CREST Telexistence Communication Systems Project, supported by JST (Japan Science and Technology Corporation).

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