TELE-EXISTENCE VISUAL DISPLAY FOR REMOTE MANIPULATION WITH A REAL-TIME SENSATION OF PRESENCE

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ABSTRACT

A method is proposed to develop a visual display for a tele-existence manipulation system, which enables a human operator at the controls to perform remote manipulation tasks dexterously with the feeling that he or she exists in the slave anthropomorphic robot in the remote environment. An anthropomorphic robot with an arm having seven degrees of freedom has been designed and developed as a slave robot. The robot's structural dimensions are set very close to those of humans, and it is designed to mimic the movements of humans. In order to assure that the three dimensional view through the tele-existence system will maintain the same spatial relation as by direct observation in the wide range of work space, it is important for the tele-existence visual system to have the function of convergence. A prototype visual camera system with the function of convergence has been designed and constructed. The effect of the camera convergence and the display convergence was quantitatively studied by psychophysical experiments. An advanced visual display mechanism is proposed based on the results obtained.

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 systematic research for the development of tele-existence by feeding back rich sensory information which the remote robot has acquired to provide the operator with a real-time sensation of presence.

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 tele-vehicle system was constructed and the feasibility of the method was evaluated [3]. The principle of active power assistance [4] was applied for controlling the visual display with one degree of freedom [5] and two degrees of freedom [6]. In order to study the use of the tele-existence system in the artificially constructed environment, the visual tele-existence simulator was designed, a pseudo-real-time binocular solid model robot simulator was made, and its feasibility was experimentally evaluated [7].

An anthropomorphic robot mechanism with an arm having seven degrees of freedom [6] has been designed and developed as a slave robot for feasibility experiments of teleoperation using the tele-existence method. An impedance controlled active display mechanism and a head mounted display have also been designed and developed as the display sub-system for the master. The robot's structural dimensions are set very close to those of humans, and it is designed to mimic the movement of humans. In order to assure that the three dimensional view which will maintain the same spatial relation as by direct observation in the wide range of work space, it is important for the tele-existence visual system to have the function of convergence.

In this report, a prototype visual camera system with the function of convergence has been designed and constructed. The effect of the camera convergence and the display convergence was quantitatively studied by psychophysical experiments. An advanced visual display mechanism is proposed based on the results obtained.

2. TELE-EXISTENCE

With the advent of science and technology it has become possible to envision teleoperation with a sensation of presence. The concept of projecting ourselves by using robots, computers and cybernetic human interfaces is called Tele-Existence [1], Telepresence [8,9], or Artificial Reality [10], and a lot of effort has been made for the realization of this concept. This concept also provides an extension of human sensing and muscular capabilities [1,2].

Figure 1 shows a conceptual system of 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 the robot's ultrasonic, infrared and other, otherwise invisible, sensory information with the computer graphics-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 exist at other environments where the robots are working. He or she will monitor the work through the robot's sensors, and if necessary conduct the task on behalf of the robot as if he was doing the work himself (ideally) or as if he was working inside the robot (practically).

The basic configuration of the tele-existence system is shown in **Fig. 2.** 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 human retinae. 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 those of the head and/or eyeballs are precisely measured in real time, (b)robot sensors and effecters 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 operator's eyes in a manner which assures that he sees 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.

3. TELE-EXISTENCE ANTHROPOMORPHIC SLAVE ROBOT

Figure 3 shows a general view of the anthropomorphic slave robot designed and developed. 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.

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 $\pm$ 1 mm.

The dimensions and arrangement of the degree of freedom of the robot are designed to mimic those of the human being. 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.

The motion range of each degree of freedom is set so that it will cover the human movement, 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 is used as an actuator for each joint except the elbow extension/flexion, which includes conventional gears. The location of the motors are 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 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.

4. Slave Robot Visual Convergence Function

When remote manipulation task is taking place, an operator usually observes the distance of 300 mm to 1000 mm, where the slave hands are located. At the same time it is necessary to see a distance of several meters to look around the environment. In order to assure that the three dimensional view will maintain the same spatial relation as by direct observation in the wide range of work space, it is important for the tele-existence visual system to have the function of convergence. A prototype visual camera system with the function of convergence has been designed and constructed. The effect of the camera convergence and the display convergence was quantitatively studied by psychophysical experiments. An advanced visual display mechanism is proposed based on the results obtained.

4.1 Slave Camera System with Convergence Capability

Figure 4 shows a general view of the experimental hardware camera system with the function of convergence. Two cameras are placed in parallel 70 mm apart from each other. The left camera turns inside to maintain an appropriate convergence to an object which is located just in front of the right camera. Focusing and irising are automatically conducted for both cameras.

The principle of the convergence mechanism is shown in **Fig. 5.** An Infrared laser beam is transmitted from the LED placed inside the right camera, through the object lens via an appropriate optical system. The reflected beam from an object in front of the right camera is sensed by the Silicon Photo Cell (SPC) placed inside the left camera. The direction of the left camera is controlled so that the reflected beam is sensed at the center of the SPC, which assures the convergence of the two cameras at the object point.

Figure 6 shows the servo mechanism of the convergence control and focus control systems. A motor which is controlled according to the reflected beam position on the SPC turns the focusing gear. A cam mechanism attached to the gear is turned simultaneously, which turns arm 1. Since the pivot of the arm is fixed to the left camera, and one end of the arm is fixed to the body of the apparatus, the movement of the arm causes the convergence movement of the left camera.

The convergence movement is transmitted to the right camera by another cam mechanism. Using this motion and another sensor system comprising an LED, pinhole and SPC, the focusing of the right camera is attained.

4.2 Display Experiment

In order to clarify the effects of the relations between camera convergence and display convergence, the following experiments were conducted.

The characteristics of human direct observation and that through the camera and display apparatus under several convergence angles were compared. Subjects observed two rectangular figures of different sizes at several distances in a dark room (as direct observation: control) or through the display apparatus (as comparison experiments).

Figure 7 shows the experimental arrangement. The stereo camera with the convergence mechanism is placed in front of two 14 inch CRTs set 380 mm apart from each other. The distance between the camera and one of the CRTs (left side from the camera) is fixed to 2,000 mm, while the other CRT (right side from the camera) is located at 2,000 + Δd mm, where Δd takes the value of 0, 100, 200, or 300 at each session of the experiment.

The images on the CRTs are controlled by two computers (PC 9801), respectively. On the left CRT, a white rectangular shape of width 100 mm and of height 150 mm is displayed at a luminance of 30 Cd/mm^2 against a black background as a reference. On the right CRT, a rectangular shaped image with the same luminance and height but with one of seven different widths (85, 90, 95, 100, 105, 110, or 115) is displayed randomly for each session of the experiment. A human subject is asked to answer which image is larger (the constant method) for several distance conditions through the tele-existence display. The camera convergence and 3-D display convergence conditions were also varied.

Two convergence angles at the camera side are chosen so that the two cameras converge at the distance of infinity (C-CV: ∞) and 2,000 mm (C-CV: 2,000 ;right parallel and left 2 deg). Four convergence angles at the 3-D display side are chosen so that the two displays converge at the distance of infinity (D-CV: ∞), 2,000 mm (D-CV:2,000 : left 1 deg and right 1 deg), 2,000 mm (C.D (R) C.D. (L) 2,000 ; right parallel and left 2 deg), and 500 mm (D-CV:500 ; left 4 deg and right 4 deg).

The right CRT display was placed at a distance of 2,000, 2,100, 2,200, or 2,300 mm. For each distance one of the seven different width rectangles was displayed five times randomly, and the equivalent size that humans observe was estimated by using Spearman's average method [11] under the all combination of the camera convergence and 3-D display convergence.

Control experiments were also done using the same subjects by directly observing the CRTs in the dark room.

The 3-D display which was designed according to the tele-existence display design procedure [3] was used for the experiment. **Figure 8** shows the structure of the display used. As shown in the figure, mirrors were turned to appropriate angles to meet the convergence conditions of the experiment.

4.3 Experimental Results

The following psychophysical phenomenon is known:

$$\text{Perceived Size} \propto \text{Visual Angle} \times \text{Distance},$$

where Perceived Size is the perceived (subjective) size of an object, Visual Angle is the visual angle or size of the human retinal image, and Distance is the distance from a human observer to the object. This means that the perceived size of the observed object is kept constant in spite of the change of distance in an appropriate distance range. This is known as size constancy.

Figure 9 and **Fig. 10** show the experimental result of a subject (MMK) for camera convergences of C-CV:∞ and C-CV:2,000, respectively. Two other subjects showed the same tendency.

The results of direct observation (mark ⊙) reflect the phenomenon of size constancy, i.e., that human subjects judge that two identical rectangles seem to have the same width in spite of the different distances to the two rectangles. This means human subjects can appropriately gather information of distance by the convergence information of their eyes in direct observation.

When the subjects viewed objects through the 3-D display with C-CV: and D-CV: ∞ , the same size constancy held. This means that human can maintain a high fidelity sensation of distance by using the convergence of their eyes through a tele-existence display of this type.

On the other hand, other combinations of convergence angles of camera and display showed poor results.The human observers could not maintain the size constancy. In the figures, the lines show the changes in the equivalent width of the rectangles which has the same visual angle (or the size of the image on the retina) when displayed at some distance away from the reference. Although some corrections have been made in the human brain to keep size constancy, convergence of the camera and display from the parallel result in the loss of distance information, which leads to the dependence on the retinal size information.

5. CONCLUSIONS

In order to assure that the three dimensional view will maintain the same spatial relation as by direct observation, it is important for the tele-existence visual system to have the function of convergence. A prototype visual camera system with the function of convergence has been designed and constructed. The effect of the camera convergence and the display convergence was quantitatively studied by psychophysical experiments.

The experimental results suggest that we can maintain the size constancy of objects displayed on the 3-D display with parallel arrangement of two displays and parallel arrangement of two cameras with separation equal to the distance between two human eyes. The conventional method of convergence of two cameras and two displays could not maintain the size constancy.

From the results, the mechanism in **Fig. 11** has been proposed. In the proposed mechanism the distance between two lenses are fixed to the distance between two eyes (about 65 mm) at both the camera side and display side. Two CCDs at the camera side and two CRTs (or LCDs) at the 3-D display side move in parallel to create the appropriate effect of convergence, thus maintaining the relation necessary to develop the sensation of presence.

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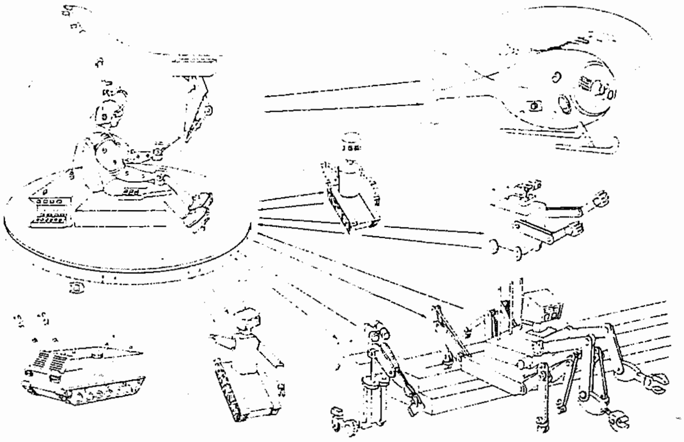

Fig. 1 Telerobotic human augmentation system using tele-existence technology.

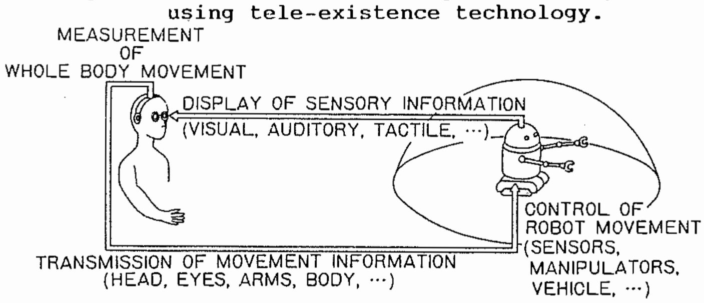

Fig. 2 Principle of tele-existence.

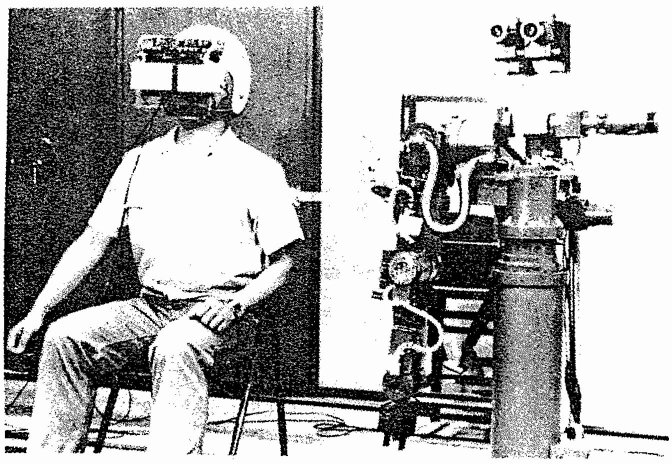

Fig. 3 General view of the anthropomorphic slave robot.

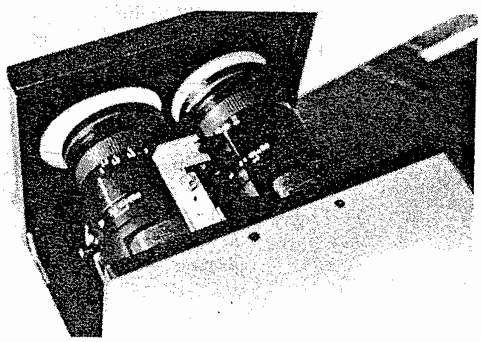

Fig. 4 General view of the experimental hardware.

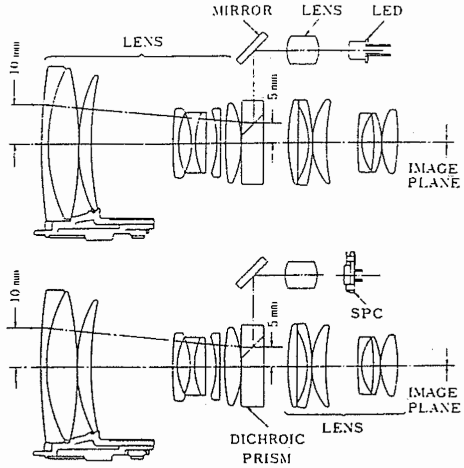

Fig. 5 Principle of the camera convergence control.

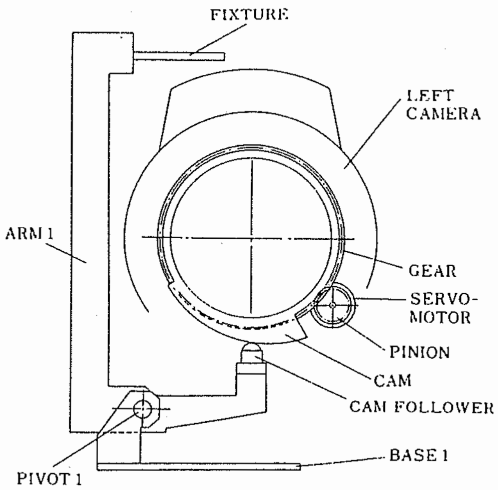

Fig. 6 Convergence mechanism.

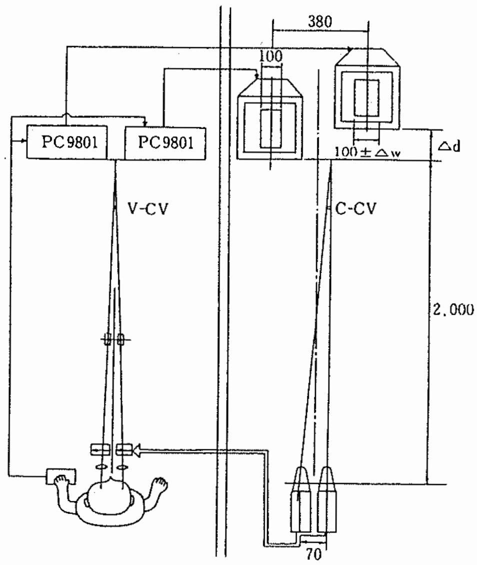

Fig. 7 Experimental arrangement.

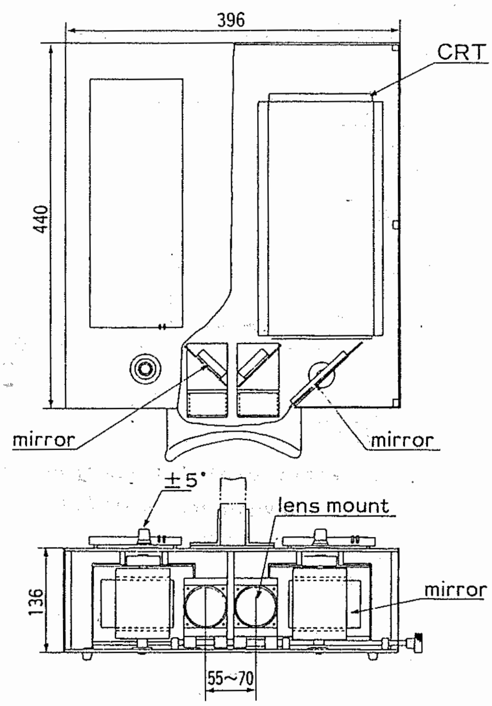

Fig. 8 3-D Display.

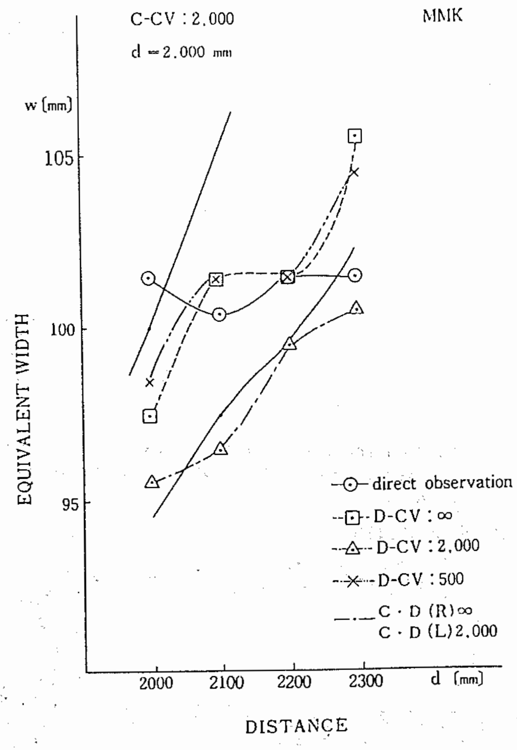

Fig.10 Experimental result for a subject MMS.

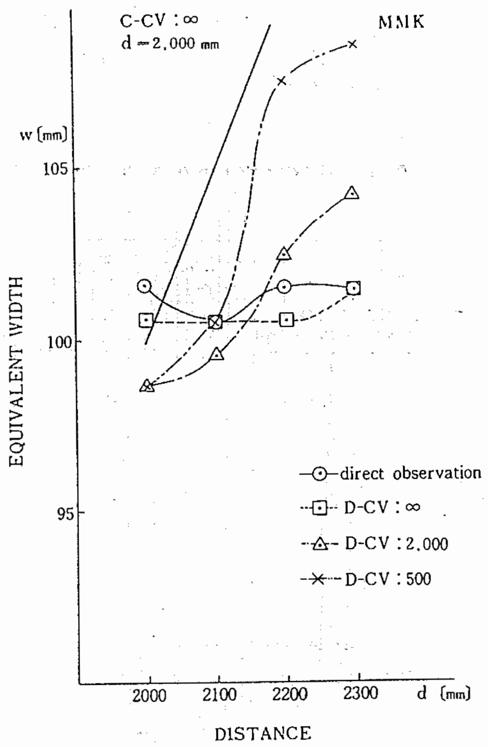

Fig. 9 Experimental result for a subject MMS.

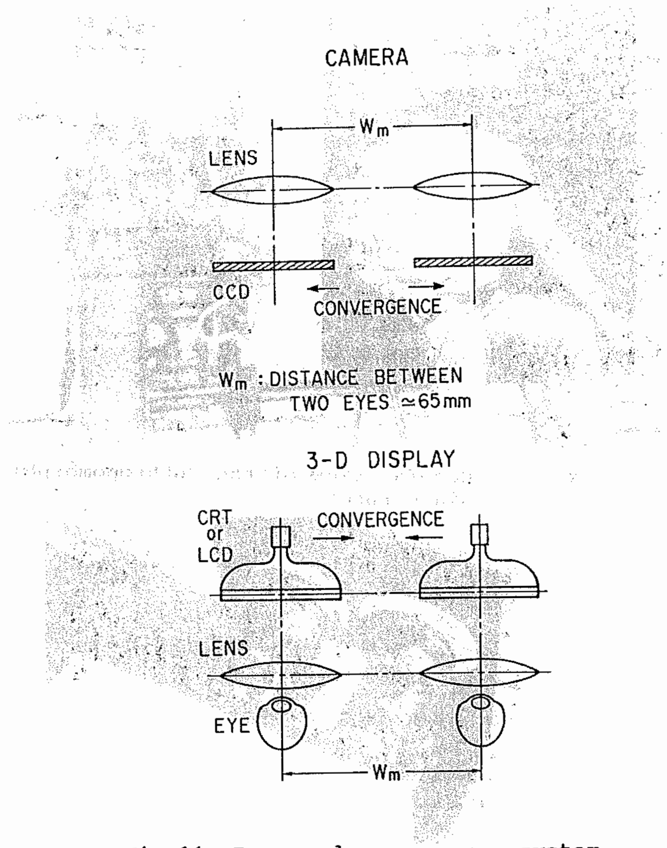

Fig.11 Proposed convergence system.