Tele-Existence Experimental System for Remote Operation with a Sensation of Presence

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Abstract:
Tele-existence is a concept of 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. The concept was proposed in 1981 in Japan and has been studied as one of the key technologies of the national large scale project of the Advanced Robot Technology since 1983. Following the theoretical consideration of the feasibility of the concept, several tele-existence experimental systems for remote operation have been designed and developed, and evaluation experiments of a tele-existence remote operation system have been conducted. By making a comparison of a tele-existence remote operation system with a conventional teleoperation system, efficacy of the tele-existence system is verified and the superiority of the tele-existence method is demonstrated through several experimental tasks.

Keywords: Teleoperation, Tele-Existence, Telepresence, Artificial Reality, Virtual Reality

1. Introduction

Remote operation plays an important role in a hostile environment such as those of nuclear, high temperature, and deep space. In spite of the efforts of many researchers, a teleoperation system that is comparable to the human's direct operation has not been developed. 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 is called tele-existence [1-13] or telepresence [14-16].

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. This concept was proposed in Japan in 1981 [1], and the first feasibility experiment was reported in 1982 in Japanese [2] and in 1984 in English [3]. Tele-existence has been researched and developed as one of the key technologies for the national large scale project of the Advanced Robot Technology at the Mechanical Engineering Laboratory since 1983. This technology has successfully implemented the ARTRA Demonstration Underwater Robot.

In the previous reports [3,4,5], the principle of the tele-existence sensory display was proposed. Its design procedure was explicitly defined. Experimental visual display hardware was built, and the feasibility of the visual display with the sensation of presence was demonstrated by psychophysical experiments using the test hardware.

A method was also proposed to develop a mobile tele-existence system, which can be remotely driven with the auditory and visual sensation of presence. A prototype mobile televehicle system was constructed and the feasibility of the method was evaluated [6].

The principle of active power assistance was applied for controlling the visual display with two degrees of freedom [7,8].

In order to study the use of the tele-existence system in the artificially constructed environment, the visual tele-existence simulator was designed, a quasi-real-time binocular solid model robot simulator was made, and its feasibility was experimentally evaluated [9].

In the recent papers [10,11,12], the first prototype tele-existence master slave system for remote manipulation experiments was designed and developed, and a preliminary evaluation experiment of tele-existence was conducted. Impedance control method for the tele-existence master slave manipulation was developed and was applied to an experimental master slave system [13].

In this paper, the tele-existence system has been designed and developed for conducting experimental manipulation tasks, 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 [4].

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 *am* are known, a human observer can estimate the distance to the object *dobj* and the size of the object *lobj* as follows:

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

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 $\gamma = ldis/ls$. Then by arranging $am = \gamma*as$, we have the condition of Fig.2, which is the same condition as for a direct observation. Practically, *am* 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:

$am = \beta*dobj$, where $\beta = ldis/lobj$.

The focal length of the lens *fm* 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 *am*. 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 *fs* must be selected and the appropriate values for *as* 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. Mobile Tele-Existence System

A prototype system with fundamental mobile tele-existence functions has been assembled for experimentation. The system consists of an independent mobile robot with two TV cameras, a remote control station with the visual and auditory displays with a sensation of presence, and a communication link between the human operator and the mobile robot.

During routine navigation tasks, the robot travels autonomously using the environmental map and the environmental information gathered by the visual sensors (two TV cameras and an ultrasonic sensor) and internal sensors (two odometers on the rear wheels).

The navigation process can be monitored by the operator. When the robot encounters a task which the robot is not able to manage by itself, it stops and ask the operator for help. At that time the operator controls the robot using joysticks as though he were driving that robot like an automobile, i.e., as if he were on board the robot at the position where the robot TV cameras are located.

Figure 6 the prototype tele-existence mobile robot constructed, while Fig. 7 shows the head coupled stereo display with a sensation of presence.

5. Tele-Existence Master Slave System

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. Figure 8 and Fig.9 show general views of the tele-existence master slave system designed and developed. Figure 10 and Fig.11 show the revised version of the same system.

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 1 *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 in this experiment. 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 $r = 500 \sim 1500$ [*mm*] and $\theta = 0 \sim 270$ [*deg*]. The orientation of the robot is assigned by the waist rotation angle of the robot ϕ, where $\phi = -150 \sim 150$ [*deg*].

A hand mechanism of one degree of freedom, which can either pinch or grasp, has been newly designed. It is designed to be able to pinch small objects (from diameter of 2 *mm*) and rather big object (up to diameter of 114 *mm*). It uses a parallel link mechanism and ball screw. The grasping of cylindrical objects with a minimum diameter of 15 mm can be done with contact at three points as is shown in the figure. 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 heads from TV 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, and the same locational relation 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.

A human operator wears the 3D display with a sensation of presence. 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.

Revised version of 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, an optical system using polarizers and analyzers was introduced to eliminate the unnecessary reflected image caused by the internal mirror. In the new model, 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.

6. 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 hand and eye quickly as in the case of direct operation.

Figure 11 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 few 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 12 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 13 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.

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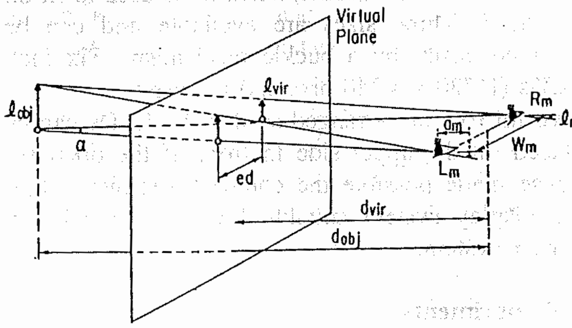

α : convergence angle
ed : equivalent disparity

Fig.1 Visual parameters of direct observation.

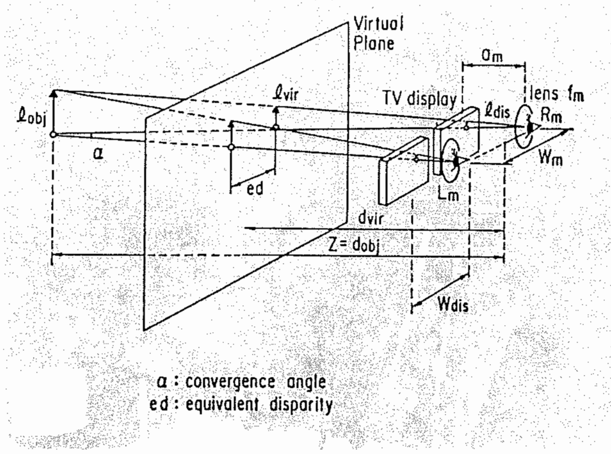

Fig.2 Visual parameters of tele-existence display.

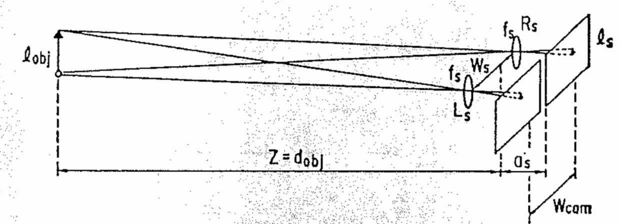

Fig.3 Visual parameters of the slave robot.

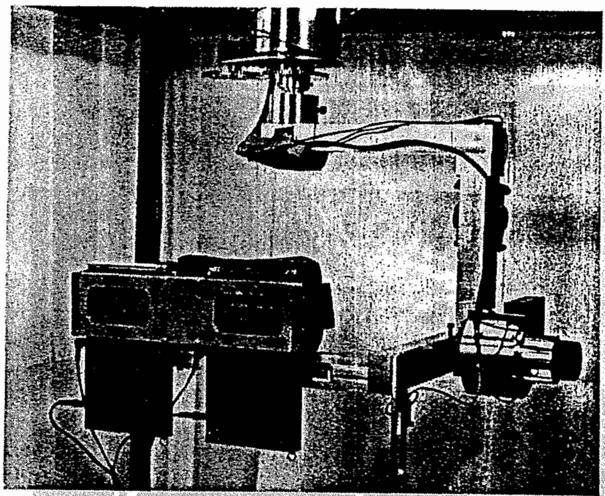

Fig.4 Impedance controlled head coupled display.

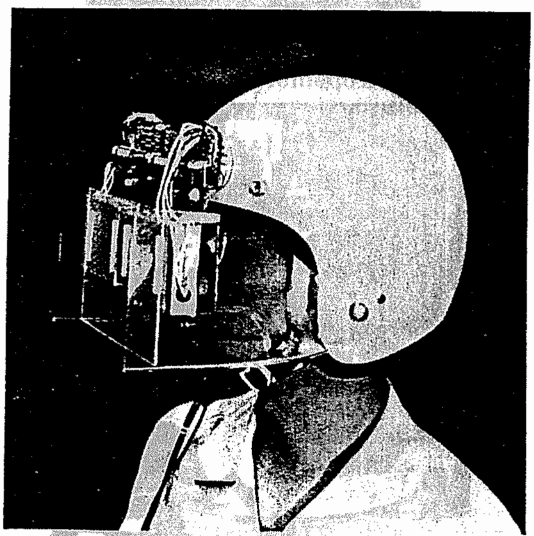

Fig.5 Head mounted stereo display.

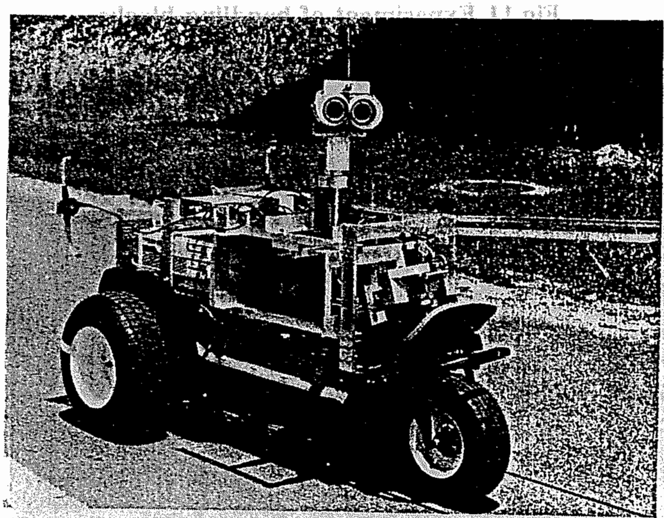

Fig.6 Prototype mobile tele-existence vehicle.

Fig.7 Control station with sensation of presence.

Fig.8 Anthropomorphic slave telerobot.

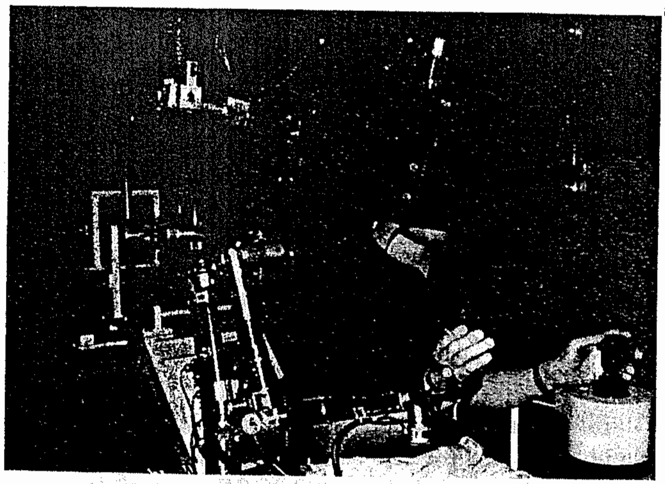

Fig.9 Master station with sensation of presence.

Fig.10 Revised local master station.

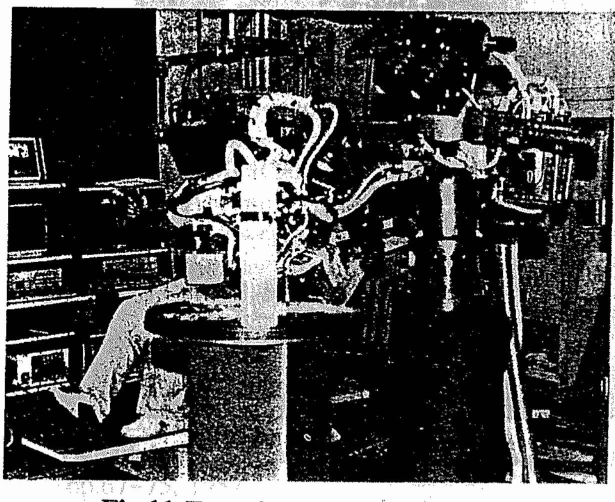

Fig.11 Experiment of handling blocks.

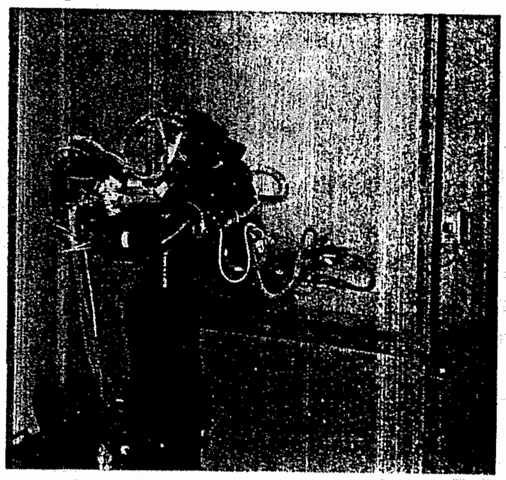

Fig.12 Experiment in hazardous environment.

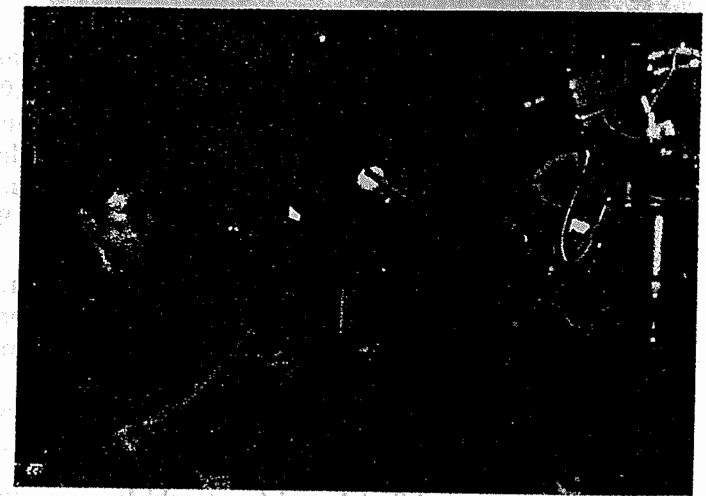

Fig.13 Human robot communication.