Artificial Reality and Tele-Existence

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Abstract:
Artificial reality or virtual reality is a technology which presents a human being a sensation of being involved in a realistic virtual environment other than the environment where he or she really exists, and enables a human to interact with the virtual environment. Tele-existence or telepresence is a concept named for the technology which enables a human being to have a real time sensation of being at the place other than the place where he or she actually exists, and to be able to interact with the remote and/or virtual environment. He or she can tele-exist in a real world where the robot exists or in a virtual world which a computer has generated. It is possible to tele-exist in a combined environment of real and virtual. Thus tele-existence and artificial reality are essentially the same technology expressed in different manners. In this paper, the concept of tele-existence is considered, and an experimental tele-existence system is introduced, which enables a human operator to have the sensation of being in a remote real environment where a surrogate robot exists and/or virtual environment synthesized by a computer.

1. Introduction

It has long been a desire of human beings to project themselves in the remote environment, i.e., to have a sensation of being present or exist in a different place other than the place they are really exist at the same time.

Another dream has been to amplify human muscle power and sensing capability by using machines while reserving human dexterity with a sensation of direct operation. In the late 1960s research and development program was planned on a powered exoskeleton that a man would wear like a garment. A concept of Hardiman was proposed by General Electric Co., for example, that a man wearing the Hardiman exoskeleton would be able to command a set of mechanical muscles that multiply his/her strength by a factor of 25, yet in this union of man and machine he would feel object and forces almost as if he or she were in direct contact. However, the project was unsuccessful because of the following reasons: (1) It is potentially quite dangerous to wear the exoskeleton when we consider the malfunction of the machine. (2) Space inside the machine is quite valuable to store computers, controllers, actuators and energy source of the machine. Thus it is not at all a practical design to use it for a human operator.

With the advent of science and technology, especially measurement and control technology, it has become possible to challenge for the realization of the dreams. The concept of projecting ourselves by using robots, computers and cybernetic human interface is called tele-existence or telepresence. Adding to project ourselves or tele-exist in a remote real world, projecting ourselves or tele-existing in a computer generated virtual world is becoming possible. The latter concept is usually called artificial reality or virtual reality.

Tele-existence aims at a natural and efficient remote control of robots by providing the operator with a real time sensation of presence. It is an advanced type of teleoperation system which enables a human operator at the controls to perform remote manipulation tasks dexterously with the feeling that he or she exists in one of the remote anthropomorphic robots in the remote environment, e.g., in a hostile environment such as those of nuclear radiation, high temperature, and deep space.

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The authors have been working on the research for the improvement of the teleoperation by feeding back rich sensory information which the remote robot has acquired to the operator with a sensation of presence, the concept which was born independently both in Japan and in the United States. It is dubbed tele-existence [1-8] in Japan and telepresence [9-11] in the United States.

In this paper, the concept of tele-existence is considered, and an experimental tele-existence system is introduced, which enables a human operator to have the sensation of being in a remote real environment where a surrogate robot exists and/or virtual environment synthesized by a computer. An experimental tele-existence system in real and/or virtual environment is designed and developed, and by conducting an experiment comparing a tele-existence master slave system with a conventional master slave system, efficacy of the tele-existence master slave system and the superiority of the tele-existence method is demonstrated experimentally.

2. Principle of the Visual Display with a Sensation of Presence

Essential parameters for human three dimensional visual perception of an object are: (1) the size of the retinal image of the object, or visual angle, (2) convergence of the two eyes, or equivalent disparity of the two retinal images, and (3) accommodation of the crystalline lenses. Adding to the above monochromatic parameters, fidelity in color is important for a realistic display.

Figure 1 shows a schematic diagram of the observation of an object in three dimensional space. The human observer measures the convergence angle α and the size of the object on the retina *lm*. Since the distance between the two eyes *Wm* and the distance between the crystalline lens and the retina a_m are known, a human observer can estimate the distance to the object *dobj* and the size of the object *lobj* as follows:

$$dobj = Wm/2tan(\alpha/2)$$
$$lobj = (dobj*lm)/a_m$$

If we think of a virtual plane at a distance of *dvir* perpendicular to the direction of the head; and project the object image onto the plane as shown in Fig. 1, and the human observer observes the projected images by using the corresponding eyes, then the observed parameters, i.e., and *lobj*, are the same and the human observer gets the same *lobj* and *dobj*. The *lobj* and *dobj* can be derived by using the equivalent disparity *ed* on the virtual plane and the projected image size on the virtual plane *lvir* as follows:

$$dobj = (Wm*dvir)/(Wm-ed)$$
$$lobj = (dobj*lvir)/dvir$$

where *dvir* is the distance to the virtual plane.

Figure 2 shows the display system which reproduces the same situation as the direct observation. Two TV displays and lens systems produce the virtual images of the size *lvir* on the virtual plane at the distance of *dvir* with the equivalent disparity of *ed*.

Figure 3 shows the slave robot's camera system, where the distance between lenses *Ws* is set to be equal to *Wm*. The distance between two CCD devices *Wcam* must be set as *Wcam* = *Wdis* = *Ws*, where *Wd* is the distance between the two centers of the TV displays. It is usually, but necessarily, set as *Wcam* = *Wdis* = *Ws* = *Wm*.

Under these conditions, we define a magnification factor γ = *ldis/ls*. Then by arranging $a_m = \gamma * a_s$, we have the condition of Fig.2, which is the same condition as for a direct observation. Practically, a_m can be determined by measuring the size of the image on the display *ldis* when monitored through the TV camera for a known size object *lobj* at the known distance *dobj* as:

$$a_m = \beta*dobj, \quad \text{where } \beta = ldis/lobj.$$

The focal length of the lens f_m must be selected to meet the condition that the virtual image of the TV display is on the virtual plane.

Ideally the virtual plane *dvir* should be controlled to coincide with the *dobj* controlling both *fm* and a_m. However, experiments revealed that if $200\ mm \leq dobj \leq \infty$, *dvir* can be fixed to 1000 *mm*, and if *145 mm* $\leq$ *dobj* $\leq$ *2000 mm*, *dvir* can be fixed to 500 *mm*. This makes the design and realization of the system more practical.

If these conditions are satisfied and the cameras and the display system follow the head movement of the operator at the cycle time of more than 300 *Hz*, the ideal condition of the direct observation is always maintained.

Adding to this, in order to have a wide view without moving the operator's head, a short focal length of the camera f_s must be selected and the appropriate values for a_s and *am* must be set. The display systems developed for tele-existence are all designed to meet these conditions.

3. Design and Control of Display Mechanism

3.1 Head Coupled Impedance Controlled Active Stereo Display

Figure 4 shows a general view of the impedance controlled head-coupled display with two degrees of freedom. It has an active power assistance mechanism and its impedance is controlled by internal feedback loop. Direct drive motors are used to attain this mechanism, and a dedicated computer controls the impedance of the display mechanism so that a human operator feels apparently lower inertia compared with the physical inertia of the system. Virtual inertia of one third of the actual inertia has been attained.

3.2 Head Mounted Stereo Display

A head mounted display is also a promising approach. A merit of the head mounted stereo display is that an operator can move around quite easily, while that the human operator must support all the weight by himself becomes its demerit. Since gravitational force and the inertia of the system can not be compensated in this system, the design of light weight display is quite important.

Figure 5 shows a head mounted display Mk.I. It weighs 1.7 *kg*, including a helmet (620 *g* for the display per se). It uses two 4 inch color liquid crystal TV displays (resolution: H320 x V220). Eye lenses which are used to attain the effect of Fig.2 are mounted on a spectacles' frame. Lighter version of the head mounted stereo display (Mk.II) has been made. Its total weight is 600 *g*.

4. Tele-Existence Master Slave System

4.1 System Architecture

The tele-existence master slave system consists of a master system with a visual and auditory sensation of presence, computer control system and an anthropomorphic slave robot mechanism with an arm having seven degrees of freedom and a locomotion mechanism.

The operator's head movement, right arm movement, right hand movement and other auxiliary motion including feet motion are measured by the master motion measurement system in real time without constraint. The measured head motion signal, arm motion signal, hand motion signal, and auxiliary signal are sent to the four computers, respectively. Each computer generates the command position of the slave head movement, the arm movement, hand movement or locomotion of the slave robot.

The servo controller controls the movement of the slave anthropomorphic robot. A six axis force sensor installed at the wrist joint of the slave robot measures the force and torque exerted upon contact with an object. The measured signal is fed back to the computer in charge of the arm control through A to D converters. Force exerted at the hand when grasping an object is also measured by a force sensor installed on the link mechanism of the hand. The measured signal is also fed back to the computer in charge of the hand control through another A to D converter.

A specially designed stereo visual and auditory input system mounted on the neck mechanism of the slave robot gathers visual and auditory information of the remote environment. These pieces of information are sent back to the master system, which are applied to the specially designed stereo display system to evoke sensation of presence of the operator.

Measured human movements (head, arm, hand, and auxiliary) are also applied to another computer which is in charge of the generation of computer graphics (Silicon Graphics IRIS 120GTX) through a dedicated computer for measurement. The graphics computer generates two shaded graphic images which are applied to the 3D visual display through superimposers. The measured pieces of information on the human movement are used to change the viewing angle, distance to the object, and condition between the object and the hand in real time (10–20 *Hz*). the operator sees the three dimensional virtual environment in front of his view, which changes according to his movement. He or she can interact with either the real environment which the robot observes, or the virtual environment which the computer generates. The virtual environment can be superimposed on the real environment.

4.2 Anthropomorphic Slave Robot

The slave robot has a three degree of freedom neck mechanism on which a stereo camera is mounted. It has an arm with seven degrees of freedom, and a torso mechanism with one degree of freedom (waist twist). The robot's structural dimensions are set very close to those of a human. The weight of the robot is 60 *kg*, and the arm can carry a l *kg* load at the maximum speed of 3 *m/s*. The precision of position control of the wrist is ± 1 *mm*. The dimensions and arrangement of the degree of freedom of the robot are designed to mimic those of the human being. The motion range of each degree of freedom is set so that it will cover the movements of a human, while the speed is set to match the moderate speed of human motion (3 *m/s* at the wrist position).

A combination of a D.C.servo motor and a harmonic drive reduction mechanism is used as an actuator for each joint except the elbow extension/flexion, which includes conventional gears. The location of the motors is designed so that the appearance of the arm resembles a human arm as closely as possible, and the range and the speed of the manipulator satisfy the necessary specifications.

The impedance control is used for the control of the system. The computer generates a pulse sequence to assign the desired position based on the calculation of the desired impedance assigned at the hand and measured force, and the impedance based position control is conducted by counting the difference between the computer generated pulse and the measured pulse from an encoder.

The locomotion system is a planar motion mechanism whose position is assigned by polar coordinate (r, θ), where r = 500 ˜ 1500 [*mm*] and θ = 0 ˜ 270 [*deg*]. The orientation of the robot is assigned by the waist rotation angle of the robot ϕ, where ϕ = −150 ˜ 150 [*deg*].

A hand mechanism of one degree of freedom, which can either pinch or grasp, has been designed. It is designed to be able to pinch small objects (from a diameter of 2 *mm*) and rather big objects (up to a diameter of 114 *mm*). It uses a parallel link mechanism and a ball screw. The grasping of cylindrical objects with the minimum diameter of 15 mm can be done with contact at three points. This makes the grasping stable. Strain gauges are placed on two finger links, respectively, which measure the grasping force. The average grasping force is 5 *kgf*. Measurement of the opening is done by an encoder attached to the DC motor. Position control with an average resolution of 0.01 *mm* is attained. A six–axis force sensor is installed at the wrist position. The hand is made of durable aluminum and weighs 620 *g* including the force sensor.

The vision system of the slave robot consists of two color CCD video cameras. Each CCD has 420,000 pixcells and has its optical system with a focal length of f=12 *mm* (field of view 40 [*deg*]) and an aperture of F 1.6. Focus is automatically controlled by the TTL AF method. The separation of two cameras are set at the distance of 65 *mm*, and the two cameras are aligned parallel to each other.

As for the auditory system, two microphones are placed 243 *mm* apart from each other, which is the same locational relation as is used for the auditory display of the master system. A small speaker is placed at the location of the mouth, which transmit the operator's voice.

4.3 Master System

A human operator put on the 3D audio visual display with a sensation of presence mounted on a helmet. The weight of the audio visual display is carried by a link mechanism with six degrees of freedom. The link mechanism cancels all gravitational force through a counter balancing mechanism with a relatively wide range of operation. It also enables the display to follow the operator's head movement precisely enough to ensure his/her ordinary head movement. Maximum measured inertial force is within 5 *kgf*. The master arm consists of ten degrees of freedom. Seven degrees of freedom are allocated for the arm itself, and an additional three are used to comply with the body movement.

The stereo visual display is designed according to the developed procedure which assures that the three dimensional view will maintain the same spatial relation as by direct observation. Adding to the fundamental design procedure (See Chapter 2.). A helmet is used to fit on the head. Three sizes are available and can be changed easily by a buckle mechanism. Six inch LCDs (H720 x V240 pixcells) are used.

Two mirrors are arranged so that the LCDs can be placed on the upper side in front of the operator. These made possible the compact arrangement of the display system suitable for the manipulation master system. An optical system using polarizers and analyzers is introduced to eliminate the unnecessary reflected image caused by the internal mirror.

5. Experiments

Three experiments which demonstrate the typical characteristics of the tele-existence master slave system were conducted.

(1)The most important features of the tele-existence include the natural three dimensional vision (close to direct observation), which follows an operator's head movement in real time. Another feature is the natural correspondence of visual information and kinesthetic information, i.e., an operator observes the slave's anthropomorphic arm at the position where his/her arm is supposed to be. This allows the operator at the control to perform tasks which need coordination of hands and eyes quickly as in the case of direct operation. Figure 6 shows a general view of an experimental manipulation task of building blocks randomly placed on a table against a natural background under natural lighting condition. Block building is usually done within tens of seconds without training, whereas conventional teleoperation using the same master, the slave and a conventional two dimensional TV as a monitor takes training. A trained operator takes several minutes to attain the same task.

(2)The combination of fundamental tele-existence technology with other advanced technology such as virtual environment display and impedance control makes it possible to use robots in hazardous environments. Figure 7 shows that the robot works on the supposition that a pipe of a chemical plant is leaking and the plant is filled with toxic gas. The operator analyzes the situation using a virtual model environment of the plant generated by the computer according to the blueprint of the plant while the robot goes to the plant. The model environment is displayed by using the same display which is used for the tele-existence operation. When the robot arrives at the plant, the operator observes the situation through the robot's sensors as if he/she were at the spot. The operator conducts the emergency action by closing the valve and pushing the switch of the exhaust fan. The model environment can be superimposed on the real scenery. Impedance control of the slave robot's manipulator helps conduct quick manipulation tasks like closing valves and pushing switches.

(3)By using tele-existence, natural human robot communication becomes possible. In other words, robots can be used in such situations that human robot collaboration is necessary. Figure 8 shows an example of human robot communication. The robot presents an egg to a lady on behalf of a person at the control.

By conducting these experiments, efficacy of the tele-existence master slave system was verified and the superiority of the tele-existence method was experimentally demonstrated.

Conclusions:

The concept of tele-existence and/or artificial reality is considered, and an experimental tele-existence system is introduced, which enables a human operator to have the sensation of being in a remote real environment where a surrogate robot exists and/or a virtual environment synthesized by a computer. A tele-existence master slave system for remote manipulation experiments is designed and developed, and an evaluation experiment of a tele-existence master slave system is conducted. By conducting several manipulation experiments using the tele-existence system, efficacy of the tele-existence master slave system has been verified and the superiority of the tele-existence method has been experimentally demonstrated.

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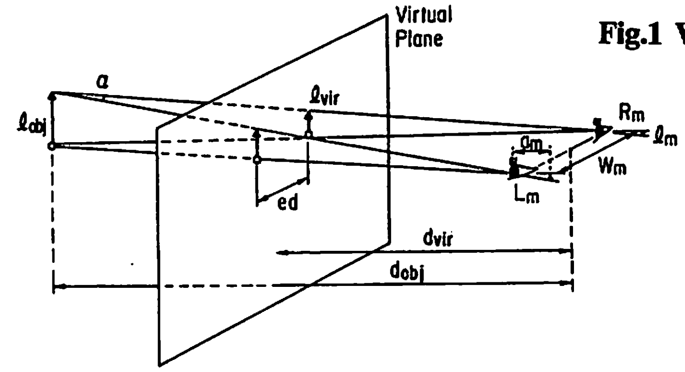


Fig.1 Visual parameters of direct observation.

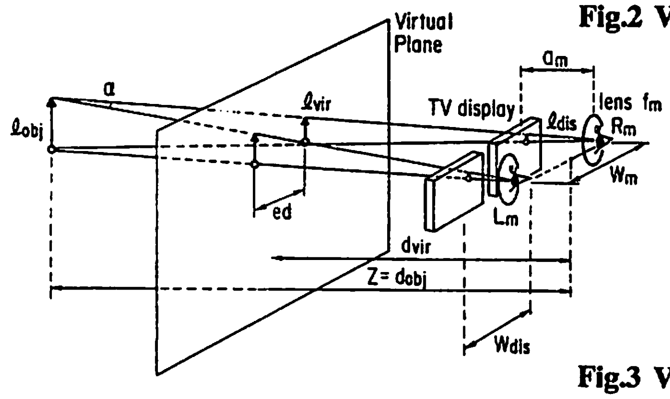
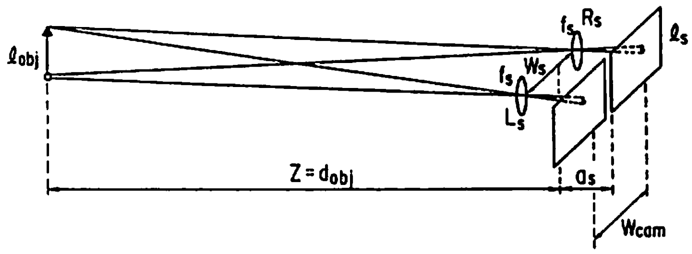


Fig.2 Visual parameters of tele-existence display.

Fig.3 Visual parameters of the slave robot.



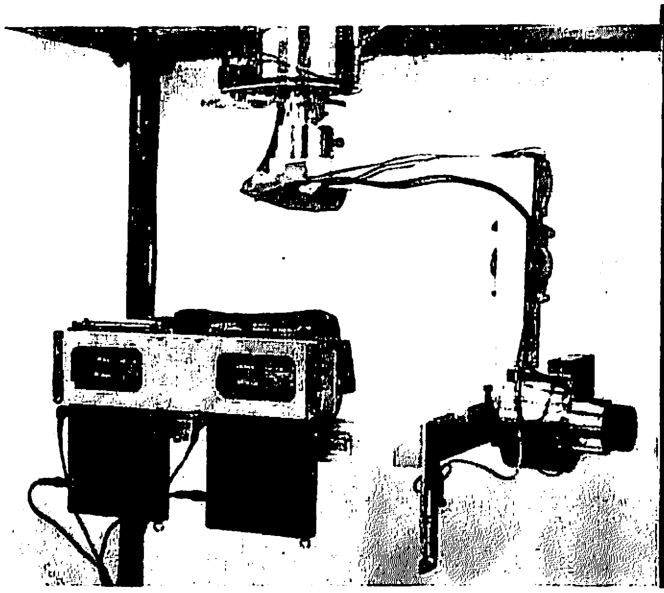


Fig.4 Impedance controlled head coupled display.

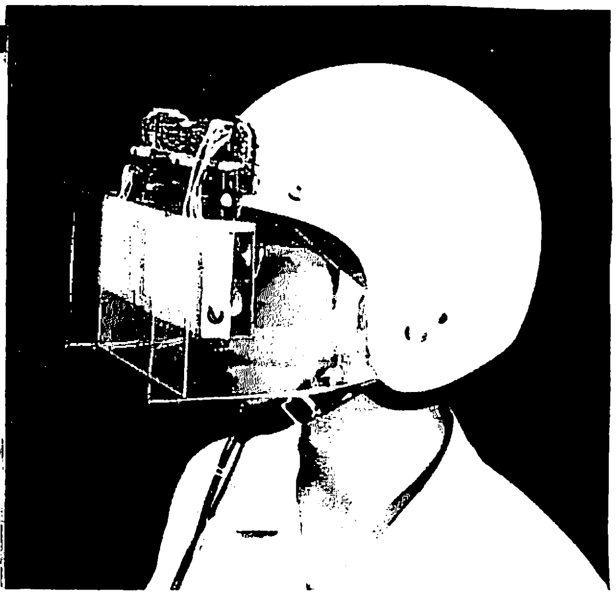


Fig.5 Head mounted stereo display.

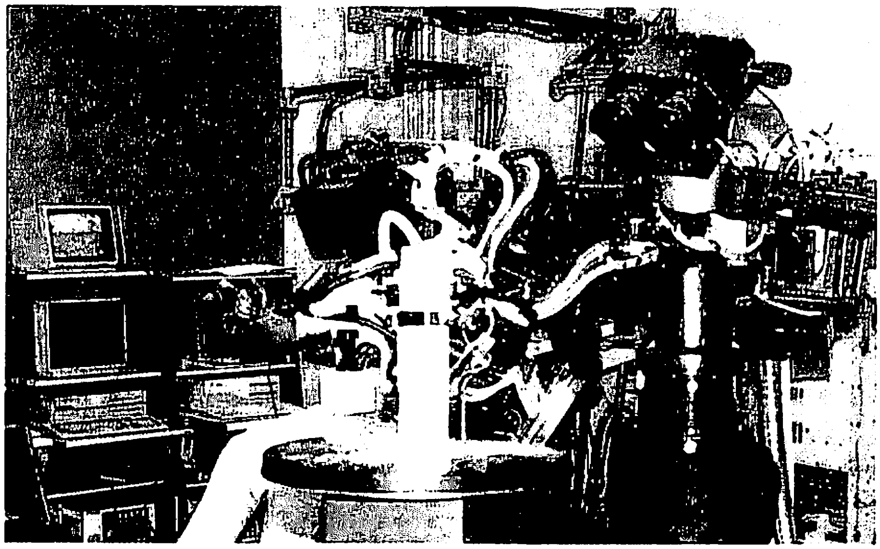


Fig.6 Experiment of handling blocks.

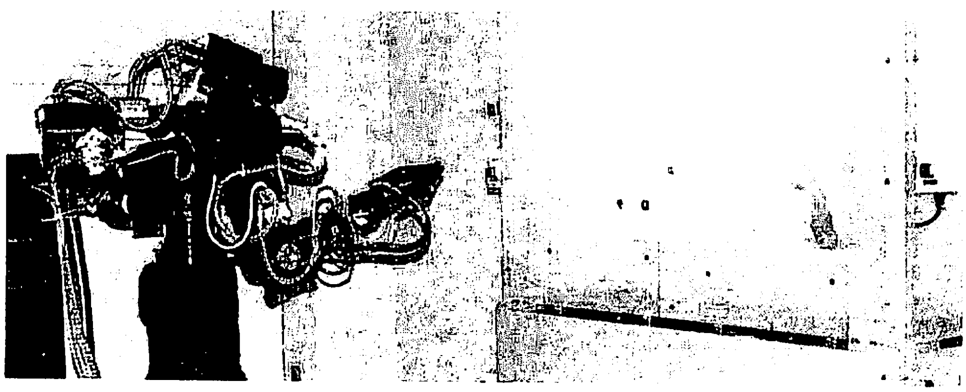


Fig.7 Experiment in hazardous environment.

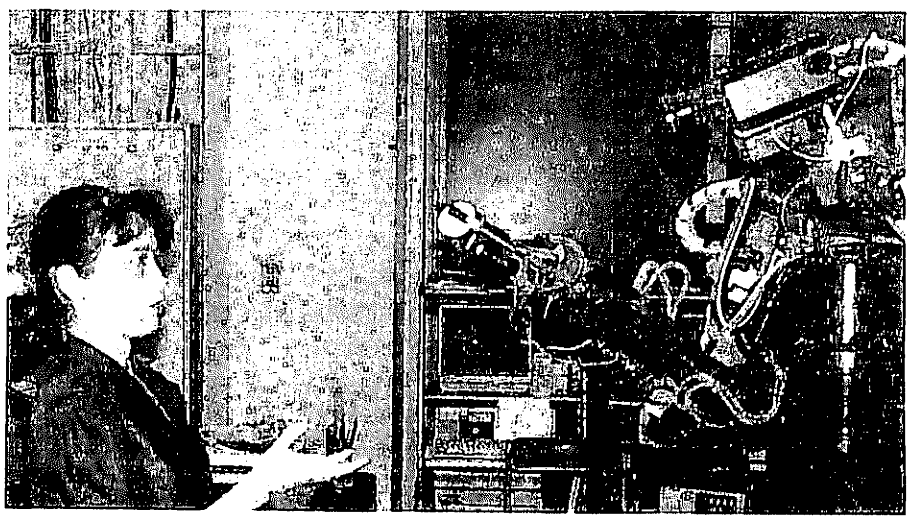


Fig.8 Human robot communication.