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Tele-existence (I): Design and Evaluation of a Visual Display with Sensation of Presence

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Summary: The tele-existence system is a teleoperator system that 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. The Mechanical Engineering Laboratory has started an 8-year national project of advanced robotics to realize this tele-existence system. In this paper the project goal is described first. Next, the visual display system that measures the operator's head movement, controls the slave robot's vision system according to the movement, and displays the acquired two visual images to both the operator's eyes through head-mounted CRT displays, whose images in turn fuse to give the visual sensation (which is very natural), when designed and constructed. Evaluation of the system has been carried out by measuring the metric of binocular visual space of a human operator with or without the display device. The experiment reveals that the metric of the binocular visual space viewed with the naked eye can be reserved in tele-existence system by servoing the focal length of the display lenses and the angle of the convergence of the two CRTs appropriately.

Introduction

Remote operation plays an important role in such hostile environments as nuclear, high temperature and deep space. In spite of the efforts of many researchers a teleoperation system that is comparable to man's direct operation has not yet been developed. There are three problems to be solved for the realization of an ideal remote operation system: (1) to design an anthropomorphic slave manipulator with human dexterity; (2) to measure human movement thoroughly and establish the control scheme of a slave manipulator (design of a master system); (3) to present the human operator with sensory information of the slave robot's environment as naturally as possible.

Problems (1) and (2) have been studied as teleoperator systems.[1] However, problem (3), the problem of remote presence, has not been studied enough. A conventional three-dimensional display presents a very unnatural scene to the operator, entailing an awkward operation and exhaustion of the operator.[2]

An ideal teleoperation system should be such a system that at the remote-control site a human operator can perform remote manipulation tasks dexterously with the feeling that s/he exists in the slave anthropomorphic robot in the remote environment. We call this type of advanced robot teleoperator system with real-time sensation of remote presence a tele-existence system. A pioneering study for a realistic three-dimensional display was conducted by Sutherland[3] as a head-mounted three-dimensional display to demonstrate the 'kinetic depth effect', i.e. moving perspective images appear to be strikingly three-dimensional even without any stereo presentation. He used only line drawings generated by the computer and did not use the real scene.

At Kernforschungszentrum Karlsruhe GmbH,[4] DCAN and CEA,[5] MBA Co. (personal communication), University of California in Los Angeles (J Lyman, personal communication) and Naval Ocean Systems Center,[6] pioneering studies using real scene have been proposed and some experiments have been conducted.

The idea *per se* has shown promise, but much remains unsolved toward the realization of an ideal tele-existence system including general design procedures, evaluation methods and test and evaluation in specific work environments.

In this paper the National Tele-existence Project is outlined for the first time. Then the fundamental idea of the tele-existence visual-display method and design procedure is proposed. A method of evaluation of the visual display is proposed and typical results are shown.

Tele-existence

The Japanese Ministry of International Trade and Industry has just started its 8-year National Project dubbed JUPITER (JUvenescent PIoneering TEchnology for Robot) to research and develop advanced robot technology for the system that avoids the need for humans to work in potentially hazardous working environments.

The Mechanical Engineering Laboratory is in charge of the fundamental research for the realization of the tele-existence system.

The final version of the tele-existence system will consist 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 computer-graphics-generated pseudorealistic sensation of presence. In the remote-presence subsystem realistic visual, auditory, tactile, kinesthetic and vibratory displays must be realized. In this paper, however, only the visual display is discussed as the first step.

Then, how can we display a realistic scene to the operator? How can we maintain the relationship between an object and a robot's upper extremities (arms and hands) at the remote site?

Figure 1a shows the traditional concept of a three-dimensional display. All waves coming into a robot at the remote site are recorded at ideally infinite points on a closed surface enclosing the robot. These recorded waves are transmitted and played back in real time at the corresponding points on a surface enclosing an operator.

The above method of wave reconstruction has the following disadvantages: (1) it is difficult to create an adequate recording and playback system so as to enclose a robot or operator. This results in a small display, entailing lack of realistic feeling; (2) when an operator tries to handle an object, s/he sees both robot's upper extremities and her/his upper extremities; it is thus difficult to avoid the feeling of remoteness (in other words, the relation between the object and upper extremities cannot be preserved in this type of display).

Figure 1b shows a new type of display with robot technology. This 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 retinas. What we can see are only two-dimensional pictures on the retinas changing in real time according to the movement of the eyeballs and the head. We reconstruct the world image in the brain and project back the reconstructed image to the real three-dimensional world.

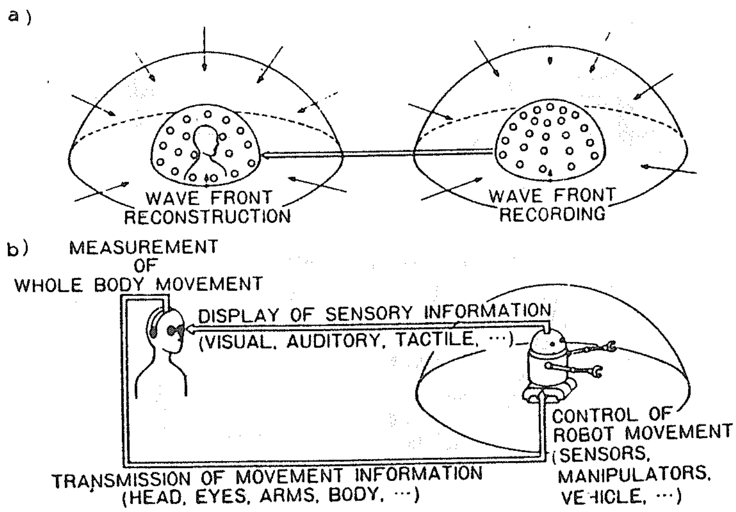

Figure 1 (a) Concept of wave-front reconstruction display and (b) tele-existence display

In a new type of robotic display: (a) human movements, including head and eyeballs, are precisely measured in real time; (b) robot sensors are constructed anthropomorphically in function and size; (c) movements of the robot sensors are controlled precisely to follow the human operator's movement; (d) pictures taken by the robot sensors are displayed directly to the human eyes in a manner to induce the feeling of presence.

Thus an operator sees the robot's upper extremities instead of her/his own at the position her/his upper extremities should be. The robot's upper extremities are controlled to track in real time precisely the same movement and force condition of the operator's and are seen through the visual display and felt by the tactile communication subsystem.

Visual-display design

Essential parameters for human perception of the monochromatic three-dimensional space are: (1) accommodation of the crystalline lens; (2) visual angle, i.e. retinal image size; (3) convergence of two eyes or disparity of two retinal images.

An ideal visual-display system should control all three parameters of display device in real time so that it would coincide with the parameters seen directly with the naked eyes. These conditions can be realized, as shown in Figure 2.

Suppose two posture-controlled TV cameras on board the robot in the remote

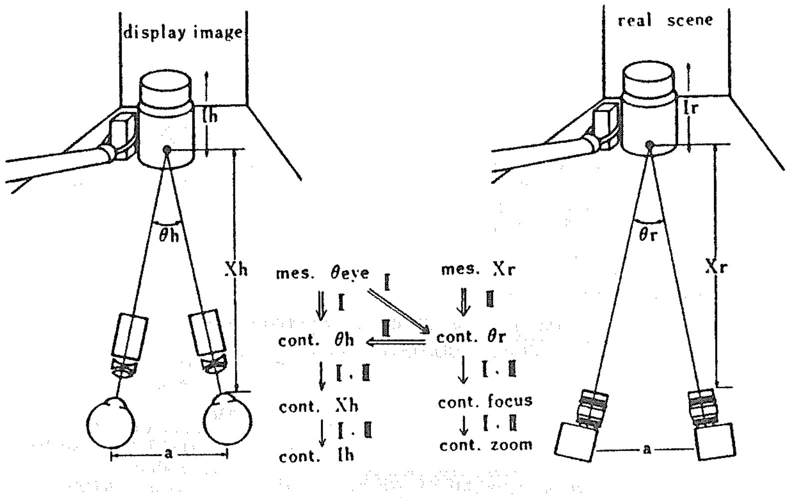

Figure 2 Ideal display method of tele-existence system

environment see the object at the distance of Xr. This distance is measured by the robot using the method of disparity[7] or ultrasonic measurement.[8] The foci of the two cameras are adjusted to the distance Xr. The two cameras are controlled so that the two lines of sight converge at the object location. The convergence angle θr and visual angles Vr (or object size Ir) for both the right and the left camera are calculated.

In the left-hand side of Figure 2, an ideal display method is proposed. The above parameters are considered in displaying the scenes taken by remote TV cameras as follows: two CRT displays with appropriate lens systems are placed immediately in front of an operator's eyes. Remote scenes taken by left and right cameras are displayed on left and right CRTs which, in turn, are focused by the lens systems on the corresponding left and right retinas respectively. The visual angle Vh at which each eye sees the object on the CRT display is controlled so that $Vh = Vr$. The location of a virtual image of the object picture on the CRT is controlled to be at the distance of $Xh = Xr$. The convergence angle of the two CRT displays is also servoed to $\theta h = \theta r$.

Thus each eye of the operator sees the same image that would be seen directly in the remote environment.

Among the three parameters of display, crystalline lens accommodation plays the least important role. If we accommodate to 1m, for instance, it covers the convergence range of 20cm to infinity. This fact leads to the simpler design method as shown in Figure 3. In the simpler design the location of virtual image is set at a fixed distance (e.g. $hL = hR = 2$m). However, visual angle (image size) and convergence angle are strictly controlled to coincide with the condition of which a direct observation can be made with naked eyes.

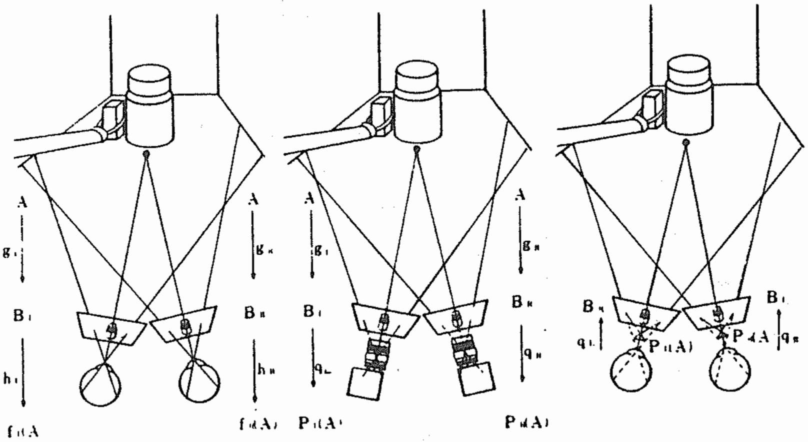

Figure 3 Simpler display method of tele-existence system

Such a condition can be realized easily by finding the transform qL from the plane BL to $PL(A)$ and the transform qR from the plane BR to $PR(A)$. Then by realizing the inverse transform qL^{-1} and qR^{-1} using the lens system of the display, we can easily get the appropriate virtual images at the planes BL and BR.

Experiments

Experimental Apparatus

Figure 4 shows the experimental-system diagram used for the evaluation of the design concept. Only one degree of freedom, i.e. the operator's right and left head turning, is measured by the goniometer in this experimental set-up.

The turntable, where two MOS (metal-oxide-semiconductor) TV cameras are mounted, is servoed after the goniometer measurement (Figure 5). Video signals from the cameras are displayed on CRT displays of the binocular display device which can be fixed with respect to the operator by the special cross-hairs (Figure 6).

The focal length of the object lens of the TV camera and that of the eye lens of the binocular display apparatus can be changed.

Evaluation Experiments

It is found that the so-called visual space has a uniquely determined non-Euclidean metric, or psychometric distance function, the numerical parameters of which depend on the individual observer.[9]

These parameters of visual space can be measured, for example, in a dark room with the observer's head and therefore approximately also the rotational centres

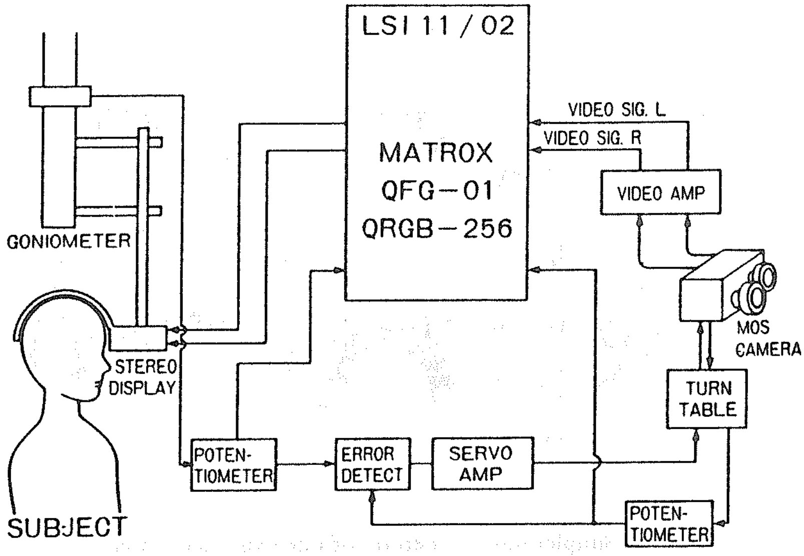

Figure 4 Schematic diagram of the experimental system

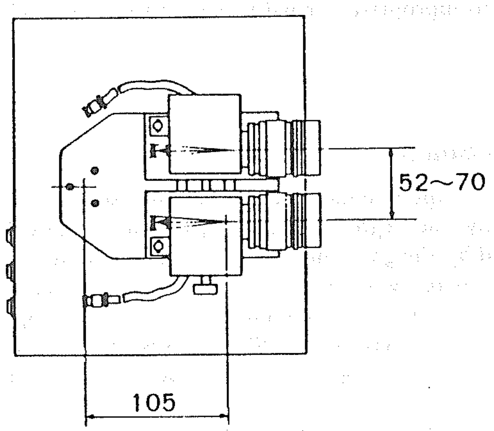

Figure 5 MOS TV cameras mounted on a turntable

of her/his eyes, fixed by means of a head rest[10] and precisely measuring the individual parameters of the Helmholtz horopter.[11]

Figure 7 shows an example of Helmholtz horopter. An observer, placed into the above described position, is given the task of arranging a number of light points (three in this case) so that they appear to lie on a horizontal straight line, symmetric

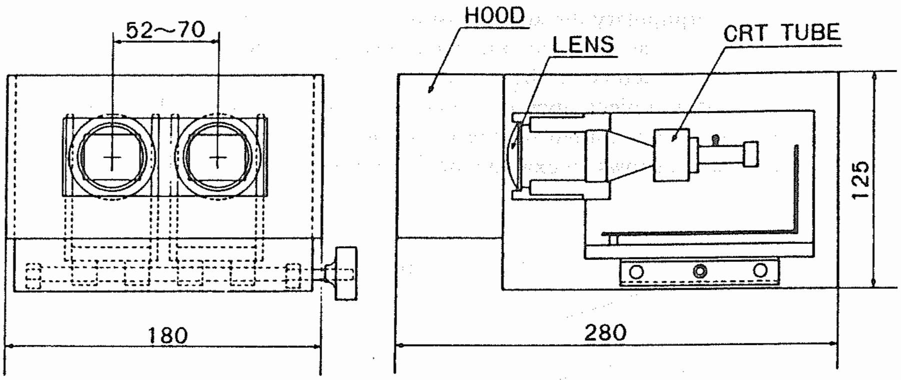

Figure 6 Binocular visual-display apparatus

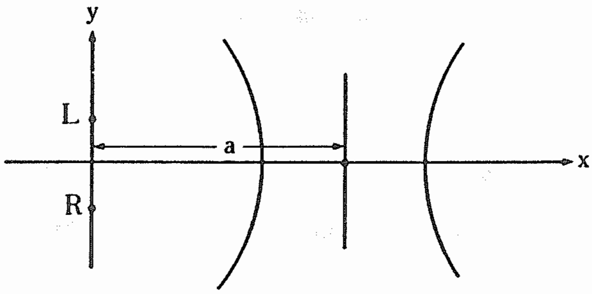

Figure 7 Helmholtz horopter curves for different fixations

to the median plane. It is found that the points are set consistently on certain physical curves which are, in general, not straight in the physical sense. The form of these so-called horopter curves depends on the distance x of the centre point. At a certain distance $x = a$ the horopter is practically straight. At nearer distances, $x < a$ the horopters are concave to the observer; at greater distances, $x > a$, they are convex. These horopter curves can be described as follows:[10,12]

$$\frac{\cosh[\sigma(\gamma+\mu)]}{\cosh[\sigma(\gamma_0+\mu)]} = \cos\varphi$$

where angle γ is the bipolar parallax, approximating to the convergence angle, and angle φ is the bipolar latitude in x-y space, γ is the co-ordinate of the intersection point of the horopter with x axis and σ and μ are individual parameters of the horopter. Angle γ and angle φ, in terms of Cartesian co-ordinates, can be expressed with sufficient accuracy as

$$\gamma = \frac{p\cos^2\varphi}{x}$$

$$\tan \varphi = y/x$$

where p is the interpupillary distance measured in centimeters.

In the design of the realistic binocular display of the tele-existence system, these individual parameters of the binocular visual space, i.e. σ and μ, were used. First, σ and μ of a subject operator under the condition that s/he sees directly with naked eyes were measured by the three-rod Helmholtz frontal-plane horopter experiment. Figure 8 shows an example of the results.

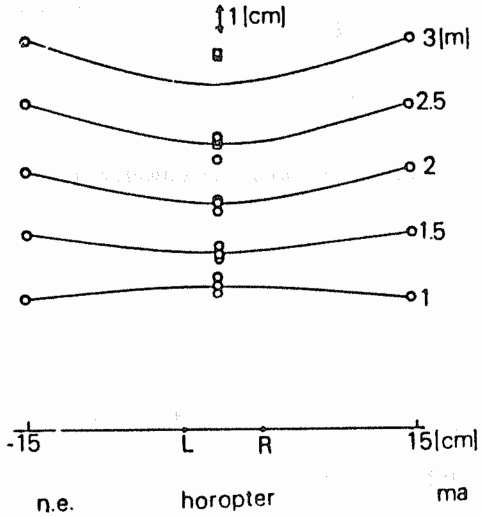

Figure 8 An example of the results for direct observation

Next the same experiments of the horopter were repeated under the condition of indirect observation with the tele-existence system for several values of object lens and eye lens focal lengths. Figure 9 shows an example of the experiments observed through tele-existence system. These experiments reveal that the optimal focal lengths are functions of the distance between the object and the TV cameras.

Figure 10 shows an example of the results for the distance of 2m. In this example, the condition that object lens focal length o = 13mm and eye lens focal length e = 50mm gives the best result in a sense that the parameters are almost the same.

This supports our design concept that the best display can be obtained by servoing not only the convergence but also the image size by controlling the focal length of the eye lens. A new test hardware with the ability to exercise such control is now being designed and experiments made on trial.

Conclusions

(1) The concept of tele-existence, advanced type of teleoperator with real-time

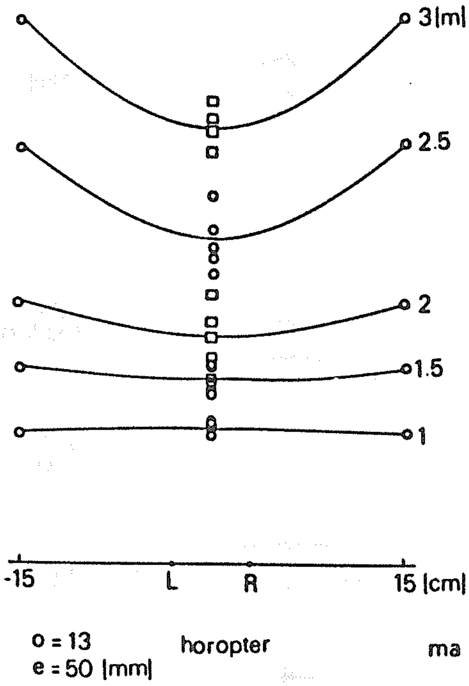

Figure 9 Indirect observation

sensation of presence by using robot technology, was proposed and evaluated.

(2) A design method of binocular display with sensation of presence was proposed.

(3) A binocular monochromatic display system with one degree of freedom of movement was made on trial according to the design procedure of (2).

(4) A psychophysical experimental method using the measure of visual space to evaluate the correspondence between directly observed visual space and visual space observed indirectly through the tele-existence system was proposed.

(5) Evaluation experiments were conducted by using the horopter measurement method as proposed in (4).

(6) The results showed a good correspondence between direct visual space and indirect visual space through tele-existence system, if the display conditions are appropriate.

(7) Further experiments are being planned with a new experimental system with binocular colour display with six degrees of freedom of movement.

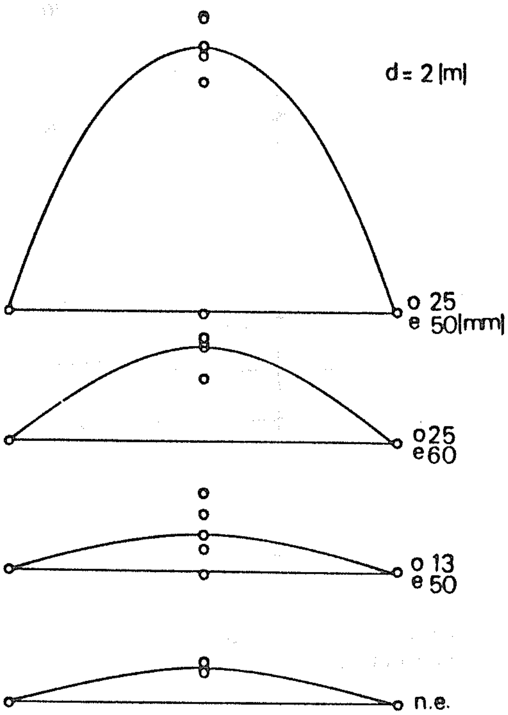

Figure 10 Horopter curves

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