ROBOTIC TELE-EXISTENCE

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Abstract

Tele-existence is an advanced type of teleoperation system that enables a human operator at the controls to perform remote manipulation tasks dexterously with the feeling that he or she exists in the remote anthropomorphic robot in the remote environment. In this report the concept of the tele-existence is shown, the principle of the tele-existence display method is explained, some of the prototype systems are described, and its space application is discussed.

1. Introduction

Tele-existence aims at a natural and efficient remote control of robots by providing an operator a real time sensation of presence. It is an advanced type of teleoperation system that 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 several remote environments [1,2]. Similar concept is called artificial reality [3] or telepresence [4].

Fundamental studies for the realization of the tele-existence system are now being conducted in the authors' division of the Mechanical Engineering Laboratory (MEL) as part of the National Large Scale Project called JUPITER (JUvenescent PIoneeing TEchnology for Robots), which is a research and development program of advanced robot technology for a system that avoids the need for humans to work in potentially hazardous working environments, such as nuclear power plants, under sea, and disaster areas.

In previous papers [1,2], the principle of the tele-existence display method was proposed. Its design procedure was explicitly defined. Experimental display hardware was made, and the feasibility of the visual display with a sensation of presence was demonstrated by psychophysical experiments using the test hardware. In the latest paper [5], a method was proposed to realize a mobile tele-existence system, which can be remotely driven with the auditory and visual sensation of presence. A prototype system was constructed and the feasibility of the method was evaluated. The effectiveness of the proposed system was evaluated by navigation experiments of the mobile robot through an obstructed space. Several display and operation methods were compared quantitatively using the time elapsed, smoothness of the travelled path and the number of collisions as the criteria for comparison.

In this report the concept of the tele-existence is shown, the principle of the tele-existence display method is explained, some of the prototype systems are described including an anthropomorphic robot with seven degrees of freedom arm, which is designed and developed as a slave robot for feasibility experiments of teleoperation using tele-existence method.

2. Tele-existence

In tele-existence, an autonomous anthropomorphic robot is placed at a remote site and an information transmission communication channel is established between human and robot. The operator's movements and physical status are sensed and transmitted to the robot via this communication channel. The transmitted signals override the autonomy of the robot and directly control the robot's motor system to reproduce the exact movements of the operator in its artificial eyes, neck, hands, legs, and feet. Information picked up by the artificial sensory organs of the robot are transmitted back to the operator via the communication channel to the operator's sensory organs.

Take vision for example. Whichever direction the operator looks, the robot will look in the exact same spot. The operator will see on his retinae the image seen by the robot, in exactly the same manner as it would be seen by a human in the same position. If the operator were to bring his arm in front of his eyes, he would see the robot's arm being brought into his field of view in exactly the same relative position as his own arm. Thus the operator is able to maintain his or her visual sensation and proprioceptive sensation coherent. The operator can perform tasks via a robot at a distance yet maintain the same spacial relation among the objects, the arms and the environment as that by direct observation. Auditory and tactile sensations are also transmitted to the operator. Objects touched by the robot are also felt by the operator as tactile stimuli.

Tele-existence technology also goes beyond the scope of the human senses. Radiation, ultra-violet rays, infrared, micro waves, ultrasonic waves, and ultra low frequency sound information sensed by the robot sensors can also be utilized to augment the human operator. For example infrared information picked up by the robot sensors can be converted into visible light on the operator's display. As the display gives a realistic sensation of presence, tasks can be performed in the dark yet with the illusion that it is light. These pieces of information can also be superimposed on the visual display as three dimentional superimposition. For example, by adding distance information at the location of an object. It is also possible to display human like solid model arms instead of the mechanical robot's arms, which enhances the operator's sensation of presence.

The final version of the tele-existence system will be consisted of intelligent mobile robots, their supervisory subsystem, a remote-presence subsystem and a sensory augmentation subsystem, which allows an operator to use robot's ultrasonic, infrared and other, otherwise invisible, sensory information with the computorgraphics-generated pseudorealistic sensation of presence. In the remote-presence subsystem realistic visual, auditory, tactile, kinesthetic and vibratory displays must be realized [1].

3. Principle of Tele-Existence and Means of Realization

The basic configuration of the tele-existence system is shown in Fig. 1. Take vision as an example to explain the principle of the display which gives a sensation of presence [1].

The system is based on the principle that the world we see is reconstructed by the human brain using only two real time images on the two retinae of a human. What we get from the environment are only two-dimensional pictures on the retina changing in real time according to the movement of the eyeballs and the head. We reconstruct the three-dimensional world in the brain and project the reconstructed world to the real three-dimensional world [1].

In our new type of robotic display;
(a) human movements including a head and/or eyeballs are precisely measured in real time,
(b) robot sensors and effectors are constructed anthropomorphically in function and size,
(c) movements of the robot sensors are controlled precisely to follow the human operator's movement, and
(d) the pictures taken by the robot sensors are displayed directly to the human eyes in a manner which assures the the same visual space as is observed directly at the robot's location.

This display enables an operator to see the robot's upper extremities, which are contrlled to track in real time precisely the same movement of the operator's, instead of his/hers at the position his/her upper extremities should be.

4. Design of the Visual Display with Sensation of Presence

Essential parameters for human three dimensional 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) accomodation of the crystalline lenses. Adding to the above monochromatic parameters, fidelity in color is important for a realistic display [5].

Figure 2 (a) shows a schematic diagram of the direct 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 follow [5]:

$$dobj = Wm/2\tan(\alpha/2) \qquad (1a)$$
$$lobj = dobj*lm/am \qquad (1b)$$

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. 5, and the human observer observes the projected images by using the corresponding eyes, then the observed parameters, i.e., α 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:

$$\mathrm{dobj} = \mathrm{Wm}*\mathrm{dvir}/(\mathrm{Wm}-\mathrm{ed}) \tag{2a}$$

$$\mathrm{lobj} = \mathrm{dobj}*\mathrm{lvir}/\mathrm{dvir} \tag{2b}$$

where dvir is the distance to the virtual plane.

Figure 2(b) 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 2(c) 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) is usually ,but not necessarily, set as Wcam=Wdis=Ws, where Wdis is the distance between the two centers of the TV displays.

Under these conditions, we define a magnification factor γ = ldis/ls. Then by arranging am=γ*as, we have the condition of Fig.6, which is the same condition as for a direct observation. Practically, am can be determined by measuring the size of the image on the diplay (ldis) when monitored through the TV camera for a known size object lobj at the known distance dobj as: am = β *dobj, where β = 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 distance to 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 $< \infty$, dvir can be fixed to 1000 mm, and if 145 mm $\leq$ dobj $\leq$ 2000mm, 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, the ideal condition of the direct observation is always maintained [5]. 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.

5. Design and Control of Display Mechanisms

5.1. Master-Slave Controlled Active Display Mechanism [2]

Figure 3 shows the experimental hardware system for the evaluation study. The movement of the head of the human subject is measured in real time by the light weight goniometer with six degrees of freedom. Three translational coordinates (x,y,z) and three rotational angles (roll,pitch, yaw) are calculated by a microprocessor, and both the camera position/

orientation and the display position/orientation are servo-controlled to follow the head movement.

As the number of degrees of freedom of the allowed head movement is large, it is impossible to use the torque produced by the operator's head movement as the energy source of the movement of the display device. Even if the weight is removed by a counter balance mechanism, the inertia can not be eliminated. Therefore, it is necessary to servo-control the display device.

The active display mechanism shown in Fig. 3 has five degrees of freedom. Each degree of freedom is actuated by a direct drive torque motor (Inland Rare Earth D.D.Torque Motor). The dispaly follows the goniometer's movement like a master-slave manipulator system with the goniometer as a master and the display as a slave.

Visual displays were designed according to the procedure proposed in section 4 using two 1.5 inch color CRTs. The visual tele-existence system with these displays were experienced by several subjects. All subjects had an impression that this type of display produces very realistic feeling of remote presence. Adding to the qualitative evaluation, objective and quntitative experiments were also conducted [2].

Experiments with this hardware revealed, however, that the position/ orientation control is not enough. Subjects usually want a compliant motion which follows their head movement. Therefore, force control based on the measurement of the head movement and/or force condition becomes necessary.

5.2. Impedance Controlled Active Display Mechanism

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 can be controlled by internal feedback loop. We used direct drive motors to attain this mechanisms, and the dedicated computer controls the impedance of the display mechanisms so that the human operator feels only quite low inertia compared with the physical inertia of the system.

The dynamic equation of a system with one degree of freedom can be expressed as follows:

$$KtI + To = J\theta s^2 + Fb\theta s + Fc, \qquad (3)$$

where θ is the motor rotary angle, I is the motor current, Kt is the sensitivity of the motor torque, To is the torque caused by the manual force, J is the moment of inertia, Fb is the viscous friction coefficient, and Fc is Coulomb's friction torque.

By substituting

$$I = (\alpha J\theta s^2 + \beta Fb\theta s + \gamma Fc)/Kt, \quad (0 < \alpha, \beta, \gamma < 1) \qquad (4)$$

into equation (3), we find that

$$To = (1-\alpha)J\theta s^2 + (1-\beta)Fb\theta s + (1-\gamma)Fc, \qquad (5)$$

which exhibits the effects attainable by multiplying the inertia force, viscous friction force, and Coulomb's friction force $(1-\alpha)$, $(1-\beta)$, and $(1-\gamma)$ times as high, respectively. In other words, it is possible to redesign the motion equations of the system (or impedance of the system) into an arbitrary form through internal feedback [6,7]. An extention of the method to the multiple degrees of freedom system is shown in [6].

Figure 4(a) shows the impedance controlled display using two 3 inch color LCDs, and Fig. 4(b) shows the anthropomorphically arranged slave camera system with two degrees of freedom. When operators actually wore the display and moved it by neck force, the reaction force caused by inertia appeared to be lighter, and they reported that the difference was particularly noticeable when the display was moved swiftly. Operators felt that the system is quite similar to a passive mechanism of lighter weight.

5.3. Head Mounted Display

A Head mounted display is also a promising design approach. The merit of the head mounted 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 the head-mounted display Mk. I. It weighs 1.7 Kg, including a helmet (620 g for the display). 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(b) are mounted on a spectacles' frame. Lighter version of the head mounted display Mk. II has been made. Its total weight is 600 g.

6. Tele-Existence Experimental Systems

6.1. Mobile Tele-Existence System [5]

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 color 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 asks 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's TV cameras are located.

Figure 6(a) shows the head-linked display with a sensation of presence used in the system, while Fig. 6(b) shows the prototype tele-existence mobile robot constructed.

6.2. Tele-existence Manipulation System

Figure 7 shows a general view of the anthropomorphic slave robot with an operator wearing head-mounted display explained in Section 5.3. Figure 8 shows an operator using the impedance controlled display explained in Section 5.2. In the latter system electromagnetic sensor is used for the control of the manipulator.

The slave robot has a three degrees of freedom neck mechanism on which stereo camera is mounted. The robot's structural dimensions are set very close to those of human's, and it is controlled to follow the human movement.

The human operator's head movement is measured in real time using electromagnetic sensor and the slave robot's neck is controlled to follow the master's movement. The streo color video signals are sent to the human operator and displayed as a fused image, which keeps the distance, direction and size of the object as those of the direct observation.

7. Tele-Existence Simulator

Extension of the tele-existence to the artificially constructed environmental information has been sought, the visual tele-existence simulator has designed, pseudo-real-time binocular solid model robot simulator has been made, and its feasibility has been experimentally evaluated [8].

Two main situations for the simulator usages are:
(1) To provide the operator information of the remote environment which human senses do not work but the robot's sensors do. For example, at night infrared sensor information is converted to visible light to see an object in the dark. It is also possible to superimpose range information gathered by the robot's ultrasonic and/or laser range sensors to the three dimensional visual display. The operator can effectively use this piece of information to augment human ability.
(2) To provide totally artificial but realistic environmental information to the operator, e.g., realization of virtual terminal or virtual console for the operator [3]. The operator can enjoy variety of consoles without changing them physically. This can also be used for the simulation study for training and also for optimal parameter selection and evaluation of man-machine system. The usage of the system as scientific tools for the analysis of human visual sensation, motion control and sensor-motor coordination is also possible.

As the first step toward the goal, a solid model robot manipulator with pseudo-real-time shading capability was constructed. By using the specially designed binocular optical system, three dimensional observation, which can exactly assign the distance and the size of the manipulator and an object, became possible.

8. Space Applications

Wide variety of application of tele-existence technology to space can be conceived, including tele-observation, tele-maintenance, tele-construction, tele-experiment, and tele-experience.

In Japan the Space Robot Resarch Planning Committee for the Ministry of International Trade and Industry has been organized. In the committee a space robot which replace some of the human extravehicular activities is being planned. Tele-existence will be intensively applied for the design of the space tele-robot.

In order to apply tele-existence technology to a tele-robotic system whose slave robot is located far away and the time delay for communication can not be neglected, it is important for a slave robot to be autonomous. Foundamental study for the realization of tele-existence using autonomous robots as slaves under the circumstances is now being conducted in the authors' laboratory.

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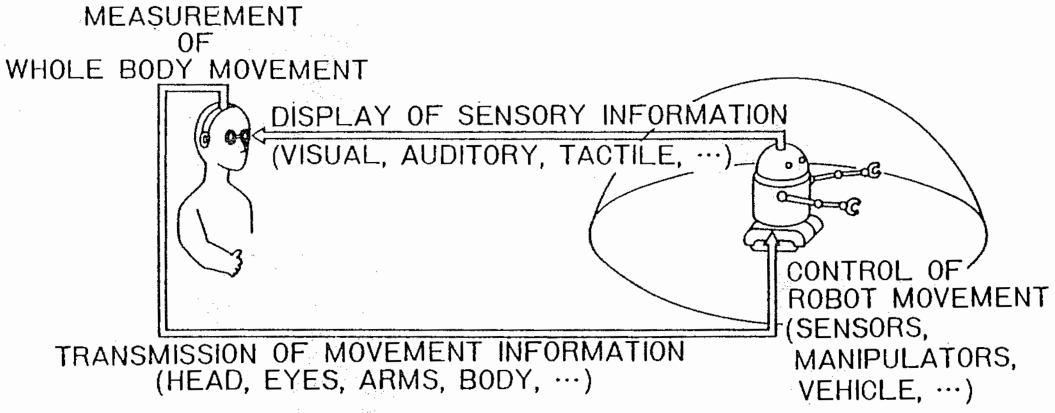

Fig. 1 Concept of the tele-existence.

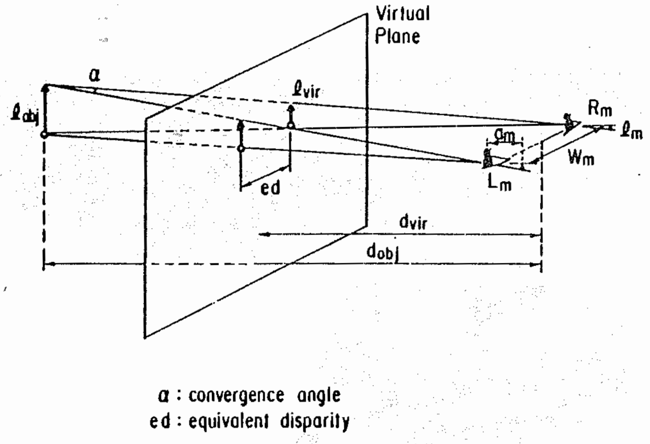

Fig. 2(a) Visual parameters of direct observation.

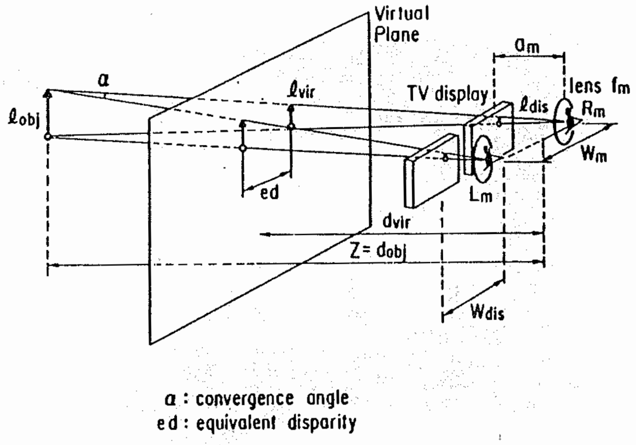

Fig. 2(b) Parameters through the display.

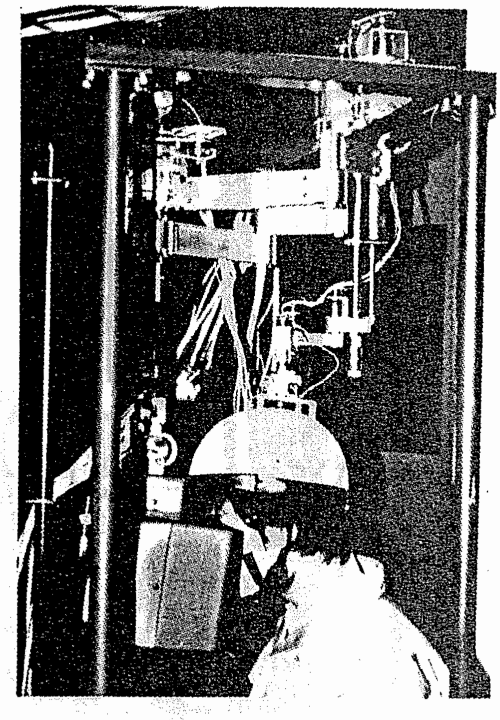

Fig. 3 Master-slave controlled active display.

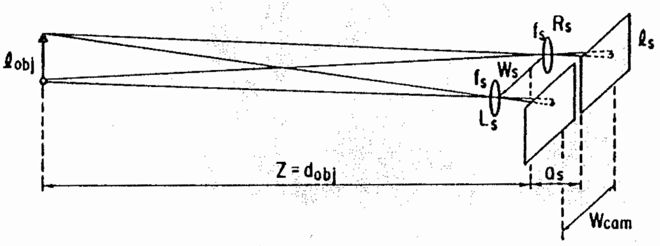

Fig. 2(c) Parameters of the slave robot.

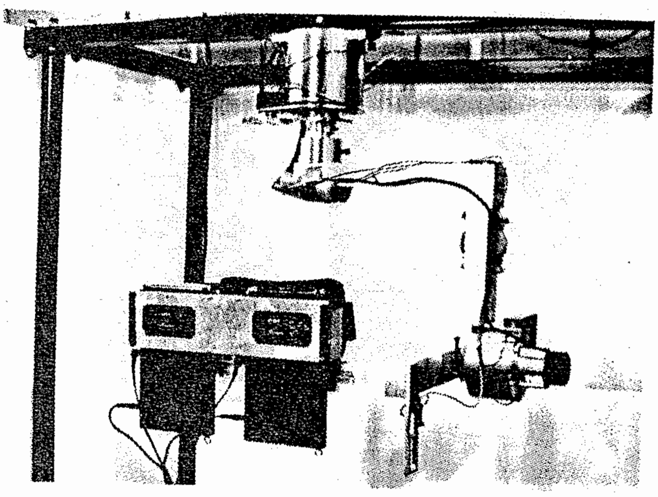

Fig. 4(a) Impedance controlled active display.

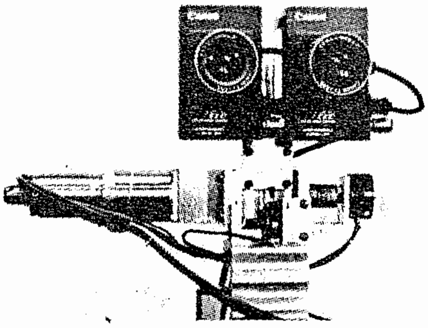

Fig. 4(b) Slave camera system.

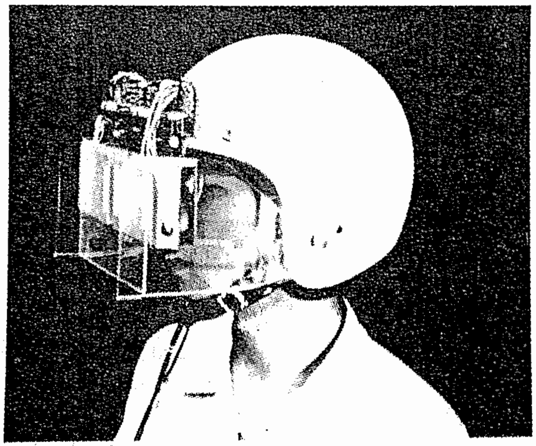

Fig. 5 Head mounted display.

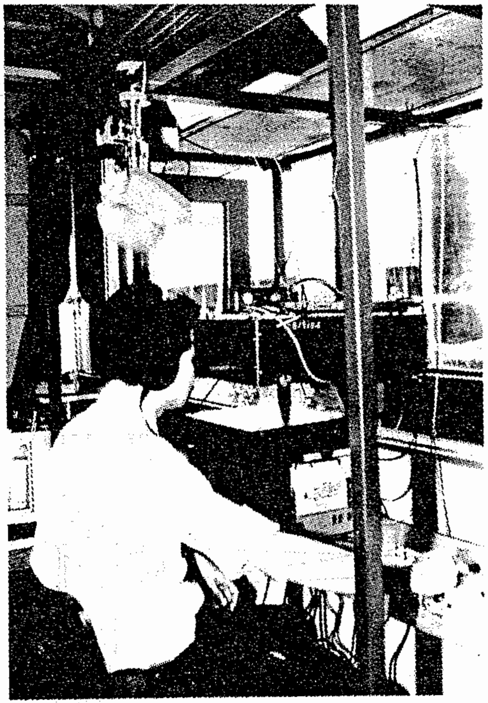

Fig. 6(a) Head-coupled display.

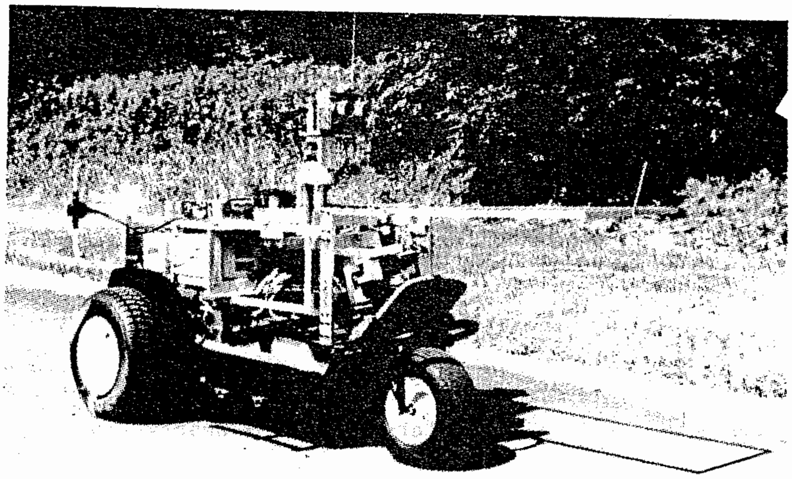

Fig. 6(b) Tele-existence mobile robot.

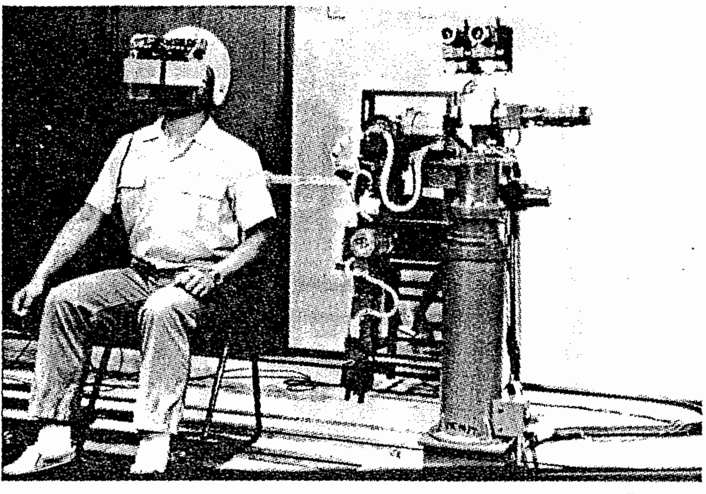

Fig. 7 Anthropomorphic slave robot.

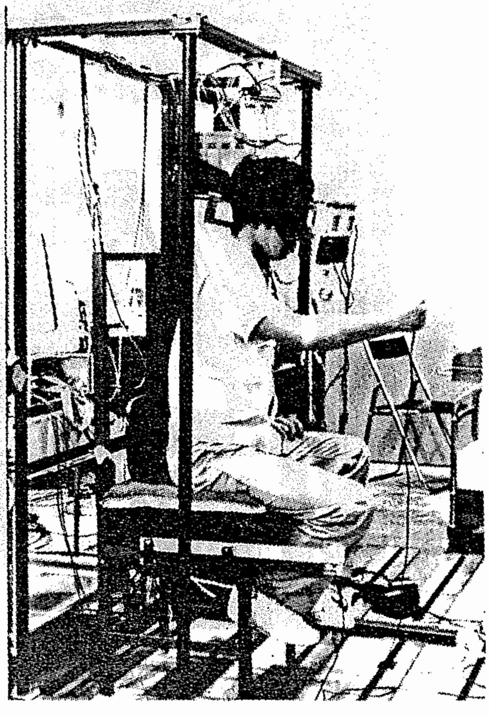

Fig. 8 Operation using impedance controlled display.