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Evaluation Experiments of a Teleexistence Manipulation System

Abstract

A teleexistence manipulation system was evaluated quantitatively by comparing tasks of tracking a randomly moving target under several operational conditions. The effects of various characteristics, e.g., binocular vision and the effect of natural arrangement of the head and the arm, are analyzed by comparing quantitatively the results under these operational conditions. A human tracking transfer function was measured and used for comparison. The results revealed the significant dominance of the binocular vision with natural arrangement of the head and arm, which is the most important characteristic of teleexistence.

1 Introduction

Teleexistence 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 that enables a human operator 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 authors have been working on research to improve teleoperation by feeding back rich sensory information, which the remote robot has acquired, to the operator with a sensation of presence. This concept was born independently both in Japan and in the United States, and is dubbed teleexistence (Tachi & Abe, 1982: Tachi, Tanie, Komoriya, & Kaneko, 1984) in Japan and telepresence (Akin, Minsky, Thiel, & Kurtzman, 1983; Pepper, Cole, & Spain, 1983; Hightower, Spain, & Bowles, 1987; Stark, Kim, Tendick, Hannaford, Ellis, et al., 1987) or virtual environment (Schmandt, 1983; Brooks, 1986; Fisher, McGreevy, Humpheries, & Robinett, 1986) in the United States. Origins of the concept could be dated back to the 1960s, and pioneering research includes a head-mounted three-dimensional display (Sutherland, 1968) and a mobility aid simulator (Mann, 1965).

In our first reports (Tachi & Abe, 1982; Tachi et al., 1984), the principle of the teleexistence sensory display was proposed, and 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 teleexistence 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 (Tachi, Arai, Morimoto, & Seet, 1988). To study the use of the teleexistence

Presence, *Vol. 3, No. 1, Winter 1994*, 35–44

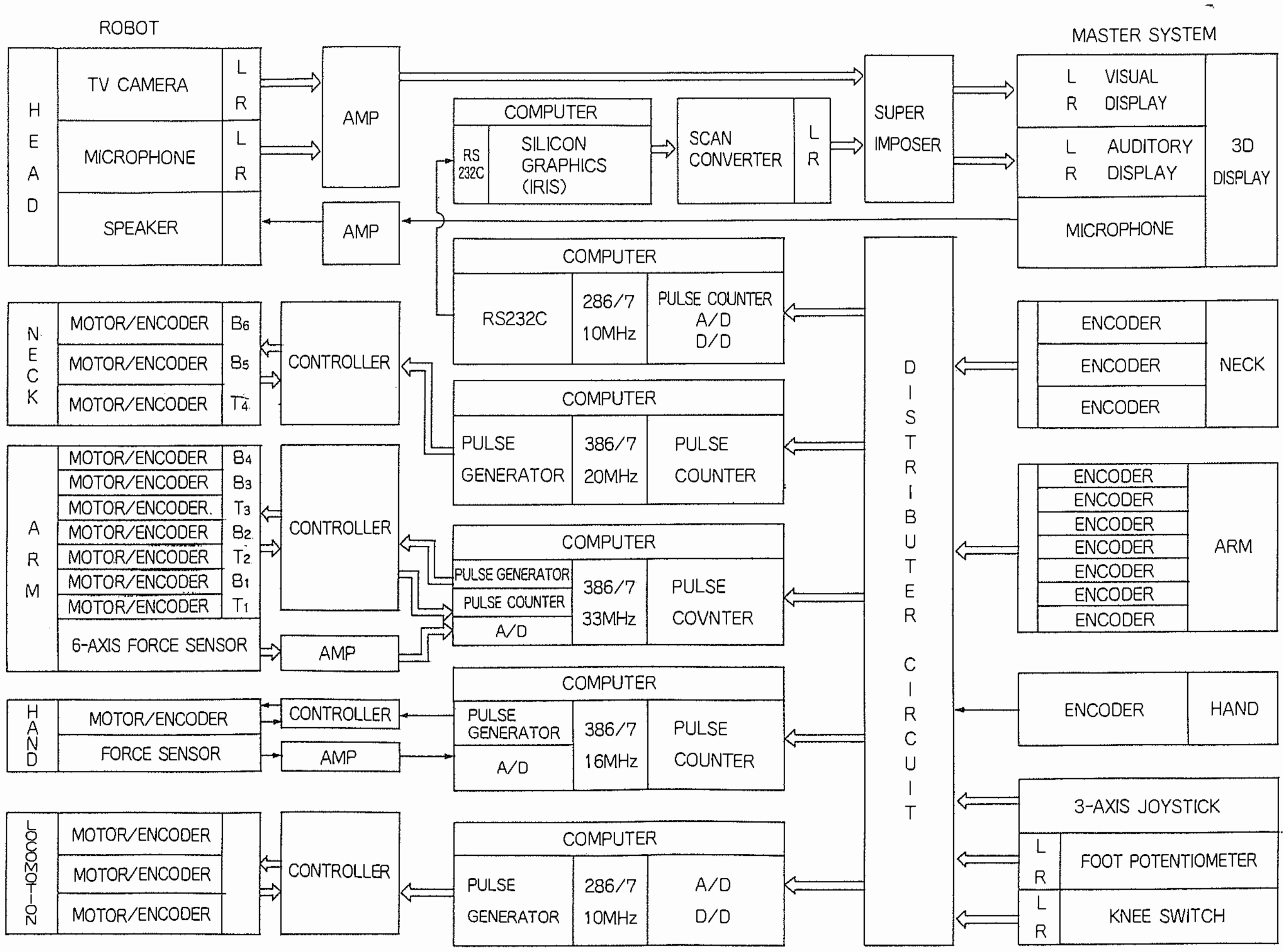

Figure 1. *Block diagram of the teleexistence master–slave system.*

system in the artificially constructed environment, the visual teleexistence simulator was designed, a quasi-real-time binocular solid model robot simulator was made, and its feasibility was experimentally evaluated (Tachi, Arai, & Maeda, 1988).

In the recent papers (Tachi, Arai, & Maeda, 1989, 1990), the first prototype teleexistence master–slave system for remote manipulation experiments was designed and developed, and a preliminary evaluation experiment of teleexistence was conducted. An experimental teleexistence system for real and/or virtual environments was designed and developed, and by conducting an experiment comparing a teleexistence master–slave system with a conventional master–slave system, efficacy of the teleexistence master–slave system and the superiority of the teleexistence method was demonstrated experimentally (Tachi et al., 1991).

In this paper, quantitative evaluation of the teleexistence manipulation system is conducted through tracking tasks by using a teleexistence master–slave system.

2 Teleexistence Master–Slave System

Figure 1 shows a schematic diagram of the teleexistence master–slave manipulation system. The teleexistence master–slave system consists of a master system with a head-coupled three-dimensional visual and audi-

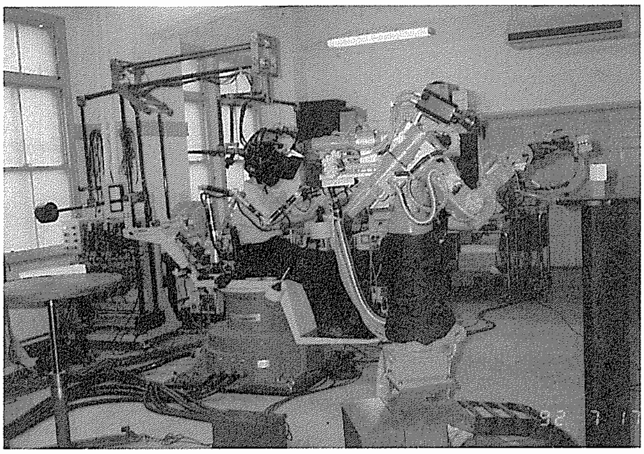

Figure 2. *General view of the teleexistence master–slave manipulation system.*

tory display and a master manipulator, computer control system, and an anthropomorphic slave robot mechanism with an arm having seven degrees of freedom, a gripper hand, and a locomotion mechanism.

A human operator is seen wearing a 3D audio visual display that is designed to ensure the same distance and size cues as of direct observation at the place where the robot exists (Fig. 2). The audio visual display is carried by a link mechanism with six degrees of freedom. The link mechanism cancels all gravitational force through a counterbalancing mechanism, which allows the operator's unconstrained movement in a relatively wide range of operation space (up/down: $-500 \sim 400$ mm; right/left: $-300 \sim 300$ mm; forward/backward: $-300 \sim 800$ mm). It also enables the display to follow the operator's head movement precisely enough to permit ordinary head movement. As for the rotational movement, the mechanism is designed so that the three axes of the rotations meet at one point. A parallel link mechanism is also used to attain the roll motion and also for the load bearing. The arrangement of the degrees of freedom is made such that the most important yaw motion (pan) is available at any orientation. The maximum inertial force applied to the operator remains within 5 kgf (Fig. 3).

The master arm has 10 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 operator's head movement, right arm movement, right hand movement, and other auxiliary motion (including a joy stick operation and 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 computers. There are four computers (Intel 286/386) that generate the command position of the slave head movement, the arm movement, hand movement, and locomotion of the slave robot, respectively. All programs were written in C language and run under MS-DOS, and the program sizes are 11572, 76983, 22611, and 86375 bytes, respectively. Calculation at each computer is synchronized by the motion of the human operator through the master system so that all computers are automatically coordinated.

The servo controller controls the movement of the slave anthropomorphic robot. The slave robot has a locomotion mechanism and a hand mechanism. The robot also has three degrees of freedom in the 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 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/sec at the wrist position). The weight of the robot is 60 kg, and the arm can carry a 1 kg load at a maximum speed of 3 m/sec. The precision of position control of the wrist is ± 1 mm. 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, which is used to control the mechanical impedance of the robot's arm to the compliant predetermined value.

The robot is moved by 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 ro-

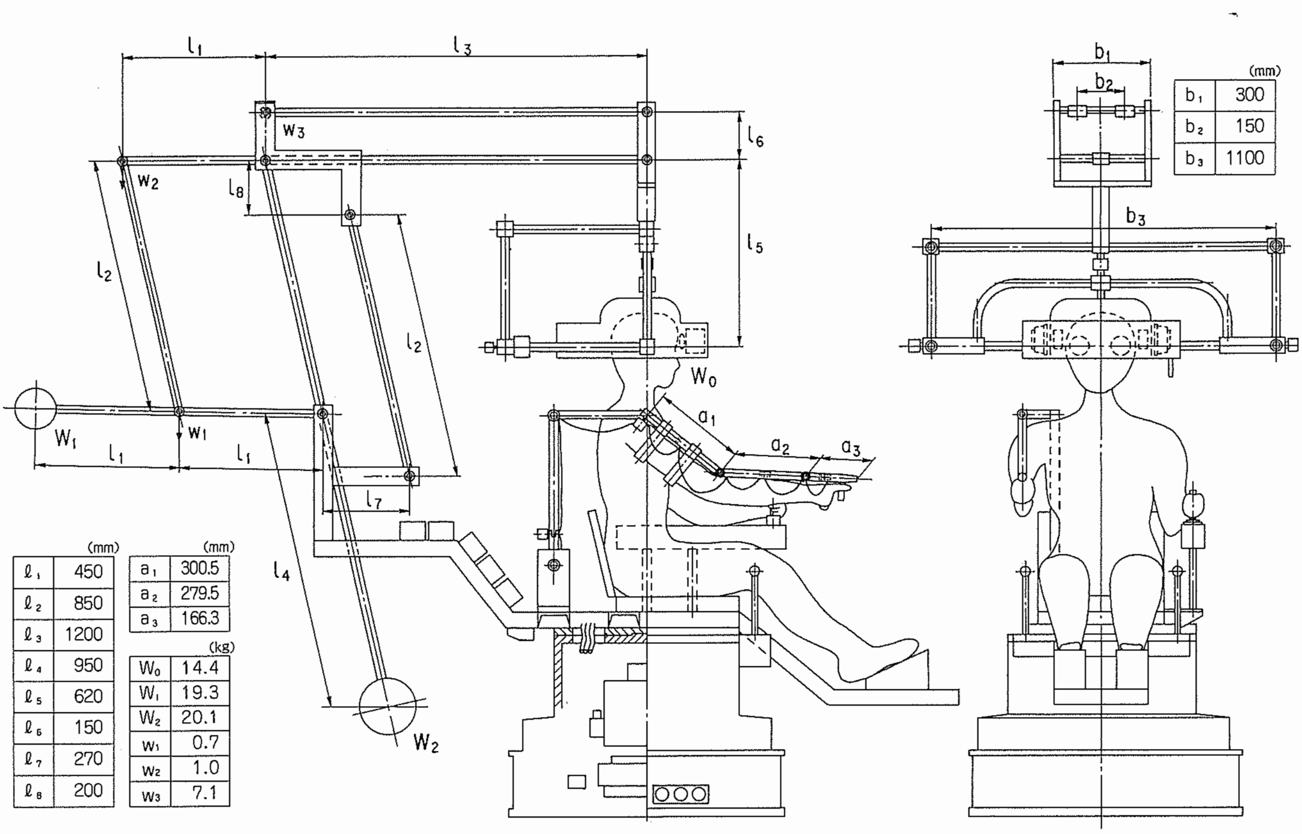

Figure 3. *Teleexistence master system.*

tation 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 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 ball screw. The grasping of cylindrical objects with a 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. A 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 pixels and has its optical system with a focal length of $f = 12$ mm [field of view 40 (deg)] and an aperture of F1.6. Focus is automatically controlled by the TTL AF method. The separation of two cameras is 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 transmits the operator's voice.

Figure 4 shows a general view of the anthropomorphic teleexistence slave robot under operation.

The stereo visual and auditory input system mounted on the neck mechanism of the slave robot gathers visual and auditory information of the remote environment.

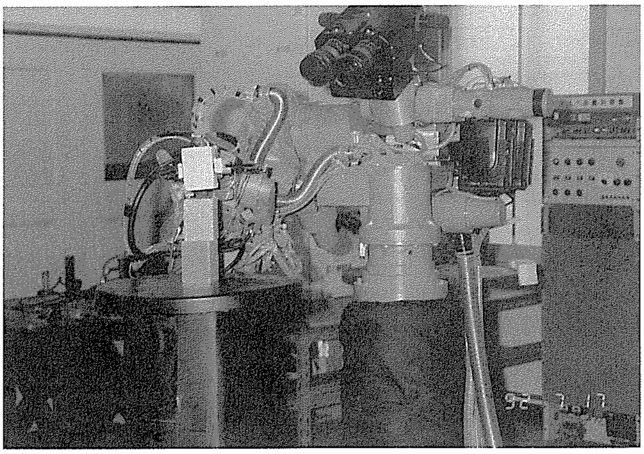

Figure 4. *Teleexistence anthropomorphic robot under operation.*

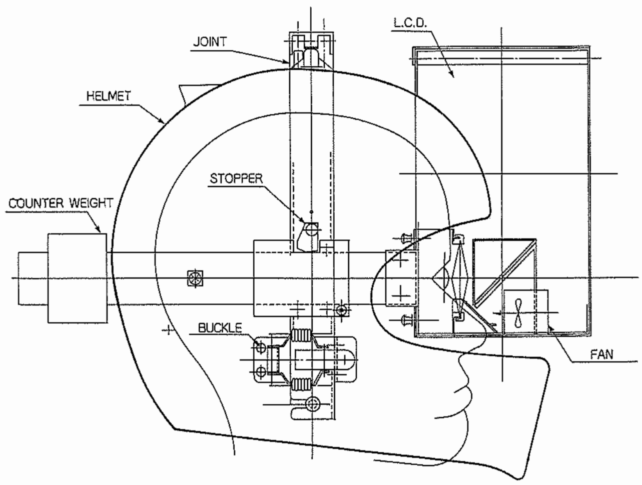

Figure 5. *Teleexistence head-mounted display.*

These pieces of information are sent back to the master system, which are applied to the specially designed stereo display system to evoke the sensation of presence in the operator. 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. Operators observe the 3D virtual environment in front of their view, which changes according to their movement.

The stereo visual display is designed according to the developed procedure which assures that the 3D view will maintain the same spatial relation as by direct observation (Tachi et al., 1988b; Maeda & Tachi, 1992). A pair of 6-in. LCDs (H720 × V240 pixels) with a convex lens system is used. The compact arrangement of a display system suitable for the manipulation master system was made possible by arranging the two mirrors so that the LCDs can be placed on the upper side in front of the operator (Fig. 5).

3 Experiments

Experiments which quantitatively evaluate the typical characteristics of the teleexistence master–slave system were conducted.

The most noticeable distinction of teleexistence and/or virtual reality from the conventional human–machine interface is that the virtual environment where the user is supposed to exist has the following features: (1) The virtual environment is a 3D space that is natural to the user (*Sensation of Presence*); (2) it allows the user to act freely and allows the interaction to take place with natural movement in real time (*Real-Time Interaction*); and (3) it has a projection of him or herself as a virtual human or surrogate robot (*Self-Projection*).

Thus, the most important features of teleexistence include the natural 3D vision (closely approximating direct observation), which follows the operator's head movement in real time, and the natural correspondence of visual information and kinesthetic information, i.e., an operator observes the slave's anthropomorphic arm at the position where his or her arm is supposed to be. This is regarded as the basis of the feeling of teleexistence. This allows the operator at the control to perform tasks that require coordination of hand and eye quickly, as in the case of direct operation.

To prove experimentally and quantitatively evaluate the effect of the three features of teleexistence, the following experiment was conducted. The following five visual display methods were compared:

1. Direct Observation:
2. HMD(B): Binocular Head-Mounted Display and the stereo camera mounted on the slave robot, whose directions, i.e., pitch, roll, and yaw, are controlled to follow the movement of the operator;

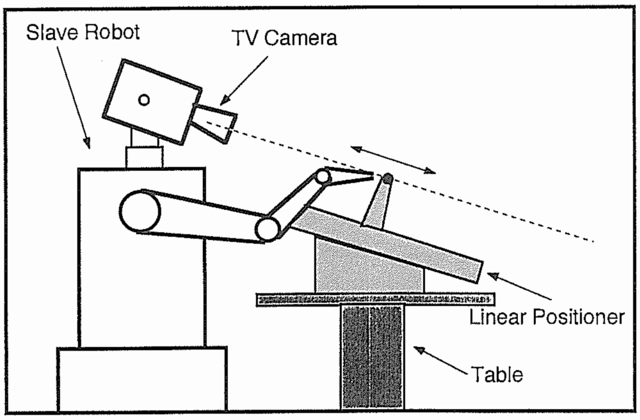

Figure 6. *Experimental arrangement.*

3. HMD(M): Monocular Head-Mounted Display and one camera mounted on the slave robot, whose directions, i.e., pitch, roll, and yaw, are controlled to follow the movement of the operator;
4. CRT(H): Conventional CRT display placed in front of the operator with a field of vision of 45° and a camera placed at the eye position of the robot head, whose direction is fixed to the direction of the movement of the target;
5. CRT(O): Conventional CRT display placed in front of the operator with a field of vision of 45° and a camera placed 30° outside of the robot, of which direction is fixed to the direction of the movement of the target.

The head-mounted display used was designed according to the procedure that has been described previously (Tachi et al., 1988b; Maeda & Tachi, 1992). In the HMD(M) mode, only the right side display of the binocular system is used. The field of vision is 40° for each eye, as in the last section.

Figure 6 shows the experimental arrangement of the slave robot and the linear positioner. A target is fixed to the moving part of the linear positioner, which is driven by a random noise with a maximum stroke of ±100 mm along the depth axis of the operator's observation coordinate. The operator was asked to place the tip of the slave manipulator at the position of the target using the master manipulator under several display conditions

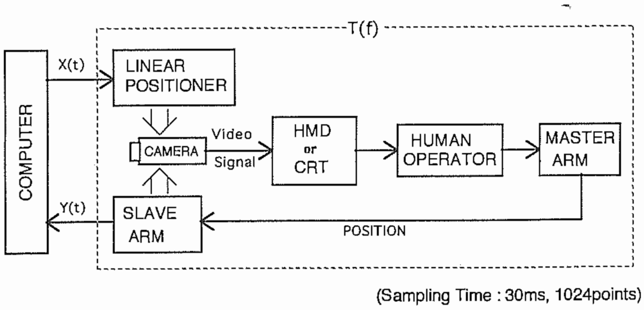

Figure 7. *Block diagram of the evaluation system.*

(conditions 2 through 5). Since the target moved randomly, the operator tried to follow the target (tracking). In this experiment, the target's moving direction was elaborately arranged so that it coincides with the direction of observation in order to eliminate mutually dependent effects and single out the effects of the head motion of the operator, the binocular observation, and the matching of kinesthetic information and visual information.

Under condition 1 (direct observation), the operator was at the position of the slave robot replacing the robot, and tracks the target using the master manipulator observing the target directly. This condition was used for the control data.

Pseudorandom noise was used as the target position input, as follows:

$$x(t) = \sum_{k=0}^{n} a_0 p^{-k} \sin(2\pi f_0 p^k t + \phi_k)$$

where $p = 1.25$, $n = 17$, $f_0 = 0.0326$ Hz, and ϕ_k is a random number.

The experimental tracking system is shown in Figure 7. In the figure, pseudorandom noise $x(t)$ was applied to the linear positioner with a target, and an operator tried to follow the random movement of the target by the manipulation of the master manipulator, observing the target and the slave manipulator through a head-mounted display or conventional CRT display under several display conditions. The human operator's tracking trajectory $y(t)$ along the linear positioner's coordinate was calculated by using the kinematics of the slave manipulator and the measured seven joint angles of the manipulator. The performance was evaluated by comparing the transfer function of the human operator $T(f)$, which was estimated by using $x(t)$ and $y(t)$ for each of the above mentioned display methods.

$T(f)$ is estimated as follows:

$$T(f) = \Phi_{xy}/\Phi_{xx} = E[X(f)^{*}Y(f)]/E[X(f)^{*}X(f)]$$

where Φ_{xy} is the cross-spectrum between the input signal $x(t)$ and output signal $y(t)$ and Φ_{xx} is the power spectrum of the signal $x(t)$. The signals $x(t)$ and $y(t)$ are measured during a finite time to determine their Fourier transforms. Upper case letters denote the Fourier transform of the corresponding lower case letter signals. The asterisk denotes the complex conjugate and E denotes an ensemble mean, respectively.

The control cycle of the master–slave system and the linear positioner is 10 msec. Output response was sampled every 30 msec. FFTs (fast Fourier transform) of 1024 points were employed and the cross-spectrum was measured using the frequency averaging technique for each of the display methods. This process was repeated five times to obtain an ensemble average of the cross-spectrum, and then the transfer function was estimated as the ratio of the average cross-spectrum and power spectrum for each display method.

Figure 8 shows an example of the transfer function. Amplitude (gain) and phase of the human transfer function $T(f)$ under the tracking task are shown as a function of frequency. As a first-order approximation, the crossover model can be applied. According to the crossover model of McRuer (McRuer & Jex, 1967; Sheridan & Ferrell, 1974) the transfer function $T(f)$ in the region of the crossover frequency can be described as follows:

$$T(f) = (\omega_c/j\omega)\exp\{-j\omega T_e\}$$

where ω_c is the crossover frequency corresponding to the tracking human's gain compensation K_e using the display, and T_e is the effective time delay due to both reaction time and neuromuscular dynamics.

Overall performance of the model is improved by increasing equivalent gain and reducing the equivalent time delay. The two parameters K_e and T_e describe the

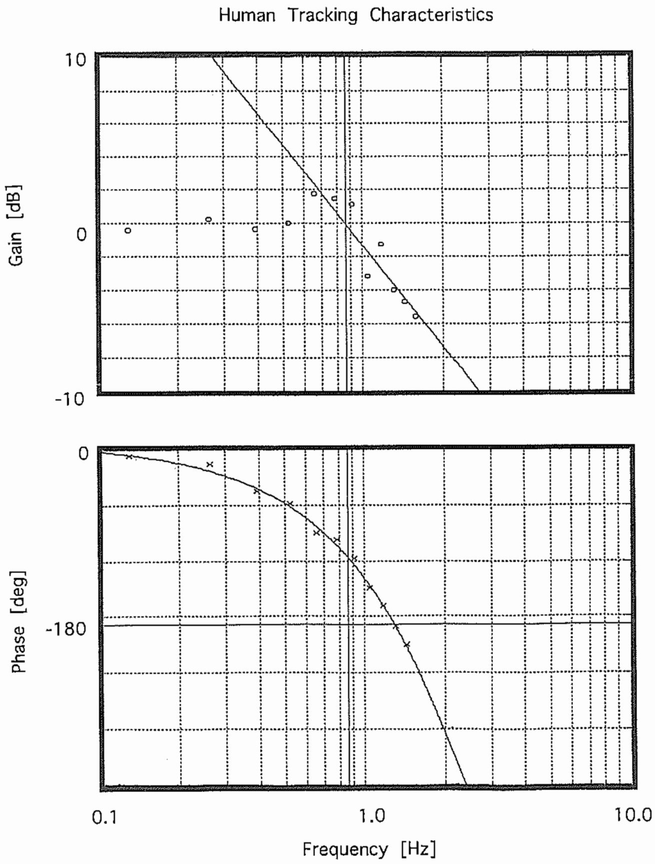

Figure 8. *An example of the human tracking characteristics measured.*

overall characteristic of the human tracking using this display just as was the case in the evaluation of the mobility aids for the blind (Tachi, Mann, & Rowell, 1983). Thus, the quantity

$$EV(i) = K_e(i) + 1/T_e(i)$$

was selected to determine and evaluate quantitatively the effectiveness of each display method, where (i) is the display method number.

To estimate the effective gain and the effective time delay, a line with a slope of −20 dB/decade was fitted to the amplitude of the transfer function near the crossover frequency, and using the least-squares method, the crossover frequency f_c was measured for each of the five display schemes. The phase margin ϕ_m was measured as

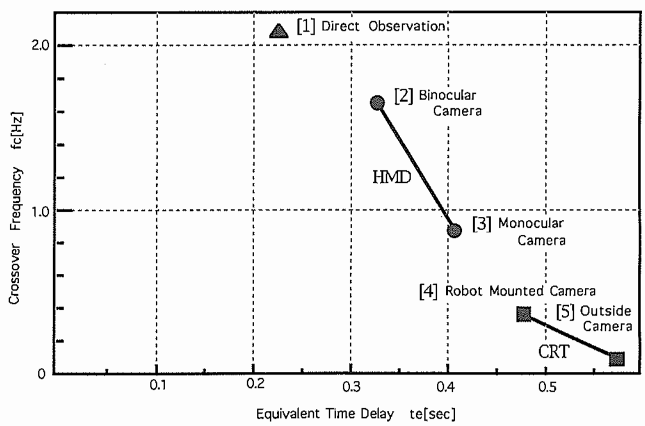

Figure 9. *Comparison result.*

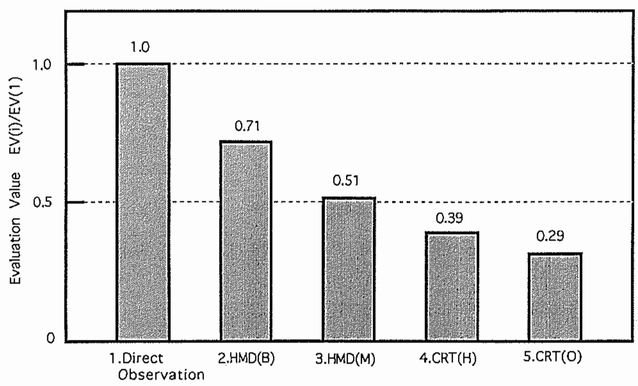

Figure 10. *Comparison result using the EV criterion.*

$\phi_m = 180 - P_c$, where P_c is the phase value at the crossover frequency.

The effective gain K_c and the effective time delay T_c were calculated using the following formula:

$$K_c = 2\pi f_c$$

$$T_c = 1/K_c\,(\pi - \phi_m \cdot \pi/180)$$

Figure 9 shows the result for an operator using each of the five display schemes. These two parameters f_c and T_c are plotted in Figure 9, which clearly shows the dominance of HMDs over the conventional CRT's. When HMDs are used, operators can control the directions (pitch, roll, and yaw) of the slave camera according to the movement of their heads, while size and perspective view of the slave manipulator and the target are the only cues for the case of CRTs. This is the main reason for the difference.

In the HMD group, the binocular display is better than the monocular display. Since no translational movement of the slave camera is allowed in this experiment, the dominance of binocular display is what is expected. Although we did not conduct quantitative evaluation for the monocular display, which allows the translational motion of the slave camera followed by the human operator's head movement, our preliminary experiments suggested that the performance of monocular HMD improved with translational movement with the use of motion parallax. The effect of motion parallax needs further quantitative evaluation.

The difference among CRT groups is due to the arrangement of the camera and the slave manipulator. If we limit the arrangement only for the type as of condition 5, i.e., the line of sight of the camera coincides with the direction of linear movement of the target, this result clearly indicates the effectiveness of natural arrangement of the camera and the manipulator close to the locational relations of human eyes and an arm.

The experiment was conducted for five operators (all males in their thirties), and they showed the same tendency though their absolute evaluation values are different. Figure 10 shows the normalized evaluation value of each display scheme averaged. The performance under direct observation was used as a standard and its value was set to 1.

Figure 11 shows the comparison result, in which root mean square error of the output from the input is used as a criterion for comparison. The comparison results showed the same tendency as was shown when the EV criteria was used.

The HMD(B) display type results were superior to all other conditions except direct observation. The method of observation was not the only difference between the direct observation and the HMD(B); the use of a master manipulator as the tracking manipulator means the direct observation is free from the disadvantageous effect of the slave manipulator dynamics.

Future experiments are necessary to resolve these differences.

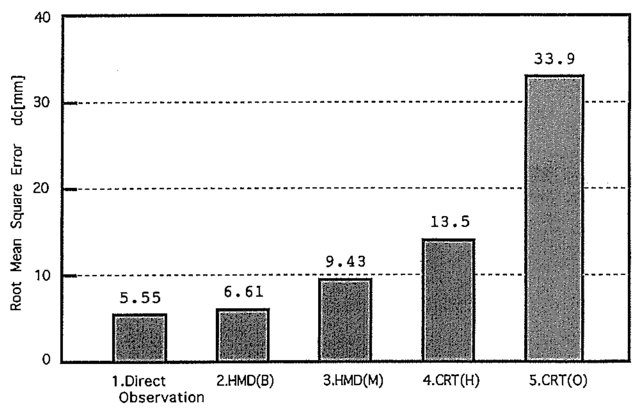

Figure 11. *Comparison result using the root mean square value.*

4 Conclusion

An experimental teleexistence system is realized that enables a human operator to have the sensation of being in a remote real environment where a surrogate robot exists. A teleexistence master–slave system for remote manipulation experiments was designed and developed, and an evaluation experiment of a teleexistence master–slave system was conducted. By comparing a teleexistence master–slave system with a conventional master–slave system, efficacy of the teleexistence master–slave system was verified and the superiority of the teleexistence method was demonstrated through tracking experiments.

The comparison results revealed the clear superiority of binocular vision with the natural arrangement of the head and the arm, which is the most important characteristic of teleexistence.

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