Tele-Existence in Real World and Virtual World

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Abstract - Tele-existence 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 is, and is 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 generates. It is possible to tele-exist in a combined environment of real and virtual. According to the concept, an experimental tele-existence system in real and/or virtual environment is designed and developed, and an evaluation experiment of a tele-existence system is conducted and efficacy of the tele-existence system is verified and the superiority of the tele-existence method is demonstrated through several experimental tasks.

I. Introduction

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 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 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 [1-6] in Japan and telepresence [7-9] in the United States.

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 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 [2]. The principle of active power assistance was applied for controlling the visual display with two degrees of freedom [3,4]. 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 [5].

In the recent paper [6], 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.

In this paper, 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.

II. 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 different 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 exoskeleton that a man would wear as a garment, typical example of which was the Hardiman proposed by General Electric Co. It was proposed that a man wearing the Hardiman exsoskeleton would be able to command a set of mechanical muscle that multiply his strength by a factor of 25, yet that in this union of man and machine he would feel object and force 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 exsoskeleton when we consider the possible malfunction of the machine.

(2) Space inside the machine is quite valuable to store computers, 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 dream. The concept of projecting ourselves by using robots, computers and cybernetic interface is called Tele-Existence, Telepresence.

The final version of tele-existence system will be consisted of intelligent 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 computer-generated quasi realistic sensation of presence. In the remote-presence subsystem, realistic visual, auditory, tactile, kinesthetic display must be realized [1].

Using this system, a human operator can be in a safe and comfortable place and at the same time be present or exist 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.A. 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 movement 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 to to follow precisely to the human operator's movement, and (d) the picture taken by the robots sensors are displayed directly to the human eyes in a manner which assures the same visual space as is observed directly at the robot's location.

The display enables the 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 where his/her upper extremities should be.

III. Tele-Existence Master Slave System

Figure 1 shows the schematic diagram of the tele-existence master slave manipulation 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.

A. Slave Anthropomorphic 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 [4].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.

B. Master System with a Sensation of Presence

Figure 2 shows a general view of the tele-existence master system. A human operator wears a stereo audio visual 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 (up/down: -500 ~ 400 mm; right/left: -300 ~ 300 mm; forward/ backward: -300 ~ 800 mm). 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.

Stereo visual display is redesigned according to the developed procedure which assures that the three dimensional view will maintain the same spatial relation as by direct observation [1,2]. 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[6]. 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.

C. Impedance Control of the System

Let $X_s \in \Re^6$ and $X_m \in \Re^6$ define the positions and orientations of the slave manipulator and master manipulator in Cartesian space, respectively, and $\theta_s \in \Re^7$ and $\theta_m \in \Re^7$ be the vectors of joint coordinates of the slave and the master, respectively. The relationship betweeen the operation coordinates X_s and X_m and joint coordinates θs and θm is

$X_s = f_s(\theta_s)$; $X_m = f_m(\theta_s)$

or

$\dot{X}_s = J_s(\theta_s)\,\dot{\theta}_s$; $\dot{X}_m = J_m(\theta_m)\dot{\theta}_m$

where fs and fm ($\Re^7 \rightarrow \Re^6$) represent the forward kinematics of the slave manipulator and that of the master manipulator, respectively, and $J_s = \partial f_s/\partial\theta_s \in \Re^{6x7}$ and $J_m = \partial f_m/\partial\theta_m \in \Re^{6x7}$ are Jacobian matrices of the slave and master manipulators, respectively . The position and orientation of the slave manipulator is controlled by the position control method with the impedance information supplied as the modified reference position. The computer generates a pulse sequence to assign the desired position (master position modified by the impedance control law), and the position control is conducted by counting the difference between the computer generated pulse and the measured pulse from an encoder. Angular velocity is estimated by using a frequency-voltage converter.

A desirable behavior for the slave manipulator is to realize the dynamics of the Cartesian mass-spring-damper system described as the mechanical impedance as follows:

$F = M\ddot{e} + B\dot{e} + Ke$

where M, B, K $\in \Re^{6x6}$ are the positive-definite diagonal matrices representing desired mass, damping, and stiffness, respectively, F is the applied force/moment vector, and $e = X_s - X_m$. Parameters M, B, and K are selected to show the desirable contact behavior , i.e. small mass, compliant and stable.

In order to attain this dynamics, the following reference signal $(\theta_s)_k$ is applied to the slave manipulator at each discrete time of k (cycle time is τ). First the desired impedance behavior is approximated by the difference equation, and using the estimated applied forces and moments measured by the force/torque sensor installed at the wrist of the slave manipulator, the desired difference between the slave position and master position at the time of k , i.e., e_k, can be estimated as follows:

$e_k = C_1 e_{k-1} + C_2 e_{k-2} + C_3 F$

where $e_k = (X_s)_k - (X_m)_k$,

$C_1 = C_4\,(2M + \tau B)$,

$C_2 = -C_4\,M$,

$C_3 = \tau^2 C_4$,

$C_4 = (M + \tau B + \tau^2 K)^{-1}$

Under the supposition that the desired difference between the master and the slave is quite small, we will assume that the following equation holds:

$e_k = J_m\,\Delta\theta_k$

where $\Delta\theta_k$ is the desired difference between the master and the slave in joint space.

Using the pseudo-inverse of the Jacobian matrix, J_m^+, $\Delta\theta_k$ is calculated:

$\Delta\theta_k = J_m^+\,e_k$

where $J_m^+ = J_m^T\,(J_m J_m^T)^{-1}$

The reference signal for the position control of the slave manipulator is calculated as follows and applied to the slave arm joint position control circuit.

$(\theta_s)_k = (\theta_m)_k + \Delta\theta_k$

In the experiment the following impedance is set for three translational direction (x,y,z). For the orientational directions, impedance is set so that the $\Delta\theta_k = 0$ to attain the conventional position control.

$$M = \begin{bmatrix} 6 & 0 & 0 \\ 0 & 6 & 0 \\ 0 & 0 & 6 \end{bmatrix} \text{ kg},$$

$$B = \begin{bmatrix} 100 & 0 & 0 \\ 0 & 100 & 0 \\ 0 & 0 & 100 \end{bmatrix} \text{ N·s/m},$$

$$K = \begin{bmatrix} 50 & 0 & 0 \\ 0 & 50 & 0 \\ 0 & 0 & 50 \end{bmatrix} \text{ N/m}.$$

The cycle time of the master slave manipulation control, τ, is about 3 ms by using

33 MHz-386 processor with 387 co-processor. C language is used for the programming of the control.

IV. 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 3 shows a general view of an experimental manipulation task of inserting a bar into the targets randomly placed on against a natural background under natural lighting condition. Bar insertion 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 a minute 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 4 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 5 shows an example of human robot communication. The robot presents an egg to a lady on behalf of a person at the control.

V. Conclusion

By conducting these experiments, the feasibility of the proposed concept of tele-existence in the real world and virtual worlds was experimentally verified. The efficacy of the tele-existence master slave system was also verified and the superiority of the tele-existence method was experimentally demonstrated.

References

[1]S.Tachi et al.,"Tele-existence (I) -Design and evaluation of a visual display with sensation of presence-," Proceedings of the 5th Symposium on Theory and Practice of Robots and Manipulators (RoManSy 84), pp.245-254, CISM-IFToMM, Udine, Italy, June 1984.

[2]S.Tachi, H.Arai, I.Morimoto and G.Seet,"Feasibility experiments on a mobile tele-existence system,"The International Symposium and Exposition on Robots (19th ISIR), Sydney, Australia, November 1988.

[3]H.Arai, S.Tachi and I.Miyazima, Development of a power-assisted head-coupled display system using a direct-drive motor," Advanced Robotics, vol.3, no.2, pp.123-130, 1989.

[4]S.Tachi, H.Arai and T.Maeda, "Development of an Anthropomorphic tele-existence slave robot, "Proceedings of the International Conference on Advanced Mechatronics (ICAM), pp.385-390, Tokyo, Japan, May 1989.

[5]S.Tachi, H.Arai and T.Maeda, "Tele-existence simulator with artificial reality (1), -Design and evaluation of a binocular visual display using solid models -," Proceedings of the IEEE International Workshop on Intelligent Robots and Systems (IROS'88), pp.719-724, 1988.

[6]S.Tachi, H.Arai and T.Maeda,"Tele-Existence Master Slave System for Remote Manipulation," IEEE International Workshop on Intelligent Robots and Systems (IROS'90), pp.343-348, 1990.

[7]J.D.Hightower, E.H.Spain et al., "Telepresence: A hybrid approach to high-performance robots," Proceedings of the '87 International Conference on Advanced Robotics (ICAR), pp.563-573, Versailles, France, October 1987.

[8]L.Stark et al.,"Telerobotics: Display, Control, and Communication Problems," IEEE Journal of Robotics and Automation, vol.RA 3, no.1, pp.67-75 ,1987.

[9]S.S.Fisher et al., "Virtual environment display system," ACM 1986 Workshop on Interactive 3D Graphics, pp.1-11, Chapel Hill, North Carolina, October 1986.

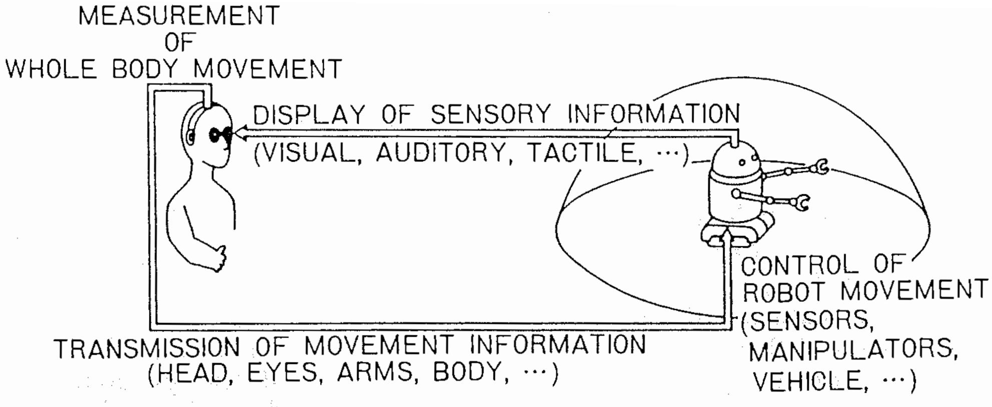

Fig.1 Concept of Tele-Existence.

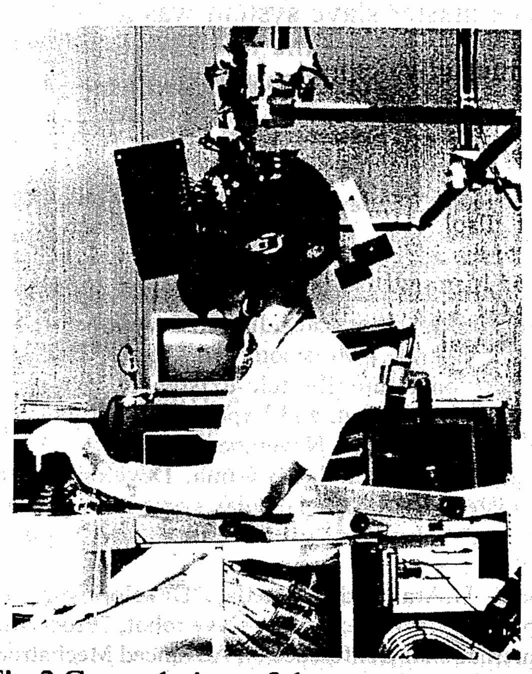

Fig.2 General view of the master system .

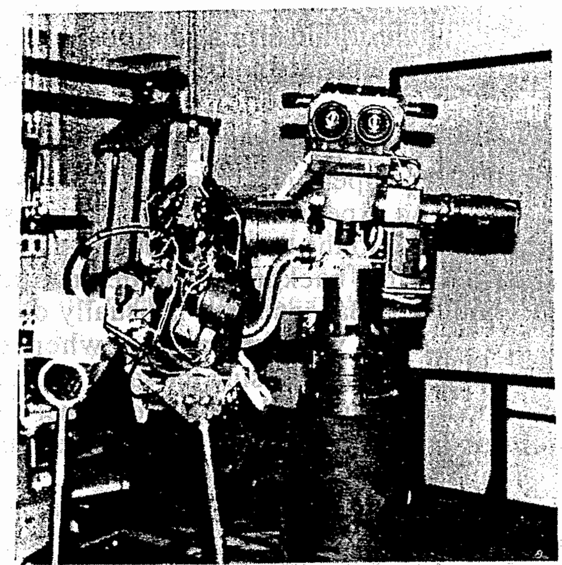

Fig.3 Experiment of inserting bars into targets.

Fig.4 Experiment in hazardous environment.

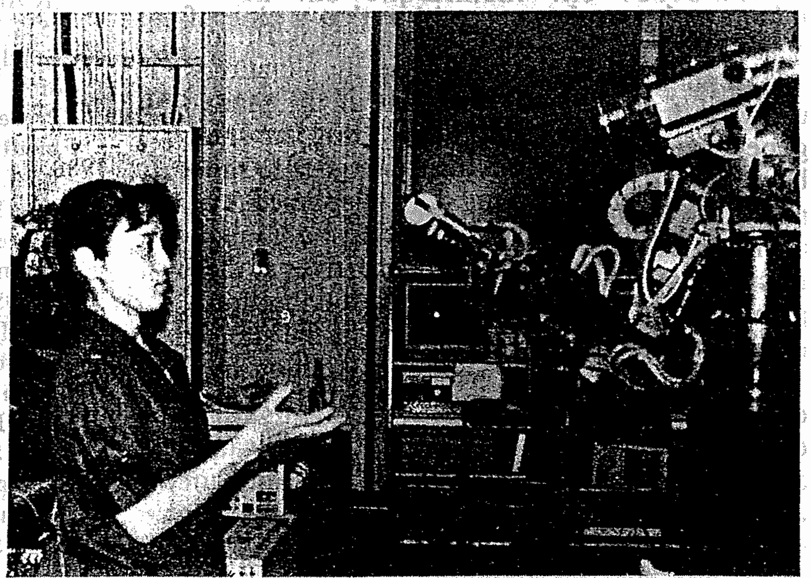

Fig.5 Human robot communication.