Head movement compensation algorithm in multi-display communication by gaze

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***Abstract*— An influence of head movements on the gaze estimation accuracy when using a head mounted eye tracking system is discussed in the paper. This issue has been examined for a multi-display environment. It was found that head movement (rotation) to some extent does not influence on the gaze estimation accuracy seriously. Acceptable results were obtained when using eye-tracker to communicate with a computer via in two displays simultaneously.**

Keywords—eye tracking; gaze tracking; head movement compensation; multi-display environment; multi display; head rotation

I. Introduction

In our previous work we introduced the method for gaze communication in multi-display environment [1]. The presented method used tagged by Light Emitting Diodes (LED) computer monitors (displays) combined with a head-mounted eye-tracker equipped with scene and eye tracking cameras. Scene tracking camera registered LEDs (markers) position and represented them as a cloud of points. By analyzing the mutual position of the detected LEDs the algorithm estimated displays position and returned its parameters (ID, size, resolution). Although it is easier to absorb a knowledge when a complex information is presented on several monitors/screens [6], communication in multi-display seems to enforce additional head movements. Large head movements may cause some errors in point of regard (POR) estimation especially when considering head mounted eye trackers. Lots of different methods compensating the influence of head movements are implemented in remote gaze tracking systems [2][3][4]. The head movements compensation algorithm is very important part of every gaze tracking interface. However, it strongly depends on the adopted model of a gaze point estimation. Very common method for POR estimation implemented in head mounted eye trackers is Pupil Cornea Reflection (P-CR) vector method [5]. However this method may have some limitations considering gaze communication in multi-display environment.

The presented model of communication assumes that the user calibrates gaze tracking interface according to the primary screen position and control a cursor on any of configured displays. Implemented mathematical model enables the change of visual attention between the screens of different position in 3D environment. Moreover, properly established rules for gaze-based communication in the multi-display environment are also important for a mobile eye-tracker, additionally equipped with a micro-display. In this paper we are trying to establish the range of head movements in case of work with multiple screens that will not cause significant loss of accuracy. The proposed algorithm based on perspective transform is evaluated according to the results of head rotation measurements. We also propose another algorithm including additional information about head-to-screen movement and check its accuracy.

II. Methods and Materials

A. Basic interface description

The general concept of the interface and the detection algorithms were presented, as already mentioned, in the earlier works [9][10][11].

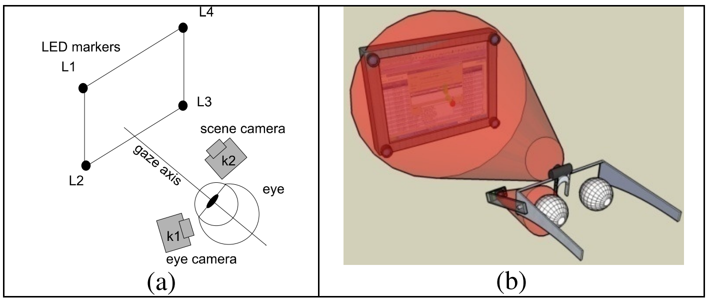


Figure 1. Basic concept of eye tracking interface

The developed algorithm for gaze estimation relies on the perspective transforms used as a tool to establish relationship between captured pupil image, image captured by scene camera and screen pixel space. Diagram below (Fig. 2) presents the way of calculating the POR by means of to the described algorithm. First transformation matrix "T1" is calculated due in order to calibrate the system. Four points form first image-space (pupil positions registered in image captured by "K1") and corresponding points of second image-space (screen corners' positions detected in image captured by "K2") are needed to calculate the coefficients of the transformation matrix. All the input data are captured during 4-point calibration procedure.
By calculating T1 it is possible to estimate fixation point in "K2" image-space (virtual point of regard - Vpor):

$$Vpor = \begin{bmatrix} X \\ Y \\ W \end{bmatrix} = T1 \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad (1)$$

where: x, y - pupil coordinates in k1 image space; Vpor - "Virtual point of regard" pupil position representation in k2 image space; T1 – the transformation matrix.
The matrix T1 has the following form:

$$T1 = \begin{bmatrix} a1 & a2 & a3 \\ a4 & a5 & a6 \\ a7 & a8 & 1 \end{bmatrix} \quad (2)$$

The elements of the matrix a1 to a8 have to de determined in the calibration procedure.

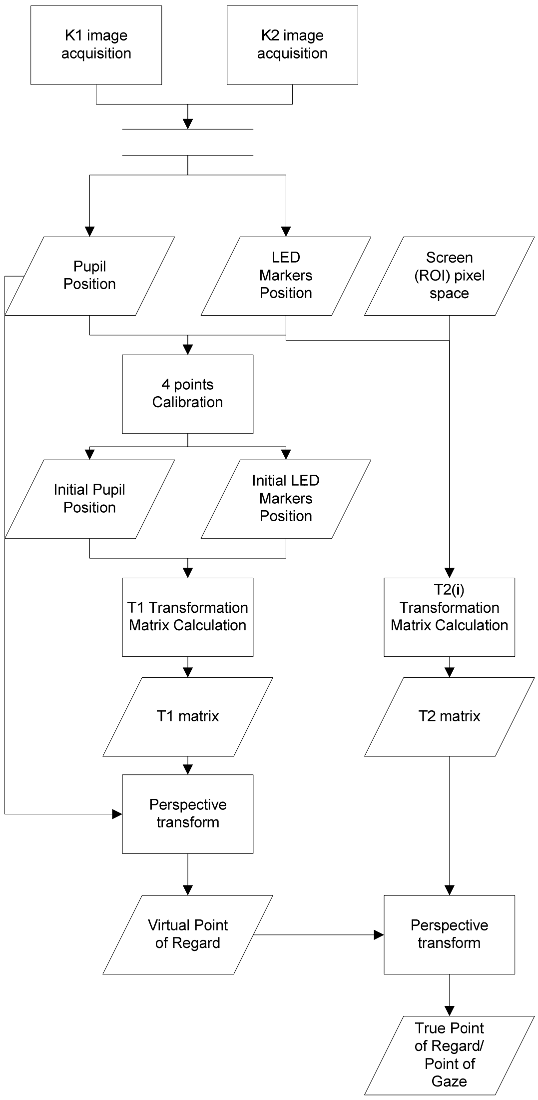


Figure 2. Block diagram of the POR estimation algorithm

The coefficients of T1 can be obtained from the equation:

$$\begin{bmatrix} X_s \\ Y_s \end{bmatrix} = M_1 * \begin{bmatrix} a1 \\ a2 \\ a3 \\ a4 \\ a5 \\ a6 \\ a7 \\ a8 \end{bmatrix} \quad (3)$$

where:

$$M_1 = \begin{bmatrix} x_p & y_p & 1 & 0 & 0 & 0 & -X_s x_p & -X_s y_p \\ 0 & 0 & 0 & x_p & y_p & 1 & -Y_s x_p & -Y_s y_p \end{bmatrix} \quad (4)$$

where X_s, Y_s are coordinates of screen corners (calibration points) positions in K2 and x_p, y_p are corresponding pupil position in K1.
However, to establish point of regard within actual region of interest (ROI), it is necessary to relate the screen's pixel space with K2 image-space. To compensate potential head movements, second transformation matrix T2 is calculated for every new captured frame.
The coefficients of T2(i) can be obtained for calibration point represented by current screen corners directly from equation:

$$\begin{bmatrix} X \\ Y \end{bmatrix} = M_2 * \begin{bmatrix} a1 \\ a2 \\ a3 \\ a4 \\ a5 \\ a6 \\ a7 \\ a8 \end{bmatrix} \quad (5)$$

where:

$$M_2 = \begin{bmatrix} X_s & Y_s & 1 & 0 & 0 & 0 & -X\ X_s & -X\ Y_s \\ 0 & 0 & 0 & Y_s & Y_s & 1 & -Y\ X_s & -Y\ Y_s \end{bmatrix} \quad (6)$$

where X, Y are calibration points coordinates (in real screen pixel space coordinate system) and X_s, Y_s are corresponding points in K2. The true point of regard can be computed according to the formula:

$$Tpor(i) = \begin{bmatrix} X \\ Y \\ W \end{bmatrix} = T2(i) \begin{bmatrix} x_v \\ y_v \\ 1 \end{bmatrix} = T2(i) T1 \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad (7)$$

where: x, y - pupil center coordinates represented in image captured by "k1", T1 - transformation matrix (transformation between k1 and k2 image-space), x_v, y_v - "virtual" point of regard coordinates represented in "k2" image-space, T2(i) - temporary transformation matrix (transformation between k2 image-space and real screen pixel space), Tpor(i) - temporary "true point of regard", gaze point represented regarding the screen coordinates, X/W, Y/W - fixation point coordinates
According to the mathematical dependencies the algorithm should compensate head movements as long as the K1, K2 and users eye stay in constant geometrical relationship.
The use of perspective transform and automatic aggregation of the virtual fixation allows to establish the point of regards within certain ROI. However, the change of the head to ROI position changes the initial conditions. . As a result, different

transform matrix could be implemented. Testing the algorithm a certain similarity was noticed regarding head to screen movements and corresponding pupil positions.

It is possible to estimate the new input points and calculate new transformation matrix according to the vector representing the difference between primary ROI position (captured while the calibration) and its current position using the following relationship:

$$L(L_x, L_y) = C_0(C_{0x}, C_{0y}) - C_t(C_{tx}, C_{ty}) \tag{8}$$

where: L - x, y coordinates of ROI center displacement; C_0 - x, y coordinates of ROI center during calibration procedure; C_t - current x, y coordinates of ROI position in image captured by scene camera

The relation between registered ROI position and corresponding pupil position can be estimated with a displacement vector:

$$d = \begin{bmatrix} \frac{L_x}{E_{xmax}} \\ \frac{L_y}{E_{ymax}} \end{bmatrix} \tag{9}$$

where: d - displacement vector; E_{xmax} - maximum absolute difference of ROI's corners position in X axis registered by scene camera; E_{ymax} - maximum absolute difference of ROI's corners position in Y axis registered by scene camera

The pupil offset vector can be calculated by multiplying this differences with the displacement factor:

$$p_o = \begin{bmatrix} p_{xmax} * d_x \\ p_{ymax} * d_y \end{bmatrix} \tag{10}$$

where: p - pupil offset; p_{xmax} - maximum absolute difference of pupil position in X axis registered during calibration; p_{ymax} - maximum absolute difference of pupil position in X axis registered during calibration

By estimating the pupil offset, T1(i) can be computed dynamically for every captured frame. The T1(i) coefficients can be obtained by solving equation:

$$\begin{bmatrix} X_s \\ Y_s \end{bmatrix} = M_3 \begin{bmatrix} a1 \\ a2 \\ a3 \\ a4 \\ a5 \\ a6 \\ a7 \\ a8 \end{bmatrix} \tag{11}$$

where M_3 is:

$$\begin{bmatrix} x_p - p_{ox} & y_p - p_{oy} & 1 & 0 & 0 & 0 & -X_s(x_p - p_{ox}) & -X_s(y_p - p_{oy}) \\ 0 & 0 & 0 & x_p - p_{ox} & x_p - p_{ox} & 1 & -Y_s(x_p - p_{ox}) & -Y_s(y_p - p_{oy}) \end{bmatrix} \tag{12}$$

So, calibration procedure is necessary to establish relation between initial screen position and corresponding pupil coordinates. Then input data for perspective transform are estimated by translating initial pupil position by p_o vector. Then the point of regard can be estimated according to the formula:

$$Tpor(i) = \begin{bmatrix} X \\ Y \\ W \end{bmatrix} = T2(i) \begin{bmatrix} x_v \\ y_v \\ 1 \end{bmatrix} = T2(i)T1(i) \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{13}$$

Additionally, the position of the point of regard (POR) can be corrected by factor representing difference between the line of sight and the pupil center.

$$Tpor = \begin{bmatrix} X_{POG} \\ Y_{POG} \end{bmatrix} - \begin{bmatrix} K_x \\ K_y \end{bmatrix} \tag{14}$$

where: X_{POR} = X/W, Y_{POR}=X/W are point of regards coordinates in 2D space.

"K" = $\begin{bmatrix} K_x \\ K_y \end{bmatrix}$ can be a constant value or it may be calculated according to additional calibration points.

B. *Measurements of head rotation while operating multi-screen environment.*

The presented method of head movement and rotation measurements was developed according to the methodology wildly used by the orthopedics [7]. In presented method the digital camera registered the position of LED markers spread on a user's head. The head rotation and head displacement were registered as two separate values. Moreover, the assumption was that the total registered head dislocation is a result of several spin section movements. However, regarding the communication in multi-display environment, the general head-to-screen dislocation was the crucial information.

The experimental stand is shown in Figure 3. The camera, located above the head of examined person, is registering subject's movement.

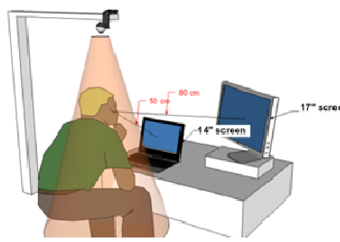


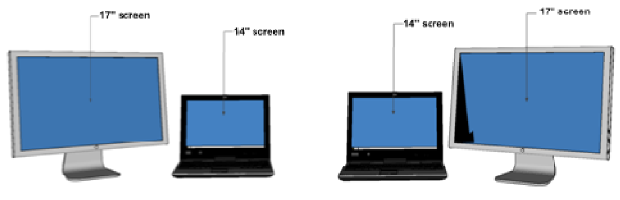
Figure 3. Head rotation measurements stand

Beside the camera, the stand consisted of two screens: 14" and 17" working in the extended display mode.

C. *Test description.*

The main purpose of a test was to estimate range and differences in head-to-screen displacement comparing two scenarios: 1. performing the tasks using single display, 2. performing the tasks when two screens working in extended display mode are used. In general, the test relied on finding the visual stimuli displayed randomly or in certain order on the screens. The size of the stimuli changed from big

(100x100px), through a medium (50x50px), to a small one (20x20px). User was obliged to find and click the visual stimuli appearing in an assumed order and then randomly. In case of measuring the head movement in two display scenario, two different screens setup were evaluated. The configuration of experimental stand is presented in Figure 4.



(a) (b)

Figure 4. Different locations of screens working in extended display mode

The results of this test reviled the range of potential head movements during the work in multi-display environment. This information is essential for head compensation algorithm implemented in the eye tracking interface that allows for hands free communication and gaze distribution registration from multiple areas of interest.

D. *Gaze tracking interface accuracy*

The test itself relied on measuring the accuracy of the gaze tracking algorithm under restricted head movements. By definition accuracy is the average difference between the real stimuli position and the measured gaze position. The accuracy was measured according to the formula:

$$AngAccuracy = arctan\left(\frac{PixAccruacy * PixToCmRatio}{d}\right) \tag{15}$$

where:

$$PixAccuracy = \sqrt{(Target_X - MeanFix_X)^2 + (Target_Y - MeanFix_Y)^2} \tag{16}$$

and:

$$MeanFix_X = \frac{1}{N}\sum_{i=1}^{N} Fix_X(i) \tag{17}$$

$$MeanFix_Y = \frac{1}{N}\sum_{i=1}^{N} Fix_Y(i) \tag{18}$$

where: N - number of attempts; Fix_X, Fix_Y - fixation point coordinates registered for specific test point.; $MeanFix_X$, $MeanFix_Y$ - average value of fixation points coordinates registered for a specific test point; PixAccuracy - accuracy represented in pixel values; $Target_X$, $Target_Y$ - test point coordinates; AngAccuracy - accuracy represented in degrees; PixToCmRatio - pixel to centimeters ratio; d - distance between gaze tracking interface (user) and screen.

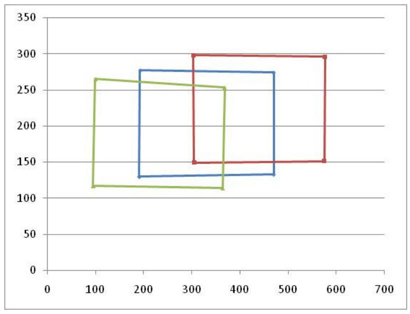
E. *Accuracy test*

After establishing the average possible head rotation in configured multi-display environment, the accuracy of applied head movements compensation algorithms was measured. Ten users were involved in accuracy testing. The angular accuracy was measured for natural head-to-screen position (0 degree rotation angle) and the head rotated by an angle of 5 and 10 degrees in right and left direction. The angle of the head rotation was measured by additional camera (Fig. 1). In order to ensure correct angle of subject's head rotation during the measurements, chin rest was used for stabilizing the head position.

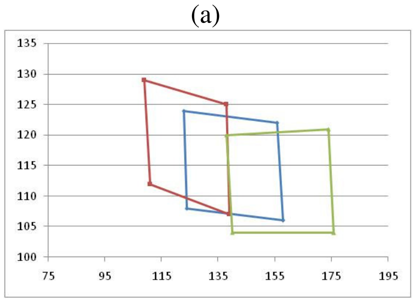
Accuracy measurement is based on stimulus points on a screen. The participants were asked to focus their gaze on each of the point during a trial test. The target points position were used in order to calculate accuracy, as a reference point in relation to the measured gaze point. In described experiment two different configuration of stimuli points were used. The accuracy was measured according to 9 and 16 points spread symmetrically across the screen. Points were presented in the order for 2-3 seconds.

III. RESULTS

The second of the proposed algorithms relied on a certain similarity between absolute screen position represented in K2 image space and corresponding pupil position represented in K1 image space.



(a)



(b)

Figure 5. The relation between a) screen position and b) corresponding pupil position change

Figure 5a presents registered ROI position, represented in K2 image space, for different head positions. The new set of pupil positions (represented in K1 image space), corresponding to registered ROI's corners are presented in Figure 5b. The difference between real and estimated input data for perspective transform calculation are presented in Figure 6.

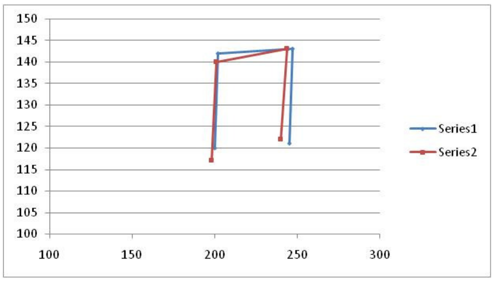


Figure 6. Pupil coordinates corresponding to current screen position - 5 degree head rotation. a) real data, b)estimated data

Before both algorithms could be evaluated the top limit of head rotation angle had to be estimated. It was assumed that the head tilt could influence the results of head rotation measurement. Accuracy of presented method was calculated. The results are presented in Table I.

TABLE I. THE INFLUENCE OF HEAD TILT ON ROTATION ANGLE MEASUREMENT

tilt range[°]	*Rotation range*[°]	*Max Error*[°]
0-5	0-70	0,24%
5-10	0-70	0,97%
10-15	0-70	2,21%
15-20	0-70	3,96%

The test was performed to assess the range of potential head movements in multi-display environment communication. Fifteen people in different age (from 18 to 80) and different computer skills took part in the test. Average (avg) value of head-to-screen rotation (in degrees) was measured as well as total maximum (max) and average value of maximum (avg. max) values registered for particular users. The results of measurements in case of one-screen environment are presented in Table II.

TABLE II. RESULTS OF HEAD ROTATION ANGLE MEASUREMENTS IN SINGLE DISPLAY ENVIRONMENT

rotation\Content size	*small*	*medium*	*Large*
Avg[°]	3,77	3,33	3,66
Avg. max[°]	7,40	6,74	5,74
Max[°]	13	12,50	12

The measurements were repeated in standard two-screen configuration (primary unit in front of the user and secondary screen placed someplace behind the first one). Table III presents the head-to-screen rotation measured regarding the primary screen.

TABLE III. RESULTS OF HEAD ROTATION ANGLE MEASUREMENTS IN MULTI DISPLAY ENVIRONMENT - CONTENT DISPLAYED ONLY ON PRIMARY SCREEN

rotation\Content size	*small*	*medium*	*Large*
Avg[°]	9,37	8,88	10
Avg. Max[°]	14,87	13,94	14,77
Max[°]	31	19,50	27

Results for the head-to-screen rotation measured in reference to the secondary screen are presented in Table IV

Measurements were repeated for content displayed randomly on screens working in extended display mode. Two different screens configuration were examined (Fig. 4).

TABLE IV. RESULTS OF HEAD ROTATION ANGLE MEASUREMENTS IN MULTI DISPLAY ENVIRONMENT - CONTENT DISPLAYED ONLY ON SECONDARY SCREEN

rotation\Content size	*small*	*medium*	*large*
Avg[°]	7,56	8,2	8,85
Avg. Max[°]	9,5	11,1	10,25
Max[°]	17	18,5	17,5

The results of head rotation angle measurements regarding the primary screen position (Fig. 4b) are presented in Table V.

TABLE V. RESULTS OF HEAD ROTATION ANGLE MEASUREMENTS IN MULTI DISPLAY ENVIRONMENT - CONTENT DISPLAYED ONLY RANDOMPLY ON BOTH SCREENS

rotation\Content size	*Small*	*medium*	*Large*
Avg[°]	7,16	9,61	10,5
Avg. Max[°]	8,58	12,33	11,92
Max[°]	22	31	23

Table VI contains the results head rotation measured with respect to the secondary screen position.

TABLE VI. RESULTS OF HEAD ROTATION ANGLE MEASUREMENTS IN MULTI DISPLAY ENVIRONMENT - CONTENT DISPLAYED ONLY RANDOMLY ON BOTH SCREENS

rotation\Content size	*Small*	*medium*	*Large*
Avg[°]	11,11	9,75	10,21
Avg. Max[°]	15,94	13,37	13,85
Max[°]	25,5	18,5	28

The similar measurements were made for the additional screen placed on the left of primary one (extended desktop mode - Fig. 3a).

TABLE VII. RESULTS OF HEAD ROTATION ANGLE MEASUREMENTS IN MULTI DISPLAY ENVIRONMENT - CONTENT DISPLAYED ONLY RANDOMLY ON BOTH SCREENS

rotation\Content size	*Small*	*Medium*	*Large*
Avg[°]	7	9,6	7,91
Avg. Max[°]	8,37	10,1	9,41
Max[°]	17	19,5	15,5

Table VII shows head rotation measured in reference to the primary screen, while Table VIII presents the measurements obtained with respect to the secondary one.

TABLE VIII. RESULTS OF HEAD ROTATION ANGLE MEASUREMENTS IN MULTI DISPLAY ENVIRONMENT - CONTENT DISPLAYED ONLY RANDOMLY ON BOTH SCREENS

rotation\Content size	*Small*	*medium*	*Large*
Avg[°]	8,2	10,3	10,4
Avg. Max[°]	10,7	11,4	20,1
Max[°]	17,5	18	50,5

The proposed and developed algorithms were evaluated by means of the accuracy test. The result of the basic algorithm, for 9-points test grid ("-" stands for counter-clockwise head rotation), are presented in table IX.

TABLE IX. THE ACCURACY MEASURED FOR 9 TEST POINTS

Accuracy/angle	*-10*	*-5*	*0*	*5*	*10*
Max[°]	2,60	1,5	1,3	1,7	2,17
Min[°]	0,58	0,36	0,20	0,28	0,29
Avg[°]	1,10	0,72	0,76	0,88	0,95

Results obtained for 16-point test grid are presented in table X.

TABLE X. ACCURACY MEASURED FOR 16 TEST POINTS

Accuracy/angle	***-10***	***-5***	***0***	***5***	***10***
Max[°]	2,57	1,42	1,45	1,60	1,47
Min[°]	0,60	0,29	0,12	0,15	0,20
Avg[°]	1,02	0,76	0,74	0,74	0,75

The same values were measured for the POR estimation algorithm that includes information of head to screen movement. Table XI contains the results for test 9-points grid.

TABLE XI. ACCURACY MEASURED FOR 9 TEST POINTS

Accuracy/angle	***-10***	***-5***	***0***	***5***	***10***
Max[°]	4,17	2,25	0,81	1,72	2,33
Min[°]	0,05	0,03	0,06	0,02	0,00
Avg[°]	1,34	0,75	0,76	0,79	0,87

Table XII shows the results for test containing grid of 16-points.

TABLE XII. ACCURACY MEASURED FOR 16 TEST POINTS

Accuracy/angle	***-10***	***-5***	***0***	***5***	***10***
Max[°]	3,97	1,71	0,91	0,91	1,11
Min[°]	0,09	0,11	0,04	0,04	0,07
Avg[°]	1,05	0,67	0,87	1,05	1,08

IV. DISCUSSION

In this paper we evaluated the POR estimation algorithm used for gaze communication in multi-display environment. To compensate the head movements a perspective transform was used. However, the algorithm itself does not return any information on the rotation or translation. In presented example the perspective transformation is used twice, first time to establish relation between pupil position represented in K1 image space and static points represented in K2 space. Second use of perspective transformation relates captured data (current screen/ROI position and pupil coordinates) with actual screen. Because it is computed for the values updated with every captured frame it significantly reduce the influences of head movements on the POR estimation. However, we noticed that it might be possible to use information on the difference in tracked screen position to tune the POR estimation algorithm and perhaps obtain more accurate results. To perform the accuracy measurements potential head rotation had to be established.

To measure the head rotation angle a single camera stand was used. It simplifies and reduces the calculations but it also influenced the accuracy of the measurements. That is due to the fact that head position is calculated based on 2D representation of LED markers position and head tilt might influence the results. The potential error of the measurements was calculated (table I). The investigated range of tilt reflects the range of potential head movement of a healthy person [8]. It is easy to notice that for head tilt above 15° the error significantly increased. The error above 5% was beyond acceptance. However, it was assumed that angle range of head tilt is not so significant during work with multi-display environment and it is certainly below 20 degrees.

In the first part of this experiment we established the head rotation while following the content of different size in single, and multi-screen environment. Our studies revealed, that by extending the work space with additional display increased the head to screen rotation range, even when stimuli content was displayed only on one screen (Table II-IV). However in case of two display configuration the rotation range remained constant even for content displayed randomly within extended display (Table V-VIII). Moreover, conducted experiment showed that head rotation depends on the content size. Although measured maximum head rotation is up to 31 degrees the average value oscillated around 10 degrees. This value was regarded as a top limit of head rotation in POR estimation algorithms evaluation. The study revealed that the accuracy remains constant below 10 degrees rotation and then rises. Results shows that proposed algorithm for gaze tracking in multi-display environment works very stable for head rotation up to 10 degrees. Moreover, there are no significant changes between registered results of average accuracy for different head rotation angles (Table IX, X). Additional information about head-to-screen movement had no positive influence on the accuracy results (Table XI, XII). It drives us to the conclusion that the additional information about head rotation is not crucial in POR estimation regarding the typical head-to-screen rotation. The use of perspective transformation is sufficient to compensate typical head movements that may appear in communication within multi-display environment.

V. CONCLUSIONS

Presented models seem to work stable in multi display environment. These results are essential as one of presented models will be implemented in currently developed platform for perceptual computing - eGlasses. Using eye-tracker as a part of electronic eye-wear it is also important to distinguish between the observed displays (e.g. portable micro-display and a screen of a monitor), subjects or other objects. For example, natural features of faces can be used as markers to distinguish between different faces observed by electronic glasses. The analysis of gaze direction in reference to a particular face and their characteristic features (e.g. eyes, mounts, nose) can be used to investigate behavior of the user of the eye-wear (to which parts of the given face the user looks during a conversation). Additional information can be also captured, e.g. heart rate of the observed person [12] or color of the observed part of object [13].

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