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HYBRID METHOD FOR DETECTING INFLUENTIAL FACTORS FOR TRACKING CAMERAS IN A CAVE

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Abstract: The industrial world increasingly uses Virtual Reality technology in design and research processes, in order to improve quality, but also to stick to the concept of a green technology. The accuracy and precision of VR systems such as the Cave Automatic Virtual Environment (CAVE), directly influences the range of possibilities of these processes. So, the aim of this paper is to describe a hybrid method (Monte Carlo Method and Design Of Experiment using Hadamard matrix) used to adjust tracking system cameras in a CAVE. A model of the tracking system is created based on factors of the camera, adjustable or not. This method provides a classification in order of influence of these adjustable factors over the CAVE tracking accuracy. This hybrid method also improves the accuracy of the VR system from *Aix Marseille Université* and to run the application of a knee surgery with high quality of immersion.

Keywords: Monte Carlo Method, Design Of Experiment, Hadamard matrix, Virtual reality, Camera, Tracking system, Accuracy.

1. INTRODUCTION

The Cave Automatic Virtual Environment (CAVE) consists of a three walls environment, cameras (eight in the studied system) and projectors as shown in Figure 1. A user immersed in this virtual world wears polarized glasses and gloves. Cameras are able to locate these items thanks to spherical markers tracked by cameras. This part of the system is the "tracking system" [1]. The technology used by the system in place strongly influences the quality of the immersion experienced and sensed by the user. The user uses polarised glasses (Figure 2). These devices provide information to know the location of the user in the CAVE, using the tracking of optical markers.

So, before loading an application inside a virtual reality system, checking the compatibility between the precision required by the application and the real accuracy delivered by the CAVE is a compulsory step. This paper focuses on the tracking system.

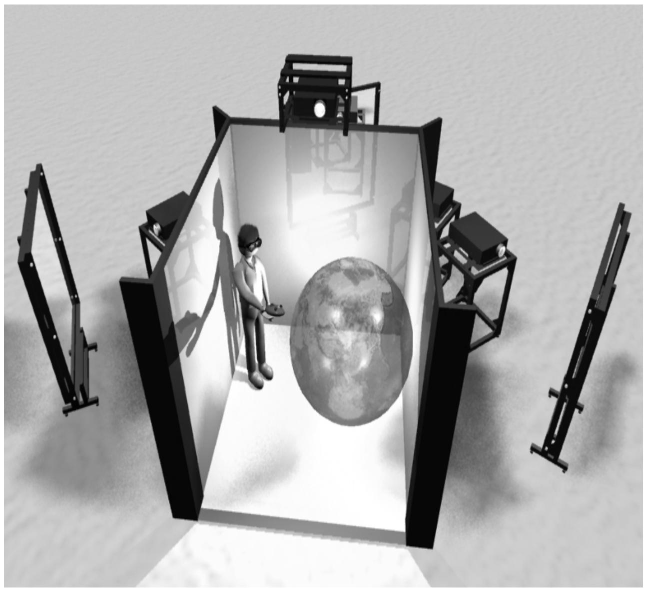

Figure 1. Cave Automatic Virtual Environment (CAVE) system

In the tracking system, the model of a camera, using the *pine-hole* model (Figure 3) and linear algebra, provides coordinates of the image of a marker tracked by a camera *i* inside the image frame, $M(u_i,v_i)$, in function of its coordinates inside the camera frame, $S(x_i,y_i,z_i)$. These coordinates are given in function of the extrinsic and intrinsic factors of the camera [2].

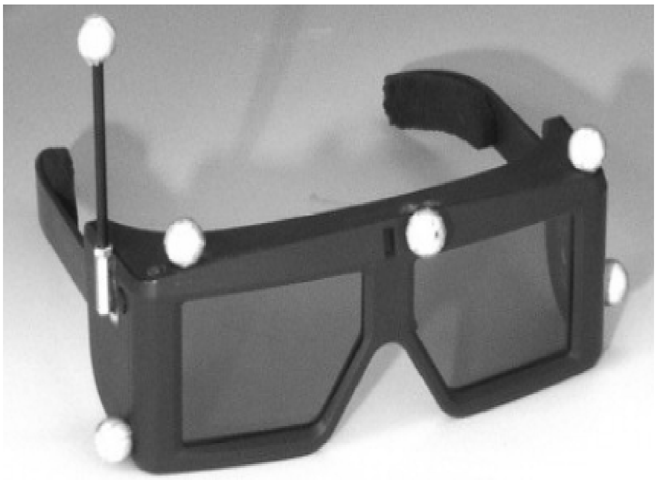

Figure 2. Polarized glasses and markers used for tracking

Extrinsic factors define the position and the orientation of the camera. Position of the camera is obtained from direct coordinates of the centre of the lens, inside the axis system of the CAVE. Orientation is obtained thanks to yaw, roll and pitch angles.

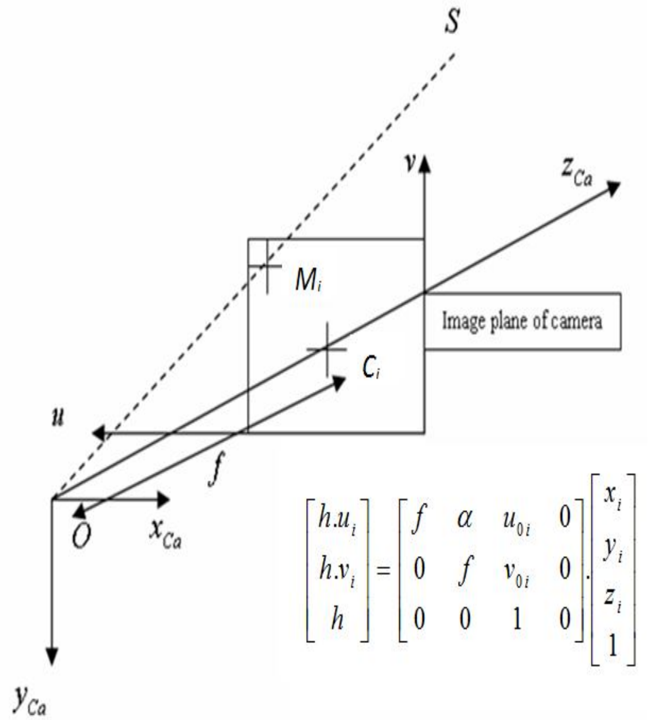

Figure 3. Pine-hole model and its associated matrix, with h as the scale factor

Intrinsic factors define proper characteristics of the camera, such as the focus distance f, the skew coefficient α, defining the angular error between horizontal and vertical direction of pixels, (u_{0i}, v_{0i}) such as coordinates of the point of intersection between the focus axis and the image plane of the camera i, C_i on Figure 3.

In order to complete this model, many distortions have to be considered. These can be radial, image decentring, and prismatic. (1) describes the detailed model R3D1P1, a non-linear camera polynomial distortion model [3]:

$$\begin{cases} \Delta_{xi} = x_{Mi}.\sum_{n=1}^{3} r_{ni}.\rho^{2n} + d_{1i}.(2x_{Mi}^2 + \rho_{Mi}^2) + 2d_{2i}.x_{Mi}.y_{Mi} + p_{1i}.\rho_{Mi}^2 \\ \Delta_{yi} = y_{Mi}.\sum_{n=1}^{3} r_{ni}.\rho^{2n} + d_{2i}.(2y_{Mi}^2 + \rho_{Mi}^2) + 2d_{1i}.x_{Mi}.y_{Mi} + p_{2i}.\rho_{Mi}^2 \end{cases} \quad (1)$$

$\rho_{Mi}^2 = (x_{Mi}^2 + y_{Mi}^2)$ is the squared distance between C_i and M_i, r_{ni} $(1 \le n \le 3)$, d_{mi} and p_{mi} $(1 \le m \le 2)$ are distortion parameters of camera i and $\overrightarrow{C_i M_i} = (x_{Mi}; y_{Mi})^T$.

CB_i is the transformation matrix used to get the coordinates (X_i, Y_i, Z_i) of S inside the frame of camera i, from its coordinates (X, Y, Z) inside the frame of the CAVE R_W:

$$\begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix} = CB_i \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} r_{i11} & r_{i12} & r_{i13} & -t_{xi} \\ r_{i21} & r_{i22} & r_{i23} & -t_{yi} \\ r_{i31} & r_{i32} & r_{i33} & -t_{zi} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (2)$$

Then, equation (3) describes the full model providing coordinates of the image marker, given inside the image frame of camera i, in function of $S(X,Y,Z)$:

$$\begin{cases} u_i = f.\dfrac{X.r_{i11} + Y.r_{i12} + Z.r_{i13} + t_{xi}}{X.r_{i31} + Y.r_{i32} + Z.r_{i33} + t_{zi}} + \alpha.\dfrac{X.r_{i21} + Y.r_{i22} + Z.r_{i23} + t_{yi}}{X.r_{i31} + Y.r_{i32} + Z.r_{i33} + t_{zi}} + \Delta_{xi} + u_{0i}, \\ v_i = f.\dfrac{X.r_{i21} + Y.r_{i22} + Z.r_{i23} + t_{yi}}{X.r_{i31} + Y.r_{i32} + Z.r_{i33} + t_{zi}} + \Delta_{yi} + v_{0i}. \end{cases} \quad (3)$$

Then, these factors are subjected to disturbances, according to data collected, using Mersenne Twister algorithm. Their probability density functions (PDF) is chosen uniform.

The full model provides a variation of the estimated location of the marker M_i in the image plane of the camera.

This variation is called projection error (e_i). It is the distance between the theoretical location and the "perturbed" one. After computing projection errors for each camera using the full model, the least squares method minimizes these projection errors to calculate the estimated location of S in R_W. The deviation $\overrightarrow{dM}(dX, dY, dZ)^T$ between theoretical and estimated locations of S is also computed. Using the set of factors, a Monte Carlo simulation provides the variance covariance matrix V_M and the average deviation $\overrightarrow{dM}$. The error zone, an ellipsoidal shape, is created.

A CAVE with eight tracking cameras count until one hundred and twenty eight significant factors, sixteen per camera [4]. In order to improve the quality of immersion of the user, so the accuracy of the tracking system of the CAVE, it is important to target adjustable factors which have an important influence over the accuracy of the system. Therefore, the process of calibration can be improved.

2. HYBRID METHOD

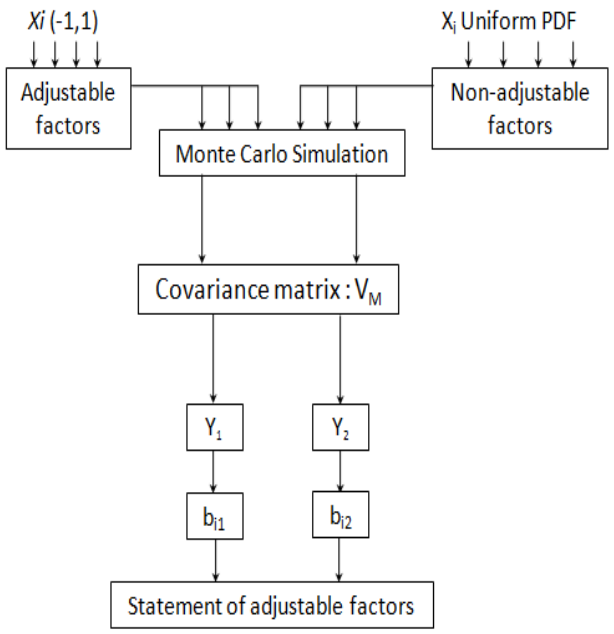

Figure 4. Flowchart of Hybrid Method (MCM, DOE).

As the flowchart from the Figure 4 explains, the first step of this hybrid method is to detect adjustable factors. It is assumed that intrinsic factors cannot be modified and/or adjusted by the user. Indeed, cameras used are standard ones (ARTtrack in Aix Marseille Université CAVE). So, the only factors we can work on are extrinsic factors, from the position and the orientation of cameras.

Cameras are fixed on the framework of the CAVE. Their positions are defined as the location of lens optic centre using direct coordinates in R_W (CamiTX, CamiTY, CamiTZ) referring to the camera *i* and the orientation of the optic axis using yaw, roll and pitch angles, CamiRX and CamiRY. Depending on the location of cameras inside the framework, some adjustments of the position are possible or not. Then, twenty six extrinsic factors are adjustable (Cam1TY, Cam2TZ, Cam3TX, Cam3TZ, Cam4TX, Cam5TX, Cam6TX, Cam6TZ, Cam7TZ, Cam8TY) and CamiRX, CamiRY for $1 \le i \le 8$. These factors of position and orientation of cameras are detailed in Figure 5.

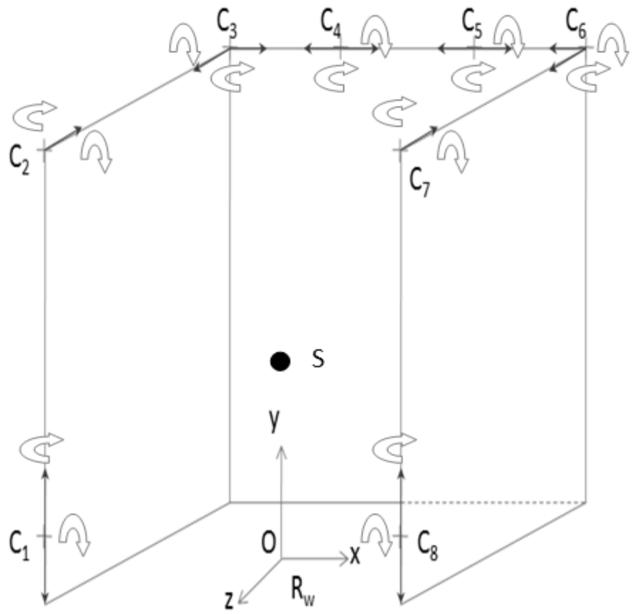

Figure 5. Available translation and rotation nobilities of cameras

The processing for adjustable and non-adjustable factors is different. Non-adjustable factors (x_i) are subjected to disturbances, using Mersenne Twister algorithm as explained previously, whereas values affected to adjustable factors are chosen by the DOE experiment matrix [5].

Concerning adjustable factors, only lower and higher values of the factors domain are considered. So, two levels are chosen per factor: the experimental model has to be 2^{28}. But, in order to decrease the number of experiments, the experimental matrix chosen is a Hadamard matrix. Regarding the number of line, so the number of experiments, which has to be a multiple of four, and the number of factors, the Hadamard matrix design is 28x26. -1 is assigned to the lower value of the factors domain and +1 is assigned to higher one. The DOE analysis leads to twenty eight Monte Carlo simulations.

Two responses in function of factors X_i, provided by the covariance matrix after Monte Carlo simulations: the average dimension of the error zone, Y_1; the distortion of the error zone, Y_2, such as:

$$\begin{cases} Y_1 = m = \frac{1}{3}.tr(V_M) \\ Y_2 = \sqrt{\frac{3}{2}.\sum D_{ij}^2} \end{cases} \text{, where } D = V_M - m.I \quad (4)$$

The screening is used to detect factors that *could* be influential. Screening models chosen are linear systems, written in function of : *Y*, the response vector ; *X*, the experimental matrix ; *B*, vector deduced from the b_i coefficients and *E* the error vector :

$$Y_i = X.B_i + E \qquad (5)$$

The matrix E describes two kind of errors : the lack of fit of the model and experimental errors introduced by Mersenne Twister algorithm.

This system gets a number of equations greater than the number of unknowns. Twenty eight equations and twenty six unknowns are counted. An estimate of coefficients matrix $\hat{B}_i$ is introduced in order to simplify the linear system:

$$\hat{Y}_i = X.\hat{B}_i \qquad (6)$$

The least square method is used to solve the system. The estimate of coefficient b_i are obtained, $\hat{B}$:

$$\hat{B}_i = (X^T.X)^{-1}.X^T.Y_i \qquad (7)$$

Then, statistical tools are used to create a statement of factors, concerning their influence on responses.

3. STATISTICAL TOOLS

Two tools are used to analyse and state influences of factors: the graph of effects and the Bayesian analysis.

Regarding the graph of effects, this is assumed that b_i factors are propagated as a Gaussian law and var(b_i) as a khi-square law. Then is deduced that $\frac{b_i - E(b_i)}{\sqrt{\text{var}(b_i)}}$ follows a Student law. The degree of freedom is one, because twenty seven factors b_i and twenty eight different equations given by the Hadamard matrix are considered. The Student table provides : $t_{0,025} = 12{,}7$.

A 5% risk is chosen. So, 95% of b_i values belong to this range of confidence :

$$\left[-t_{0,025}.\sqrt{\text{var}(\hat{b}_i)};+t_{0,025}.\sqrt{\text{var}(\hat{b}_i)}\right] \qquad (8)$$

Then, in order to look after the range of confidence of b_i coefficients, the error matrix of two answers $Y1$ and $Y2$ $E(E_1, E_2)^T$ can be computed thanks to :

$$E_i = Y_i - X.\hat{B}_i \qquad (9)$$

Var(b_i) is computed using the distortion matrix :

$$\text{var}(b_i) = (X^T.X)^{-1}.\sigma^2_{E_i} \qquad (10)$$

Regarding the Bayesian analysis, the principle of the test is to calculate after the event that every factor is active [6][7]. Two parameters are considered :

- the probability that a factor is active a priori (p) ;
- the ratio between variances of active factors and variances of every non-active factors (q).

Then, the aim is to calculate probabilities after the event for every combination (p,q) for ranges : $0{,}1 \leq p \leq 0{,}4$ and $5 \leq q \leq 20$.

4. EXPERIMENTS

The studied CAVE intends to run the application of a knee surgery in order to train surgery students. So, the location of the marker studied in Monte Carlo simulations is (0, 1200, 0), given in millimetres.

The model is programmed in Visual Basic and the number of cycles is thirty thousand. Depending on characteristics of computers used, a simulation spends between four and six hours.

Factor	Domain
Cam1TY	[-4;4]
Cam2TZ	[-8;0]
Cam3TX	[0;8]
Cam3TZ	[0;8]
Cam4TX	[-4;4]
Cam5TX	[-4;4]
Cam6TX	[-8;0]
Cam6TZ	[0;8]
Cam7TZ	[-8;0]
Cam8TY	[-4;4]

Table 1. Domain of factor concerning position of cameras

The domain of every factor has to be chosen (See tables 1 and 2). As previously said, concerning position of cameras, their location influences this domain, whereas the domain of factors about orientation keep being the same whatever the factor. The domain per adjustable factor are noted in Table 1 and Table 2. The unity used for the position is the millimetre and the one used for orientation is degree. These variations are given in function of the theoretical location and orientation of cameras inside the frame of the CAVE given in Figure 5.

Factor	Domain
Cam$_i$RX	[-2;2]
Cam$_i$RY	[-2;2]

Table 2. Domain of factor concerning orientation of cameras, $1 \leq i \leq 8$, i integer.

5. RESULTS ANALYSIS FOR Y1

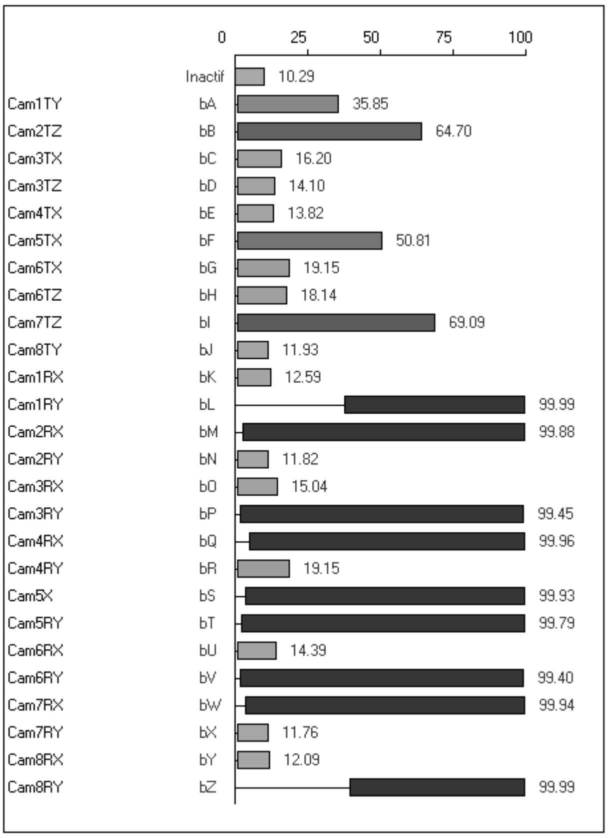

Figure 6. Bayesian analysis of Y1

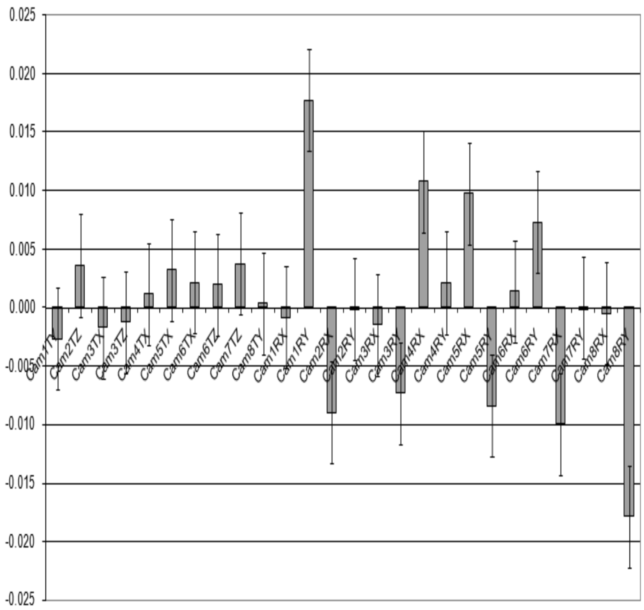

Figure 7. Graph of effects of *Y1*

These two analysis are strongly similar and lead to the same conclusions :

- position of the camera inside the CAVE does not influence the dimension of the error zone ;
- only orientations of camera are adjustable factors influencing the dimension of the error zone.
- the symmetry of the CAVE is respected ;
- influential factors over Y1 are : Cam1RY, Cam2RX, Cam3RY, Cam4RX, Cam5RX, Cam6RY, Cam7RX and Cam8RY.

A thinking has to be led concerning Cam4RY and Cam5RY because in this case, the symmetry is not respected.

6. RESULTS ANALYSIS FOR Y2

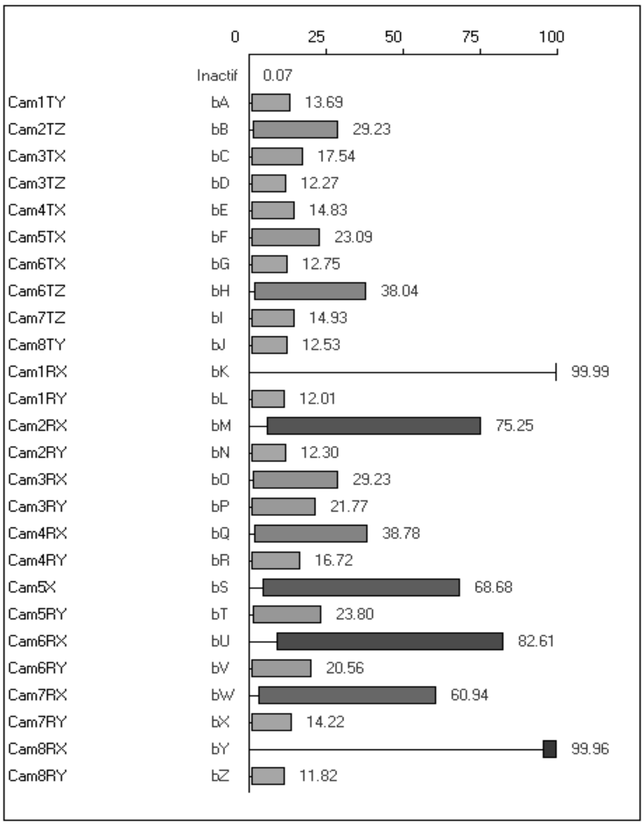

Figure 8. Bayesian analysis of Y2

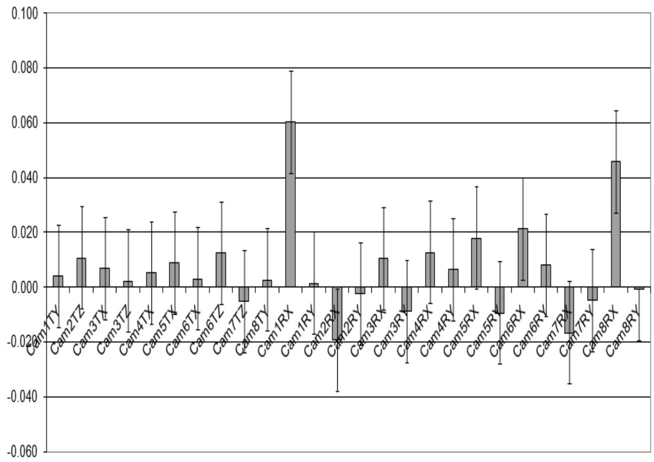

Figure 9. Graph of effects of *Y2*

These two analysis are strongly similar and lead to the same conclusions :

- position of the camera inside the CAVE does not influence the distortion of the error zone ;

- only orientations of camera are adjustable factors influencing the distortion of the error zone.
- the symmetry of the CAVE is respected ;
- influential factors over Y2 are : Cam1RX, and Cam8RX.

Another reflection can also be led to know if factors concerning orientation of camera 2, 3, 4, 5, 6 and 7, around X-axis influence the distortion of the error zone. Anyway, camera 1 and 8 strongly influence it in comparison of others.

7. CONCLUSION

As a conclusion from the application of this hybrid method, combining Monte Carlo simulations and Design Of Experiment, the only adjustable factors which have to be considered for influencing strongly the dimension and the distortion of the error zone is orientation of cameras.

The next step of this research will be to analyse possible interactions between these factors and to create the response surfaces of Y1 and Y2.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

References:

[1] Thomas A. DeFanti, Gregory Dawe, Daniel J. Sandin, Jurgen P. Schulze, Peter Otto, Javier Girado, Falko Kuester, Larry Smarr, Ramesh Rao, "The StarCAVE, a third-generation CAVE and virtual reality OptIPortal", Future Generation Computer Systems, Volume 25, Issue 2, February 2009, Pages 169-178

[2] A. G. Buaes, A low cost one camera tracking system for indoor wide-area augmented and virtual reality environments, Post graduation program in Electrical engineering, 2006.

[3] C. Ricolfe-Viala, A.J. Sanchez-Salmeron, Robust metric calibration of non-linear camera lens distortion, Pattern Recognition 43, 2010, 1688-1699.

[4] F. Ezedine, W. M. Wan Muhamad, J.M. Linares, "Uncertainty Calculation Of A Multicamera Tracking System In A Cave", Advanced Mathematical and Computational Tools in Metrology and Testing, vol.9 (F Pavese, M Bär, J-R Filtz, A B Forbes, L Pendrill, H. Shirono, eds.), Series on Advances in Mathematics for Applied Sciences vol. 84, World Scientific, Singapore, pp.151-158, 2012.

[5] J. Chaves-Jacob, J.M. Linares, J.M. Sprauel, "Using statistical confidence boundary of a D.O.E. Response surface to estimate optimal factors", Advanced Mathematical and Computational Tools in Metrology and Testing, vol.9 (F Pavese, M Bär, J-R Filtz, A B Forbes, L Pendrill, H. Shirono, eds.), Series on Advances in Mathematics for Applied Sciences vol. 84, World Scientific, Singapore, pp.74-81, 2012.

[6] R. Kacker, R. Kessel, K.-D. Sommer, "Only non-informative Bayesian prior distribution agree with the GUM type A : Evaluations of input quantities", Advanced Mathematical and Computational Tools in Metrology and Testing, vol.9 (F Pavese, M Bär, J-R Filtz, A B Forbes, L Pendrill, H. Shirono, eds.), Series on Advances in Mathematics for Applied Sciences vol. 84, World Scientific, Singapore, pp.216-223, 2012.

[7] G.A. Kyriazis, "Bayesian inference in waveform metrology", Advanced Mathematical and Computational Tools in Metrology and Testing, vol.9 (F Pavese, M Bär, J-R Filtz, A B Forbes, L Pendrill, H. Shirono, eds.), Series on Advances in Mathematics for Applied Sciences vol. 84, World Scientific, Singapore, pp.232-243, 2012.