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Analysis of luminance distribution uniformity in CAVE-type virtual reality systems

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ABSTRACT

In recent years, many scientific and industrial centres in the world developed a virtual reality systems or laboratories. The effect of user "immersion" into virtual reality in such systems is largely dependent on optical properties of the system. In this paper, problems of luminance distribution uniformity in CAVE-type virtual reality systems are analyzed. For better characterization of CAVE luminance nonuniformity corner and edge CAVE nonuniformity were introduced. Based on described CAVE-type virtual reality laboratory, named Immersive 3D Visualization Lab (I3DVL) just opened at the Gdansk University of Technology, luminance nonuniformity of the system is evaluated and discussed. Data collection of luminance distribution allows for software compensation of intensity distribution of individual images projected onto the screen (luminance non-uniformity minimization) in the further research.

1. Introduction

The idea of virtual reality (VR) has been known for several decades. First attempts to build virtual reality systems for especially military purposes were made during World War II or even before [1]. But only the rapid development of computer science and visualisation systems allows developers to concentrate on creating very realistic computer generated worlds. In recent years, many scientific and industrial centres in the world attempted to develop a virtual reality systems or laboratories [2–15]. To achieve the best quality and experience of virtual reality, a combination of three basic elements is needed: interaction with generated world, ability to move freely and perception of depth. Those three elements are commonly referred in literature as I3: Interaction + Immersion + Imagination [16].

Virtual reality systems vary in configuration and complexity. Among many types of such systems there can be distinguished military simulators with Head Mounted Displays (HUD), non military systems using cybernetic helmets (e.g., Oculus), high resolution display wall (powerwall), rotating sphere (virtusphere) with cybernetic helmet [9], rotating sphere with projection just onto the sphere [3], CAVE-type (Cave Automatic Virtual Environment) systems consisted of three, four, five, or six projection screens and arranged in different forms [2,4–7,13–15]. For a better experience of virtual reality these systems often use a three-dimensional (3D) projection (active stereo projection, polarization separation projection or projection with spectrum separation) [5,17–18]. For improvement of immersion and interaction with virtual environment in such systems surrounding sound generator and body motion tracking are often used [5].

One of the most important aspects of virtual reality laboratory is to provide the user with a high level of immersion feeling [19]. The purpose is that the user during simulation is fully "immersed", avoids simulator sickness and does not recognize elements of CAVE construction: directions, door position, borders between projection screens. This immersion level depends on many factors: system configuration (number of screens), spatial sound, quality of mechanical fitting of screens, type of projection (2D or 3D), and quality of image. Nonuniformity of optical parameters (luminance, colour) are among the key factors which may deteriorate image quality and decrease immersion feeling.

A modern virtual reality laboratory, named Immersive 3D Visualization Lab (I3DVL), has opened at the Gdansk University of Technology (December 2014) [20]. According to a subjective opinion of participants, the CAVE (I3DVL) operates very well. However, from an objective point of view it is very important to quantify optical properties of the CAVE (luminance distribution uniformity in, contrast distribution, colour space, screen properties-gain and bidirectional scattering distribution function). The planned research program is very extensive and time-consuming, thus, described in the manuscript research is the first stage of research concerning

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the problem. Estimation and quantification of mentioned parameters are of great importance for improvement visual quality of the CAVE.

2. Luminance uniformity of the CAVE

CAVE-type virtual reality system can be considered as projection based tiled display system. A critical factor for tilling applications is the distribution of the illumination field. Ideally the illumination field would have no falloff, in practice, however, brightness of the single screen fallsoff from the centre of the image to the edges [21,22].

Luminance uniformity is a parameter of how well the luminance remains constant. However, nonuniformity is usually the desired metric [21]. Let us assume luminance measurement at several points of screen (e.g., 5 or 9). In this case the screen luminance nonuniformity N (sampled nonuniformity according standards) is defined by [23]:

$$N = 100\%\frac{L_{max} - L_{min}}{L_{max}} = 100\%\left(1 - \frac{L_{min}}{L_{max}}\right), \quad (1)$$

where: L_{min} and L_{max} are the minimum and maximum luminance of that sample set (5 or 9 points), respectively [23].

CAVE-type system, however, is a tilled multi-screen system, Additionally, it differs from a typical large-format flat tiled display system (e.g. PowerWall) in four respects: (a) arranged in a specific spatial form, eg. a cube; (b) the screens interact to each other; (c) it is not possible for the user to see all of the CAVE screens at the same time (while for the large-format, flat screen it is usually possible); (d) viewing angles can be different for each screen and are dependent on the user position.

Thus, similarly to Eq. (1), let us introduce the non uniformity for the whole CAVE, defined by:

$$N_{CAVE} = 100\%\left(1 - \frac{L_{CAVEmin}}{L_{CAVEmax}}\right), \quad (2)$$

where: $L_{CAVEmin}$ and $L_{CAVEmax}$ are respectively minimum and maximum luminance of samples of the whole CAVE system (e.g. 54 samples, 9 samples × 6 screens).

In situation described above, when the user can see relatively small part of CAVE screens at the same time (e.g., one screen), it will be more convenient to define CAVE nonuniformity as an average of nonuniformities calculated separately for each screen:

$$N_{CAVE\ A} = \frac{1}{n}\sum_{i=1}^{n} N_i, \quad (3)$$

where: n is the number of screens, N_i is the nonuniformity calculated for i-th screen.

Luminance differences of the measured screen or multi-screen system are not the only important parameters. The gradient of the luminance shift over the screen is also important. A screen that slowly changes (small luminance gradient) in luminance 20% over its entire surface would not readily be noticed to the eye [22]. If a luminance change occurs over a one-degree range from the user perspective (high luminance gradient), it would be noticeable. This applies also to multi-screen systems. In CAVE-type multi-screen system luminance gradient can occur at the intersection of projection screens. Let us define corner and edge CAVE nonuniformity:

$$N_{COR} = 100\%\left(1 - \frac{L_{CORmin}}{L_{CORmax}}\right), \quad (4)$$

where: L_{CORmin} and L_{CORmax} are respectively the minimum and maximum luminance of the points close to the CAVE corner (3 data points per corner for 9-point sampled measurements of the whole CAVE system).

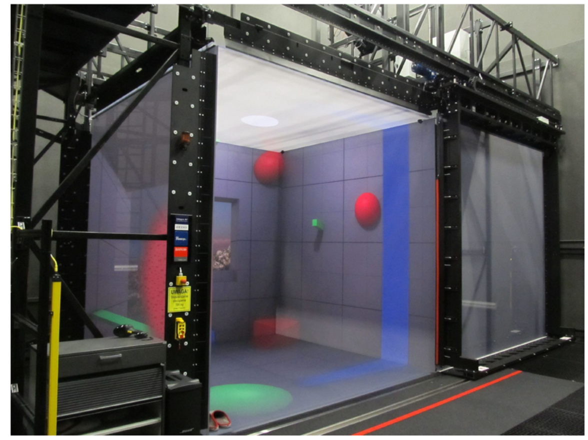

Fig. 1. View of the I3DVL: "classic" CAVE at Gdansk University of Technology.

Edge nonuniformity can be defined as average nonuniformities of all pairs of measurement points closed to the edge and placed on both sides of the edge:

$$N_{ED} = 100\%\frac{1}{m}\sum_{j=1}^{m}\left(1 - \frac{L_{jmin}}{L_{jmax}}\right), \quad (5)$$

where: m is the number of pairs of points close to the edge, L_{jmin} and L_{jmax} are respectively the minimum and maximum luminance of samples of j-th pair (m = 3 pairs of data per edge for 9-point sampled measurements of the whole CAVE system).

Although the subject of the article is luminance distribution, however for better readability of the results, in some situations the contrast will be determined. In the presence of ambient light, the contrast (contrast ratio) C_{CR} can be defined as [21]:

$$C_{CR} = \frac{L_{scmax} + L_{refl}}{L_{scmin} + L_{refl}}, \quad (6)$$

where: L_{scmax} and L_{scmin} are the maximum ("on" state) and the minimum ("off" state) luminance of screen itself (without ambient light) respectively, L_{refl} is the luminance of screen caused by the reflected light.

Based on Eqs. (2)–(6) and measurements performed in the I3DVL, luminance nonuniformity was calculated and discussed.

3. Immersive 3D visualization lab

I3DVL is the CAVE-type laboratory consisting of six rigid square screens, with edges of about 3.4 meters each, coated with diffusing layer, arranged in the form of a cube [12,20]. Wall and ceiling screens are acrylic, while the floor screen is glass-acrylic to ensure an adequate mechanical strength. To allow access to the CAVE, one of walls is an automatic sliding door. The view of the CAVE is presented in Fig. 1.

Movement in a computer generated virtual world in CAVE is limited due to a limited size of the installation. To solve this problem, many laboratories developed sophisticated devices, allowing moving without changing location [20,24–25].

In I3DVL implementation of such a mechanism is carried out using a partially transparent sphere rotating on rollers. A user can be entered into the sphere (spherical walk simulator) through a special hatch. In the laboratory this rotating transparent sphere (Virtusphere [10]) with a user inside is placed in the centre of the cubic CAVE using a dedicated mechanism (trolley) (Fig. 2). Average observer eye level should coincide with the geometric centre of the sphere which provides the direction of observation perpendicular

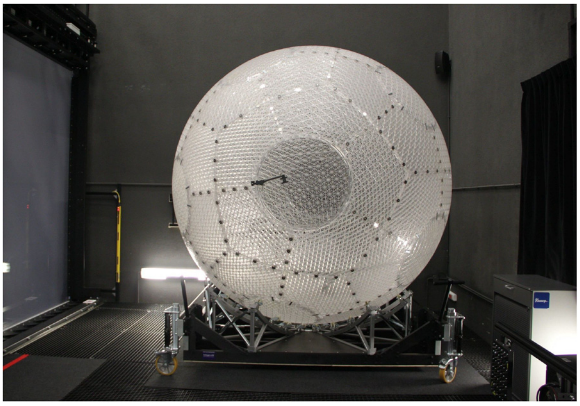

Fig. 2. View of the I3DVL: spherical walk simulator placed on a dedicated trolley.

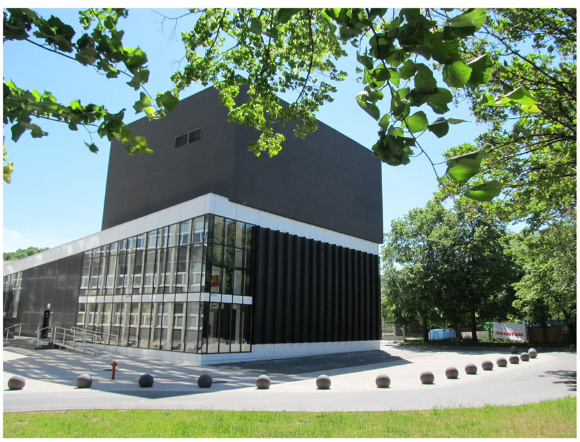

Fig. 3. Dedicated building for virtual reality laboratory (I3DVL).

to the surface of the sphere and to minimize the distortion of the image in the case of projection on screens surrounding the sphere.

Alternatively, in order to broaden the range of applications, both CAVE and rotating sphere can work separately as two different virtual reality systems [6].

High quality components and equipment are used in the laboratory. Omnidirectional view is achieved via the stereoscopic rear projection onto all six flat screens. The whole image is displayed by 12 digital three-chip DLP projectors with the resolution of 1920 × 1200 pixels (WUXGA), two projectors per screen. Thus, the final resolution of an image on the single screen, taking into account the edge blending technique, is of 1920 × 1920 pixels. Two techniques of a 3D projection were implemented: active stereo and technique with spectrum separation (active Infitec). Applied projectors have an additional option – built-in color filter wheel with two sets of interference filters (R_1, G_1, B_1 for the left eye and R_2, G_2, B_2 for the right eye). This color filter wheel can be remotely turned on or turned off (inserted or removed from the optical path of the projector). This means, that one projector could support both 3D projection techniques. Additionally, for both techniques one projector could provide two complementary images for left and right eye, respectively. Mentioned techniques require the user to wear glasses with LCD shatters or with interference filters, respectively.

A dedicated building to house the I3DVL was erected (Fig. 3). Projectors (Galaxy NW 7 series), rigid projection screens and part of mechanical structure were provided by BARCO (Belgium). The integrator of the whole system was Integra AV (Poland) [26].

Fig. 4. The measurement setup.

4. Measurement geometry and setup

According to recommendation of the ICDM [23], measurements could be taken for one of the following configurations: normal to the screens (an infinity observer) or from the user point of view (vantage point) [20]. Because of a relatively small distance from the user to the screens, an infinity observer was not taken into account. For vantage point measurement the spot meter was mounted on a tripod with a rotating (horizontally and vertically) head. As a spot meter a Konica Minolta luminance meter (CS-200) was used, supported by a portable computer with dedicated software cs10w. Luminance measurements using CS-200 are independent of the distance to the screen, so there is no need to take into account changes of this distance. The view of the measurement setup is shown in Fig. 4.

Let us consider two basis configurations of I3DVL. The first one is when the spherical walk simulator is placed into the CAVE [Fig. 5a)]. As the user head (eye level) coincides with the geometric centre of the sphere, it is also placed near the geometrical centre of the CAVE (central user position – CUP). This is the best situation (user position) due to expected maximum symmetry. However, even in this case, the user is relatively near the screens, which results in a wide range of observation angles. Additionally, because of lack of space in the building outside the CAVE, projectors throwing rate is about 1:1, thus, range of projection angles is also significant.

The second configuration is when CAVE system is used without the spherical walk simulator, as a "classic" CAVE [Fig. 5b)]. It is the worst case of projection geometry. The user can move freely on the floor of the CAVE, so the angle of observation can be extremely high (extreme user position – EUP) [8]. In order to protect acrylic screens from damage (e.g., scratches) optical warning signal is applied (Fig. 6). This signal turns on when the user is at a distance below 0.5 m from the screen. Finally, the user can move within the area, marked by a red line in Fig. 5b).

The measurement setup allowed for accurate luminance measurements. The accuracy of CS-200 is given as L± 2%, and the repeatability as L ± 0,5%. Taking into account the accuracy of the measurement setup positioning and possible influence of both measurement setup and its operator (located inside the CAVE), the absolute accuracy of luminance measurement can be estimated as L ± 5%. Accuracy of the nonuniformity evaluation can be even better, as it is a relative parameter, thus, the CS-200 repeatability should be applied rather than an absolute accuracy.

5. Measurement results and discussion

The performed measurements are related to the just designed, operating CAVE. All projectors were turned on and screens illuminated. For all measurements 1° measuring angle of CS-200

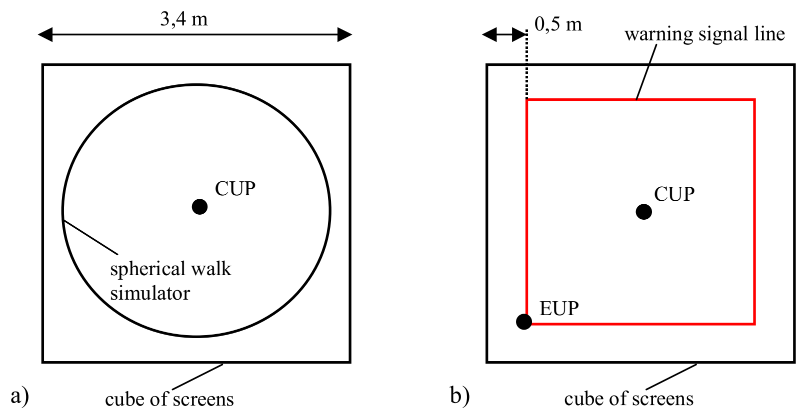

Fig. 5. I3DVL configuration: a) spherical walk simulator is placed into the CAVE, b) "classic" CAVE; CUP – central user position, EUP–extreme user position.

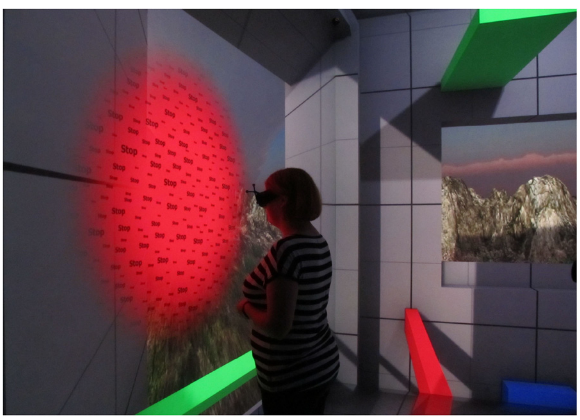

Fig. 6. View of the CAVE while warning signal is turned on.

luminance meter was selected, while signal acquisition time was set to 30 s. During measurements any 3D glasses were not used (2D measurements), however, color filter wheel of projector was turned on, which results in small values of measured luminance. All projectors have built-in a mechanism, that automatically fit their luminous flux to the smallest one.

In the first step 9-point luminance data for each screen were collected. Location and numbering of measurement points (for each screens) are presented in Fig. 7a).

In this case the luminance meter was placed in the centre, about 1.6 m above the floor, corresponding with average user height (central user position – Fig. 5). Measured data (luminance) are presented in Table 1. Using formulas (1)–(3) luminance nonuniformity was calculated for each screen separately and for the whole CAVE respectively. The results are presented in Table 1.

The screen luminance nonuniformity of about 50% is quite a significant value. However, due to a low luminance gradient over the screen, it would not be noticed as strong as it would be in other case (high luminance gradient). Taking into account the specific CAVE geometry (high projection angles and high viewing angles) this is a good result. It can be also noticed that maximum and minimum luminance are different for each screen. It is caused mainly by the geometry of the whole system which has to be placed into the main hall of the laboratory providing just enough space for transport of the sphere, configuration change etc. This results in asymmetric position of projectors relative to the screens (using projector lens-shifting), projection onto top and bottom screens using mirrors, slightly different focal length of projector lenses.

In the second step the corner and edge CAVE nonuniformities for selected corners and edges [Fig. 7b)] were evaluated for in this case two different user positions (Fig. 5): a) user in the middle of the CAVE (CUP) and b) user near the corner of the CAVE (EUP). The measured data and calculated corner and edge nonuniformities are presented in Table 2 (luminance for central user position was rewritten from Table 1). In case of a), corner nonuniformity can be significant for selected corners (T1L3F1 corner), while for the other tested corner and edge nonuniformity reach medium values. In the case of b), nonuniformities for all tested corners and edge are significant.

In the case of b), luminance was additionally measured when only just measured screen was illuminated (projectors turned on), while other screens were not active (projectors turned off). Applying Eqs. (4) and (3) to the measured data, corner and edge nonuniformities can be calculated. The obtained results (measurements and calculations) are also presented in Table 2.

Some of the measurement results may seem surprising. Let us consider the following case (EUP). When only the front screen is illuminated, the luminance of the top corner T1 is 5.7 cd/m^2. If all screens are illuminated, the luminance of T1 increases to 6.9 cd/m^2, meaning that the top projector (mainly) only adds 1.2 cd/m^2. The explanation of this fact is as follows. Front projectors (pair of projec-

Table 1
Results for 9-point flat screen nonuniformity measurements for all CAVE screens.

Screen/ field number	Luminance [cd/m^2]									Nonuniformity N [%]
	1	2	3	4	5	6	7	8	9	
F – front	5.38	8.34	5.73	6.07	10.78	6.32	5.32	8.36	5.58	50.6
R – right	5.08	8.26	5.85	5.97	10.98	6.71	5.56	8.86	6.32	53.7
L –left	5.78	9.56	6.47	6.28	11.24	6.93	5.32	8.59	5.83	52.7
B – bottom	5.33	5.67	5.51	8.57	10.19	9.08	5.80	5.49	5.30	50.0
T – top	7.54	7.60	8.52	10.00	10.83	11.44	7.04	7.07	8.79	35.3
D – door	8.34	10.65	7.91	7.97	11.60	8.64	7.95	10.62	8.64	31.8
N$_{CAVE}$										**56.2**
N$_{CAVEA}$										**45.6**

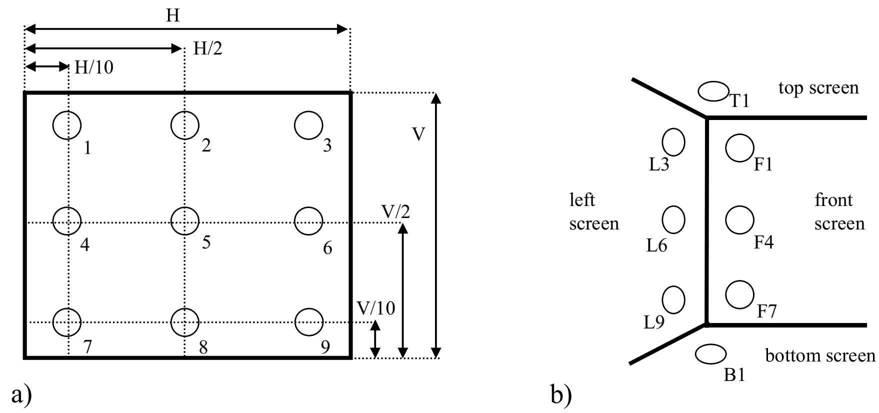

Fig. 7. Arrangement and numbering of measuring points: a) single screen measurements [24], b) corner and edge measurements.

Table 2
Results for corner and edge nonuniformity measurements for selected corners and edges.

field mark (Fig. 7)		T1	L3	F1	L6	F4	L9	F7	B1
Luminance [cd/m^2] for central position of the user (all screens bright)		7.54	6.47	5.38	6.93	6.07	5.83	5.32	5.33
nonuniformity for the user central position N [%]	corner	28.6			–		8.7		
	edge	–	12.7						–
Luminance [cd/m^2] for extreme position of the user (all screens bright)		6.89	5.28	7.25	5.66	7.84	5.18	6.96	5.27
nonuniformity for the user extreme position N [%]	corner	27.2			–		25.6		
	edge	–	26.9						–
Luminance [cd/m^2] for extreme position of the user (only one screen bright)		5.70	2.29	6.00	2.47	6.89	2.21	6.12	3.90
nonuniformity for the user extreme position N [%]	corner	61.8			–		63.9		
	edge	–	63.3						–
Contrast (contrast ratio) C_{CR}		5.79	1.77	5.80	1.77	8.25	1.74	8.29	3.85

tors) illuminates field F1 (and its neighbourhood) under a relatively high angle (projector throw rate of about 1:1). The screen scatters the incident light, and the maximum of the scattered light is near the direction of illumination (according to previous work [8]). This means that the T1 field of the top screen is quite well illuminated by this scattered light. Next the light is partially reflected from the top screen (T1) and reach the observer (in extreme position). It is a quite significant amount of light. In the case when top projector is on (top screen illuminated), top projector illuminates field T1 under high angle, too. Similarly to the front screen, the maximum of scattered light is near the direction of illumination. The angle between illumination direction and observation direction (for T1 and EUP) is very high, of about 90 degrees or even more – thus, results in a small amount of scattered light that reaches the observer (and minor increasing of T1 luminance).

While analyzing the case of user extreme position, on the first sight it can be noticed that the nonuniformities calculated when only one screen is illuminated are much greater than those obtained for the case of all screens illuminated. This proves the high interaction between screens. However, the analysis of that case is more complex.

The multi-reflected and multi-scattered light increases the luminance indeed, but this is "false" light, not contributing to the content itself, adversely affecting contrast ratio of the displayed screen. Thus, based on the collected data, contrast ratio for selected points was calculated. Two simplifying assumptions were made, viz.: (I) luminance of the completely dark screen is much lower than the luminance caused by ambient light, and (II) the ambient light caused by the examined screen itself (multi-reflection) in negligible in comparison with the ambient light caused by others screens. The obtained results (Table 2) of contrast ratio range from 1.74 to 8.25 indicating a very high degradation of contrast.

On the other hand, in selected cases the interaction between screens may have a positive effect on the sense of "immersion". In a scenario where a large, uniform object (e.g., sand, grass or perfectly blue sky, without any important details) is placed in a corner or edge region of a screen, the corner or edge will be quite well noticed, especially in the case of luminance differences between the screens. When such object extends over more than one screen, the light emitted by one screen and reflected by the other results in equalizing the luminance, reducing visibility of corners and edges, thus, increasing the feeling of "immersion". Of course this effect depends on the position of the user inside the CAVE.

6. Conclusions

Only a few CAVE-type laboratories in the world consist of six screens forming a closed space. I3DVL is one of such installations and the first one that allows the user to move inside the CAVE using spherical walk simulator. That is why basic research carried out are of great importance for the characterization, improvement and development of these facilities.

Due to the complexity of the installation, parameters defined for flat displays may not describe well its quality. Thus, corner and edge CAVE nonuniformity were introduced for better characterization of such installations.

According to users' opinion I3DVL provides a high level of "immersion" in virtual environment. However, there are same luminance differences, especially for user position far from the CAVE centre, that is mainly caused by the standard geometry of the CAVE-type system. Obtained results (luminance distribution) allow also for further software luminance compensation for better CAVE quality.

Acknowledgements

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