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Calibration Method of Visual Parameters for See-Through Head-Mounted Display

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Abstract – It is expected that See-Through Head-Mounted Display(STHMD), which superimposes the virtual environment generated by computer graphics(CG) on the real world, can vividly execute various simulations and designs by using both of the real and virtual environment around us. In STHMDs, information given as a virtual environment has to exactly match with the real environment, because both environments are visible. This is one of the problems to be solved for practical use. Particularly for matching of locations and size between real and virtual objects, disaccordance is likely to occur between the world coordinate of the real environment where the user of STHMD actually exists and that of the virtual environment described as parameters of CG, which directly causes displacement of locations where virtual objects are superimposed. This must be calibrated so that the virtual environment is superimposed properly. Among causes of such errors, we focused both on systematic errors of visual parameters caused in manufacturing process and differences between actual and supposed location of user's eye on STHMD when in use. The former is required to be calibrated only once after the fabrication of STHMDs, whereas the latter has to be calibrated every time users start using STHMDs. We have proposed calibration methods which are suitable to properties of these causes of errors. In the method, the direct fitting of the virtual cursor drawn in the virtual environment onto targets in the real environment is performed. Then, based on the result of fitting, he least square method identifies values of the visual parameters which minimize differences between locations of virtual cursor in the virutal environment and targets in the real environment. Application of the method to the STHMD which we have made is also reported. The differences between the virtal cursor and targets in the real environment due to systematic errors caused in the manufacturing process were reduced to about $1mm$ per target, which was less than one–thirtieth of that before the calibration. The differences between the virtal cursor and targets in the real environment due to the location of user's eyes were also reduced to about $2mm$ per target, which was a half of that before the calibration. This result was well enough to prove the effectiveness of the calibratoin methods.

1 Introduction

It is expected that See-Through Head-Mounted Display(STHMD), which superimposes the virtual environment generated by computer graphics(CG) on the real world, can vividly execute various simulations and designs by using the real environment around us. It is also expected that it would achieve simplification and improvement of efficiency of various works, because it graphically offers the information on the objects in 3 dimentions, which is necessary to go ahead with the work instead of offering them in the form of documents.

However, information given as a virtual environment or virtual objects has to match with the real environment, because both environments are visible. This is one of the problems to be solved for practical use[1]. Particularly for matching of locations and size between real and virtual objects, disaccordance is likely to occur between the world coordinate of the real environment where the user of STHMD actually exist and that of the virtual environment described as parameters of CG, which directly causes displacement of locations where virtual objects are superimposed. This must be calibrated so that the virtual environment is superimposed properly.

What are first considerd as the origins of such displacement are as follows:

- Systematic errors of visual parameters caused in manufacturing process
- Differences between actual and designed location of user's eye on STHMD

The former is eliminated by calibrating just once after its fabrication, and the latter must be calibrated as a process of initialization every time users start using STHMD.

Hirose, Kijima, Sato and Ishii have used somatic sensations of human being to calibrate them[1], but precise matching between the points in the real and virtual environment has not been performed. From the standpoint that the matching of location and size between objects in both environment is crucial, virtual environment must be directly fitted onto the real environment point by point. In this paper, we proposed a calibration method in which the direct fitting of the virtual cursor projected by STHMD onto targets in the real environment was performed, and reported the result of application of this method to the STHMD which we have made.

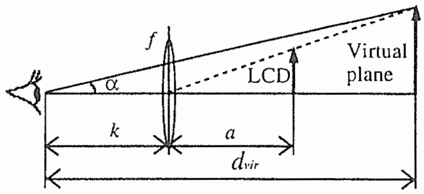

Fig. 1. Optical system of HMD

2 System configuration

2.1 Designing and manufacturing a prototype of STHMD

In short, STHMD is a device which generates two virtual planes from palaner images displayed on LCD etc., one for the right eye and the other for the left, placed at the distance d_{vir} which is derived from the optical system in Fig.1 as follows[2]:

$$d_{vir} = k + \frac{fa}{f-a} \quad (1)$$

It reproduces the binocular vergence and parallax, which are important for three-dimensional space perception, by projecting two images with the parallax equal to the interocular distance which is set at the design stage of STHMD, i.e., an image obtained at a viewpoint equivalent to the location of left eye in the real environment on the left virtual plane and likewise on the right.

The focus of the crystalline lens of a human operator is generally fixed at the distance d_{vir} to simplify the optical system like Fig.1. Although it is not completely independent of the convergence due to the mutual reaction, there is a research on what extent the disaccordance between them is allowed to. For example, it is known that the natural perception of 3-D space is possible within the distances between $20cm$ and infinity when $d_{vir} = 1m$ [2]. Hence, this becomes a standard values of d_{vir} when designing the optical system of STHMD.

Two 5.7-inch LCDs are used in our prototype. The wider the field of view is, the better perception of 3-D space is obtained. There is, however, a trade-off because the resolution of the images decreases as the field of view increases. For example, the specifications of our prototype is shown in Table 1.

Fig. 2 outlines a portion of STHMD which holds optical systems, illustrated eye mark roughly indicating the designed location of users' eyes. This portion is mounted on the full-face helmet so that the user can wear this optical system just in front of his/her face. The mark "P" drawn in Fig.2(b) indicats a plate on which marks are put to be used for the calibration of eye's displacement, which will be described in section 3.2. We shall also take this plate as the basis on which the dimension of STHMD is defined. When we use expressions such as "designed location of the virtual plane" or "designed location of user's eye", we mean

Table 1. Specification of HMD

Field of view		d_{vir}	Interocular distance
Horizontal	Vertical		
40°	30°	$1m$	$65mm$

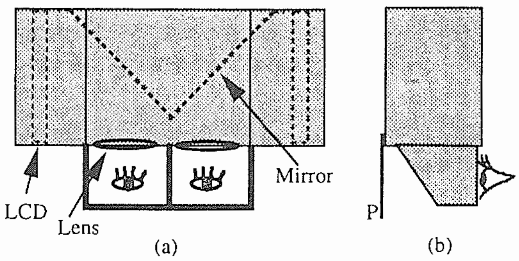

Fig. 2. Outline of HMD

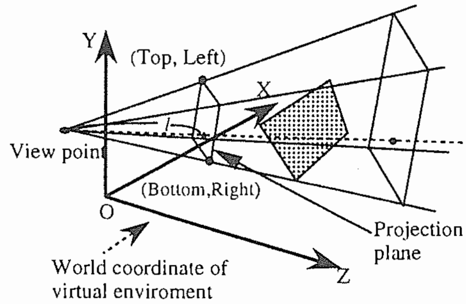

Fig. 3. Generation of virtual environment

that they are measured from it and thier values are given by the design.

2.2 Generation of the virtual environment

To generate a virtual environment, a "world coordinate system" is defined first in the CG program, then the virtual objects are placed relative to it. The projection transformation on this environment gives planar images and these are projected on the LCDs. The typical ones among the ways of projection transformaion are perspective projection and window projection. While the former has viewpoint, line of sight, and vertical and horizontal angle of field of view as the visual parameters, the latter defines the shape of projection plane by specifying (Top, Left) and (Bottom, Right) at a moderate distance ("l" in Fig3) instead of defining angles of field of view. Although the line of sight is perpendicular to the projection plane in both projections, the window projection can realize an asymmetric viewing frustum, whereas the perspective projection makes only a symmetric one. Therefore, the window projection is desireble for our purpose. Accordingly, visual parameters we mean here are viewpoint, line of sight, and shape of the projection plane(Top, Left), (Bottom, Right). It is better to give l a small value because objects nearer than l are ommitted when the projection transformation takes place and are invisible on LCD. But setting $l = 0.1m$ is sufficient because natural fusion of two planar images does not occur within this distance when $d_{vir} = 1m$.

To superimpose the virtual environment precisely on the real one, it is crucial that the visual parameters mentioned above are set correspondent to the realized location of virtual plane of the prototype. The realized location of the virtual plane is , however, likely to differ from designed location and the differnce between

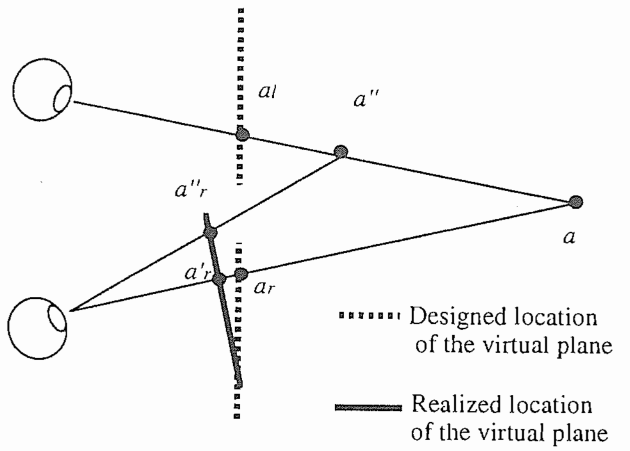

Fig. 4. Effect of systematic errors of visual parameters caused in manufacturing process

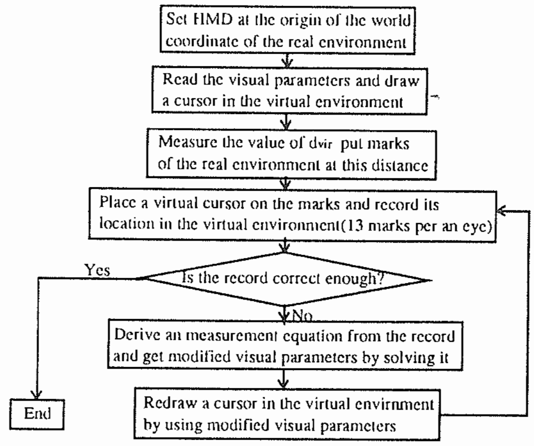

Fig. 5. Process of calibration

them is unpredictable. Besides, acutual location of user's eyes are fixed only when he/she wears HMD. Therefore it is impossible to reflect these factors on visual parameters beforehand and they must be calibrated one by one in the following procedures.

3 Calibration method to eliminate the errors

3.1 Calibration of errors caused in the manufacturing process

Errors produced in the manufacturing process mean errors of the realized optical system of HMD and, as mentioned above, this is observed as the shift of virtual planes from the designed location. Fig. 4 illustrates such an circumstance.

A point a drawn in the virtual environment is projected onto the virtual planes for right and left eyes according to the designed locations of virtual planes as a_l and a_r indicate. When the realized virtual plane for right eye, for example, is not located as designed and it is not reflected on the visual parameters, a human operator feels that the point is drawn at a'' instead of a, i.e., the location of a''_r on the realized virutal plane remains as exactly same as that of a_r on the supposed virtual plane. If the visual paremeters are set according to the realized location of the virtual plane, the image of point a is supposed to be a'_r. So, we have to measure the realized locations of virtual planes and modify the visual parameters according to them.

3.1.1 Process of calibration

The calibration is done in the following process. Fig. 5 shows its flowchart.

1. Set HMD at the origin of the world coordinate of the real environment.
2. Read visual parameters and draw a cursor in the virtual environment.
3. Measure the distance to realized virtual plane (d'_{vir}) and put marks of the real environment at this distance.
4. Place a virtual cursor on the marks and record its location expressed in the virtual environment.
5. Compare recorded locations with original locations calculated according to the designed visual parameters.Calibration will end if differences between them are small enough, and the visual parameters at this time are used hereafter as a result of calibration. Otherwise, derive an measurement equation from the result of measurement and go on into the next step. The measurement equation describes the relation between the result of measurement and errors of the visual parameters. This equation is defined in section 3.1.4, and solved in section 3.1.5 to estimate the visual parameters.
6. Estimate the modified visual parameters from the measurement equation.
7. Redraw the virtual environment and return to step 4.

3.1.2 Mesuring the displacement of the virtual objects

Details of step 1 through 4 of the process above are described here. The world coordinate system and marks for fitting are required first in the real environment to measure the shift of the virtual plane and to consecutively execute the calibration. Fig.6 shows the outline of the experiment system for this purpose. LEDs as the marks of the real environment are put on the pannel. The axis Z of the coordinate system runs through its center and is perpendicular to it. The axis Y is a vertical line directioned upward and the axis X is assigned to constitute a right-handed system. HMD is set in the coordinate system so that the midpoint of designed locations of both eyes comes to the

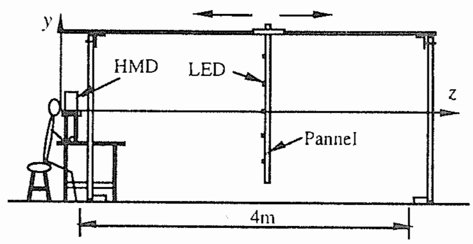

Fig. 6. Measurement system for calibration

origin and lines of sight are directed to the infinity point, i.e., the unit being mm, the designed location of left and right eye is placed at (32.5, 0.0, 0.0) and (-32.5, 0.0, 0.0), respectively and the center of designed location of the virtual plane for left and right eye is (32.5, 0.0, 1000.0) and (-32.5, 0.0, 1000.0), respectively. The pannel, holded by two rails, can move in the range $0.5m < z < 4m$. For convenience, the measurement is performed at $0.5m, 1m, 2m$, and $4m$.

The virtual HMD is set likewise in the virtual environment, i.e. the location of left and right eye is (32.5, 0.0, 0.0) and (-32.5, 0.0, 0.0), respectively and the center of the projection plane for left and right eye is (32.5, 0.0, 100.0) and (-32.5, 0.0, 100.0), respectively. The mark in the virtual environment is a cross-shaped cursor, which is movable by a joystick.

As shown in Fig.6, a human operator directly handles a virtual cursor in the situation equivalent to that he/she is wearing the HMD. The effects of two causes of error itemized in section 1 can coexist. The latter, however, can be eliminated by putting the pannel at d'_{vir}, the distance to the center of realized virtual plane, because it only result in a parallax between points on the virtual plane and on the pannel. Reversely, it is possible to place the pannel at d'_{vir} by using this phenomenon, i.e. when the operator swings his/her face up and down or left and right and moves the pannel back and forth, observing the virtual cursor drawn on the center of virtual plane, a distance is obtained at which a movement parallax between the virtual cursor and LED on the center of the pannel disappears. Although the value of d'_{vir} is not directly the distance to realized vitrual plane, it is derived from d'_{vir}.

Then, putting the pannel at $z = d'_{vir}$, we measure the shift of the virtual plane only due to errors produced in the manufacturing process. The operator moves the virtual cursor so that it overlaps each LED, and records its location expressed in the coordinate system of the virtual environment. Although the HMD is originaly a device for a binocular perception of the space, measurement for left and right eye can be done separetely because the optical system for an eye is independent of the other. It is also favorable to avoid complex mutual intervention of visual parameters of both eyes.

If the recorded locations of the virtual cursor are correct enough, we can exit from the calibration process according to the flowchart. Otherwise, we have to continue the calibration.

3.1.3 Consideration about the result of measurement

Before going on into step 5 of the calibration process, the process to derive the measurement equation, let's take a look at a relation among the locations of supposed virtual plane, realized virtual plane and the pannel. It is also necessary to consider the relation between the result of measurement and the shift of realized virtual plane from the designed location. The world coordinate system $(O - x'y'z')$ cognizable through HMD coexists with a world coordinate system of the real environment $(O - xyz)$ in the experiment system, but the axis z' is still toward the center of the realized virtual plane "B" (expressed as a thick dotted line in fig.7) because, as shown in Fig.7, its location is different from that of suppossed virtual plane "A" (expressed as a thick solid line in Fig.7) and the difference is not reflected on the visual parmeters at this stage of calibration. The value of d'_{vir} in Fig.7, the distance to the center of plane "B" (the mark ○ on "B"), is already known as the result of step 3, and the pannel is located at this distance.

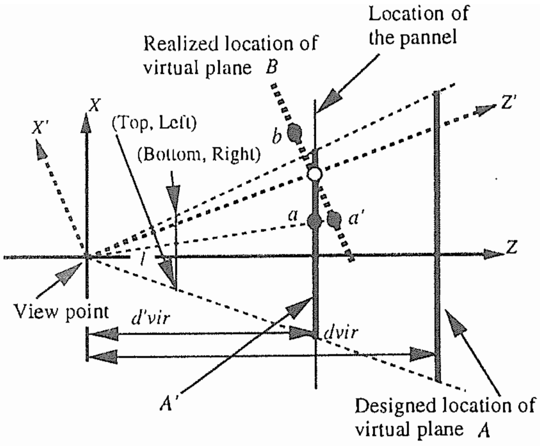

Fig. 7. Information obtained by the measurement

Instead of comparing between locations of realized and supposed virtual plane, here we define a plane "A'" on the pannel and try to calculate the location of "B" relative to it. "A'" is a substitute for "A" and the marks of the real environment are put on it. There is no difference between locations of projecton planes based on "A" and "A'". Both are given by (Top, Left) and (Bottom, Right) in Fig.7. Hence, for the purpose to calculte the location of "B", whether to use "A" or "A'" does not make eny differences.

Now, suppose that there is an LED a on "A'" whose location expressed in $O - xyz$ is, for example, $\boldsymbol{a}_{real} = (a_x, a_y, d'_{vir})^T$. The virtual cursor whose location is considered to be equal to a is drawn at the point b before the calibration has been done. The b expressed in the coordinate $O - x'y'z'$ is equal to a expressed in $O - xyz$, i.e., $\boldsymbol{b}_{vir} = (a_x, a_y, d'_{vir})^T$. Namely, the location of b relative to "B" is exactly the same as that of a relative to "A'". The measured location of the cursor, which is obtained by putting the cursor on an LED, is expressed as $\boldsymbol{a}'_{vir} = (a'_x, a'_y, d'_{vir})^T$ in $O - x'y'z'$.

If we know the map F which maps $\boldsymbol{a}_{real}$ onto $\boldsymbol{b}_{real}$, we can calcutate the location of "B" by operating F on "A'". As the value of $\boldsymbol{a}_{real}$ is already known, we need the value of $\boldsymbol{b}_{real}$. But it is not measureable. Hence, we have to express F by known values, $\boldsymbol{a}_{real}$ and $\boldsymbol{b}_{vir}$, and measured value $\boldsymbol{a}'_{vir}$.

3.1.4 Relation between displacement of the virtual plane and visual parameters

As mentioned in the previous section, the location of the projection plane is based on the location of the virtual plane. A rectangle defined by (Top, Left) and (Bottom, Right) in Fig.8 represents the location of the projection plane based on "A'" which we defined in Fig.7. These are obtained by reduceing "A'" in the direction of $\boldsymbol{p}$ by l/d'_{vir}. The vector $\boldsymbol{p}$ indicates the line of sight among the visual parameters. Its starting point means the view point and terminal is the center of "A'", and its length $||\boldsymbol{p}||$ is d'_{vir}. On the other hand, the realized virtual plane "B" is located differntly from "A'". The projection plane based on "B" is given by (*Top, Left*) and (*Bottom, Right*). The vector $\boldsymbol{p}'$ also indicates the line of sight and is perpendicular to "B". Its starting point is also a view point, but its terminal is not necessarily the center of "B". The values of (*Top, Left*) and (*Bottom, Right*) are obtained by reducing "B" in the direction of $\boldsymbol{p}'$ by $l/||\boldsymbol{p}'||$, but $||\boldsymbol{p}'||$ is not necessarily d'_{vir}.

The calibration method which we propose here uses following eight parameters to define a map from "A'" to "B":

- change of the direction of the viewing vector $\boldsymbol{p} \rightarrow \boldsymbol{p}'$ (described by ZYX euler angles, α, β, γ)
- shift of the center of the projection plane from the viewing vector (d_x, d_y) and change of length of the viewing vector(d_z)
- change of the shape of the virtual planes (horizontal magnification a, vertical magnification b)

and calculate the location of "B". Then, we calculate the values of (*Top, Left*) and (*Bottom, Right*) by reducing "B" in the direcion of $\boldsymbol{p}'$ by $l/||\boldsymbol{p}'||$.

A matrix R:

$$R = \begin{pmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma & 0 \\ s\alpha s\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma & 0 \\ -s\beta & c\beta s\gamma & c\beta c\gamma & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$(s\alpha = \sin\alpha, c\alpha = \cos\alpha \text{ etc.}) \tag{2}$$

describes the change of the viewing vector and the other parameters are collectively represented as a matrix A:

$$A = \begin{pmatrix} a & 0 & 0 & d_x \\ 0 & b & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{3}$$

With these matrices, a relation between $\boldsymbol{a}_{real}$ and $\boldsymbol{b}_{real}$ and the value of $||\boldsymbol{p}'||$ are described as

$$\boldsymbol{b}_{real} = RA\boldsymbol{a}_{real} \tag{4}$$

$$||\boldsymbol{p}'|| = d'_{vir} - d_z, \tag{5}$$

respectively. Inverse transformation of (4):

$$\boldsymbol{a}_{real} = A^{-1}R^{-1}\boldsymbol{b}_{real} \tag{6}$$

is equivalent to

$$\boldsymbol{a}_{vir} = A^{-1}R^{-1}\boldsymbol{b}_{vir}. \tag{7}$$

This is because that the mapping of $\boldsymbol{a}$ onto $\boldsymbol{b}$ is not affected by whether it is expressed in $O - xyz$ or $O - x'y'z'$. Because z component of $\boldsymbol{a}'_{vir}$ is always d'_{vir}, we can express the relation between $\boldsymbol{a}'_{vir}$ and $\boldsymbol{a}_{vir}$ as

$$\boldsymbol{a}'_{vir} = \begin{pmatrix} \frac{d'_{vir}}{[\boldsymbol{a}_{vir}]_z} I & 0 \\ 0 & 1 \end{pmatrix} \boldsymbol{a}_{vir}, \tag{8}$$

(I : 3-dimension unit matrix)

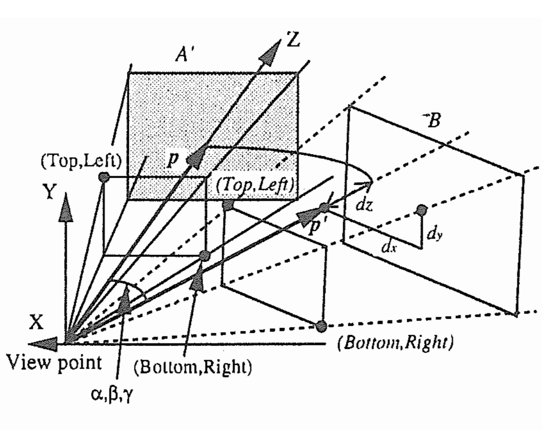

Fig. 8. Relation between the shift and rotation of virtual plane and visual parameters

where $[\boldsymbol{a}_{vir}]_z$ is z component of $\boldsymbol{a}_{vir}$. With these results, the relation between the known value $\boldsymbol{b}_{vir}$ and observed value $\boldsymbol{a}'_{vir}$ is described as

$$\boldsymbol{a}'_{vir} = \begin{pmatrix} \frac{d'_{vir}}{[\boldsymbol{a}_{vir}]_z} I & 0 \\ 0 & 1 \end{pmatrix} A^{-1}R^{-1}\boldsymbol{b}_{vir}. \tag{9}$$

Considering that the left hand of (9) is a function of the parameter vector $\boldsymbol{x}= (a, b, \alpha, \beta, \gamma, d_x, d_y)$, we have

$$\begin{aligned} \boldsymbol{a}'_{vir} &= \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{b}_{vir}) \qquad (10) \\ &= \begin{pmatrix} \dfrac{d'_{vir}\{a_x c\alpha c\beta + a_y s\alpha s\beta - d'_{vir} s\beta - d_x\}}{a \cdot \{a_x(c\alpha s\beta c\gamma + s\alpha s\gamma) + a_y(s\alpha s\beta c\gamma - c\alpha s\gamma) + d'_{vir} c\beta c\gamma - d_z\}} \\ \dfrac{d'_{vir}\{a_x(c\alpha s\beta s\gamma - s\alpha c\gamma) + a_y(s\alpha s\beta s\gamma + c\alpha c\gamma) + d'_{vir} c\beta s\gamma - d_y\}}{b \cdot \{a_x(c\alpha s\beta c\gamma + s\alpha s\gamma) + a_y(s\alpha s\beta c\gamma - c\alpha s\gamma) + d'_{vir} c\beta c\gamma - d_z\}} \\ d'_{vir} \end{pmatrix}. \end{aligned}$$

Then we can calculate $\boldsymbol{x}$ by solving (10).

3.1.5 Estimation using modified Marquardt method

It is desirable to modify the visual parameters so that $\boldsymbol{a}'_{vir}$s are mapped onto $\boldsymbol{b}_{vir}$s with a minimum RMS error. Among such methods, the least square method, a numerical solution which minimizes an error sum of squares with weight

$$S = (\boldsymbol{a}'_{vir} - \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{b}_{vir}))^T \Sigma^{-1} (\boldsymbol{a}'_{vir} - \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{b}_{vir})) \tag{11}$$

$$\left(\Sigma_{ij} = \begin{cases} \sigma_i^2, & i = j \\ 0, & i \neq j \end{cases} \right)$$

is generally well known. A nonlinear least square method is required to calculate $\boldsymbol{x}$ in our calibration method because $\boldsymbol{h}(\boldsymbol{x}, \boldsymbol{b}_{vir})$ is obviously a nonlinear model as (10) indicates. The modified Marquardt's method is selected here.

Gauss–Newton method, the fundamental nonlinear least square method, modifies $\boldsymbol{x}$ repeatedly by

$$\boldsymbol{x}^{(k+1)} = \boldsymbol{x}^{(k)} + \Delta\boldsymbol{x}, \tag{12}$$

where $\Delta\boldsymbol{x}$ is a modifier vector which is calculated as

$$(H^T\Sigma^{-1}H)\Delta\boldsymbol{x} = H^T\Sigma^{-1}\boldsymbol{v}. \tag{13}$$

The equation (13) is called a normal equation and is derived from derived from the measurement equation

$$\boldsymbol{v} = \boldsymbol{a}'_{vir} - \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{b}_{vir}) \tag{14}$$

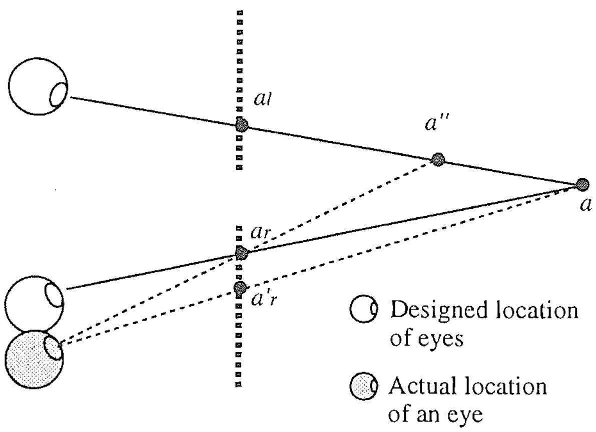

Fig. 9. Effect of differences between actual and designed location of user's eye

and Jacobian matrix

$$H_{ij} = \frac{\partial h_i}{\partial x_j}. \tag{15}$$

On the other hand, adding a diagonal matrix λI to (13), the modified Marquardt's method employs

$$(H^T\Sigma^{-1}H + \lambda I)\Delta \boldsymbol{x} = H^T\Sigma^{-1}\boldsymbol{v} \tag{16}$$

to calculate $\Delta \boldsymbol{x}$. The estimation starts with $\lambda = 0$, and the degree of nonlinearity is checked at every repetition. The λ increases when it is large and decreases when it is small, which makes convergence of $\Delta \boldsymbol{x}$ more stable and rapid, and the whole calculation ends with the final value of λ being 0.

Thus, $\boldsymbol{x}$ is estimated and visual parameters are recalculated based on it. Then we can eliminate the systematic errors caused in the manifacturing process.

3.2 Calibration of differences between actual and designed location of user's eye on STHMD

3.2.1 Measurement of the effect of differences between actual and designed location of user's eye

As the result of the calibration above, points drawn in the virtual environment overlap real points through the whole space when user's eyes are correctly located as desiged. It is, however, not always the case, because the interocular distance of user and the shape of his/her face vary from one to another.

Errors due to a parallax appear between points in the real and virtual environment when actual location of user's eye differs from the designed value, because HMD projects all points on the virtual plane located at distance d_{vir} regardless of thier actual distances. Fig. 9 illustrates the effect of differences between actual and designed location of user's eye. A point a drawn in the virtual environment is projected onto the virtual planes for right and left eyes according to the designed locations of both eyes as a_l and a_r indicate. When the right eye, for example, is not located as designed and it is not reflected on the visual parameters, a human operator feels that the point is drawn at a'' instead of a. If the visual paremeters are set according to the actual location of the right eye, the image of point a is supposed to be a'_r. So, we have to measure the actual locations of user's eyes and modify the visual parameters according to the result.

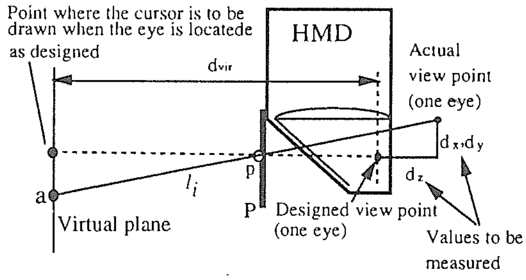

Fig. 10. HMD setup for calibration of eye's displacement

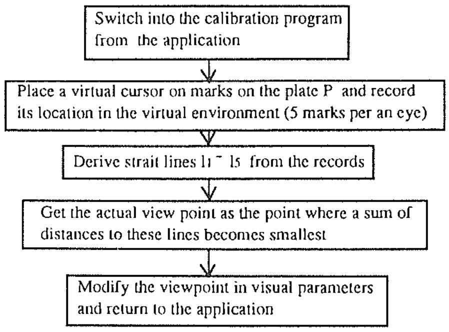

Fig. 11. Process of calibration eye's displacement

We can not use as same method as mentioned in section 3.1, in which the HMD is fixed at the origin of $O - xyz$, because the calibration of this error should be done as a initializing process every time when a user starts using HMD. Besides, it is convenient that marks for the calibration are fiexed at HMD because a difference between the actual and designed location of eye means a locational relation between user's eye and HMD. This is why we put a removable plate P on HMD as shown in Fig.2 and made it a basis on which the designed location of user's eyes etc. is defined

The original cause for errors due to a parallax is user's individual parameters mentioned above, but considering that it eventually appears as a shift of each eye from the designed location gives us a clearer idea. Hence, similar to the situation in section 3.1, we can discuss the calibration for an eye independently to that of the other. It is done through a following simple process. Fig.11 shows its flowchart.

1. Switch into the calibration process from the application.
2. Place a virtual cursor on marks on the plate P and record its location expressed in the virtual environment (Fig.10). Five marks are prepared for each eye.
3. Derive staraight lines $l_1 \sim l_5$ from the recorded values and the marks on P (Fig.10).
4. Calculate user's actual view point (d_x, d_y, d_z) as a point from which the sum of distances to starìght lines $l_1 \sim l_5$ becomes smallest.
5. Modify the view point among the visual parameters and re-

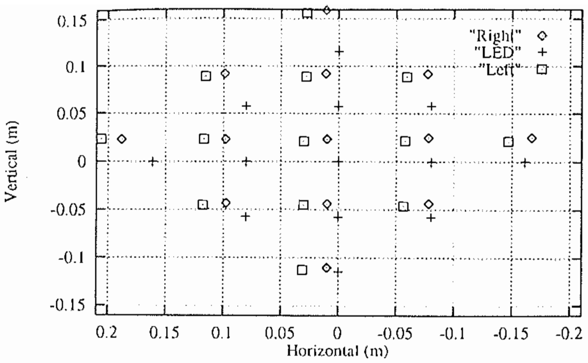

Fig. 12. Measured location of cursor at dvir before calibration

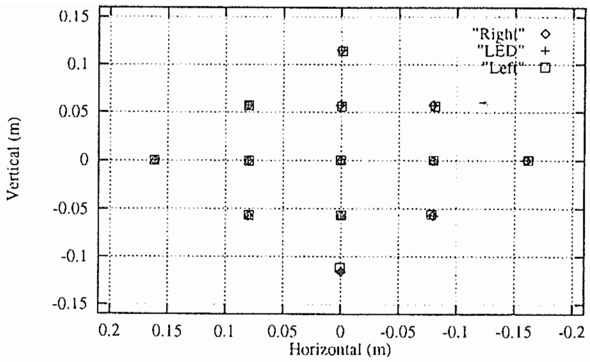

Fig. 13. Measured location of cursor at d_{vir} after calibration

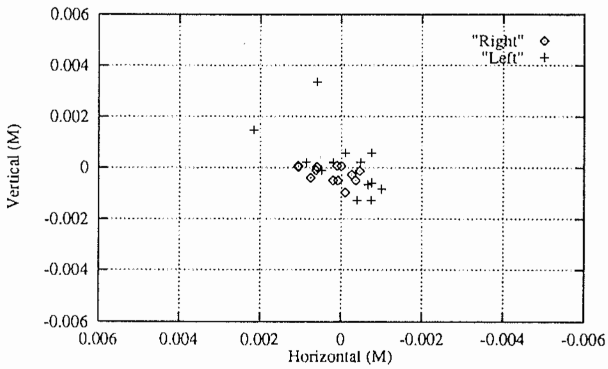

Fig. 14. Distribution of error at each point

turn to the application.

3.2.2 Calculate the actual locations of user's eyes

Measured location of the virtual cursor being $\boldsymbol{a}_i = (a_i^0, a_i^1, d_{vir})$ and the corresponding mark on the plate P being $\boldsymbol{p}_i = (p_i^0, p_i^1, p_i^2)$, a straight line l_i is expressed as

$$l_i : \begin{pmatrix} x \\ y \\ z \end{pmatrix} = (\boldsymbol{a}_i - \boldsymbol{p}_i)t + \boldsymbol{p}_i$$
$$= \begin{pmatrix} a_i^0 - p_i^0 \\ a_i^1 - p_i^1 \\ d_{vir} - p_i^2 \end{pmatrix} t + \begin{pmatrix} p_i^0 \\ p_i^1 \\ p_i^2 \end{pmatrix}. \quad (17)$$

Although $\boldsymbol{a}_i$ is a vector expressed in $O-x'y'z'$ and $\boldsymbol{p}_i$ is expressed in $O-xyz$, they can be directly used to calculate l_i as if they are expressed in the same coordinate system because $O-x'y'z'$ has precisely overlapped $O-xyz$ as the result of the calibration described in section 3.1. The sum of distances from the point $\boldsymbol{d}=(d_x, d_y, d_z)$ to each straight line is

$$L = \sum_{i=1}^{5} \frac{|\boldsymbol{d}-\boldsymbol{p}_i|^2|\boldsymbol{a}_i-\boldsymbol{p}_i|^2 - \{(\boldsymbol{d}-\boldsymbol{p}_i)\cdot(\boldsymbol{a}_i-\boldsymbol{p}_i)\}^2}{|\boldsymbol{a}_i-\boldsymbol{p}_i|^2} \quad (18)$$

and the actual location of user's eye is calculated as $\boldsymbol{d}$ which minimize L. We can calculate the value of $\boldsymbol{d}$ by a linear least square method, becuse (18) a linear model.

Thus, the visual parameters are modified based on $\boldsymbol{d}$ and, as the result, the STHMD can superimposes the virtual environment precisely on the real environment, wherever the realized virtual planes are located and wherever user's eyes are.

4 Experiment

In this section, we apply the proposed calibration method to the STHMD which we have made and show its effectiveness.

4.1 Elimination of systematic error caused in the manufacturing process

The STHMD being set at the origin of the world coordinate system of the real environment, we measured the value of d'_{vir} according to step 3 of Fig.5. It turned out that d'_{vir} was equal to $870mm$. Then we put the pannel at $z = 870mm$ to eliminate the effect of locations of observer's eyes at this stage of calibration and, the values of $\boldsymbol{a}'_{vir}$, locations of the virtual cursor which overlaps LEDs on the pannel, were measured.

Fig. 12 show the result of measurement. The horizontal and the vertical axis of Fig.12 represent the value of x and y on the pannel, respectively. Although the measurement was done with the pannel being at $z = 870mm$, these values were converted as if it was located at $z = 1m$.

Because the HMD was set at the same location both in the real and the virtual environment, the virtual cursor was supossed to correctly overlaps marks "+" which indicates locations of $\boldsymbol{b}_{vir}$, namely, it should have been that $\boldsymbol{a}'_{vir} = \boldsymbol{b}_{vir} = \boldsymbol{a}_{real}$, if there was no difference between realized and designed location of the virtual planes. Its actually measured locations of $\boldsymbol{a}'_{vir}$ for both eyes were, however, such as shown in Fig.12, exposing the shift of the virtual planes due to errors produced in the manufacturing process. Hence, we had to go on to derive the measurement equation

$$\boldsymbol{a}'_{vir} = \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{b}_{vir}) \quad (19)$$

to estimate the shift of realized virtual plane.

Table 2 summarizes how the visual parameters were calibrated through the process mentioned above. As the result of using the modified parameters, errors expressed in Fig.12 were rduced as shown in Fig.13. Fig.14 shows the distribution of error at each point "+" in Fig.13, a difference of $\boldsymbol{b}_{vir}$ from $\boldsymbol{a}'_{vir}$. RMS errors for left and right eye were $1.5mm$ and $0.7mm$, respectively.

There is an error of around $1 \sim 2mm$ in the location of drawn virtual cursor due to a low resolution of LCD. Besides, it must be considered that the experiment system also contain about several

Table 2. Visual parameters obtained by calibration

	Designed value	Actual value	
		Left eye	Right eye
$d_{vir}(mm)$	1000	854	869
Line of sight(mm)	(0,0,1000)	(13.4,4.29,870)	(-10.7,5.72,870)
Location of projection plane at $z = 0.1m$ (Right,Bottom)(mm)	(-36.0,-27.2)	(-38.6,-26.3)	(-32.9,-27.0)
Location of projection plane at $z = 0.1m$ (Left,Top)(mm)	(36.0,27.0)	(28.4,20.7)	(34.3,20.2)

millimeters of error because this large system is handmade, which directly becomes an error of the location of LED. The result of calibration is satisfactory under such a condition.

4.2 Elimination of errors due to the location of user's eye

As the result of the calibration above, points drawn in the virtual environment should have overlapped real points through the whole space when user's eyes were correctly located as desiged. But we could not get such a good result because locations of observer's eyes were different from those designed. Fig. 15 clearly shows the effect of a parallax. A group of the result of measurement at $z = 0.5mm$ has a tendency to shift to the left, whereas the other groups which consist of the results of measurement at $z = 1m, 2m,$ and $4m$ have the opposite tendencies, which corresponds whether z is less than d'_{vir} or not. Moreover, it is clearly observed that the tendency to shift to the right grows greater as the difference between the values of z and d'_{vir} becomes greater.

So, we also calibreted the effect according to Fig.11. The result of estimation of $\boldsymbol{d}$ which produces errors expressed in Fig.15 was $(d_x, d_y, d_z) = (-0.4mm, -0.7mm, -23.5mm)$, and errors were reduced as shown in Fig.16 by recalculating the view point among the visual parameters based on the estimated value of $\boldsymbol{d}$. Table 3 shows the result of comparison of RMS errors between before and after the calibration. It was also satisfactory under the experimental condition.

5 Conclusion

Matching of location and size between objects in the real enviroment and in the virtual enviroment is a crucial matter when

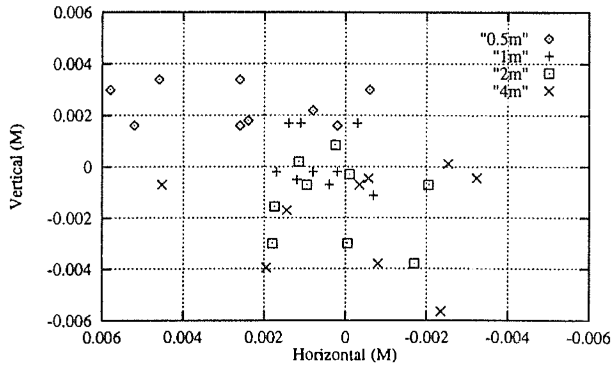

Fig. 15. Error caused by displacement of the eye(Right eye)

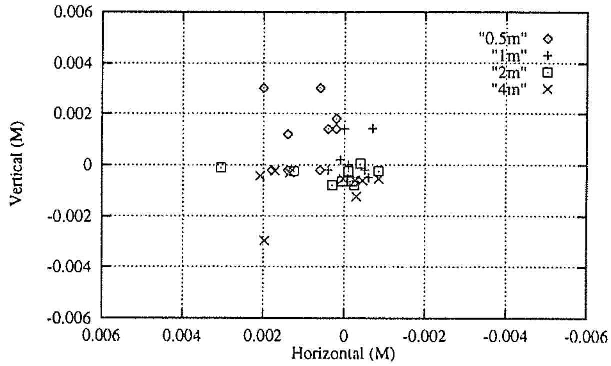

Fig. 16. Result of calibration of eye's displacement

Table 3. Comparison of RMS error

	$0.5m$	$1m$	$2m$	$4m$
Before calibration(mm)	4.2	1.5	2.4	3.6
After calibration(mm)	2.1	0.9	1.3	1.7

tring to put STHMD into a practical use. In this paper, we have proposed a calibration method in which a precise correspondence between points in the real environment and superimposed virtual cursor are taken care. Namely, we devided the causes of errors between them into

- Systematic errors of visual parameters caused in manufacturing process
- Differences between actual and designed location of user's eye on STHMD

and proposed methods to calibrate them independently, and demonstrated thier effectiveness by executing them with our prototype.

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