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EVALUATION EXPERIMENTS OF TELE-EXISTENCE MANIPULATION SYSTEM

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Abstract

Tele-existence manipulation system has been evaluated quantitatively by comparing tasks of tracking a randomly moving target under several operational conditions. 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. Human tracking transfer function is measured and is used as the criterion for the comparison. The comparison result revealed the significant dominance of the binocular vision with natural arrangement of the head and the arm, which is the most important characteristic of tele-existence.

1.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 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 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 in Japan and telepresence or virtual reality in the United States [1-18].

In our first reports [3,8], 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 tele-vehicle system was constructed and the feasibility of the method was evaluated [13]. 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 [14].

In the recent papers [15,16], 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. An experimental tele-existence system in real and/or virtual environment was 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 was demonstrated experimentally [17].

In this paper, quantitative evaluation of the tele-existence manipulation system is conducted through tracking tasks by using a tele-existence master slave system designed and developed according to the concept of tele-existence.

2.Tele-Existence Master Slave System

Figure 1 shows a general view of the tele-existence master slave manipulation system experimentally constructed. 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, a gripper hand, and a locomotion mechanism.

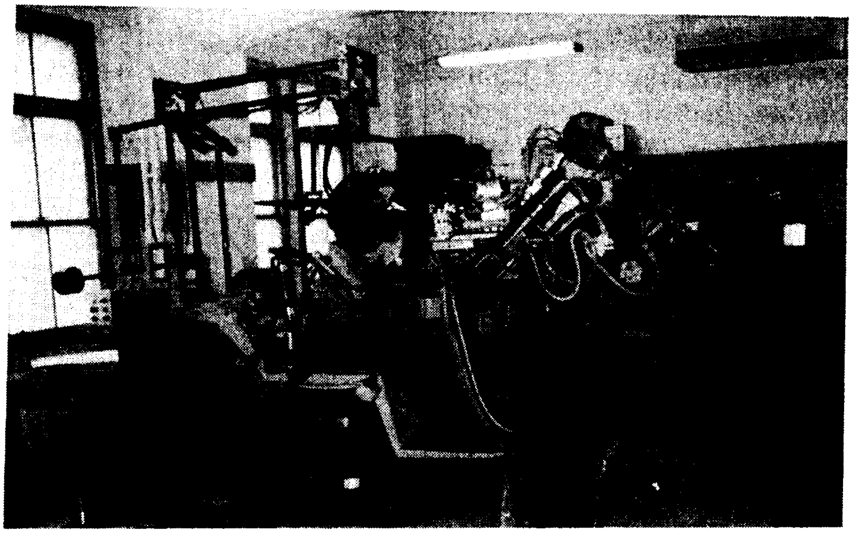

Fig.1 General View of the Tele-Existence Master Slave Manipulation System.

A human operator wears a 3D 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, which allows the operator's unconstrained movement in a relatively wide range of operation space. It also enables the display to follow the operator's head movement precisely enough to ensure his/her ordinary head movement. Maximum inertial force which is inevitably applied to the operator remains 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 (Fig.2).

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 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. The slave robot has a locomotion mechanism and a hand mechanism. The robot has also 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 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). 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. 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 pre-determined value.

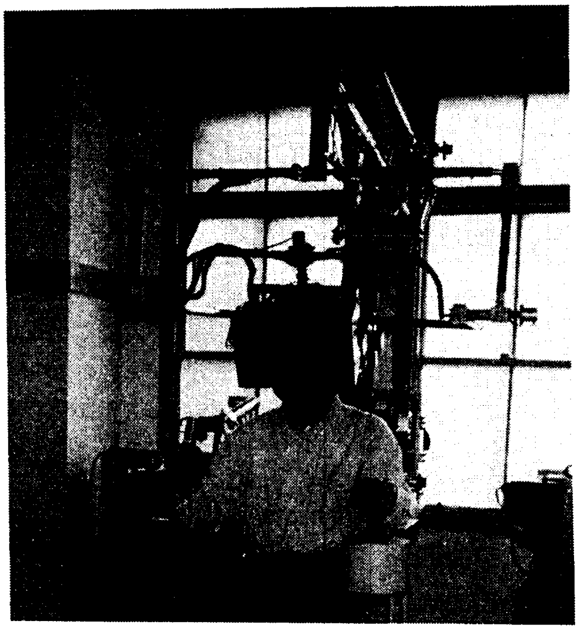

Fig.2 Tele-Existence Master System.

Figure 3 shows a general view of the anthropomorphic tele-existence slave robot under operation.

A 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. 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. The operator observes the three dimensional virtual environment in front of his/her view, which changes according to his/her movement.

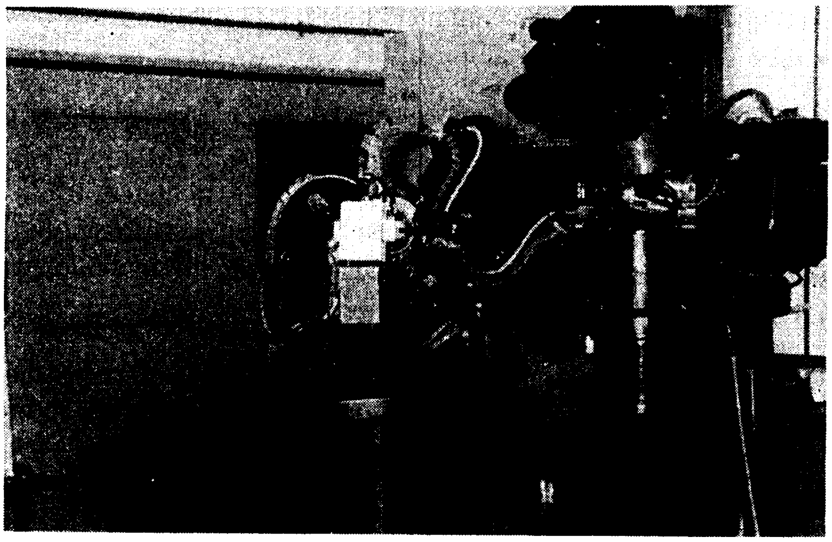

Fig.3 Tele-Existence Anthropomorphic Robot under Operation.

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 [8,18]. Two pairs of a six inch LCD's (H720 x V240 pixcells) with a convex lens system are used. Two mirrors are arranged so that the LCD's 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.

3. Experiments

Experiments which quantitatively evaluate the typical characteristics of the tele-existence master slave system were conducted.

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

Thus 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 is regarded as the basis of the feeling of self projection.

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.

In order to prove experimentally and quantitatively evaluate the effect of the three features of the tele-existence, 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,

3.HMD(M): Monocular Head Mounted Display and one of the camera mounted on the slave robot,

4.CRT(H): Conventional CRT display placed in front of the operator with a field of vision of 45 degrees and a camera placed at the eye position of the robot head,

5.CRT(O): Conventional CRT display placed in front of the operator with a field of vision of 45 degrees and a camera placed outside of the robot;

The head mounted display used is designed according to the procedure which has been described in the previous reports [8,18]. In the HMD(M) mode, only the right side display of the binocular system is used. The field of vision is 40 degrees for each eye as is described in the last section.

Figure 4 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 operators observation coordinate. An operator is asked to place the tip of the slave manipulator at the position of the target using the master manipulator under several display conditions (Condition 2 through 5). Since the target moves randomly, the operator tries to follow the target (tracking). Under the condition 1 (direct observation), an operator is at the position of the slave robot replacing the robot, and tracks the target using the master manipulator observing the target directly. This is used for the control data.

Pseudo-random noise is 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 system is described as a tacking system shown in Fig. 5. The transfer function of the human operator T(f) is estimated for each of the above mentioned display methods 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), respectively. The signal x(t) and y(t) are measured during finite time in order 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 ms. Output response is sampled at the sampling period of 30ms. FFT's (fast Fourier transform) of 1024 points are employed and the cross spectrum is measured using the frequency averaging technique for each of the display methods. This process is repeated five times to obtain an ensemble average of the cross spectrum, and then the transfer function is estimated as the ratio of the averaged cross spectrum and power spectrum for each display method.

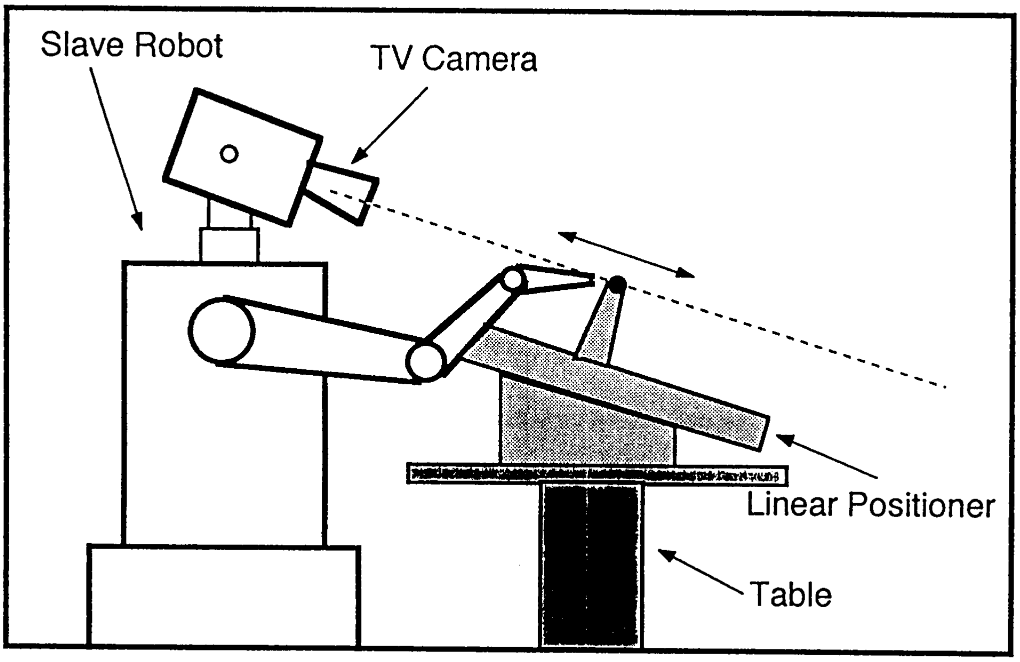

Fig.4 Experimental Arrangement.

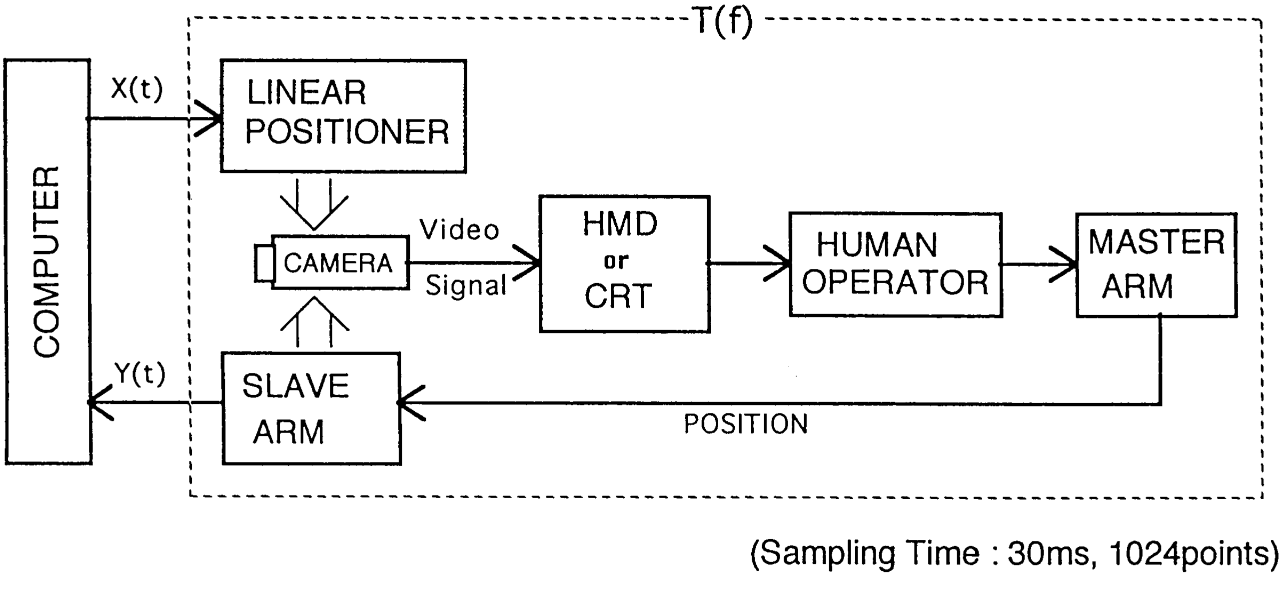

Fig.5 Block Diagram of the Evaluation System.

Figure 6 shows an example of the transfer function obtained. As a first-order approximation, the crossover model can be applied. According to the crossover model of McRuer, 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.

For the model, overall performance is improved for higher equivalent gain and smaller equivalent time delay. The two parameters K_e and T_e describe the overall characteristic of the human tracking in use of the display. Thus the quantity

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

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

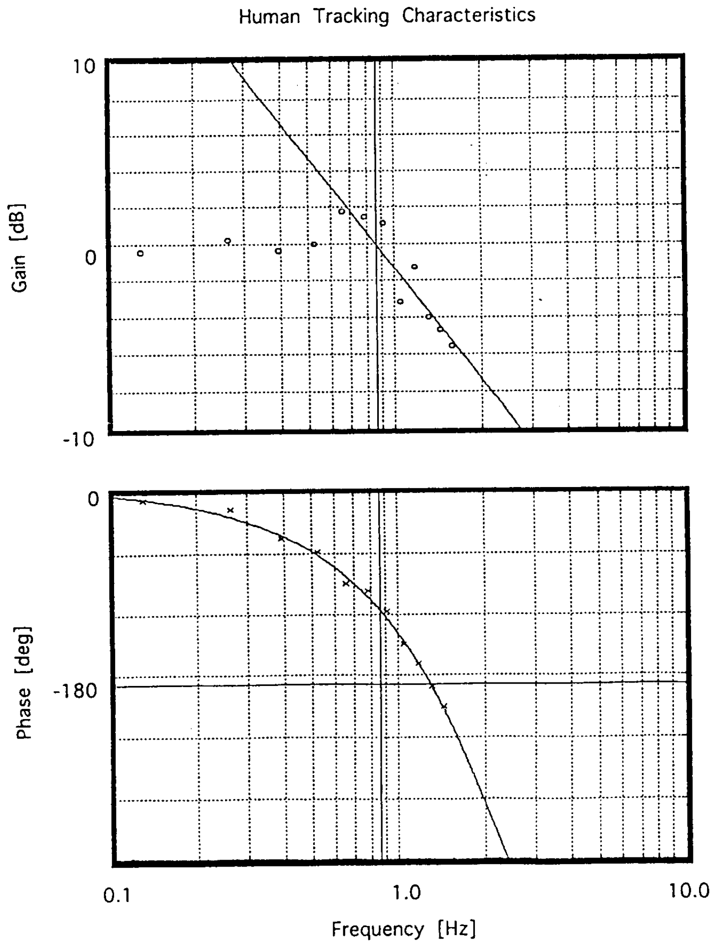

Fig.6 An Example of the Human Tracking Characteristics Measured.

In order to estimate the effective gain and the effective time delay, a line with slope of −20 dB/decade was fitted to the amplitude of the transfer function near the crossover frequency, and using the least square method, the crossover frequency fc was measured for each of the 5 display schemes. The phase margin ϕ_m was measured as $\phi_m = 180 - P_c$, where P_c is the phase value at the crossover frequency.

The effective gain K_e and the effective time delay T_e were calculated using the following formula:

$K_e = 2\pi f_c$

$T_e = 1/K_e\,(\pi - \phi_m\pi/180)$.

Figure 7 shows the result for a subject with each of the 5 display schemes. These two parameters f_c and T_e are plotted in Fig.7, which clearly shows the dominance of HMD's over the conventional CRT's. In the HMD group, the binocular display is better than the monocular display. The difference among CRT group is caused by the arrangement of the camera and the slave manipulator. This clearly indicates the effectiveness of natural arrangement of the camera and the manipulator close to the locational relations of human eyes and an arm.

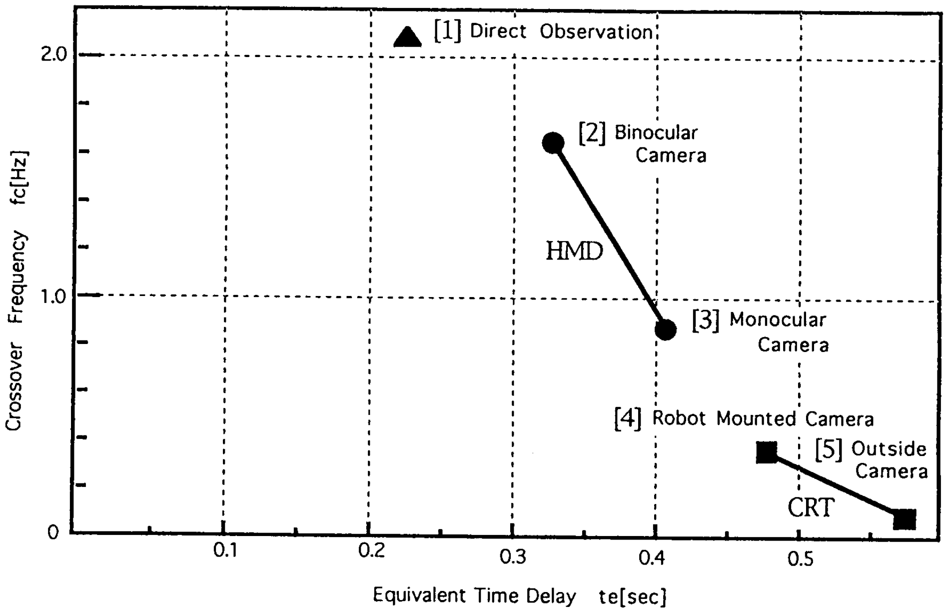

Fig.7 Comparison Result.

Figure 8(a) shows the normalized evaluation value of each display scheme. The performance under direct observation is used as a standard and the value for it is set to 1.

Figure 8(b) shows the comparison result, in which root mean square error of the output from the input is used as a criterion for comparison. The same tendency is noticeable.

The display type HMD(B) shows the most superior result except that of the direct observation. The difference between the direct observation and the HMD(B) is not only the observation method but also the use of master manipulator as for the tracking manipulator, that means the direct observation is free from the disadvantageous effect of the slave manipulator dynamics.

Additional experiment might be necessary to resolve these effects, which is left for the future.

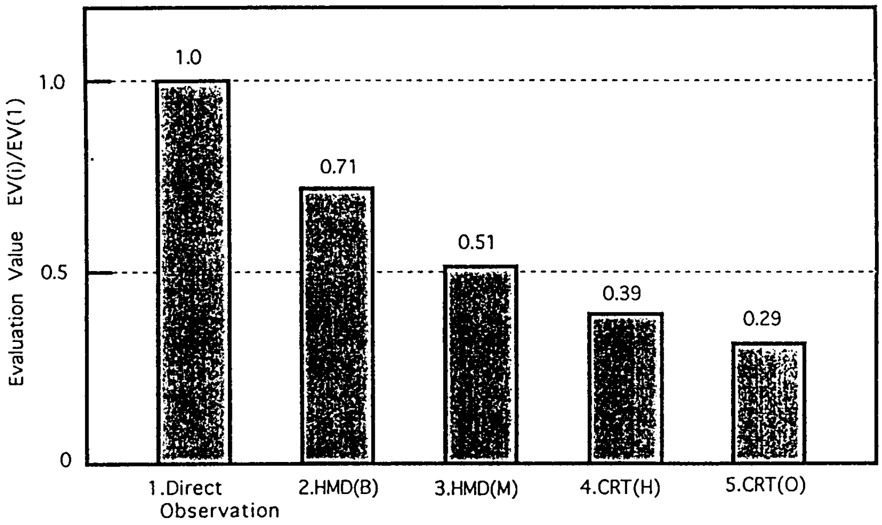

Fig.8(a) Comparison Result using the EV Criterion.

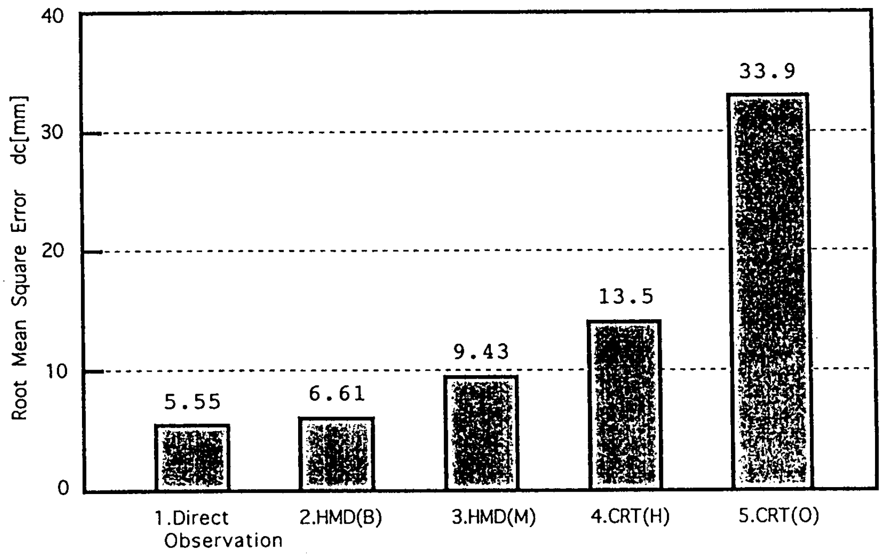

Fig.8(b) Comparison Result using the Root Mean Square Value.

4.Conclusion

According to the concept of tele-existence, an experimental tele-existence system is realized, which enables a human operator to have the sensation of being in a remote real environment where a surrogate robot exists. A tele-existence master slave system for remote manipulation experiments is designed and developed, and an evaluation experiment of a tele-existence master slave system is conducted. By making a comparison of a tele-existence master slave system with a conventional master slave system, efficacy of the tele-existence master slave system is verified and the superiority of the tele-existence method is demonstrated through tracking experiment.

The comparison result revealed the significant dominance of the binocular vision with natural arrangement of the head and the arm, which is the most important characteristic of tele-existence.

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