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FEASIBILITY EXPERIMENTS ON A MOBILE TELE-EXISTENCE SYSTEM

by

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SUMMARY: A method is proposed to realize a mobile tele-existence system which enables a human operator at the controls to perform remote tasks dexterously with the feeling that he or she exists in the slave mobile robot in the remote environment. A prototype system was constructed and the feasibility of the method was evaluated. The system consists of an independent mobile robot with two TV- cameras, a remote control station with visual and auditory displays with a sensation of presence, and a communication link between the human operator and the mobile robot. The effectiveness of the proposed system was evaluated by navigation experiments of the mobile robot through an obstructed space. Several display and operation methods are compared quantitatively using the time elapsed, smoothness of the travelled path and the number of collisions as the criteria for comparison.

INTRODUCTION

A typical potential use of the third generation robot [1] is to liberate humans from work in potentially hazardous working environments. These include, for example, work in nuclear power plants, undersea operations and rescue operations in disaster areas.

One robot system which can be used in these areas will be the human-robot system that consists of several intelligent mobile robots, a supervisory control sub-system, a remote operator and a communication sub-system between them.

Figure 1 shows the author's concept of a human-intelligent robot system which copes with essential work in hazardous working environments.

Planning, scheduling and task sharing by several robots can be handled by a supervisory controller [2]. Simultaneously, each robot consecutively sends a work progress report to the supervisory controller.

The reports are compiled and processed by the supervisory controller and selected information is transmitted to the human operator through visual, auditory and tactile channels. The operator gives macro commands to each of the robots via a voice recognition device.

When an intelligent robot is confronted with a task which is beyond its own capacity, the control mode is switched to the highly advanced type of teleoperation,i.e., telepresence, remote-presence or tele-existence [3,4,5,6].

We call this advanced teleoperation, TELE-EXISTENCE [5]. Tele-existence tries to enable a human operator at the controls to perform remote manipulation tasks dexterously with the feeling that he or she exists in the remote anthropomorphic robot in the remote environment.

Fundamental studies for the realization of the tele-existence system are now being conducted in the authors' division of the Mechanical Engineering Laboratory as part of the National Large Scale Project called JUPITER(JUvenescent PIoneering TEchnology for Robots), which is a research and development program of advanced robot technology for a system that avoids the need for humans to work in potentially hazardous working environments, such as nuclear power plants, under sea, and disaster areas.

In previous papers [5,6],the principle of the tele-existence display method was proposed. Its design procedure was 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.

In this paper a method is proposed to realize a mobile tele-existence system, which can be remotely driven with the auditory and visual sensation of presence. A prototype system was constructed and the feasibility of the method was evaluated. The effectiveness of the proposed system was evaluated by navigation experiments of the mobile robot through an obstructed space. Several display and operation methods are compared quantitatively using the time elapsed, smoothness of the travelled path and the number of collisions as the criteria for comparison.

SYSTEM CONFIGURATION

A prototype system with fundamental mobile tele-existence functions has been assembled for experimentation.

Figure 2 shows the schematic diagram of the experimental system. The system consists of an independent mobile robot with two TV color cameras, a remote control station with the visual and auditory displays with a sensation of presence, and a communication link between the human operator and the mobile robot.

The head movement of the human operator is measured in real time and the robot's vision system is controlled to follow the movement of the operator. The robot can be navigated either by autonomous control or by the command of the operator. The images acquired by the robot's vision system are transmitted and displayed to the operator's two eyes through head-linked CRT displays with an appropriate lens system. The two images in turn fuse to give a very natural visual sensation.

The remote station is controlled by a micro- processor (PC9801 VM2 with D-board 16 and micro-VAX II). The movement of the human operator's head and the position of the control knob and switches are measured in real time, processed by the computer, and are sent to the mobile robot via a wireless modem (HD-9600-ACH).

The mobile robot is a battery operated-three wheeled cart, which is controlled by a micro-processor (PC 9801 VM2) with a co-processor (D-board 16). Command signals are received by an on-board wireless modem (HD-9600/B-ACH) and pieces of processed information are used to control the movement of the TV cameras, direction and velocity control of the propulsion subsystem, steering subsystem, and the brake subsystem.

Two video signals from the two color TV cameras are transmitted in turn to the remote station by two UHF transmitters (Ch.22 and Ch.26).

Video signals are received by the UHF receivers and are conveyed to the visual and auditory display either directly or through computer superimposers.

Two CRT displays with appropriate lens systems are placed immediately in front of the operator's eyes. Remote scenes taken by left and right cameras on board the robot are displayed on left and right CRTs, which are focussed by the lens systems on the corresponding left and right retinae, respectively. The visual angle with which each eye sees the object on the CRT display is controlled so that it coincides with that of the direct observation. The disparity of the two corresponding pictures on the two CRTs is controlled so that the distance to the displayed object is always kept at the same distance as that of the real object [5,6].

Auditory information is displayed by a head set. The left and right signals are received from the microphones fixed to the left and right TV cameras, respectively.

During routine navigation tasks, the robot travels autonomously using the environmental map and the environmental information gathered by the visual sensors (two TV cameras and an ultrasonic sensor) and internal sensors (two odometers on the rear wheels). Visual information is processed remotely by the micro VAX II, while ultrasonic and odometer signals are processed by the micro-processor on board the robot.

The navigation process can be monitored by the operator. When the robot encounters a task which the robot is not able to manage by itself, it stops and asks the operator for help. At that time the operator controls the robot using joysticks as though he were driving that robot like an automobile, i.e., as if he were on board the robot at the position where the robot's TV cameras are located.

Figure 3 shows the prototype tele-existence mobile robot and Table 1 shows its specifications. Fig. 4 shows the head-linked display with a sensation of presence used in the system.

PRINCIPLE OF THE DISPLAY WITH A SENSATION OF PRESENCE

Essential parameters for human three dimensional perception of an object are: (1) the size of the retinal image of the object, or visual angle, (2) convergence of the two eyes, or equivalent disparity of the two retinal images, and (3) accomodation of the crystalline lenses. Adding to the above monochromatic parameters, fidelity in color is important for a realistic display[6].

Figure 5 shows a schematic diagram of the direct observation of an object in three dimensional space. The human observer measures the convergence angle (α) and the size of the object on the retina (lm). Since the distance between the two eyes (Wm) and the distance between the crystalline lens and the retina (am) are known, a human observer can estimate the distance to the object (dobj) and the size of the object (lobj) as follow:

$$dobj = Wm/2\tan(\alpha/2)$$
$$lobj = dobj * lm/am$$

If we think of a virtual plane at a distance of dvir perpendicular to the direction of the head; and project the object image onto the plane as shown in Fig. 5, and the human observer observes the projected images by using the corresponding eyes, then the observed parameters, i.e., α and lobj, are the same and the human observer gets the same lobj and dobj. The lobj and dobj can be derived by using the equivalent disparity (ed) on the virtual plane and the projected image size on the virtual plane (lvir) as follows:

$$dobj = Wm*dvir/(Wm-ed)$$
$$lobj = dobj*lvir/dvir$$

where dvir is the distance to the virtual plane.

Figure 6 shows the display system which reproduces the same situation as the direct observation. Two TV displays and lens systems produce the virtual images of the size lvir on the virtual plane at the distance of dvir with the equivalent disparity of ed.

Figure 7 shows the slave robot's camera system, where the distance between lenses Ws is set to be equal to Wm. The distance between two CCD devices (wcam) is usually ,but not necessarily, set as Wcam=Wdis=Ws, where Wdis is the distance between the two centers of the TV displays.

Under these conditions, we define a magnification factor γ = ldis/ls. Then by arranging am= γ*as, we have the condition of Fig.6, which is the same condition as for a direct observation. Practically, am can be determined by measuring the size of the image on the diplay (ldis) when monitored through the TV camera for a known size object lobj at the known distance dobj as:
am = β *dobj, where β = ldis/lobj.

The focal length of the lens (fm) must be selected to meet the condition that the virtual image of the TV display is on the virtual plane.

Ideally the distance to the virtual plane (dvir) should be controlled to coincide with the dobj controlling both fm and am. However, experiments revealed that if
200 mm $\leq$ dobj $< \infty$, dvir can be fixed to 1000 mm, and if 145 mm $\leq$ dobj $\leq$ 2000mm, dvir can be fixed to 500 mm. This makes the design and realization of the system more practical.

If these conditions are satisfied and the cameras and the display system follow the head movement of the operator, the ideal condition of the direct observation is always maintained.

In order to have a wide view without moving the operator's head, a short focal length of the camera (fs) must be selected and the appropriate values for as and am must be set.

The display system of Fig. 4 is designed to meet these conditions.

EXPERIMENTS

In order to evaluate the effect of the application of the tele-existence display to the mobile robot system, a comparison between a conventional display and a tele-existence display was conducted.

Figure 8 shows the task that the remote operator should execute. The goal is set at a distance of 25 m; two cylindrical obstacles block the way. The remote operator controls the mobile robot, observing the situation using either a conventinal two dimensional display (14 inch TV monitor) or the tele-existence diplay. The operator uses a joystick which assigns the velocity and the direction of the mobile robot's travel.

Three operational modes are set for the tele-existence display and conventional display as shown in Fig. 9. In independent-mode, the camera is controlled to follow the head movement of the human operator and the steering is controlled by the operator using the joystick. In the follow-steering mode, the camera follows the movement of the steering, which is also controlled by the operator using the joystick. In the look-ahead mode camera is fixed in the forward looking direction.

Preliminary experiments revealed the fact that it is quite helpful for the remote operator to have a reference which indicates the orientation of the robot's body. Therefore, a rectangular frame with a reference at the center of the front side is fixed in front of the robot (See Fig.3), so that the operator can see the orientation of the robot's body through the display.

Table 2 shows the results. The table gives the time elapsed to reach the goal for the combination of the four display types and three operational modes with a fixed camera angle of 48 degrees, for a human subject (the average of three trials). For other subjects, the same tendency was observed although the absolute values varies from subject to subject.

With the conventional TV display it is quite difficult to operate. Collisions occur frequently. Both independent-mode and follow-steering mode using the tele-existence display with a reference, show the superior results. This coincides with the subjective feeling of all five subjects that these are quite natural and easy to operate.

To analyze the difference between independent-mode and follow-steering mode, trajectories of the mobile robot under two operational modes were measured and compared. Appendix 1 shows the calculation algorithm for the trajectory.

Figure 10 shows the best result for the independent-mode, while Fig. 11 shows the best result for the follow-steering mode. It was confirmed from Fig. 10 (a) that the vehicle stopped when the operator searched the environment turning his head in the independent-mode. This increased the total time elapsed and made the trajectory a little bit uneven.

In the follow-steering mode of Fig. 11(a), the tele-vehicle did not stop while searching, which reduced the time elapsed and made the trajectory smoother (fig. 11(b)).

CONCLUSION

A method was proposed to realize a mobile tele-existence system which enables a human operator at the controls to perform remote tasks dexterously with the feelings that he or she exists in the slave mobile robot in the remote environment. A prototype system was made and the feasibility of the method was evaluated.

The effectiveness of the proposed system was evaluated by navigation experiments of the mobile robot through an obstructed space. Several display and operation methods were compared quantitatively using the time elapsed, smoothness of the travelled path and the number of collisions as the criteria for comparison.

The follow-steering operational mode using tele-existence display with a vehicle direction reference showed the best result. The independent-mode was found to be useful for the operator to accurately observe the environment by stopping the tele-vehicle.

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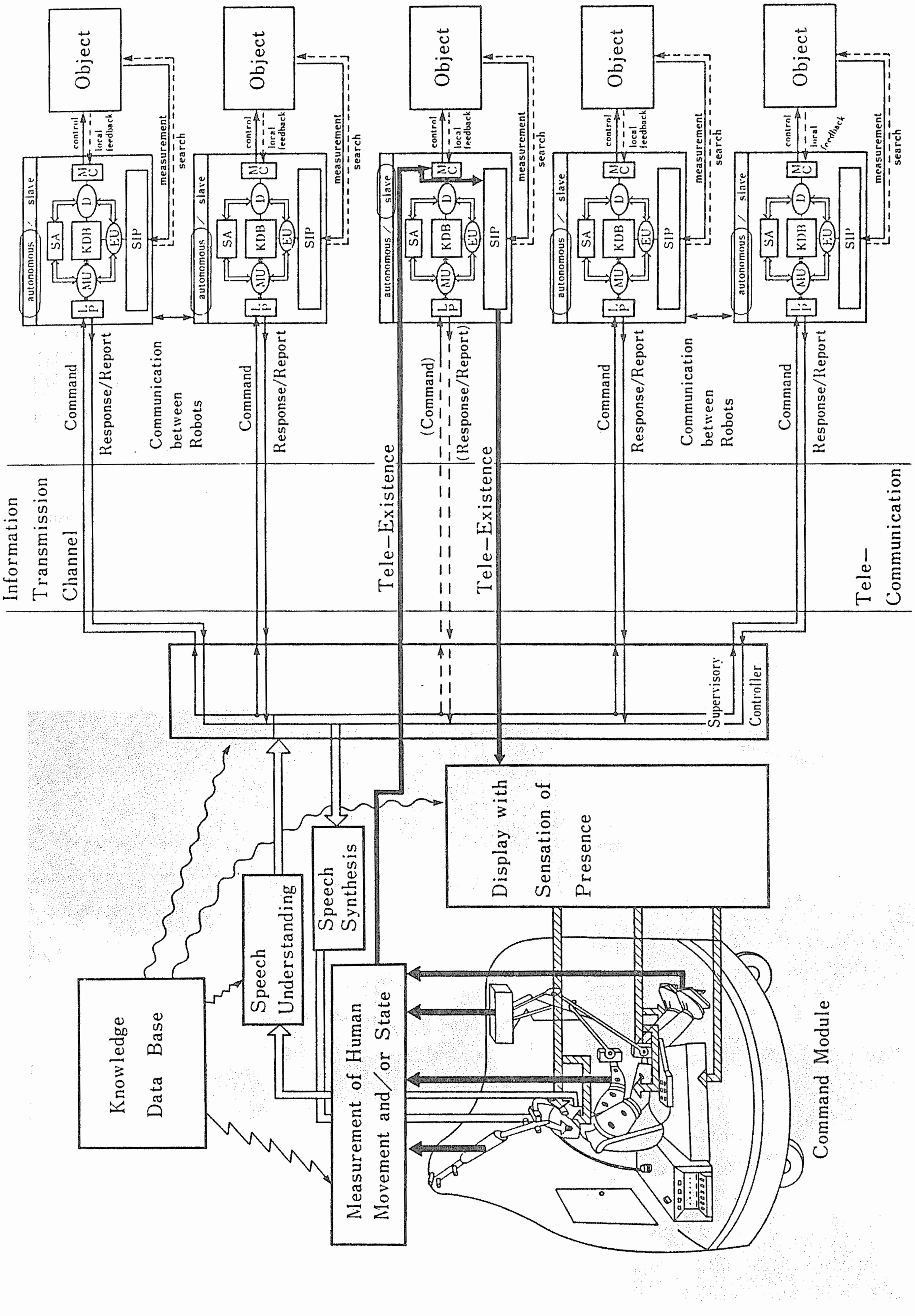

EU : Environment Understanding
D : Decision
LP : Language Processing
MC : Motion Control

SIP : Sensory Information Processing
KDB : Knowledge Date Base
SA : Situation Assessment
MU : Mission Understanding

Fig. 1 Schematic Diagram of the Human Robot System

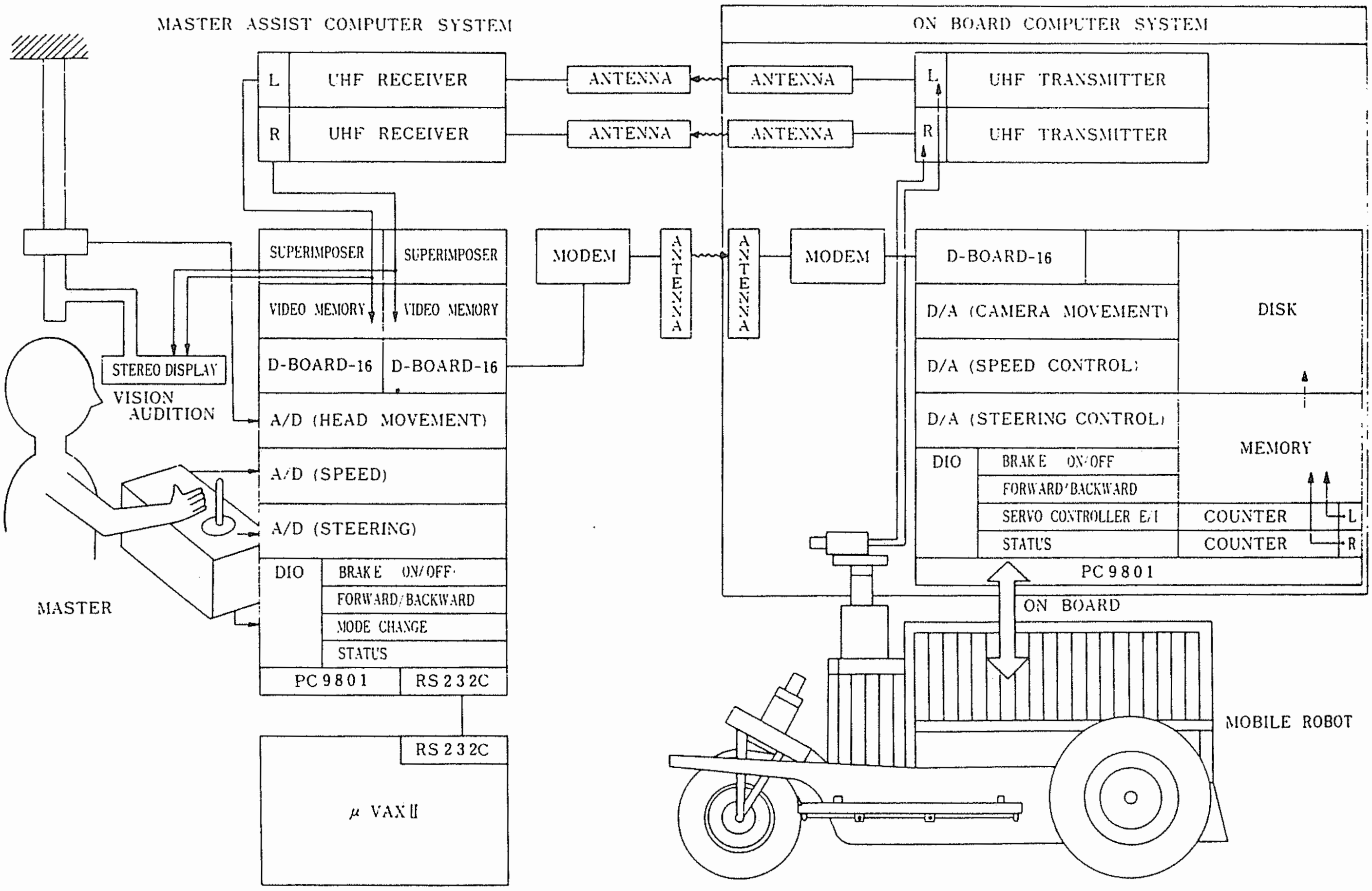

Fig.2 Experimental Mobile Tele-existence System

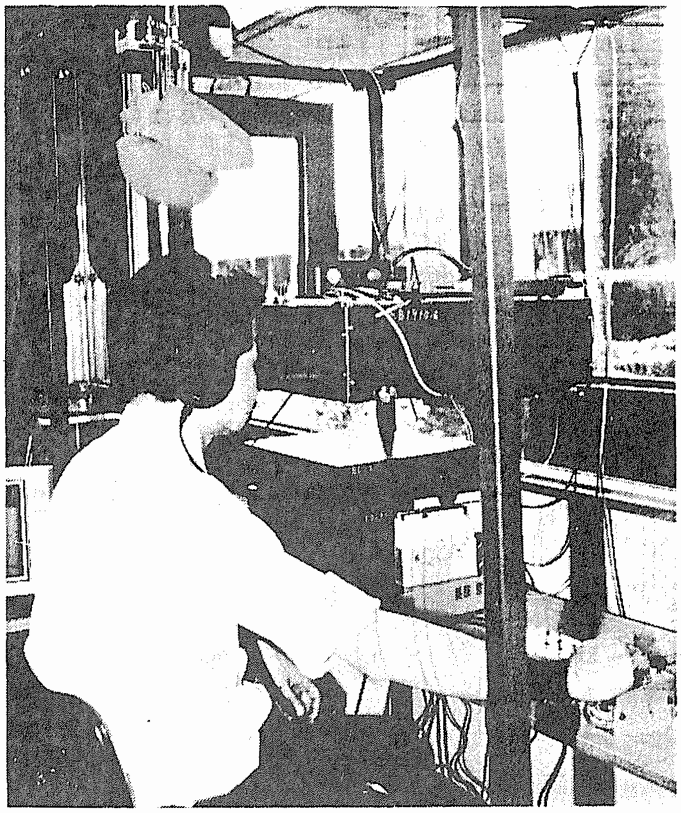

Fig.4 Head-linked Stereo Display with a Sensation of Presence

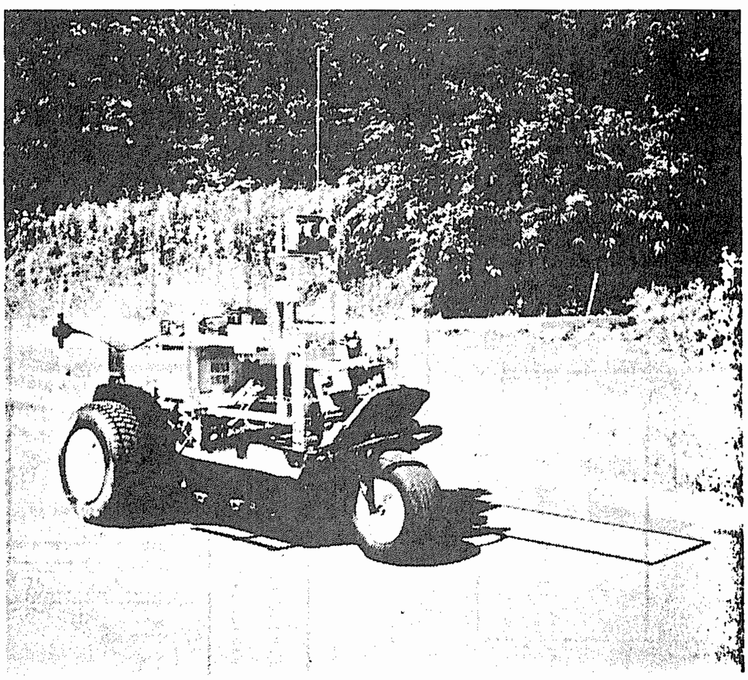

Fig.3 Prototype Mobile Tele-existence Vehicle (Tele-Vehicle I)

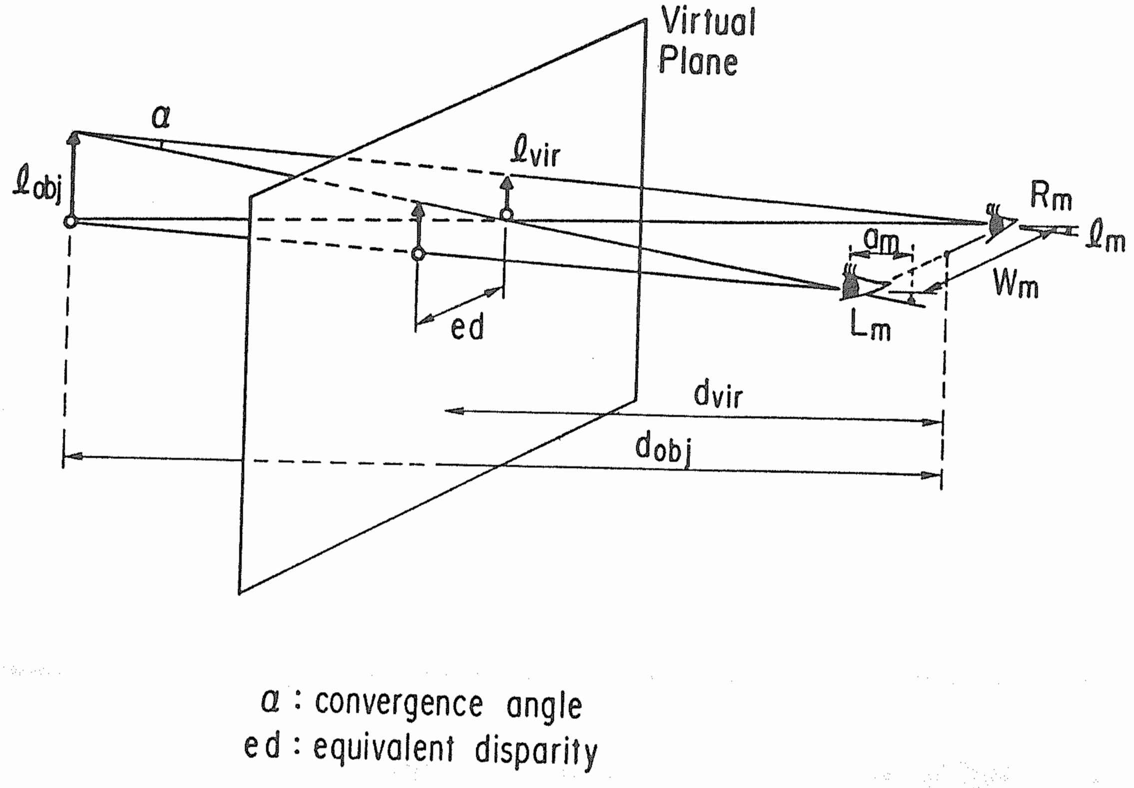

Fig.5 Visual Parameters of Direct Observation

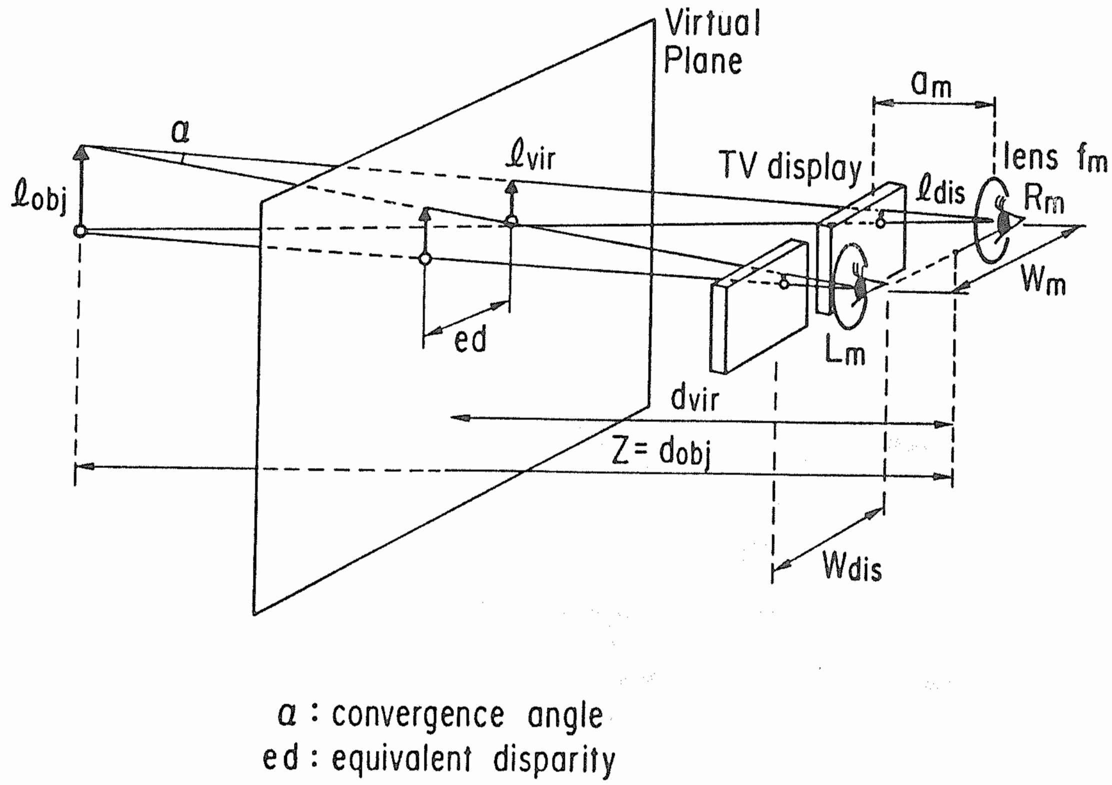

Fig.6 Visual Parameters of Tele-existence Display

CAMERA ANGLE 48°

		Lood Ahead	Follow Steering	Independent
2-D DISPLAY	without reference	difficult	difficult	difficult
	with reference	5'43"	4'35"	4'28"
TELE-EXISTENCE DISPLAY	without reference	3'18"	2'12"	2'6"
	with reference	2'40"	1'15"	1'5"

Table 2 Comparison of the Time Elapsed for Differnt Operation Modes

a) Determine direction

$Dir = Sgn(S_l + S_r)$

i) Forward : $Dir = 1$ ii) Reverse : $Dir = -1$

b) Straight motion test

Strait : $Dir = 0$

if : $Abs(S_l - S_r) < limit$

c) If reversed motion :

i) Change Sign of S_l, S_r ii) Swap S_l, S_r

d) Determine step rotation relative to cart position and orientation

$$\Delta\theta = \frac{S_l - S_r}{C\_bse}$$

$$R = \frac{S_r \cdot C\_bse}{S_l - S_r} + \frac{C\_bse}{2}$$

$\Delta y = R\sin\Delta\theta$ $\Delta x = R(1 - \cos\Delta\theta)$

e) Base ref to global co-ordinate

$\Delta y_o = Dir(\Delta y\cos\theta - \Delta x\sin\theta)$

$\Delta x_o = Dir(\Delta x\cos\theta + \Delta y\sin\theta)$

$\theta = \theta + \Delta\theta$

$X(i) = X(i-1) + \Delta X_o$

$Y(i) = Y(i-1) + \Delta y_o$

Range Suppression of θ

$-\pi \leqq \theta \leqq \pi$

if $\theta > \pi$ $\theta = 2\pi - \theta$

if $\theta < -\pi$ $\theta = 2\pi + \theta$

Additional Processing

① miscount at 0 speed ② if Limit $\leqq$ 2 st_ahead

Note :

S_l = Speed Left S_R = Speed Right

C_bse = Distance between rear wheels average time 100ms

Appendix Algorithm for the Trajectory Analysis