Proceedings of the Second International Symposium on
Measurement and Control in Robotics (ISMCR '92)
Tsukuba Science City, Japan - November 15-19, 1992

Remote Manipulation Using Virtual Environment

Eimei Oyama and Naoki Tsunemoto
Mechanical Engineering Laboratory
Namiki 1-2, Tsukuba Science City, Ibaraki 305 Japan
Susumu Tachi
RCAST, The University of Tokyo
Komaba 4-6-1, Meguro Tokyo 153 Japan
Yasuyuki Inoue
Tsukuba Research Center, Yasukawa Electric Corp.
Tohkohdai 5-9-10, Tsukuba Science City, Ibaraki 305 Japan

Abstract:

Tele-existence is an advanced type of teleoperation system that enables a human operator to perform remote manipulation tasks dexterously with the feeling that he or she exists in the remote anthropomorphic robot operating in a remote environment. In order to extend the function of a human, an extended tele-existence system with virtual reality technology was proposed. For example, when visual information cannot be used because of smoke due to fire, then a human operator still can see the virtual environment of the scene and can control the robot. The model of the environment can be constructed from the design data of the environment. Usually errors are in the model of the environment. In order to compensate for the errors, a calibration technique using model-based image measurements is proposed for matching the real image and the virtual image. After calibration, an experimental operation in the invisible environment was successfully conducted.

Keywords:Tele-existence, Artificial Reality, Superimposing Method, Nonlinear Least Square Method

1 INTRODUCTION

Tele-existence is an advanced type of teleoperation system that enables a human operator to perform remote manipulation tasks dexterously with the feeling that he or she exists in the remote anthropomorphic robot operating in a remote environment [1].

Not only the flexible control of the remote robot but also the extension of human functions by the help of robot's sensors and computer's calculation power were proposed[2]. For instance, in the case of working in smoke, environmental information is almost invisible to humans. However, the visual information of the environment can be generated with computer graphics from the environment model. Remote manipulation using the virtual environment makes it possible to do successfully operations in a smoky environment.

The environment model can be constructed from the design data of the environment. However, usually errors in the environment model are present. In order to compensate for the errors, the virtual environment should be calibrated for conformity with the real environment. Especially, a contact task is difficult when the virtual environment is not in agreement with the real environment.

In this paper, in order to operate a slave robot in an almost invisible environment, the remote manipulation using a virtual environment is presented. And a method for adjusting the environment model using model-based image measurement is presented. By estimating the parameter errors in the environment model, the calibration can be conducted successfully. After the calibration, an experimental operation in an almost invisible environment was conducted and successfully completed.

2 REMOTE MANIPULATION USING VIRTUAL ENVIRONMENT

In this section, the tele-existence system is extended by a virtual environment system. It is investigated whether this tele-existence system gives the ability to do robot manipulation in an almost invisible environment.

2.1 Extended tele-existence system

In our research on tele-existence, the extension of human functions by using the artificial reality technology was proposed[2]. Incorporation of a virtual environment simulator in a tele-existence system and improvement of the autonomy and intelligence of a slave robot can extend human functions. Figure 1 shows the conceptual diagram of the extended tele-existence system.

Using an environment simulator enables the training of a task. This facilitates the conduction of a task in real world. If the virtual environment is adequately matched to the real environment,a slave robot operated in the real environment by an operator working in the matched virtual environment is able to work in the real environment even when the sight conditions are bad. Our research discussed here is aimed at working in environments with bad sight conditions. For instance, in case of smoke due to fire. In order to prove the effectiveness of robot control by tele-existence, we constructed an experimental tele-existence system[3]. We incorporated an artificial reality system[4] into the tele-existence system and constructed an experimental extended tele-existence system.

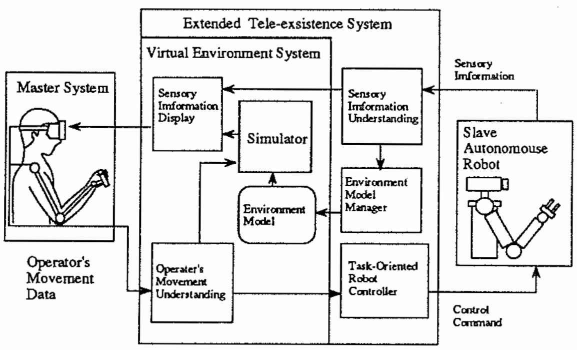


Figure 1 Extended tele-existence system

The configuration of the system is shown in Figure 2. The artificial reality system consists of one graphics computer, two scan converters and two superimposers. The graphics computer is IRIS 120 GTX. In the display system, both left and right images are displayed on the graphics computer's screen, are split by the scan converters and are sent to the stereo display system. The real image from the slave robot and the virtual environment image created by the computer can be switched or can be overlaid by the superimposer.

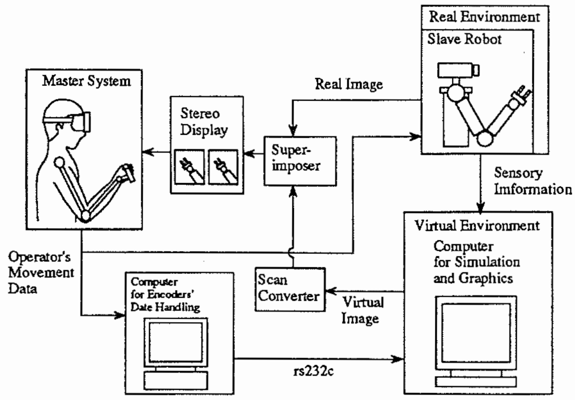


Figure 2 System configuration

The real image from the slave robot and the virtual environment image created by the computer can be interchanged or overlaid on the display by the superimposer. This function is essential for the extended tele-existence system to operate a robot. The more detail configuration of the display system will be described in the next section.

Impedance control is incorporated in the control of the slave robot[5]. By using impedance control, the slave robot arm is stable also during contact tasks involving hard objects.

For instance, a picture of the training of block stacking is shown in Figure 3.

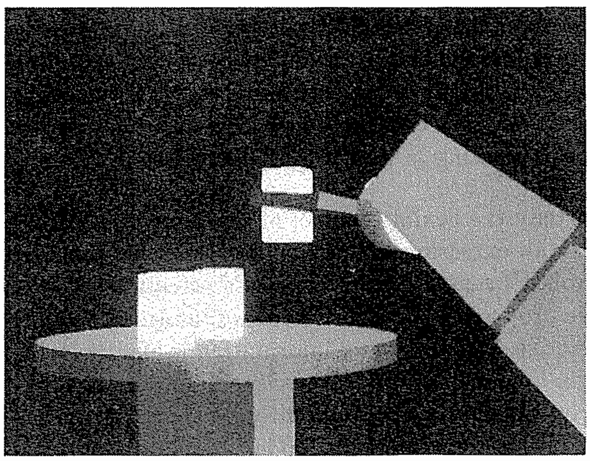


Figure 3 Virtual environment

2.2 Operation in environments with bad sight conditions

At the sites of accidents or fires in a factory, not only the conditions are unendurable for humans but also the sense of sight deteriorates highly due to smoke. Hence, the full use of human's ability becomes impossible. In order to improve the human abilities in such environments, use can be made of a virtual environment. A model of the environment can be constructed by using available design data of the site. For example, in a factory, it is often comparatively simple to make up an environment model from the design data. If the virtual environment is sufficiently similar to the real environment, a slave robot in the real environment, operated by an operator in the virtual environment, can executes tasks successfully in the real environment.

Nevertheless, an environment model is usually incomplete. There are errors in the parameters of the shapes of objects, their positions and their orientations. Those errors may cause large discrepancies between the real positions and the virtual positions of objects. Consequently, if the virtual arm grasps a virtual object, the real arm will not always grasp the corresponding real object. When visual data from the real environment is used, such discrepancies are not a problem because those discrepancies can be adjusted by the operator's visual feedback. But in cases where work must be done using only the information from the virtual environment, those discrepancies have a large effect on the operations. In order to decrease those discrepancies, the parameters of the virtual environment model should be adjusted. This can be done by using estimation techniques will be discussed in the next section.

3 MODEL-BASED IMAGE MEASUREMENT

We have developed a model-based image measurement system which make measurement equations from the image on the screen and the object model and uses the nonlinear least squares method to estimate the unknown parameters related to an object. In order to calibrate the virtual environment, we have incorporated an image measurement system in the tele-existence system. If the virtual environment and the real environment are matched on the stereo images, the operator can carry out the operation in an almost invisible environment successfully.

Let the known parameter vector be p, the unknown parameter vector x and the measurement model $f(p,x)$. The measurement value vector y is the sum of the true measurement model $f(p,x)$ and the noise vector ω_y. The measurement equation is defined as follows.

$$y = f(p,x) + \omega_y \tag{1}$$

Let the noise vector ω_y be Gaussian and the weight matrix W be the inverse matrix of the covariance matrix of the noise vector.

$$W = E(\omega_y \omega_y^T)^{-1} \tag{2}$$

The value of the unknown parameter vector x can be estimated by minimizing the following evaluation function:

$$E = (y - f(p,x))^T W (y - f(p,x)) \tag{3}$$

The algorithm to find the solution of the problem of minimizing this sort of function is called the nonlinear least square method. The model based image measurement system obtains the measurement value vector y from the images with the help of a human operator, constructs the measurement model $f(p,x)$ automatically from the object model, defines the measurement equation, solves the least square minimization problem by numerical method and estimates unknown parameter vector x.

The difference between the measurement value vector y and the measurement model $f(p,x)$ is decreased after the estimation of the unknown parameter vector x. The measurement values consists of the positions on the image corresponding particular points on the object model. The positions are matched on each values of the measurement model. the corresponding values of the measurement model. If the measurement model is the true model of the drawing of the virtual environment, the points of the virtual environment are matched on the points of the real image. And if the number of such points is enough, the image of the virtual environment and the image of the real environment can be superimposed precisely.

3.1 Measurement model

The most simple measurement model is as follows. Let the position vector of a point on the object with respect to a fixed coordinate system be x_b, the rotational transformation matrix from the object coordinates to a camera fixed coordinates be C_c^b,the translational transformation vector be x_g,the position vector with respect to the camera coordinates be $x_c = (x_{cx}, x_{cy}, x_{cz})$, the position vector respect to the screen coordinates of the camera be $x_i = (x_{ix}, x_{iy})$. Also, let the focus point of the camera be

$x_c = (0,0,0)$ and the line of sight of the camera be parallel to the x_{zc} axis, then the following equations are established:

$$x_c = C_c^b x_b + x_g \qquad (6)$$

$$x_{ix} = K_x x_{cx}/x_{cz} \qquad (7)$$

$$x_{iy} = K_y x_{cy}/x_{cz} \qquad (8)$$

K_x and K_y are constants related to the projected image of the camera on the screen. The rotational transformation matrix is the complicated nonlinear function of the parameters specifying the transformation. If the object shape is known, then C_i^b and x_g can be estimated when more than three image points are measured.

Usually the measurement equation of the image measurement is a complicated nonlinear function. The three dimensional position of a point on an object can be obtained from appropriate base vectors (e.g. $(1,1,1)^T$ in 3-dimensional space) by performing scaling transformation, rotational transformation and translational transformation. Positions of points on a screen are subject to rotational transformation, translational transformation and perspective transformation to points on the object. Taking the positions of points on the screen as measured values, the measurement model can be derived by making various complicated transformations of the base vectors. The measurement model for the positions of points on the screen are complicated. The analytical derivation of the measurement model is very tedious. However, a computer graphics system, which can draw a virtual environment, usually includes a procedure that can transform the basic vectors to the points on the screen. The numerical value of a point position can easily be obtained by using the screen drawing procedure in computer graphics. And there are some nonlinear least square methods that can be executed with only the numerical values of a measurement model.

3.2 Image measurement procedure

When formulating the measurement equation, a point on the screen and a point on the object must represent the same location. The problem of matching a point on the screen with a point on the shape model being part of the virtual environment is a problem of image recognition. At present, image recognition technology is not reliable and automatic measurement is very difficult. Consequently, the measurement equations are formulated by a person using a mouse to select both points in the virtual environment image and corresponding points in the real image on the screen. After selection these points are digitized.

The following procedure is used in the present measurement system:

(1) Send a command to the camera to head for the object to be measured and to be positioned on a screen.
(2) Taking the screen as a real image display, measure the position of the apex on the screen by and digitize that point with the mouse.
(3) Switch the screen to the virtual environment image and use the mouse to digitize the point which corresponds to the point on the real image. Select as the corresponding point the point which is nearest to the value digitized by the mouse and which also corresponds to the displayed point of the object.
(4) Repeat (1) to (3) until an adequate number of points have been obtained. The sequence in which (2) and (3) are performed is irrelevant.
(5) Select the parameters to be estimated.
(6) After obtaining sufficient points, use the estimation algorithm to estimate the unknown parameters.

Make estimates for several initial values. Select the one with the smallest residual. If an adequate estimate is not possible, repeat (1) to (3) to obtain sufficient observations.

The Marquardt method is used as the algorithm for the estimation[6]. The method requires the Jacobian matrix of the measurement model. The Jacobian matrix can be obtained through numerical differentiation.

3.3 System configuration

In this subsection, the actual configuration of the calibration system using the model-based image measurement is explained. The configuration of the extended system is shown in Figure 4. Both left and right images are displayed on the monitor for the image measurement. The real image from the slave robot and the virtual environment image created by the computer can be switched or can be overlaid on the monitor screen by the superimposer. The brightness of each one of the displayed RGB colors as being displayed ranges from 0 to 1. In the image created by the computer graphics, the superimposer displays the real image at the pixels where (R,G,B)=(0,0,1) and uses the other pixels to display the virtual environment image. In order to display the real image, the graphics screen is colored blue and the mouse cursor is non-blue colored.

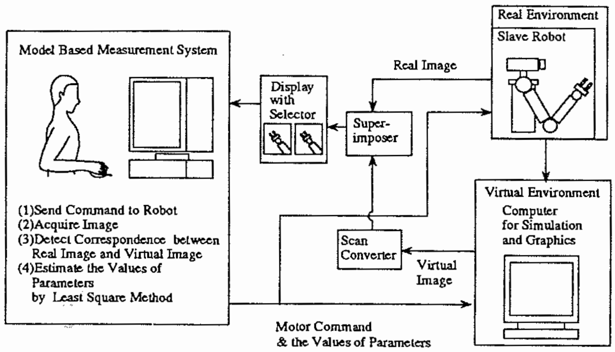


Figure 4 Calibration system

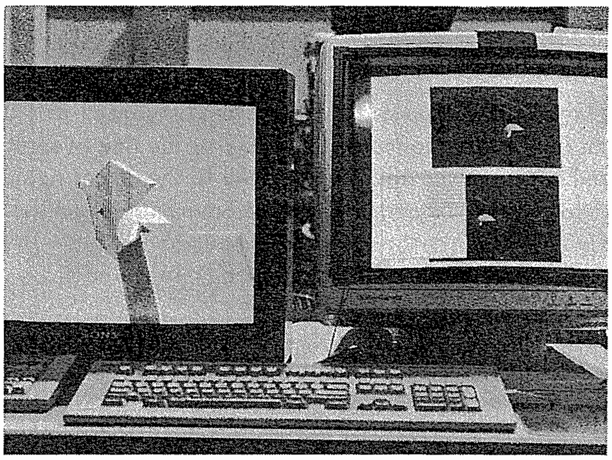


Figure 5 Virtual image

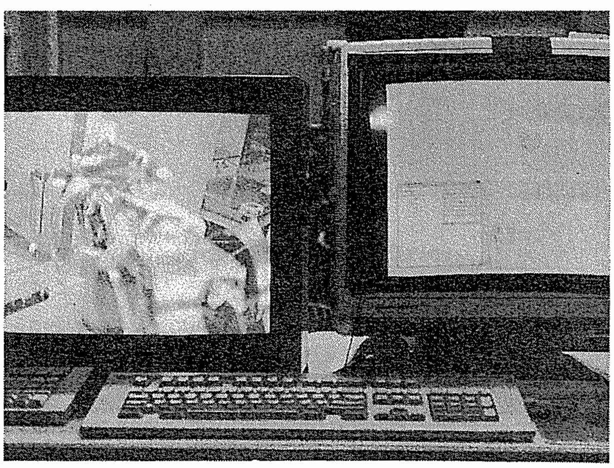


Figure 6 Real image and blue screen

Figure 5 shows the virtual image shown on a monitor screen and on a computer graphics display. Figure 6 shows how the real image appears on the monitor screen by selecting the computer graphics image blue. This has the advantage that at the same time the position of a point on the real image can be measured by moving the mouse cursor on the point and obtaining the mouse position. Another advantage of this system is that it can be realized without adding special hardware to the graphics computer system, keeping the cost of the tele-existence system down. One disadvantage is that pure blue can not be used as a graphics color.

4 EXPERIMENT

We conducted an experiment with the superimposing method by an operation in an almost invisible environment.

4.1 Tele-existence experimental environment

In order to prove experimentally the effectiveness of control by tele-existence, we created an experimental environment.

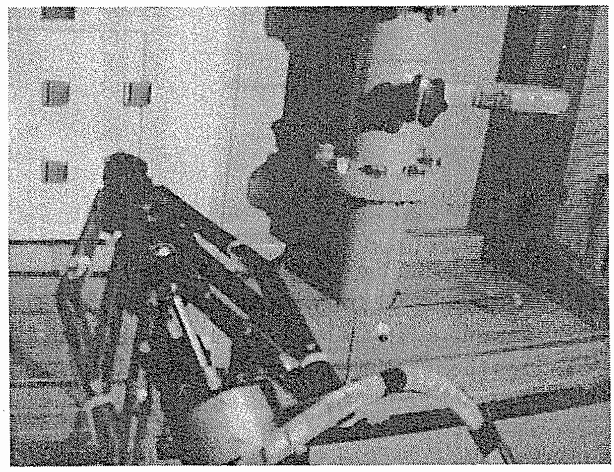


Figure 7 Tele-existence experimental environment

The environment simulates a small part of a room in a factory. The appearance of the environment is shown in Figure 7. The environment model consists of pipes, a lever, a box and a ventilating fan. There is a smoke machine to generate smoke in the environment. A lever which can be seen in the right of the photograph can be rotated to shut off the smoke. The button on the box on the left of the lever is the ventilating fan switch. This tele-existence experimental environment consists of a collection of simple shapes and the shape data was entered into the graphics computer. The shape data is described by a surface model. The environment model displayed by the computer graphics is shown in Figure 8. The lever to shut off the smoke and the button to switch on the ventilating fan, can also be operated in a virtual environment. A beep is heard when the button is pressed. The parameters which must be estimated are the errors in the values of the parameters in the movable parts of the environment model, that is the position and orientation of the robot.

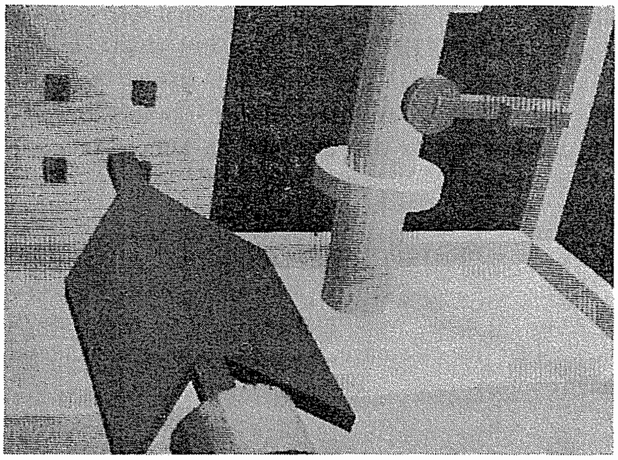
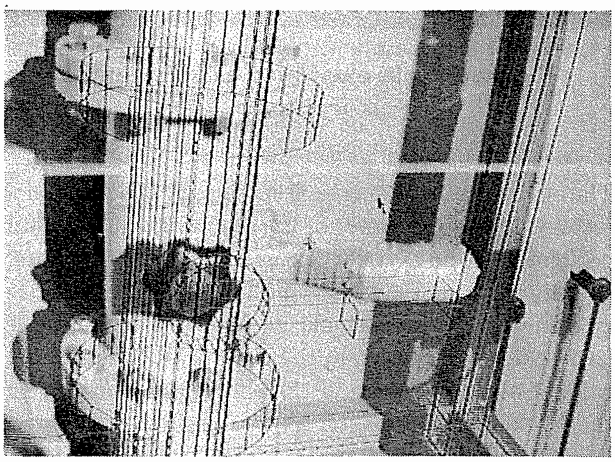


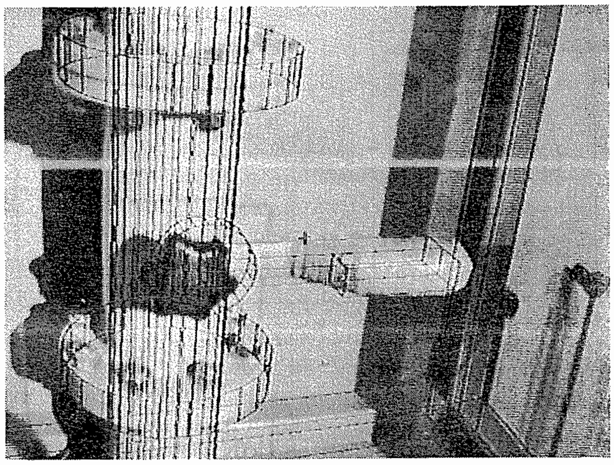
Figure 8 Environment model

4.2 Calibration experiment

Figure 9(a) shows the superimposed the real image and the virtual image (wire frame display) of the lever whose parameter errors were not estimated. Figure 9(b) shows the superimposed images after calibration.



(a) Before calibration



(b) After calibration
Figure 9 Real image and virtual image

The position error of the lever were estimated at 1.0 cm in the direction perpendicular to the line of sight and 4.5 cm in the direction parallel to the line of sight. Finally, we obtained the correct environment model. Figure 10 shows the real image and the updated virtual environment after calibration.

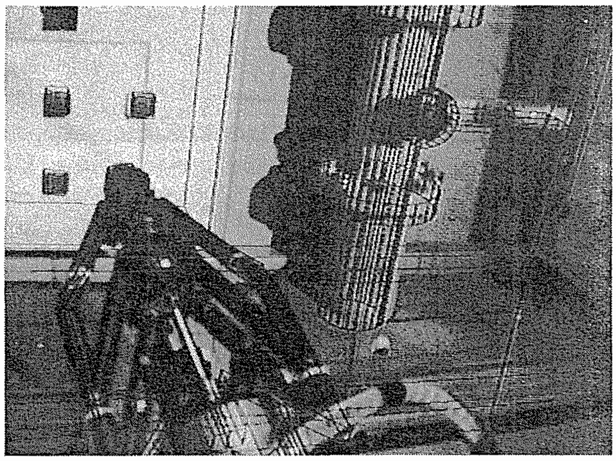


Figure 10 Result of calibration

4.3 Operation in almost invisible environment

In order to confirm the successful superposition, we conducted an experiment of the operation in an almost invisible environment by using the virtual environment. In the tele-existence experimental environment, the smoke machine generated smoke and the slave robot's sense of sight became useless. The task of pulling a lever down, which requires a comparatively low demand for precision, was performed successfully by the robot. The photo of the robot working in an almost invisible environment is shown in Figure 11.

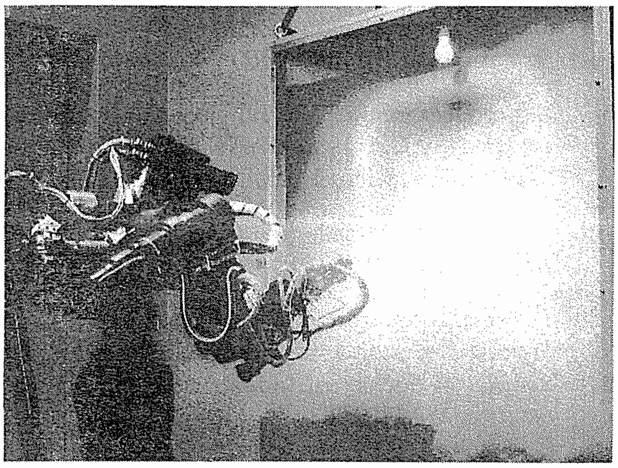
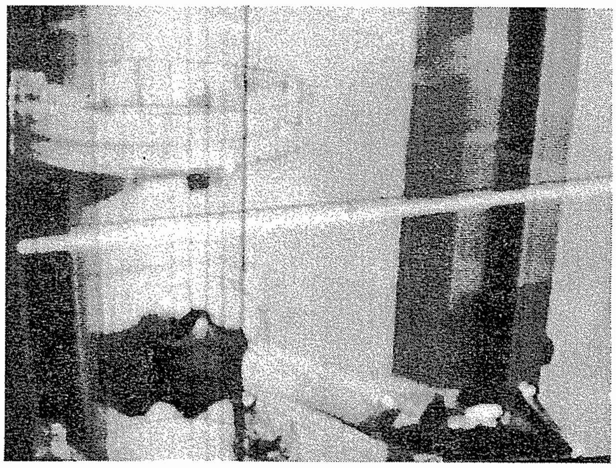
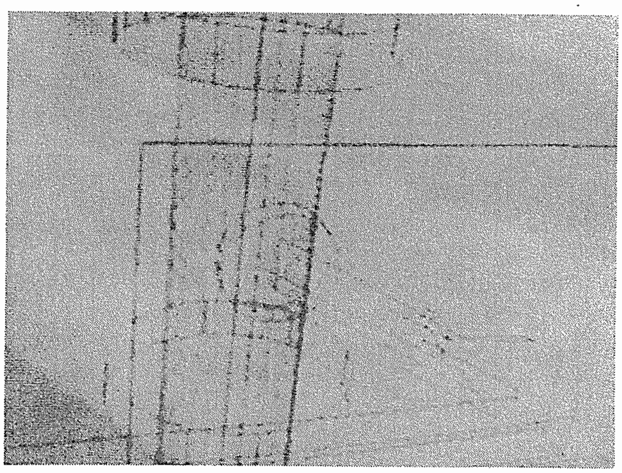


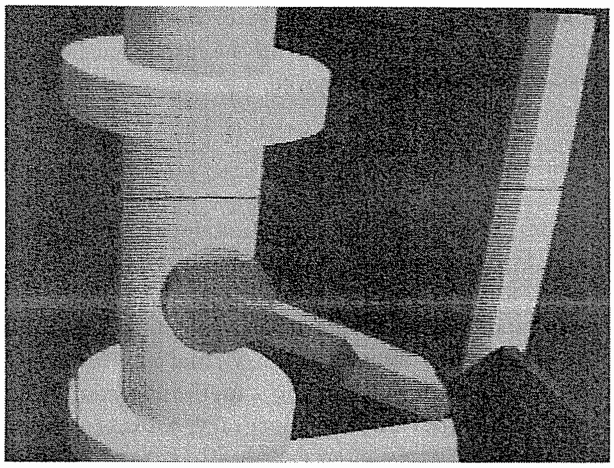
Figure 11 Operation in almost invisible environment



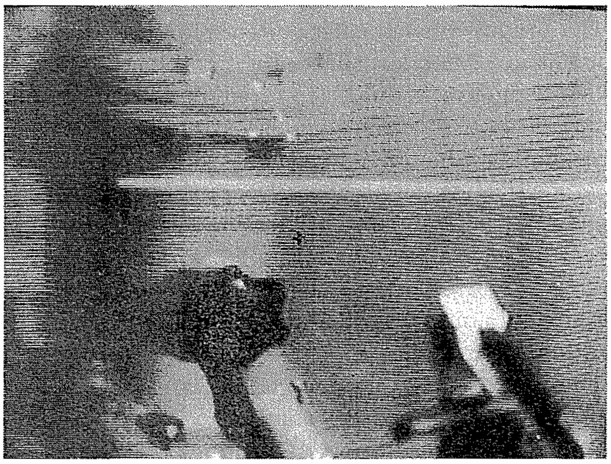
(a) Camera image of normal environment



(b) Camera image of real environment



(c) virtual environment



(d) result of operation

Figure 12 Displayed images during operation

Figure 12 shows the images displayed during the operation. Figure 12(a) shows the camera image overlaid by a wire frame model of the environment during normal operation. Figure 12(b) shows the actual camera image overlaid by the wire frame model of the virtual environment during the operation. Due to the smoke from the smoke machine, the robot's hand is almost invisible. Figure 12(c) is an image of the virtual environment seen by the operator during the operation. Figure 12(d) shows the end result when the smoke has been exhausted. The lever has successfully been pulled down. The function of the impedance control of the slave robot can compensate for the errors that still remain after the calibration. This task is a low accuracy task. The accuracy of positioning the hand relative to the lever required for pulling the lever down is lower than 5 cm in the vertical and horizontal directions. Hence, the operation was conducted successfully. In order to perform more precise operations in an almost invisible environment, the environment model needs to be more accurate. So more parameters need to be estimated. And the intelligence of the slave robot must be improved.

5 CONCLUSIONS

In order to conduct an operation in an almost invisible environment, we proposed the remote manipulation using a virtual environment. And we proposed model-based image measurement to superimpose a real environment and a virtual environment. In order to confirm that the superimposement was achieved with our objected accuracy, we successfully performed an experimental operation in an almost invisible environment.

The proposed calibration system requires the correspondence detection between the real image and the virtual environment. This procedure depends on human ability, so calibration is extraordinarily time-consuming. In order to achieve more accurate superpositioning the number of parameters to be estimated and the number of measurements to be done must be increased. But it is tedious for a human to show the correspondence between real image and virtual environment. At present, the use of markers for automatic matching is under consideration and automatic matching through image awareness based on known data is also being studied.

In cases such as the outbreak of fire, where shapes are completely altered, it would probably be impossible to achieve an adequate approximation simply by adjusting the parameters of environment models. Range sensors are needed in order to obtain shape data for three dimensional environment models. Adjustments with range sensors for modeling errors which can not be expressed with parameters, such as structural changes in the shapes of objects due to breakage, etc. are a matter for further research in the near future.

References

[1] S. Tachi, K. Tanie and K. Komoriya: "A control method of manipulator with sensory information display", Japanese Patent No.1348263, Jan. 14th, 1981.

[2] S. Tachi, H. Arai and T. Maeda: "Tele-existence simulator with artificial reality", Proceedings of IEEE International Workshop on Intelligent Robotics and System(IROS), Tokyo, Japan, 1988.

[3] S. Tachi, H. Arai and T. Maeda: "Tele-existence master slave system for remote manipulation", IEEE International Workshop on Intelligent Robotics and Systems, IROS'90, 1990.

[4] S. S. Fisher et al.: "Virtual environment display systems", ACM 1986 Workshop on Interactive 3D Graphics, Chapel Hill, North Carolina, 1986.

[5] N. Hogan :"Impedance Control Part I-III", ASME DSMC, Vol.101, pp.1-24, 1985.

[6] D. W. Marquardt: "An Algorithm for Least Square Estimation of Nonlinear Parameters", Journal of Society of Industrial Applied Mathematics, Vol.11, 1963.