064
DEVELOPMENT OF AN ANTHROPOMORPHIC TELE-EXISTENCE SLAVE ROBOT

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ABSTRACT

In this report, an anthropomorphic robot mechanism with a seven degree of freedom arm is designed and developed as a slave robot for feasibility experiments of teleoperation using tele-existence method. It has a three degree of freedom neck mechanism on which stereo camera is mounted. The robot's structural dimensions are set very close to those of humans, and can be controlled to follow the human movement. Either an impedance controlled active display mechanism or a head mounted display is provided as the display system for an operator. The operator's arm movement is measured by an electromagnetic sensor and used for the control of the slave arm.

INTRODUCTION

Remote operation plays an important role in hostile environment such as those of nuclear, high temperature, and deep space. In spite of the efforts of many researchers, a tele-operation 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 of which is called tele-existence.

Tele-existence is a teleoperator which enables a human operator at the controls to perform remote manipulation tasks dexterously with the feeling that (s)he exists in the slave anthropomorphic robot in the remote environment.

In the previous reports [1,2], the principle of the tele-existence sensory display was proposed. Its design procedure was explicitly defined. Experimental visual display hardwares were made, and the feasibility of the visual display with the sensation of presence was demonstrated by psychophysical experiments using the test hardwares. A method was also proposed to realize a mobile tele-existence system, which can be remotely driven with the auditory and visual sensation of presence. A prototype mobile tele-vehicle system was constructed and the feasibility of the method was evaluated [3]. The principle of the active power assistance [4] was applied for controlling the visual display with one degree of freedom [5]. Extension of the tele-existence to the artificially constructed environmental information was sought, the visual tele-existence simulator was designed, pseudo-real-time binocular solid model robot simulator was made, and its feasibility was experimentally evaluated [6].

In this report, an anthropomorphic robot mechanism with a seven degree of freedom arm is designed and developed as a slave robot for feasibility experiments of teleoperation using tele-existence method. An impedance controlled active display mechanism and a head mounted display are also designed and developed as the display sub-system for the master.

TELE-EXISTENCE

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 differnt place other than the place that 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 exoskelton that a man would wear like a garment. Figure 1 shows a concept of Hardiman which was proposed by General Electric Co. It was proposed that a man wearing the Hardiman exoskeleton would be able to command a set of mechanical muscles that multiply his strength by a factor of 25, yet that in this union of man and machine he would feel object and forces almost as if he 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 possible mulfunction 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 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 [1], Telepresence [7,8], or Artificial Reality [9], and a lot of efforts has been made for the realization of the concept. This concept also provides an extension of human sensing and muscular capabilities [1,2].

Figure 2 shows a conceptual system of the tele-existence.The system consists 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 pseudo-realistic sensation of presence. In the remote-presence subsystem realistic visual, auditory, tactile, kinesthetic and vibratory displays will be realized [1].

Using this system a human operator can be in a safe and comfortable environment and at the same time be present or exists at other environment where the robots are working. He or she will monitor the work through robots sensors, and if necessary conduct the task on behalf of the robot as if he were working directly (ideally) or he were working inside the robot (practically).

The basic configuration of the tele-existence system is shown in Fig. 3. 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 controlled 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.

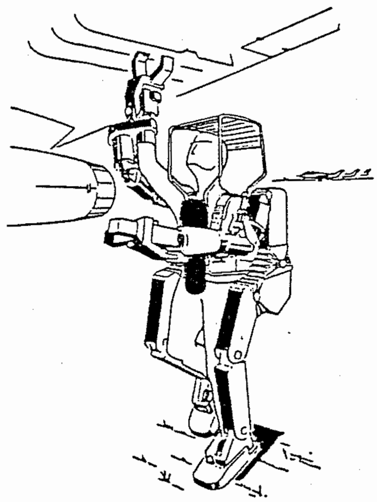

Fig. 1 Hardiman force amplifying exoskeleton proposed by General Electric [10].

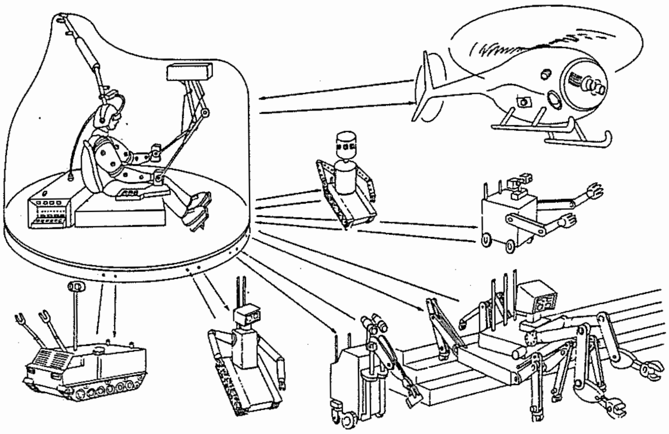

Fig. 2 Telerobotic human augmentation system using tele-existence technology.

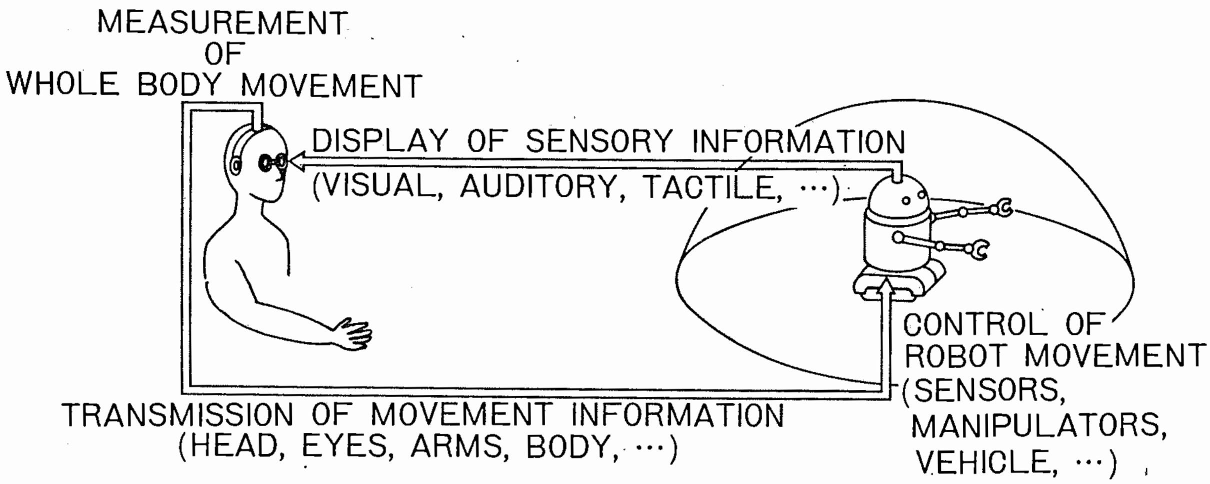

Fig. 3 Principle of Tele-existence.

TELE-EXISTENCE ANTHROPOMORPHIC SLAVE ROBOT

Figure 4 shows a general view of the anthropomorphic slave robot designed and developed. The slave robot has a three degrees of freedom neck mechanism on which 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 human's, and it is controlled to follow the human movement.

The weight of the robot is 60 kg, and the arm can carry 1 kg load at the maximum speed of 3 m/s. The precision of position control of the wrist is ± 1 mm.

The dimension and arrangement of the degree of freedom of the robot are designed to mimic those of the human's. Figure 5 shows the structure and dimensions of the robot. All three axes of the neck rotations meet at one point 50 mm above and 245 mm apart from the point where all three axes of the shoulder rotations meet. The two axes of the wrist and the two axes of the elbow are also designed to meet at one point, respectively.

Table 1 shows the maximum range and maximum speed of the each degree of freedom. The range is set so that it will cover the human movement, while the speed is set to catch up the moderate motion of human (3 m/s at the wrist position).

Combination of a D.C. servo motor and a harmonic drive is used as an actuator for each joint except the elbow extension/flextion, which includes conventional gears. The location of the motors are designed so that the appearance of the arm resembles a human arm as close as possible and the range and the speed of the manipulator satisfy the necessary set specification.

The model based control method of the type in which the model-based portion of the control law is outside the servo loop is used in this experiment.

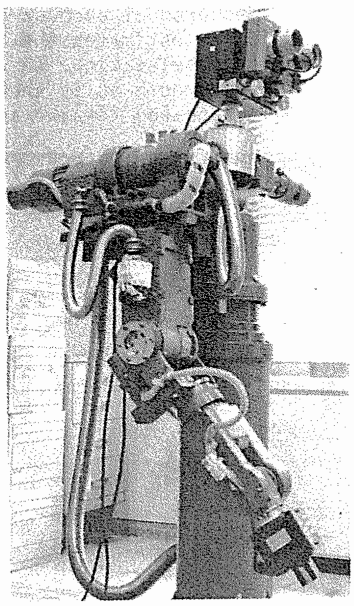

Fig. 4 General view of the anthropomorphic slave robot.

Six degrees of freedom out of the possible seven degrees of freedom (excluding B4) were controlled in this preliminary experiment.

The dynamic equation of motion of the manipulator is expressed as follows:

$$\tau = JA(\theta) + V(\theta,\dot{\theta}) + g(\theta) + F(\theta,\dot{\theta}), \quad (1)$$

where $JA(\theta)$ is the 6 x 6 inertia matrix of the manipulator, $V(\theta,\dot{\theta})$ is a 6 x 1 vector of centrifugal and Coriolis terms, $g(\theta)$ is a 6 x 1 vector of gravity terms, and $F(\theta,\theta)$ is a 6 x 1 vector of friction terms.

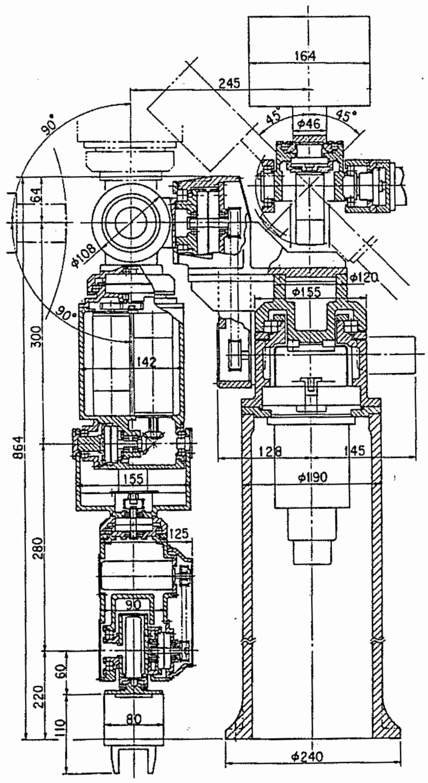

Fig. 5 Dimensions of the slave robot.

		RANGE [deg]	SPEED [deg/s]
WRIST	T_1	300(±150)	330
	B_1	300(±150)	205
ELBOW	T_2	300(±150)	150
	B_2	135(135, -0)	145
SHOULDER	T_3	300(±150)	145
	B_3	180(± 90)	150
	B_4	360(±180)	120
NECK	B_5	120(+90, -30)	240
	B_6	90(± 45)	240
	T_4	300(±150)	360
WAIST	T_5	300(±150)	180

Tab. 1 Maximum range and speed of each joint.

The following servo law is used:

$$\tau = J_A(\theta)\ddot{\theta}_d + V(\theta,\dot{\theta}) + g(\theta) + F(\theta,\dot{\theta}) + K_v\dot{E} + K_pE,$$

where $E = \theta_d - \theta$. (2)

The error equation of the system is:

$$\ddot{E} + J_A^{-1}(\theta)K_v\dot{E} + J_A^{-1}(\theta)K_pE = 0. \quad (3)$$

Actual servo system is shown in Fig. 6. The computer generates a pulse sequence to assign the desired position, and the position control is conducted by counting the differnce between the computer generated pulse and the measured pulse from an encoder. Angular velocity is estimated by using a frequenncy-voltage converter. Feedforward compensation is done by compensation filter shown in Fig. 6.

TELE-EXISTENCE MASTER SYSTEM

Impedance Controlled Active Display Mechanism

Figure 7 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. Gravitational compensation is made using a counter balance mechanism shown in Fig. 7.

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

$$K_tI + T_o = J\theta s^2 + F_b\theta s + F_c, \quad (4)$$

where θ is the motor rotary angle, I is the motor current, K_t is the sensitivity of the motor torque, T_o is the torque caused by the manual force, J is the moment of inertia, F_b is the viscous friction coefficient, and F_c is Coulomb's friction torque.

By substituting

$$I = (\alpha J\theta s^2 + \beta F_b\theta s + \gamma F_c)/K_t,$$

$$(0<\alpha, \beta, \gamma<1), \quad (5)$$

into equation (4), we find that

$$T_o = (1-\alpha)J\theta s^2 + (1-\beta)F_b\theta s + (1-\gamma)F_c, \quad (6)$$

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 [4,5]. An extention of the method to the multiple degrees of freedom system is shown in [4].

The equation of motion for the display with two degrees of freedom can be described as follows neglecting the friction term:

$$\tau_{mi}+\tau_{oi}=\sum_{j=1}^{2}J_{ij}(\theta)\ddot{\theta}_j+\sum_{j=1}^{2}\sum_{k=1}^{2}D_{ijk}(\theta)\dot{\theta}_j\dot{\theta}_k \quad (7)$$

where τ_{mi} is the motor torque of the i-th joint, τ_{oi} is the torque caused by the manual force, $J_{ij}(\theta)$ is the inertia matrix and $D_{ijk}(\theta)$ is coefficient matrix for centrifugal and Coriolis terms.

If we apply motor torque as the following equation,

$$\tau_{mi}=\alpha\{\sum_{j=1}^{2}J_{ij}(\theta)\ddot{\theta}_j+\sum_{j=1}^{2}\sum_{k=1}^{2}D_{ijk}(\theta)\dot{\theta}_j\dot{\theta}_k\} \quad (8)$$

$$(0<\alpha<1)$$

the effect of reduction of apparent inertia by $(1-\alpha)$ is obtained.

Estimation of Angular Velocity and Acceleration

In order to calculate the right hand side of the equation (8) in real time, it is necessary to estimate the angular position, angular velocity and angular acceleration of each joint in real time. Position was measured by counting pulses using an encoder (8,000 pulses/revolution). An Example of the measurement is shown in Fig. 8 (a).

Angular velocity was estimated by counting the interval between pulses. A clock of 500 kHz was used and 12 bit counter counts the interval. The reciprocal of the interval multiplied by the rotational angle for one pulse interval was used as the estimated value. The drawback of this method is that the last estimated value will be kept put out when the motor stops or rotates at extremely low speed. In order to solve the problem the last estimated value was reduced exponentially when no pulse was measured at each sampling time. Digital low pass filter estimates the angular velocity and angular acceleration. This makes the estimated value quite smooth as is shown in Fig. 8 (b) for the velocity and (c) for the acceleration.

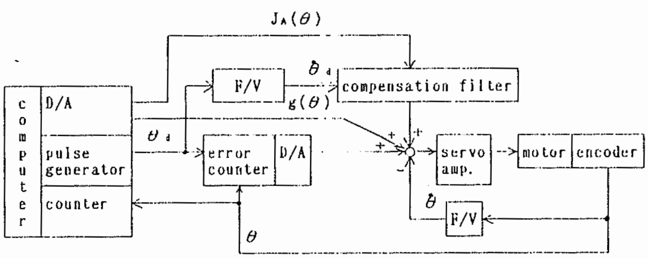

Fig. 6 Schematic diagram of the controller.

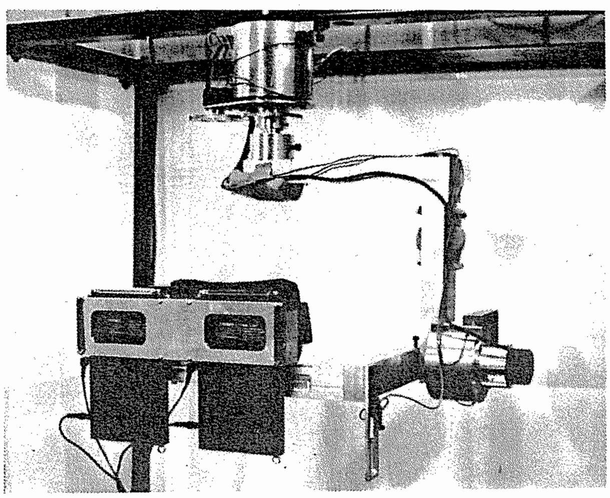

Fig. 7 Impedance controlled display mechanism.

Visual Display Design

Visual display with a sensation of presence was designed and constructed following the design procedure which assures the three dimensional view which maintains the same spatial relation as by direct observation [2,3]. The display shown in Fig. 7 used two 3 inch color LCDs.

Measurement of Human Arm Movement

The posture measurement subsystem measures the operator's wrist position and orientation in real time (60 Hz) using electromagnetic sensor (3SPACE TRACKER). This consists of a 3-axis field source and a similarly constructed 3-axis field sensor (Fig. 9). The field source's three orthogonal axes are sequentially excited with a 10 kHz carrier, which produces three coresponding orthogonal AC magnetic fields. Signals that carry the information on the location and orientation of the sensor relative to the source are induced in the three axes of the sensor which is placed in the magnetic fields. The sensor outputs are filtered, synchronously detected and digitized to produce nine measurements. The computer processes these measurements to determine the three position coordinates and three directional cosines of the sensor relative to the source. Positional accuracy is 2.5 mm and angular accuracy is 0.5 degrees in ± 1.5 m cubic measurement field.

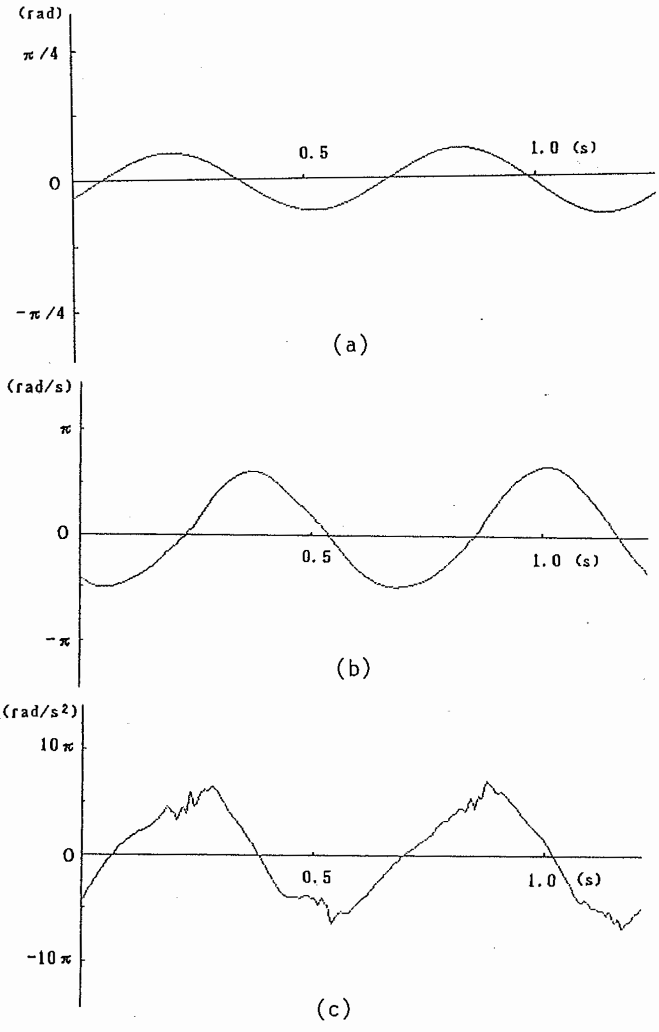

Fig. 8 Estimated rotational angle (a), angular velocity (b), and angular acceleration (c).

Preliminary Experiments

Figure 10 shows a general view of the preliminary experiments using the tele-existence manipulation sysytem.

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.

When operators operated the tele-existence manipulation system, they felt a sensation of presence with a coherent sensation between visual and kinesthetic information. This is mainly due to the fact that they saw the slave manipulator at the position where their arms should be located.

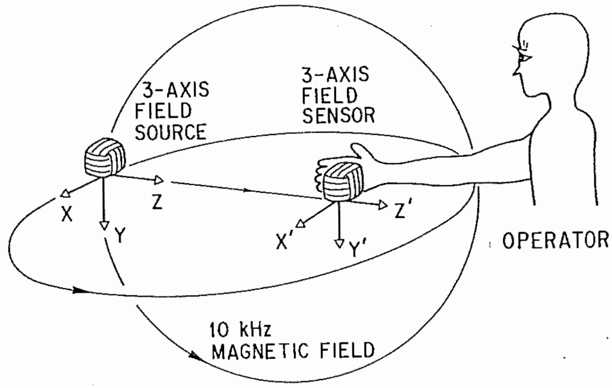

Fig. 9 Schematic diagram of the electromagnetic sensor.

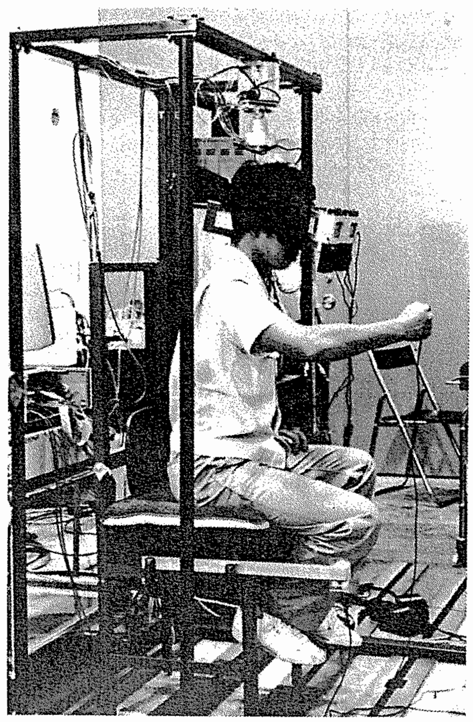

Fig. 10 General view of an operator at the control.

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 11 (a) 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 coordination with crystalline lenses are mounted on a spectacles' frame. Lighter version of the head mounted display Mk. II has been made. Its total weight is 600 g.

Figure 11 (b) shows the preliminary experiments with the head mounted display. The electromagnetic posture sensor is used for the measurement of the head position and orientation.

CONCLUSIONS

An anthropomorphic slave robot was constructed for the feasibility study of tele-existence manipulation system. It has a three degree of freedom neck mechanism on which stereo camera is mounted, a manipulator with seven degrees of freedom, a gripper, and a torso mechanism with one degree of freedom.

The operator's arm movement was measured as its wrist position and orientation (six coordinates values) by using electromagnetic sensor. The slave manipulator was controlled to follow the master's motion by considering the dynamics of the manipulator.

Two types of the display with a real time sensation of presence were constructed, i.e., the impedance controlled display and the head mounted display.

Preliminary experiments showed that operators were able to have a coherent sensation between visual and kinesthetic information, because they saw the slave manipulator at the position where their arms should be. Quantitative and systematic experiments are being planned to elucidate this effect.

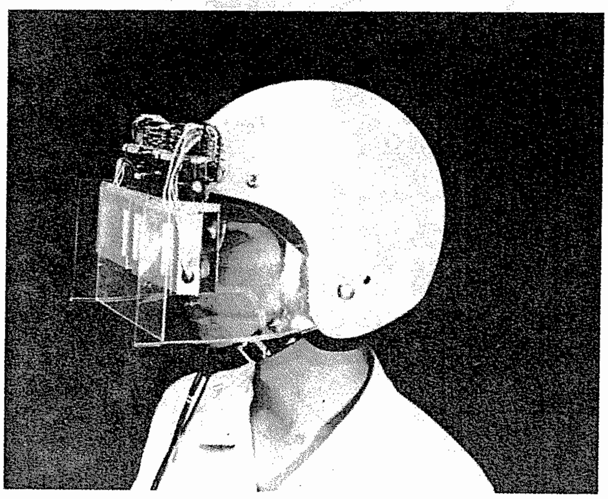

Fig. 11(a) Head-mounted display Mark-I.

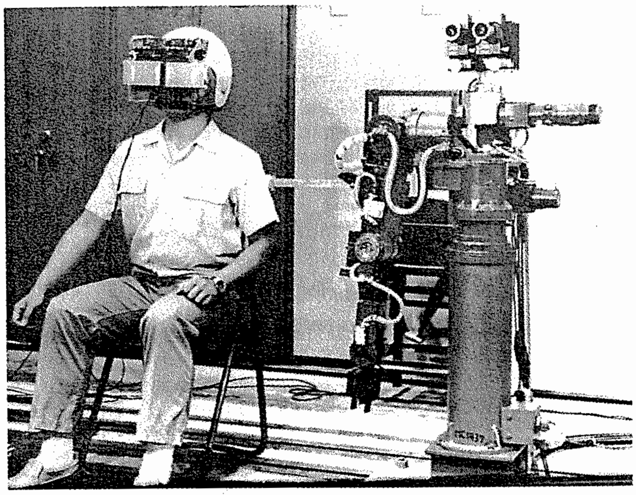

Fig. 11(b) General view of the experiments using the head-mounted display.

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