

Paper:

Design and Evaluation of a Visual Display with a Sensation of Presence in Tele-existence System

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[Received December 18, 1996; accepted January 24, 1997]

It is quite desirable for an operator at the remote controls to have a real-time sensation of presence as if he or she were in the remote anthropomorphic robot and to be able to maneuver it dexterously. This concept is called TELE-EXISTENCE. Realization of a visual display with a sensation of presence is one of the most important elements of this tele-existence. In this paper a method is proposed to realize a tele-existence display and its design procedure is explicitly defined. Experimental display hardware was made, and the feasibility of the visual display with a sensation of presence was demonstrated by psychophysical experiments using the test hardware.

Keywords: Tele-existence, Telepresence, Design principle, Visual display, Virtual reality

1. Introduction

The so-called "remote control technique" used in skillfully manipulating a machine arm (manipulator) in a remote location is called teleoperation. This concept was created along with the technology for the manipulators used in atomic power plants and in the development of power artificial limbs for amputees. In the teleoperator, the control system from man to machine is emphasized, but the sensation feedback from machine to man exists only to the extent of transmitting force information back to the operator in the form of symmetry or force feedback. So, it has not been possible to carry out work while having a sensation of presence by integrating all the sensations of working at a certain place, such as the sensations of vision and touch.

In the case in which a robot is made to work in an environment which is too dangerous for humans, it is desirable that its operator be able to carry out the task while experiencing the conditions of the work site and while having the sensation of presence, as if the human were actually at the robot's location. In recent years, studies have intensified on making the sense feedback, from machine to operator, high in presence sensation. This is often referred to as telepresence^{1,2)} or tele-existence^{3,4,5)}.

One of the important components for realizing such a system may be a real-time system capable of faithfully displaying the conditions of the environment where the robot works or the state of the robot in such a way that person feels as if he or she were together with the robot.

In this paper, a system is proposed which can display

visual information based on the sensation of presence, and its design method is clarified. In addition, based on the design method, a visual information display device is studied and its prototype is constructed. Then it is verified that the new prototype can generate the sensation of presence by evaluating its effect quantitatively through a psychophysical experiment.

Incidentally, in this paper, the remotely positioned robot is assumed to be as similar to humans, in shape and size, as possible, unless otherwise noted.

2. Basic Design of Tele-existence Visual System

Figure 1 gives the configuration of a basic tele-existence system, and a concrete method for the configuration of visual display based on the sensation of presence is explained.

Figure 1(I) shows the principle of the recording and reproduction of wave fronts in holography as conceived in the past. In other words, a closed surface is created so as to surround the remote robot, and the wave fronts entering that area are recorded at multiple points on the enclosure surface. These wave fronts are then transmitted to the location of the remote operator, and the wave fronts are reconstructed using a reproduction device on a similar enclosure surface surrounding the operator. However, this method alone would make it difficult to realize tele-existence for the following reasons:

(1) If the recording and reproduction device were to

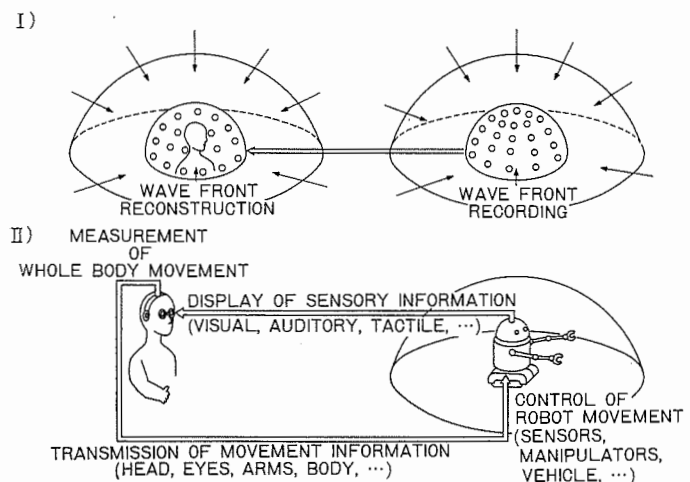


Fig. 1. Concept of wave front reconstruction (I) and tele-existence display (II).

constructed so as to reconstruct the actual environment it would be too large to be practical. In addition, in holography, the recording and reproduction of real-time information cannot be achieved with the available technology.

(2) Display of a distant background scene may be approximated by a large, two-dimensional screen, but technically, it is extremely difficult to reproduce nearby objects in actual size, three-dimensionally, and in real time without being occluded by real objects.

(3) In particular, the actual sensation of presence cannot be achieved if the hands of the operator at a place different from those of the robot. In tele-existence, the hands of the operator must be seen where those of the robot ought to appear. However, the realization of such a state is generally difficult by the use of this method. As a consequence, it is not possible to acquire the true sensation of presence based on the fact that the relationship among the background scene, the task at hand, and the hands of the robot would not produce the effect of the operator being inside the robot or being, instead of the robot, at the place where the robot is.

Figure 1(II) shows the method of configuring tele-existence based on robot technology and the human sensory structure to be proposed here. According to the method in (I), an attempt is made to reproduce all the wave fronts at the same time. But, it is not necessary to reproduce all the wave fronts at the same time, in view of the working of the human visual perception. The basis of human visual perception is a pair of images focused on the retinas, and the wave fronts received by a person as retina images at a given instant are only parts of the total wave fronts. These wave fronts change in real time with the movements of the person's head and eyes. The person then creates, inside his head, a three-dimensional world based on two images that change with time, and projects it onto a place where that object really exists.

As a result, if it is possible to measure the movements of a person's head and eyes faithfully, in real time, to move the head and the eyes of the robot in line with those movements, to transmit to the human side the pair of images created in the visual input device of the robot at that time, and to recreate these images accurately without a time delay, on the person's retinas using a suitable display device. Then, that person can receive retina images equivalent to those seen directly by the robot. In other words, using these images, the person can create inside his or her head a three-dimensional world equivalent to the one seen directly at the place where the robot exists and then project it again into the real world.

Thus, by scanning partial wave fronts continuously using a human motion measurement device and a system consisting of a display device and a slave robot, a recording and reproduction device can be produced that is small enough to be realistically configured, so problem (1), presented above, can be solved.

In addition, this method creates a state in which visual information of the direct observation on the human side is shielded and instead, visual information from the remote robot is displayed as if he were there. Moreover, as the movements of the man's hands and torso are measured faithfully and this information is used to move the manipulators and body of the robot, when the operator manipulates his own hands in front of his eyes, a configuration becomes

possible in which the robot hands appear in front of its eyes in the same position.

As a result, problems (2) and (3), which are present in the conventional display, (I), can also be solved.

3. Design of Visual Information Display System

Figure 2 shows the method of configuring an ideal visual display system. Two cameras are placed at the same distance a as that between the eyes of a person. The input mechanism loaded with these cameras is controlled in conjunction with the movement of the person's head, as stated previously.

First, the movement of a person's eyes is measured, as illustrated in I, and in conjunction with this information, the convergence angle θ_r of the cameras and the convergence angle θ_h of the CRT display device are controlled so as to obtain $\theta_r = \theta_h$. At the same time, X_r is determined, so that the cameras are focused. In the display section, the lens system situated in front of the CRT is controlled so as to obtain $X_h = X_r$ for the position of a virtual image of the CRT and $I_h = I_r$ for the size of the image.

There are three parameters acting when a person perceives space monochromatically: (1) the tension and relaxation of the crystalline lens controlling the muscles; (2) the size of retina images; and (3) the convergence angles of the two eyes. In the event that the ideal system in Fig.2 is used, the values of parameters (1) to (3) above, for the perception of the person using the system, are equal to those of parameters (1) to (3) in direct observation, respectively. As a consequence, the ideal system can receive the same visual information as that in direct observation.

Next, an attempt will be made to simplify the ideal system. An investigation of the features of a person's perception makes it clear that as for (1), if the crystalline lenses are fixed at 200mm, the natural fusion of the images takes place in a convergence range from 100 to 500mm and that if it is fixed at 1m, the fusion corresponds to a convergence range at from 200mm to infinity. As a result, the sensation of presence is not lost, even if the distance X_h in the image

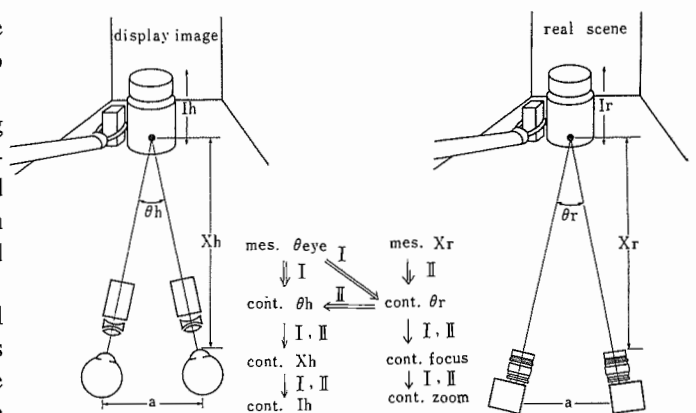


Fig. 2. Ideal visual display method of tele-existence system.

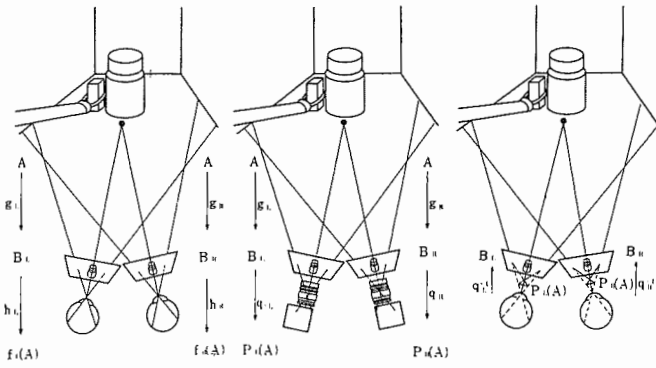


Fig. 3. Simpler visual display method of tele-existence system.

displayed in Fig.2 is constant at $X_h = 1m$. This fact was verified during an experiment on space perception by the present authors⁴⁾.

If the display distance is fixed at 1m, then there remain only two variables that need to be controlled: the size of retina images and the convergence angle of the eyes, so the device can be simplified. This simplification is illustrated in Fig.3. The focal distances of the cameras are set at those values obtained when a person's eyes look 1m ahead, and the images obtained by the cameras are denoted by $P_L(A)$ and $P_R(A)$. Then the only thing that needs to be done, using inverse transformations q^{-1}_L and q^{-1}_R of transformations q_L and q_R from B_L and B_R into $P_L(A)$ and $P_R(A)$, is to reconstitute the virtual images, B_L and B_R , in front of a person's eyes, as shown in Fig.3.

The actual design method based on the above method of recomposition is presented in Fig.4. Figure 4(a) shows the characteristics of direct observation by a human. The distance between the person's eyes is denoted by W_m and the distance from the center of the crystalline lenses to the retinas by a_m . Now, if by observing an object with a size l_{obj} located at a distance d_{obj} from the observer a convergence angle α and a size l_m of an image of the object on the retinas can be obtained, then the distance and size of the object can be determined, using the known parameters and observation values, as follows:

$$d_{obj} = \frac{W_m}{2} \cot\left(\frac{\alpha}{2}\right) \dots \dots \dots (1a)$$

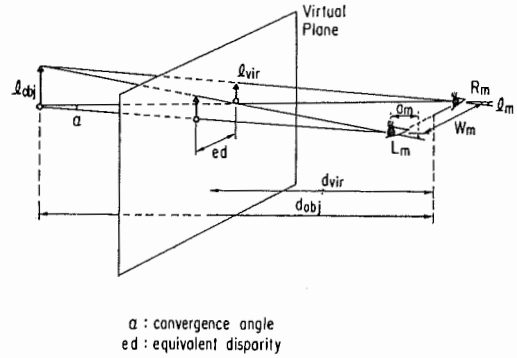
$$l_{obj} = d_{obj} \cdot l_m / a_m \dots \dots \dots (1b)$$

Now, a plane vertical to the observation direction, located at a distance d_{vir} forward of the observer, is considered in place of the actual image, and by carrying out the perspective transformation of an observed object, with its projection center at the center of the crystalline lenses, on that virtual plane, its size is denoted by l_{vir} and the shift of the left and right transformed images on the virtual plane (equivalent disparity,) by e_d .

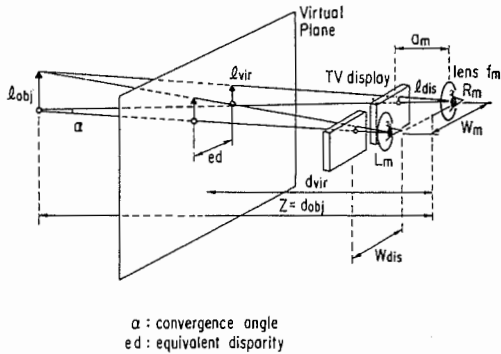
Using these symbols l_{vir} and e_d , Eq.(1) can now be rewritten as follows:

$$d_{obj} = W_m \cdot d_{vir} / (W_m - e_d) \dots \dots \dots (2a)$$

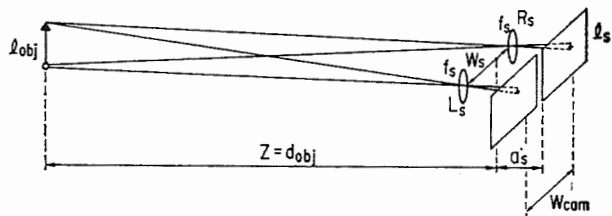
$$l_{obj} = d_{obj} \cdot l_{vir} / d_{vir} \dots \dots \dots (2b)$$



(a) Visual parameters of direct observation.



(b) Visual parameters of tele-existence display.



(c) Visual parameters of the slave robot.

Fig. 4. Design parameters of a visual display with a sensation of presence.

That is to say, instead of placing an object of a size l_{obj} at a place d_{obj} in reality, a perspective-transformation image l_{vir} of l_{obj} is placed e_d away on the virtual plane located at a distance of d_{vir} . If, at this time, the distance d_{vir} is fixed so as to be able to ignore the effects of the muscular tension and the relaxation of the crystalline lenses, then it is possible to obtain the same effect as that for the time when an object is actually observed.

Figure 4(b) shows a method for realizing the configuration in Fig.4(a). Figure 4(c) shows the configuration of the TV camera system on the side of the robot (slave) used for obtaining the image displayed on the TV at that time. The distance W_s between the lenses of the two TV cameras on the slave side is set equal to the distance E_m between the two eyes of the person (master).

$$W_s = W_m \dots \dots \dots (3)$$

The distance W_{cam} between two imaging elements (such as CCDs, etc.) of the TV cameras and the central distance W_{dis} between a pair of TV monitors are made to equal W_s . Even though different physical dimensions are involved, it

is possible to satisfy the conditions of Eq.(4) equivalently using an optical method or by an electric method involving scanning line processing, etc.

$$W_{cam} = W_{dis} = W_s \dots \dots \dots (4)$$

Under these conditions, the image enlargement ratio β (as a function of d_{obj}) and γ are defined as follows:

$$\beta \triangleq [l_{dis} / l_{obj}]_{at\ d_{obj}} \dots \dots \dots (5a)$$

$$\gamma \triangleq l_{dis} / l_s \dots \dots \dots (5b)$$

where l_{dis} is the size of the image on the TV display and l_s is the size of the image on the imaging plane of the camera. Now, if the distance between the lens of a camera with the lens at a focal distance f_s and the imaging plane is given by a_s ($f_s \cdot d_{obj} / (d_{obj} - f_s) \approx f_s$), then the TV display must be placed at a location a_m in front of an observer so as to satisfy Eq.(6) (refer to Appendix A):

$$a_m = \beta \cdot d_{obj} \dots \dots \dots (6a)$$

$$a_m = \gamma \cdot a_s \dots \dots \dots (6b)$$

Moreover, the images of the TV display are moved onto the virtual plane by placing a convex lens at a focal distance f_m in front of the eyes of the observer. In other words, f_m is used which satisfies Eq.(7):

$$f_m = \frac{a_m \cdot d_{vir}}{d_{vir} - a_m} \dots \dots \dots (7)$$

4. Production of Visual Information Display System Prototypes

4.1. Visual Information Display Unit

Two types of color display units were created on a trial basis. One was created with special emphasis on the image quality using 4-inch color CRTs; the other was intended to be lightweight and made use of 1.5-inch color CRTs. Each of these units uses MOS type semiconductor color cameras as its input cameras. The focal distance can be set arbitrarily between 12.5 and 75mm according to a computer command. The iris diaphragm can be adjusted automatically. **Figure 5** shows the 4-inch configuration, while **Fig.6** illustrates the 1.5-inch configuration. The values of β for $f_s = 12.5$ mm are 0.16 and 0.053, respectively. In addition, the values of γ are 12.9 and 4.25, respectively. As a result, the optimum parameters are determined by setting $a_m = 161$ mm and $f_m = 192 \approx 190$ mm for the 4-inch system and $a_m = 53$ mm and $f_m = 56 \approx 60$ mm for the 1.5-inch system. Furthermore, in the case of the 1.5-inch system, its convergence angle is controlled by signals from the computer. Incidentally, the weights of the displays of the 4-inch and 1.5-inch systems are about 10kg and 6kg, respectively.

4.2. Experimental System for Visual Information Dis-

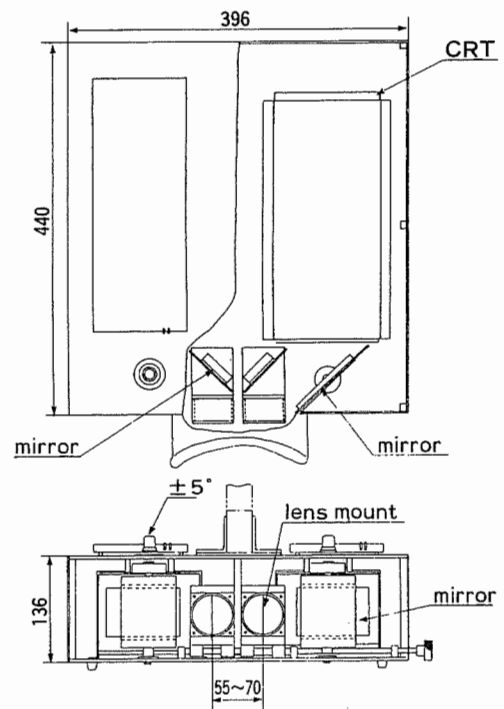


Fig. 5. Display employing 4 inch color CRTs.

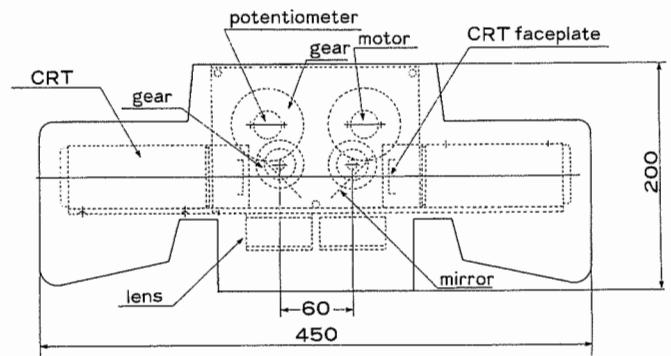


Fig. 6. Display employing 1.5 inch color CRTs with servo-controlled convergence mechanisms

play

Figure 7 shows an outline of the experimental system. The movement of the person's head is measured using a goniometer with six degrees of freedom fixed on the helmet, and put through coordinate transformation into the computer. On the basis of this information, the active visual display unit also with six degrees of freedom, is coordinated to the movements of the person. At the same time, the input mechanism, a pair of cameras with six degrees of freedom, is also coordinated to the movements of the person. However, the present system has one degree of freedom omitted.

The multi-degree-of-freedom display system is composed of a goniometer for measuring the movement of the head, with six degrees of freedom, and a master-slave type display device for minimizing the feeling of the head constraint.

One of the problems that arises when the degree of freedom of the head movement to be measured is increased, is

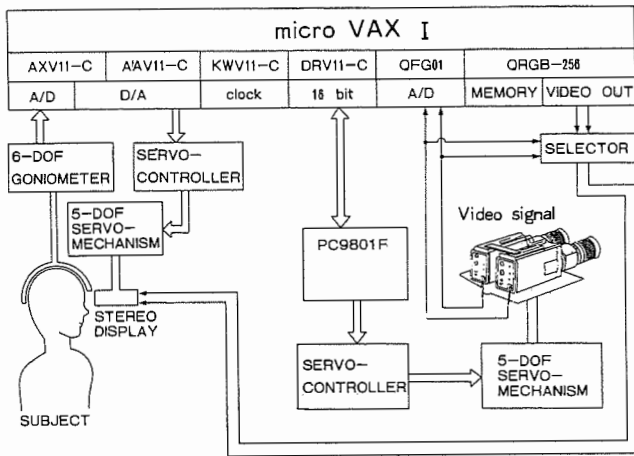


Fig. 7. Schematic diagram of the experimental system.

the feeling of constraint due to the weight of the display unit. An experiment has already been carried out with one degree of freedom, and the feeling of constraint due to the inertia of the display unit was an issue. The one-degree-of-freedom experimental apparatus was configured to allow rotation of the unified body of the goniometer and the display unit horizontally using the power of the neck⁴). The weight of the display device (about 4kg) was supported on a rotating axle, but considerable power was required for rotating and stopping the display device; it was feared that the sensation of presence would be damaged due to the feeling of constraint by the band in the head section. Here, since measurements are made of not only left and right rotations, but also back and forth vibrations, it is necessary to move the display device up and down in conjunction with these movements. If the force of inertia and gravitational force acting on the display device are to be supported by the neck, the burden on the neck increases further due to an increase in the weight of a display system which had been made to display color. Under these circumstances, the test device created here has a separate display device and goniometer with an actuator on the side of the display device, so that the burden on the neck comes entirely from the goniometer. This is a type of master-slave system in which the display device moves in conjunction with the movement of the head, measured with the goniometer in real time. However, since the goniometer and the arm of the display device must be positioned so as to overlap almost completely, it is difficult to make the shapes of the goniometer and the display device identical. In addition, the position and direction of a single point on the head section, measured with the goniometer, are not necessarily identical to the position and direction of the display device. For this reason, it is necessary to calculate coordinates that put the detector on the master side and the actuator on the slave side in a one-to-one correspondence.

A general view of the apparatus is given in Fig.8. The goniometer has a very small frictional resistance (less than 10gf) in the horizontal direction, since it has a horizontal, two-link mechanism. The weights of the helmet and the

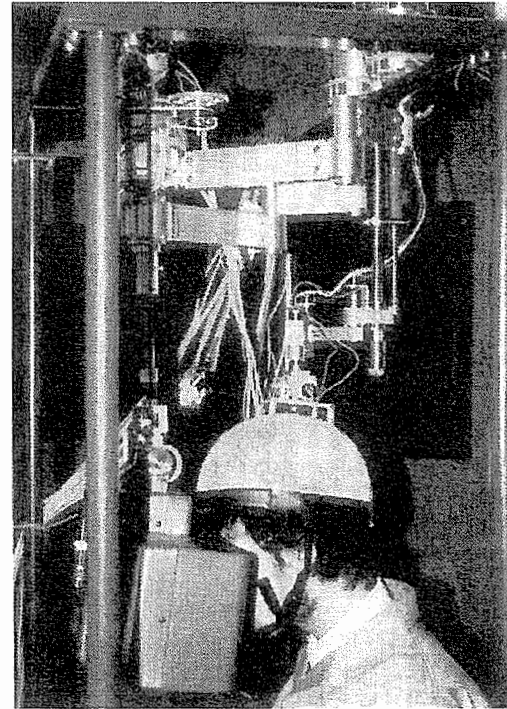


Fig. 8. General view of the experimental hardware. Goniometer with six degrees of freedom (right) and servo-controlled display mechanism with five degrees of freedom (left).

goniometer (1.4kg) are compensated, for using a spring. A total of six degrees of freedom in terms of position and posture, can be measured.

As for the display unit driving mechanism, it has five degrees of freedom, the rotational movement around the line of vision is omitted because it has nothing to do with the field of vision. With the use of a 5-joint link, the structure was made symmetric with respect to the left and right sides, and the effect of the gravitational force was made easy to compensate for by movement in the horizontal direction being independent of the vertical movement. Direct drive was achieved using a torque motor, by Inland Corp., as an actuator.

5. Evaluation of the Visual Information Display Unit

5.1. Horopter and Its Expression

The most important point in evaluating a visual display device is that the psychological visual space, as seen directly by the viewer, be in a one-to-one correspondence with the psychological visual space, as seen through the visual display device. As one of the methods for investigating this quantitatively, a method is proposed whereby the psychological visual space is approximated as a Riemann space of constant curvature and then its parameters are compared between the case of observation through the device and the case of a direct observation.

As shown in Fig.9(a), a horizontal plane at the height of the eyes of the observer is considered, and the x-axis is

defined as the forward direction inside that plane; the a y-axis is in the direction, across the face of the observer, and perpendicular to the x-axis. Here, *L* and *R* express the positions of the left and right eyes of the observer.

The head of the observer is fixed so as not to move at all in a state where no stimuli are present, such as inside a dark room, and multiple small points of illumination are presented on the horizontal plane mentioned above in front of the observer.

An attempt is made to rearrange those small illuminated points so that they are seen by the observer to be parallel to the facial plane, that parallel with the y-axis. It is not always the case that those points arranged physically in parallel are observed to be parallel, psychologically; a physical arrangement that appears to be parallel, psychologically, is seen differently depending on the distance from the observer to that parallel line.

That is to say, at a certain distance *a* from the observer,

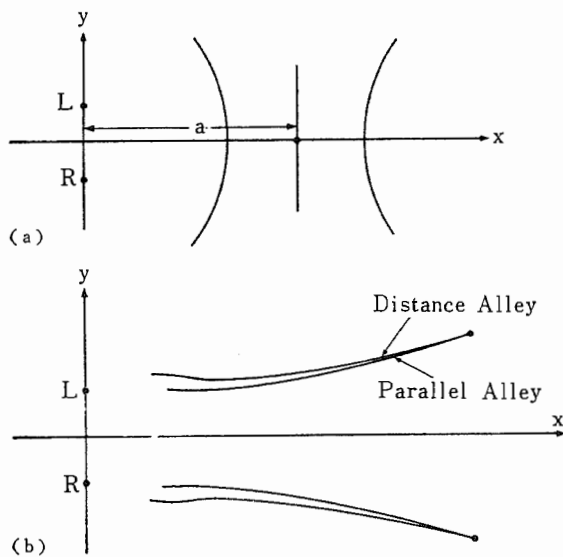


Fig. 9. Helmholtz horopter curves for different fixations (a), and distance and parallel alleys (b).

a physically straight arrangement is also observed psychologically as a straight line parallel to the facial plane, but at a longer distance, an arrangement on a convex line, relative to the observer, is observed as a straight line. On the other hand, at a closer distance, an arrangement on a concave line, relative to the observer, on the contrary, is observed as a straight line. Such curves are called Helmholtz horopters.

Figure 9(b) shows a physical arrangement that appears parallel with the x-axis, and is called Hildebrand's parallel alley. In addition, an arrangement of two points alley equidistant from the y-axis shows a different result from a parallel arrangement, and is called Blumenfeld's distance alley.

Such horopters and alleys show the same tendency regardless of who the observer is. Moreover, the specific forms of the horopters and alleys are, needless to say, different to different observers, but as long as a single person is involved, they are always constant.

Figure 10 shows a schematic of the process of mapping from the physical space coordinate system to the psychological visual space. Now, if an investigation is conducted in order to find out whether a difference exists between the transformations in direct observations and those via a dis-

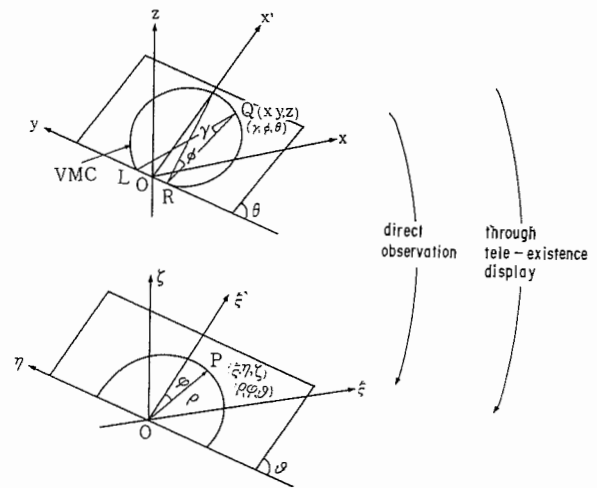


Fig. 10. Mapping from physical space (bipolar coordinates) onto visual space (polar coordinates) for direct observation and through tele-existence display with various display parameters.

play system, such as in a tele-existence system, then that display system can be evaluated. In other words, by comparing the results of horopters and alleys in direct observations with those obtained by observations via a tele-existence display system, that display system can be evaluated.

There are two ways to express horopters and alleys: over a psychological space, or directly over a physical space. The Euclidean expressions of horopters and alleys, in a psychological space, can be approximated using the following equations, after setting the coordinate system of the psychological visual space to (ξ, η, ζ), as shown in Fig.10, and assuming among the variables in the diagram that φ = φ, θ = θ, and ρ = 2exp(-σγ)⁶⁾:

$$\frac{K}{4}(\xi^2 + \eta^2) - 1 = A\xi \dots \dots \dots (8a)$$

$$\frac{K}{4}(\xi^2 + \eta^2) - 1 = B\xi \dots \dots \dots (8b)$$

$$\frac{K}{4}(\xi^2 + \eta^2) + 1 = C\eta \dots \dots \dots (8c)$$

The expressions indicated by Eq.(8) are those of horopters in a psychological visual space, and are effective in showing that a visual space is a non-Euclidean space, particularly the hyperbolic space of Lobachevski and Bolyai⁶⁾.

However, these expressions are defective in that their meanings are hard to comprehend intuitively, and also that estimation of the parameters *K*, *A*, and *σ* is not stable in general unless a fairly large number of points are measured.

The other expressions of horopters are based on a method for describing horopter curves themselves in a physical space. In general, they can be described as a group of *f*(*x*, *y*) = 0 curves.

In this case, an experiment in horopter measurement is carried out as described below. By using three illumination points, the ones at the two ends are fixed on a straight line, parallel to the facial plane, and the one in the center is moved to where it appears to be exactly on that straight line. In other words, with *x* = *r* denoting the distance from the

facial plane to the measurement point, the coordinates of the two points are fixed as $(r, -y_0)$ and (r, y_0) , where y_0 is positive. Next, the x coordinate of the small illumination point in the center is adjusted, so that at a point $(\bar{x}, 0)$ the three points are assumed to be on a straight line. Then

$$\Delta x = \bar{x} - r \dots \dots \dots (9)$$

where Δx is a function of x ; by using this $\Delta x(r)$, the horopters can be expressed. In actuality, $x_i (i = 1, \dots, n)$ are obtained, and $(\bar{x} = \sum_{i=1}^n x_i/n)$ is used.

In the present experiment, the horopters are evaluated quantitatively by using Δx of Eq.(9).

5.2. Experiment

Using two small light-emitting diodes, or LEDs, (3mm in diameter) inside a dark room, small illumination points are created, and arranged so that $y_0 = 150\text{mm}$ at points $(r, -y_0)$ and (r, y_0) . Here, r can be 1, 1.5, 2, 2.5, or 3m, and in each case, a third LED is placed in the center given by $(x, 0)$.

The central LED is placed on the x - y table whose position can be controlled, so that an operator can move the position of the LED freely by controlling the x coordinate.

A subject with his head fixed by means of a head rest, measures his a horopter by adjusting the x coordinate of the central illumination point so as to ensure that the three illumination points are put on a straight line parallel to the y -axis.

Using the same conditions, this experiment is carried out for the case of direct observation and for the case of observation via a display system.

Figure 11(a) shows examples of the experiments on horopters through direct observation, while Fig.11(b) gives examples of the results of the horopter experiments conducted by fixing the convergence angle of the display so as to make it equal to the convergence angle of direct observations at 2m. The symbols \circ and \square indicated in the central section of the diagram show the measurements. The horopter curves shown were obtained by connecting the average values of the measurements and the two ends by

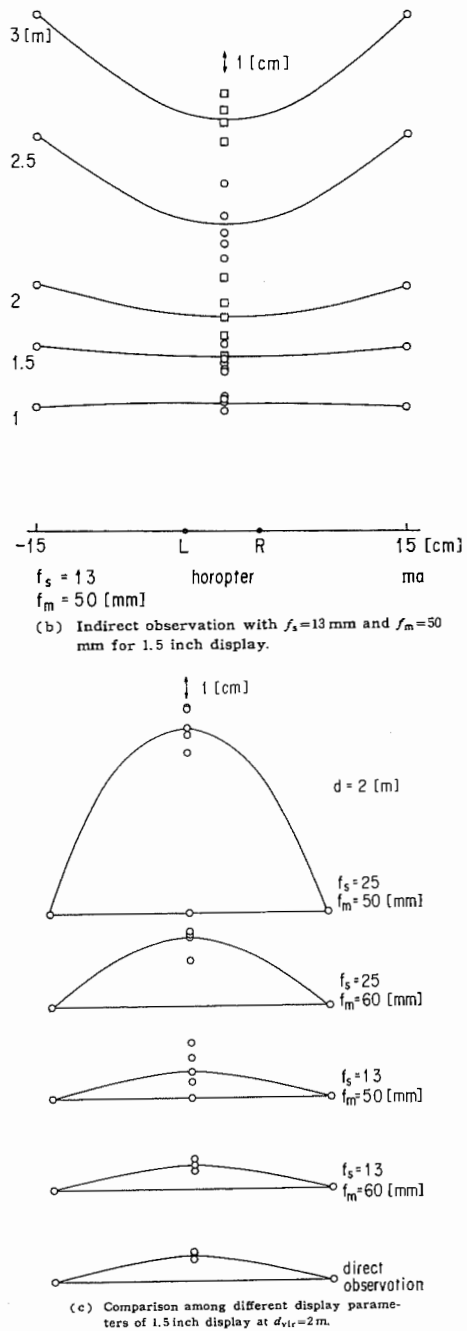
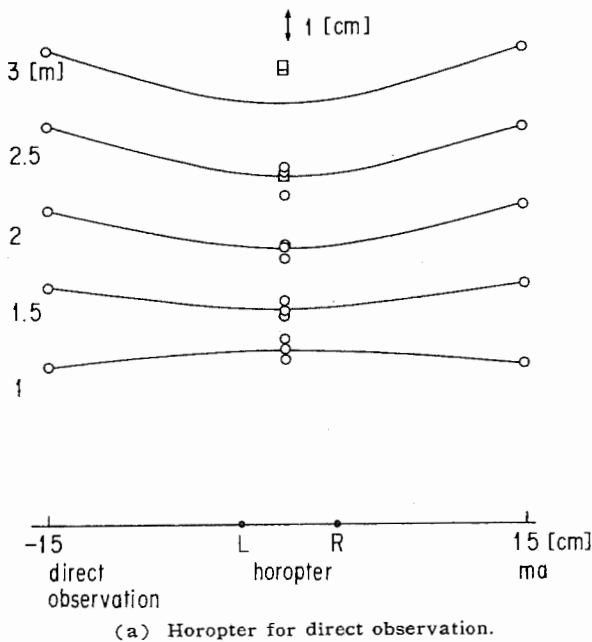
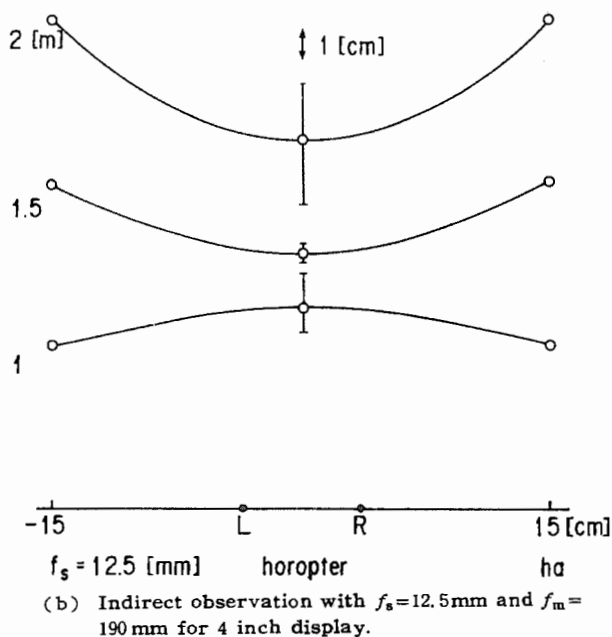
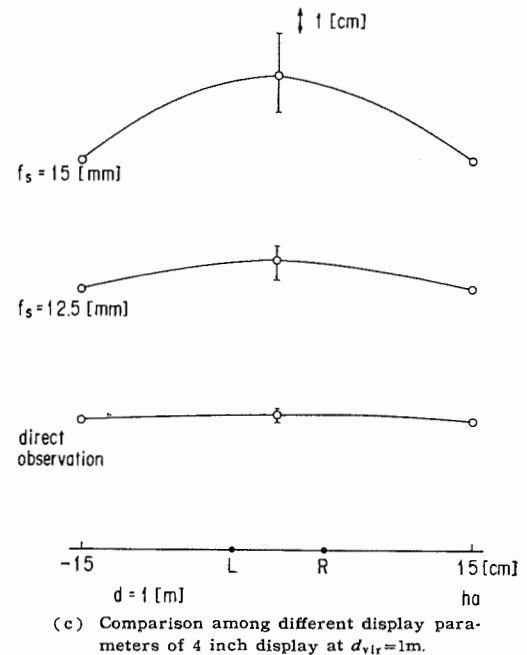
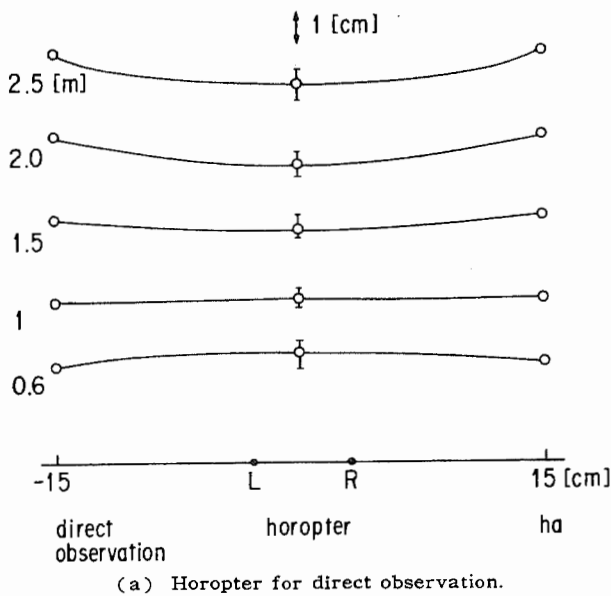


Fig. 11. Experimental results for $d_{vir} = 2\text{m}$ (subject ma).

means of smooth curves symmetric with respect to the x -axis. For the display purpose, the 1.5-inch system was used. Since $d_{vir} = 2\text{m}$ and $a_m = 55\text{mm}$, so the optimum parameters for tele-existence are given as $f_s = 13\text{mm}$ and $f_m = 57\text{mm}$. Because the convergence angle is adjusted for 2m, if there is any shift from that point, the horopters are found to be different from the one based on direct observation. Figure 11(c) compares the horopters obtained at an observation distance of 2m at various display parameters. It is seen that when the focal lengths of the eye piece and the objective lens are varied from their proper values, the size of the images on the retinas changes, or when the convergence angle varies, the horopters shift from the one for direct observation. The variance of data increases accordingly.

The relationship between the focal lengths of the eye-piece and the objective lens, which the horopter pattern best



matches the one for direct observation, is the relationship determined by the design method in Chapter 3, namely that $f_s = 13mm$ and $f_m = 60mm$. In this case, $\Delta x(r = 2m) = 11mm$ is the same as 11mm for the direct observations; thus the present design method is shown to be valid. Incidentally, for f_m , even if it is 50mm, as long as f_s is 13mm, then the average value is $\Delta x = 12mm$, which is nearly in agreement with the value for direct observation, so not much trouble is expected in practice.

Figure 12 indicates the various results in the case in which the observation distance is set at 1m. A set of five displays each is given; their average is shown by the symbol \bigcirc , with a vertical bar indicating the upper and lower limits and, therefore, the range of data variation. For this experiment, the 4-inch display was used. Since the optimum display conditions are $d_{vir} = 1m$ and $a_m = 262m$, so $f_s = 12.5m$ and $f_m = 190mm$. With f_m fixed at 190mm, f_s was varied from 10 to 12.5, 15, and 20. As a result, $\Delta x(r = 1m)$ assumed values -15, 13, 32, and 40mm, respectively. It is thus

Fig. 12. Experimental results for $d_{vir} = 1m$ using 4 inch display (subject ha).

clear that when the focal length f_s of the lens on the camera side is 12.5mm, the results most closely approached the $\Delta x = 3mm$ of the horopter of direct observation. In addition, the data variance is small for the case of 12.5mm.

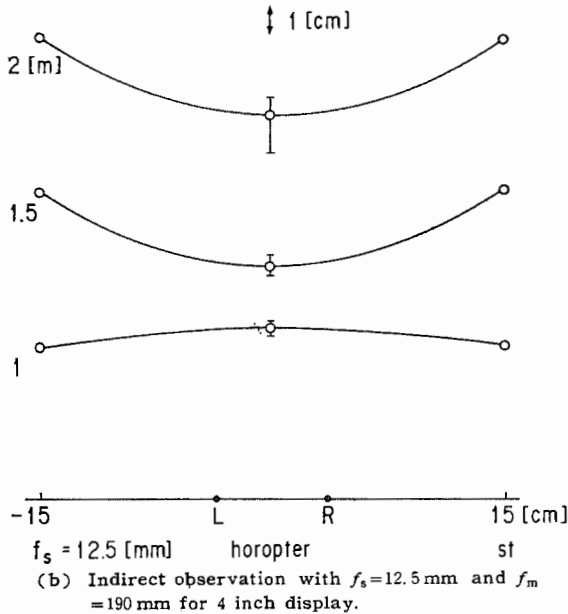
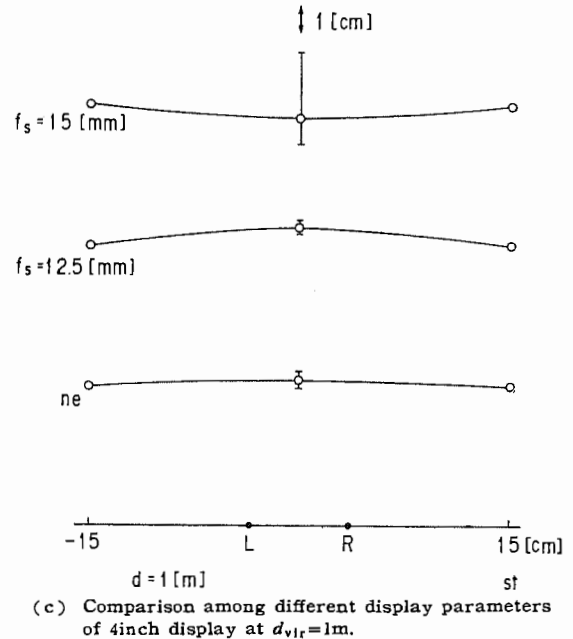
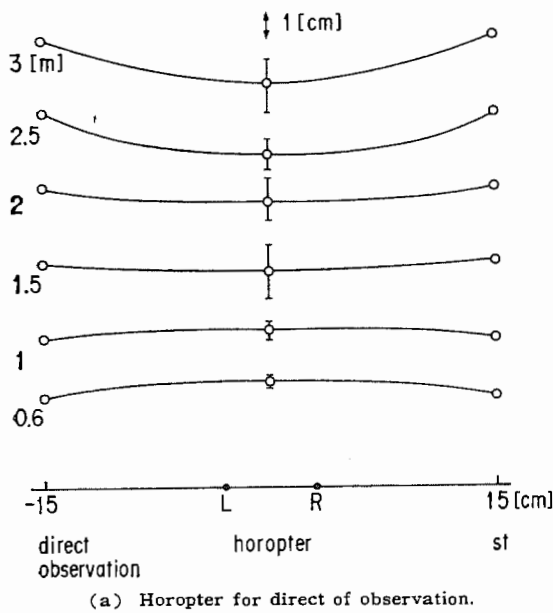
Figure 13 shows the results obtained by another operator, who also obtained the best results at $f_s = 12.5mm$, which assumed values closest to Δx for the direct observation and for which the data variance was small. It is shown by these experiments on horopters that in terms of the recognition of space, the tele-existence design method is valid.

It should be pointed out here that although these results were obtained for a horizontal plane in front of the face, even when the display plane was off horizontal, it was possible to obtain horopters, which could be regarded as equal to those for direct observation, as long as the angle of elevation was within ± 10 degrees.

Moreover, if the display range is wider, the head must necessarily move. In the test system created in Section 4, whenever the head faces the direction, the slave camera system faces the same direction accordingly. So, as long as the central section of the field of vision is considered the conditions supporting the data within the horizontal plane are maintained, and the same state as that of direct observations can be ensured for a wide range.

6. Conclusions

An effort was made to find conditions under which the convergence angle and the visual angle, with respect to the direct observation, could be maintained during observations using a tele-existence system with robot cameras and the display system. On the basis of these conditions, test display systems were created, and a psychological visual space was measured using horopters. The validity of the proposed design method was demonstrated after comparing the horopter shapes from observations using a tele-existence system



and direct observation.

Acknowledgments

This study was carried out as part of the research and development work under the national large scale project 'Advanced Robot Technology' sponsored by the Ministry of International Trade and Industry. The authors would like to express their sincere appreciation to the successive officials in charge of this project and to all the other people involved in this large scale project.

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Fig. 13. Experimental results for $d_{vir} = 1 m$ using 4 inch display (subject st).

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Appendix A

If

$$a_m \neq \gamma a_s$$

then it is not possible to get an accurate sense of distance. Suppose now that (Fig.A-1)

$$a_m > \gamma a_s$$

Since the true position of an object is given when its image is reproduced on γa_s , so the point P generated by P_R and P_L pinpoints the true position of the object (the distance PH from the y -axis to P is denoted by z).

When the image is displayed at the position a_m , then P_R and P_L move to P'_R and P'_L , respectively, in parallel with the x -axis ($a_m = \gamma a_s + a_d$).

With the use of these points P'_R and P'_L , the position of the object created can be determined, and also this position is proved to be on \overline{PH} .

If the intersection of the extensions of $\overline{L_m P'_R}$ and \overline{PH} is denoted by P' and that of the extensions of $\overline{R_m P'_L}$ and \overline{PH} by P'' , then

$$\overline{PP'} = \frac{\overline{L_m P}}{\overline{L_m P'_R}} \overline{P_R P'_R}$$

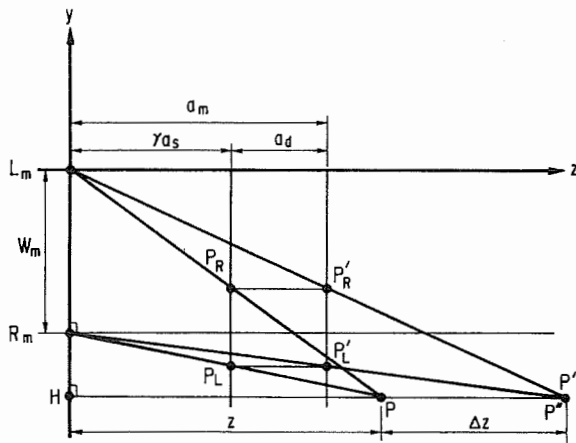


Fig. A-1

$$\frac{\overline{PP''}}{\overline{RmP_L}} = \frac{\overline{RmP}}{\overline{PlP'_L}}$$

Because

$$\overline{P_R P'_R} = \overline{P_R P'_L} = a_d$$

$$\frac{\overline{L_m P}}{\overline{L_m P_R}} = \frac{\overline{R_m P}}{\overline{R_m P_L}} = \frac{z}{\alpha a_s}$$

it is true that $\overline{PP'} = \overline{PP''}$; hence P' coincides with P'' . As a result, according to this display system, only the depth changes, and the positions of x and y remain unchanged.

If $\overline{PP'} = \Delta z$, then

$$\Delta z = \frac{a_m - \alpha a_s}{\gamma a_s} \cdot z$$

Or, the z coordinate of the object, according to this display system, is

$$z' = z + \Delta z = \frac{a_m}{\gamma a_s} \cdot z$$

Appendix B

In the event that the distance k from the lens to the eyes of an observer cannot be ignored, the display in Fig.B-1 should work well.

In this case, a_m and f_m can be given as follows:

$$a_m = \beta(d_{obj} - k) \dots \dots \dots (B-1)$$

$$f_m = \frac{a_m(d_{vir} - k)}{d_{vir} - a_m - k} \dots \dots \dots (B-2)$$

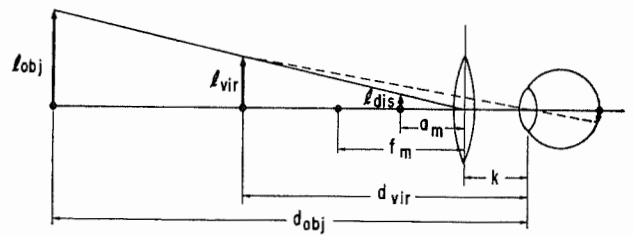


Fig. B-1

Appendix C

The features that are targeted by tele-existence are as follows.

(1) That a sophisticated sensation of presence suitable for work be obtained. The display of sensations to humans should create an extremely sophisticated sensation of presence centered on the senses of vision, hearing, and touch. This must be realized in terms of, not only the background environment and the objects, but also positional relationships between the person's hands, and others. In other words, what is seen in a tele-existence system is not the hands of its operator, but should rather be the hands of the robot as if they were in the place where the hands of the operator are. In addition, such robot hands should be dexterous enough to be able to carry out tasks just as well as human hands.

(2) That the remote robot be an intelligent robot with autonomous capabilities (alter ego of its operator). Unlike conventional remote controls, the robot itself should be autonomously functional, able to carry out routine work without an operator, and able to shift into the tele-existence mode, as a result of an order to the robot or the judgement of the operator, if necessary. If this is possible, the operator would no longer needs to carry out boring tasks, and could, instead, control multiple robots at the same time.

(3) That the expansion of human capability be possible. For instance, even if one were in a pitch-black environment, one's sensory capability would be expanded so that tasks could be performed with the sensation of working in a light place and without losing the sensation of presence. In addition, a tele-existence system should possess a power scale transformation capability for that would allow the performance of heavy work, as if it were light work, without losing the sensation of presence, or a size-scale transformation capability, for example, performing surgery on blood vessels with the sensation that rubber hoses were being handled.



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