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

A. Mazikowski

Gdańsk University of Technology, Faculty of Electronics, Telecommunication and Informatics, Department of Metrology and Optoelectronics, ul. Narutowicza 11/12, 80-233 Gdansk, Poland

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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 bi-directional 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

E-mail address: adamazik@eti.pg.gda.pl

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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: $\mathrm{L_{CAVEmin}}$ and $\mathrm{L_{CAVEmax}}$ 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: $\mathrm{L_{CORmin}}$ and $\mathrm{L_{CORmax}}$ 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).

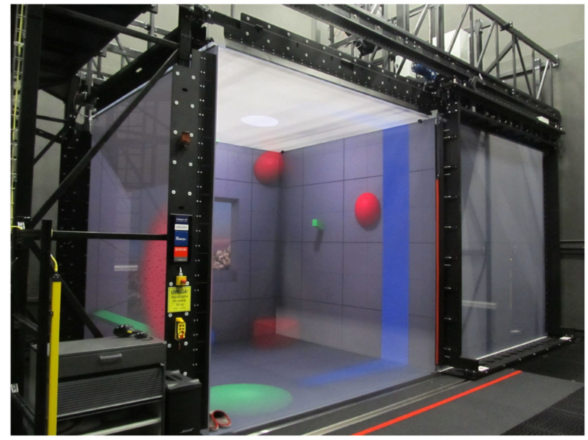

Fig. 1. View of the I3DVL: "classic" CAVE at Gdansk University of Technology.

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:

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

where: m is the number of pairs of points close to the edge, $\mathrm{L_{jmin}}$ and $\mathrm{L_{jmax}}$ 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) $\mathrm{C_{CR}}$ can be defined as [21]:

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

where: $\mathrm{L_{scmax}}$ and $\mathrm{L_{scmin}}$ are the maximum ("on" state) and the minimum ("off" state) luminance of screen itself (without ambient light) respectively, $\mathrm{L_{refl}}$ 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