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INVESTIGATION OF OPTICAL PROPERTIES OF INFITEC AND ACTIVE STEREO STEREOSCOPIC TECHNIQUES FOR CAVE-TYPE VIRTUAL REALITY SYSTEMS

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Abstract

In recent years, many scientific and industrial centres in the world developed virtual reality systems or laboratories. At present, among the most advanced virtual reality systems are CAVE-type (Cave Automatic Virtual Environment) installations. Such systems usually consist of four, five, or six projection screens arranged in the form of a closed or hemi-closed space. The basic task of such systems is to ensure the effect of user "immersion" in the surrounding environment. The effect of user "immersion" into virtual reality in such systems is largely dependent on optical properties of the system, especially on quality of projection of three-dimensional images. In this paper, techniques of projection of three-dimensional (3D) images in CAVE-type virtual reality systems are analysed. The requirements of these techniques for such virtual reality systems are outlined. Based on the results of measurements performed in a unique CAVE-type virtual reality laboratory equipped with two different 3D projection techniques, named Immersive 3D Visualization Lab (I3DVL), that was recently opened at the Gdańsk University of Technology, the stereoscopic parameters and colour gamut of Infitec and Active Stereo stereoscopic projection techniques are examined and discussed. The obtained results enable to estimate the projection system quality for application in CAVE-type virtual reality installations.

Keywords: virtual reality, projection systems, cave automatic virtual environment, Active Stereo projection, projection of spectrum separation, Immersive 3D Visualization Laboratory.

1. Introduction

The concept of *virtual reality* (VR) systems has been known for many years. The first attempts to build such systems for military purposes were made during World War II, and even earlier [1]. But only the dynamic development of computer science and visualisation systems enables the developers to create very realistic computer-generated worlds. In recent years, many scientific and industrial centres in the world extensively work in this field, starting from pioneering works [2], through analysis of development trends [3–5] and ending with advanced installations of virtual reality [6–9].

An important part is also the research related to improving quality and experience of the virtual world in various aspects (*e.g.* image quality and resolution, accuracy of tracking systems)

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as well as characterization of virtual reality systems [10–13]. A number of works concerns the problem of motion in virtual reality systems [14–17]. Selected centres also deal with the issues of modelling and data collection for the preparation of scenarios in the virtual world [18–20].

Generally, to obtain the best quality and experience of virtual reality, a combination of three basic elements is needed: Interaction, Immersion and Imagination, often mentioned in the literature as I^3 [5]. The capability to move freely and the depth perception are other factors that influence the perception of virtual reality.

Nowadays, there are two main groups of tools – head-mounted devices and CAVE-type (Cave Automatic Virtual Environment) installations, modern VR solutions based on a specially configured set of projection screens (*e.g.* in the form of a cuboid, a cube, or a reconfigurable one) [6–9, 21, 22]. The user inside the CAVE can freely look around, while in head-mounted devices his *field of view* (FOV) is limited. It is the main advantage of CAVE-type installations.

One of the most important aspects of a VR laboratory is to provide the user with a high level of immersion feeling [11]. This is achieved by combining many subsystems, but mainly by projecting three-dimensional images (3D). Additionally, for interaction with the virtual environment and better experience of "immersion" in such systems head tracking, there are often used body motion tracking, a surrounding sound generator, a smell generator, or data gloves [7].

In virtual reality systems, one of three following techniques for projection of three-dimensional images is usually applied: (I) active stereo projection, (II) projection with separation of polarization and (III) projection with spectrum separation (Infitec) [7, 23, 24]. Although all these techniques provide the user with 3D images, they vary in configuration, complexity, and principle of operation, thus may result in different stereo parameters and quality.

A modern virtual reality laboratory, named *Immersive 3D Visualization Lab* (I3DVL), has been opened at the Gdańsk University of Technology (Dec. 2014) [9]. In the author's as well as other users' opinion, the I3DVL operates well. However, for the quantitative estimation of the whole optical CAVE quality, it is necessary to determine the quantitative parameters. Previous works on I3DVL characterization can be found in [12, 13].

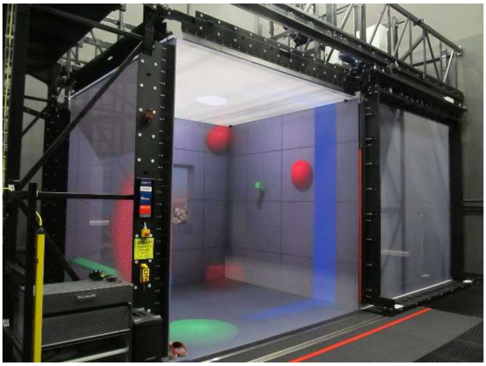
This study concentrates on the properties of 3D projection techniques (systems) that were applied in I3DVL. According to the author's knowledge, I3DVL is the only six-sided CAVE-type laboratory equipped with both Active Stereo and Infitec 3D projection techniques. Thus, there is a unique opportunity to examine properties of the mentioned 3D projection techniques in comparable conditions, e.g. using the same projectors (light spectrum, luminous flux) and projection screens.

2. Immerse 3D Visualization Lab

Since its opening in 2014, Immersive 3D Visualization Lab (I3DVL) has been used by students and employees for educational and scientific purposes, thus it is subject to continuous development. Currently, it consists of three CAVE-type installations (named BigCAVE, MidiCAVE, and MiniCAVE, respectively) and a spherical walk simulator (Virtusphere). The most advanced is BigCAVE that consists of six rigid square screens, with edges of about 3.4 meters each, coated with a diffusing layer, arranged in the form of a cube [9]. The wall and ceiling screens are acrylic, while the floor screen is glass-acrylic to provide adequate mechanical stability. A mechanism enabling to access the BigCAVE (the wall screen as a sliding door) is also applied. Other CAVE-type installations were designed for development and the testing process of new virtual reality applications and scenarios; they consist of 4 screens (MidiCAVE) and 4 computer monitors (MiniCAVE), respectively.

I3DVL is also equipped with a spherical walk simulator. Placed on a special trolley it can be moved into BigCAVE and this configuration enables unrestricted movement of the user, while a scenario is displayed on the screens of BigCAVE. Alternatively, both BigCAVE and rotating sphere (with Head Mounted Display) can work separately as two different virtual reality systems. A more detailed description of I3DVL can be found in the literature [9, 13, 14, 25, 26]. Photos of BigCAVE and the spherical walk simulator are presented in Fig. 1.

a)



b)

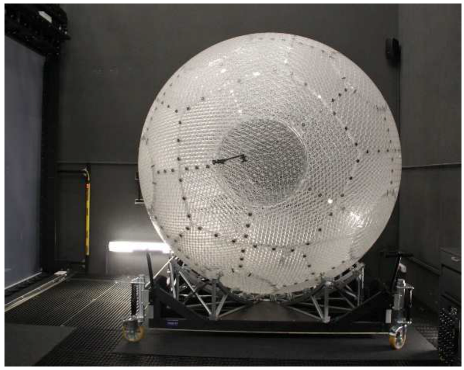


Fig. 1. Views of I3DVL: a) BigCAVE, and b) thespherical walk simulator placed on a dedicated trolley.

In BigCAVE two techniques of 3D projection were implemented: (I) active stereo and (II) a technique with spectrum separation (Infitec). The active stereo projection is based on shutter glasses. Due to the synchronization with displaying, the shutter glasses pass only every second image to each eye (separation in time). It requires a power supply of glasses, hence the method is called active. The principle of active stereoscopy is presented in Fig. 2.

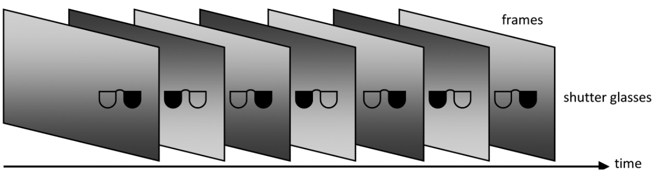


Fig. 2. The principle of active stereoscopy (with separation in time) [26].

The method with spectrum separation is based on a "wavelength triplet" technology developed by Infitec [23, 24]. In the human vision system, the colour impression is formed in the brain of the observer as a combination of stimulated different receptors: red (R), green (G), and blue (B) [26]. According to the phenomenon of metamerism [24], the same colour impression can be obtained by various stimulations, thus the images for the left and right eye are generated based on two slightly shifted sets of primary colours: $R_1G_1B_1$ and $R_2G_2B_2$, respectively for each eye of the observer.

Since the shift in the wavelength of both sets of colours is small, so the colour gamut for each eye is almost the same. The two complementary images can be separated using lightweight, inexpensive glasses with two sets of interference filters. The spectral characteristics of the light flux $\Phi(\lambda)$ of projectors for the left and right eyes as well as the transmission characteristic of the glasses are shown in Fig. 3.

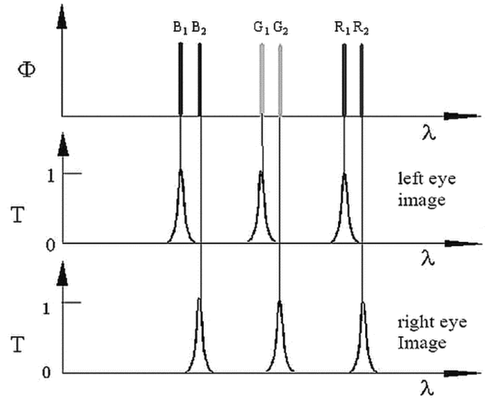


Fig. 3. The idea of the Infitec technique: examples of the light beam projector $\Phi(\lambda)$ characteristic and transmission characteristics of filters for the left and right eye, respectively [23].

The applied projectors have an additional option – a built-in colour filter wheel with the mentioned two sets of interference filters. It can be remotely turned on or 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 the left and right eyes, respectively.

3. Metrology of 3D projection displays

The optical properties of stereoscopic techniques can be considered in two categories. The first of them is related to the user's subjective assessment (*e.g.* readability of the displayed content or the impact on the user's frame of mind). The second one is the objective parameters that can be determined on the basis of measurements.

The objective parameters of metrology of displays, including parameters of stereoscopic techniques as well as these of the measurement procedure and apparatus, are determined and described in the measurement standards (Information Display Measurement Standard – IDMS) [27]. For characterization of a 3D projection system the most important are the following quantities: a stereoscopic extinction ratio and crosstalk (both black-white crosstalk and grey-to-grey crosstalk) [28], a stereoscopic contrast ratio, a stereoscopic luminance and a luminance difference. Additionally, for characterization of colour reproduction, the colour gamut separately for each eye can be determined.

The inter-channel crosstalk is a phenomenon, occurring in stereoscopic projection systems, which consists in obtaining by one eye the information intended for another eye. The occurrence of this phenomenon may lead to a situation in which either the user will not be able to correctly view the spatial image or the image will be distorted. The black-white crosstalk X_L for the left eye and X_R for the right eye can be defined as follows [27, 28]:

$$X_L = \frac{L_{LKW} - L_{LKK}}{L_{LWK} - L_{LKK}}, \qquad X_R = \frac{L_{RWK} - L_{RKK}}{L_{RKW} - L_{RKK}}, \tag{1}$$

where: L_{LKW}, L_{LKK}, L_{LWK}, L_{RKW}, L_{RKK}, L_{RWK} are the measured luminance; indexes refer to the eye (L – left eye, R – right eye), the measured pattern for the left eye (W – white, K – black) and the measured pattern for the right eye (W – white, K – black), respectively.

On the basis of the same measurements of luminance, the stereoscopic extinction ratio C_{sysL} for the left eye and C_{sysR} for the right eye can be calculated from the following relationships:

$$C_{sysL} = \frac{L_{LWK} - L_{LKK}}{L_{LKW} - L_{LKK}}, \qquad C_{sysR} = \frac{L_{RKW} - L_{RKK}}{L_{RWK} - L_{RKK}}, \tag{2}$$

where: L_{LKW}, L_{LKK}, L_{LWK}, L_{RKW}, L_{RKK}, L_{RWK} are the measured luminance, as in the previous formula (1).

Additionally, the stereoscopic luminance L_L, L_R and the luminance difference ΔL can be determined using the following formulae [27]:

$$L_L = L_{LWW} - L_{LKW}, \qquad L_R = L_{RWW} - L_{RWK}, \tag{3}$$

and

$$\Delta L = \frac{|L_L - L_R|}{\min(L_L,\ L_R)}, \tag{4}$$

while the stereoscopic contrast ratios C_L and C_R of a stereoscopic display can be expressed as:

$$C_L = \frac{L_{LWW}}{L_{LKK}}, \qquad C_R = \frac{L_{RWW}}{L_{RKK}}, \tag{5}$$

where: L_{LWW}, L_{LKW}, L_{LKK}, L_{RWW}, L_{RWK}, L_{RKK} are the measured luminance, where indexes refer to the eye and displayed patterns, as in the formula (1); $\min(L_L,\ L_R)$ is the smaller of the determined values L_L, L_R.

Determination of the stereoscopic grey-to-grey crosstalk is based on the measurement of the crosstalk between the left and right eye channels for all combinations of grey levels. A set of 5 or 9 levels for each eye is recommended according to the IDMS standard. Based on the measurement luminance, the grey-to-grey stereoscopic crosstalk X_{Lij} (for the left eye) and X_{Rij} (for the right eye) for any two grey levels can be calculated [27, 28]:

$$X_{Lij} = \left| \frac{\left(L_{Lij} - L_{Lii}\right)}{\left(L_{Lji} - L_{Lii}\right)} \right|, \qquad X_{Rij} = \left| \frac{\left(L_{Rij} - L_{Rii}\right)}{\left(L_{Rji} - L_{Rii}\right)} \right|, \quad i \neq j, \tag{6}$$

where: L_{Lij}, L_{Lji}, L_{Lii}, L_{Rij}, L_{Rji}, L_{Rii} are the measured luminance for the left and right eyes for i-th and j-th grey levels, respectively.

Finally, the average, standard deviation, and maximum of all the left eye crosstalk values X_{Lij} and all the right eye crosstalk values X_{Rij} should be calculated.

The above parameters refer to the measurements of luminance and are determined for both black-white and colour displays. For better characterization of the latter ones, additionally the colorimetric coordinates for primary colours and white balance are usually measured. The measurements are carried out for the left and the right eyes, that enables to specify the colour gamut for both display channels (eyes). Thus, it is possible to estimate the colour reproduction of the examined stereoscopic display. The measurement results are usually presented in a colour space chromaticity diagram (*e.g.* CIE 1931).

The IDMS standards contain also requirements regarding the measurement conditions. It is recommended to use fixtures for the measurement device and attachments for holding the eye-glasses as applicable, so that the instruments will be steady during tests (hand-held devices should be avoided where possible). The recommended configuration of the measurement setup is presented in Fig. 4 [27].

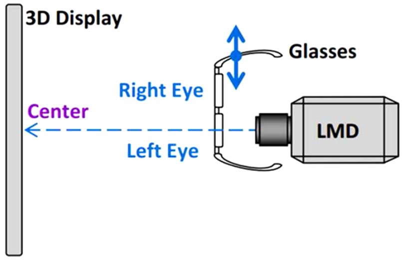


Fig. 4. The recommended measurement setup for characterization of 3D projection systems [27].

The sources of external lighting should be eliminated or minimized (including that of a computer monitor), as well as any reflective or diffusive elements close to the luminance meter. The standards recommend that the measurements be carried out in a perfectly black room and the operator should be dressed in black. Finally, the measurement conditions, especially for multi-screen displays, should be clearly indicated in the description of measurements.

4. Measurements and discussion

The taken measurements are related to the designed, operating BigCAVE "as is". According to the recommendation of IDMS [27], the measurement setup have been developed. As LMD there was used a Konica Minolta luminance and colour meter (CS-200), supported by a portable computer with dedicated software cs10w. Both the luminance and colour meter and the glasses were placed on a table to ensure that the instruments would be steady during measurements. Additionally, the glasses were mounted to a breadboard (Thorlabs) to improve mechanical stability. The developed setup is presented in Fig. 5.

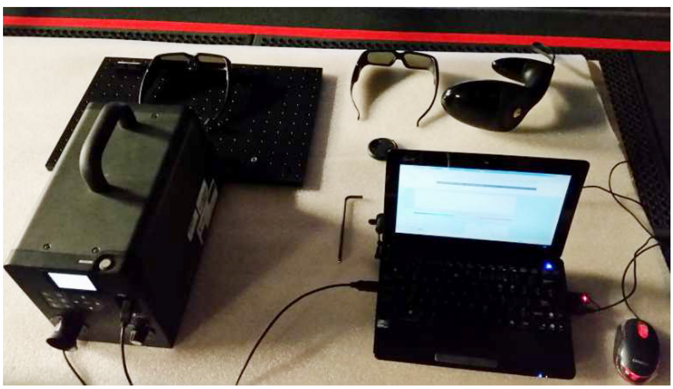


Fig. 5. A view of the measurement setup.

Moreover, CAVE is situated in a room which is painted black and absorbs most of optical radiation. Also, all outside sources of light were eliminated or minimized. BigCAVE is a multi-screen installation, but appropriate patterns were displayed on only one screen, placed just in front of the measurement device.

Based on the measurement standards, measurements for both stereoscopic projection systems: Infitec (the technique of spectrum separation) and Active Stereo (the technique of time sequential separation) available in the BigCAVE installation, were performed. The obtained stereoscopic parameters are presented in Table 1 (black-white crosstalk and stereoscopic extinction ratio), Table 2 (stereoscopic contrast ratio, stereoscopic luminance and luminance difference), and Tables 3, 4 (stereoscopic grey-to-grey crosstalk).

Table 1. Results for black-white crosstalk and stereoscopic extinction ratio.

3D projection system	Eye	Inter-channel crosstalk [%]	Stereoscopic extinction ratio
Infitec	left	0.984	101.7
	right	1.309	76.4
Active Stereo	left	1.393	71.8
	right	1.184	84.4

Table 2. Stereoscopic contrast ratio, stereoscopic luminance and luminance difference for Infitec and Active Stereo 3D techniques.

Eye channel	Displayed pattern left/right eye	Infitec 3D technique			Active Stereo 3D technique		
		Measured luminance L [cd/m^2]	Stereoscopic luminance L_L, L_R	Stereoscopic contrast ratio C_L, C_R	Measured luminance L [cd/m^2]	Stereoscopic luminance L_L, L_R	Stereoscopic contrast ratio C_L, C_R
left	white / white	2.86	2.82	286	5.79	5.70	579
	black / black	0.01			0.01		
	black / white	0.04			0.09		
right	white / white	3.91	3.80	196	6.04	5.96	604
	black / black	0.02			0.01		
	white / black	0.11			0.08		
luminance difference ΔL		34.75%			4.56%		

It can be noticed that the values of inter-channel black-white crosstalk for both projection systems are comparable, and the differences between them are relatively small. The obtained results for grey-to-grey crosstalk have confirmed the previous observations. The average values of crosstalk are small and comparable for both projection techniques and are in a range of 1 to 1.5%.

As it can be noticed, some measurements are non-monotonic, *e.g.* grey-to-grey stereoscopic crosstalk of the right eye for Infitiec 3D (Table 3). This may be caused mainly by the method of calculating crosstalk according to the formula (6). For small luminance values, even small measurement errors may quite significantly affect the value of the calculated crosstalk. In this case, as recommended in [27], the average value is reported.

Generally, the results obtained for inter-channel crosstalk are satisfactory. In the subjective perception of crosstalk, it may be noticeable when displaying extremely different images for each eye (*e.g.* white and black). In practical applications, there are no such different images displayed to the left and right eyes. For this reason, the user will not notice the effect of an influence of one eye channel onto the other.

The measurements showed that for the Active Stereo projection technique the values of the measured luminance are higher than those for the Infitec projection technique, thus resulting also in higher values of stereoscopic luminance and stereoscopic contrast ratio for the Active Stereo

Table 3. Grey-to-grey stereoscopic crosstalk for Infitec 3D technique
for the left eye (X_{Lij}) and the right eye (X_{Rij}).

left eye, X_{Lij}							**right eye, X_{Rij}**						
Eye Gray level		**R**					**Eye Gray level**		**L**				
		0	**63**	**127**	**191**	**255**			**0**	**63**	**127**	**191**	**255**
L	0	0%	0%	2.17%	1.80%	1.46%	R	0	0%	5.56%	1.20%	0.49%	0.77%
	63	0%	0%	2.86%	1.00%	1.52%		63	5.0%	0%	0%	1.08%	1.10%
	127	0%	0%	0%	1.54%	1.23%		127	0%	0%	0%	1.6%	1.32%
	191	0.91%	1.00%	1.54%	0%	1.06%		191	0%	0.54%	2.5%	0%	1.10%
	255	2.42%	0.51%	0.62%	4.12%	0%		255	0.26%	1.90%	1.64%	2.17%	0%
***X_L average* = 1.03%**			**σX_L = 1.07%**		***X_L max* = 4.12%**		***X_L average* = 1.13%**			**σX_L = 1.47%**		***X_L max* = 5.56%**	

Table 4. Grey-to-grey stereoscopic crosstalk for Active Stereo 3D technique
for the left eye (X_{Lij}) and the right eye (X_{Rij}).

left eye, X_{Lij}							**right eye, X_{Rij}**						
Eye Gray level		**R**					**Eye Gray level**		**L**				
		0	**63**	**127**	**191**	**255**			**0**	**63**	127	**191**	**255**
L	0	0%	0%	1.63%	1.67%	1.60%	R	0	0%	0%	1.55%	1.28%	1.18%
	63	3.33%	0%	2.13%	1.85%	1.69%		63	0%	0%	1.02%	1.41%	1.24%
	127	1.63%	1.08%	0%	1.69%	1.78%		127	0.78%	1.02%	0%	2.62%	1.09%
	191	2.33%	1.85%	1.69%	0%	2.23%		191	1.28%	1.06%	1.09%	0%	1.08%
	255	3.43%	4.04%	1.78%	2.95%	0%		255	0.68%	0.18%	1.52%	0.72%	0%
***X_L average* = 1.62%**			**σX_L = 1.14%**		***X_L max* = 4.04%**		***X_L average* = 0.83%**			**σX_L = 0.67%**		***X_L max* = 2.62%**	

technique. In addition, in the case of Active Stereo technique, the luminance difference ΔL is very small, while for Infitec technique it reaches higher values. This is mainly caused by the fact that the left and right eye channels for the Active Stereo technique are fully symmetrical (theoretically) while for the Infitec technique two different sets of interference filters are applied. Moreover, the use of interference filters causes the just mentioned lower measured luminance value. The luminance difference of the Infitec system is not noticeable by the user; however, it may cause one eye to dominate and thus reduce the stereo effect.

In the next step, to characterize colour properties of 3D projection techniques, colour gamut for the left and right eyes was determined. The measurements have been taken using five patterns, including three primary colours: white, black and red, green, blue, respectively.

The measured data (luminance and colorimetric coordinates) are presented in Table 5 (Infitec technique) and Table 6 (Active Stereo technique). Additionally, for better readability, the points corresponding to white and three primary colours for both projection techniques are marked in the colorimetric diagram (Fig. 6 and Fig. 7).

For Active Stereo projection technique only minor differences in the colour gamut for the left and right eyes were observed. The chromaticity coordinates differ from each other by a value less than 0.005 (that corresponds to the measurement accuracy of colour coordinates, given as ±0.002). This means that the glasses used for this type of projection enable a very good colour reproduction (no noticeable differences for both eyes). Additionally, the colour gamut for this projection technique is a bit wider than that for Infitec.

Table 5. Colour gamut for the left and right eyes, Infitec technique.

Infitec 3D technique, left eye				**Infitec 3D technique, right eye**			
Displayed pattern left eye / right eye	Luminance L [cd/m^2]	CIE 1931 colorimetric coordinates		Displayed pattern left eye / right eye	Luminance L [cd/m^2]	CIE 1931 colorimetric coordinates	
		x	y			x	y
white / black	2.85	0.303	0.332	black / white	3.88	0.342	0.320
red / black	0.63	0.636	0.346	black / red	1.15	0.676	0.312
green / black	2.18	0.310	0.578	black / green	2.92	0.284	0.601
blue / black	0.47	0.159	0.093	black / blue	0.67	0.192	0.090

Table 6. Colour gamut for the left and right eyes, Active Stereo technique.

Active Stereo 3D technique, left eye				**Active Stereo 3D technique, right eye**			
Displayed pattern left eye / right eye	Luminance L [cd/m^2]	CIE 1931 colorimetric coordinates		Displayed pattern left eye / right eye	Luminance L [cd/m^2]	CIE 1931 colorimetric coordinates	
		x	y			x	y
white / black	5.76	0.345	0.367	black / white	5.92	0.340	0.364
red / black	1.46	0.668	0.328	black / red	1.53	0.668	0.328
green / black	3.8	0.285	0.670	black / green	4.04	0.282	0.671
blue / black	0.43	0.144	0.079	black / blue	0.45	0.144	0.079

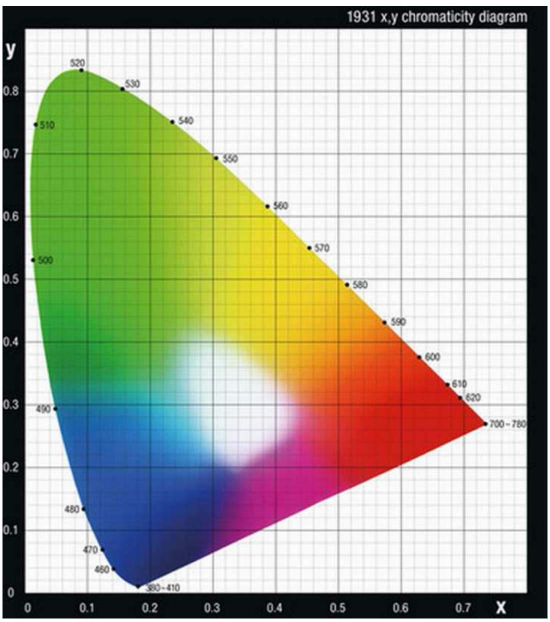


Fig. 6. A colorimetric diagram with marked red, green, blue and white points for both eye channels for Infitec 3D technique.

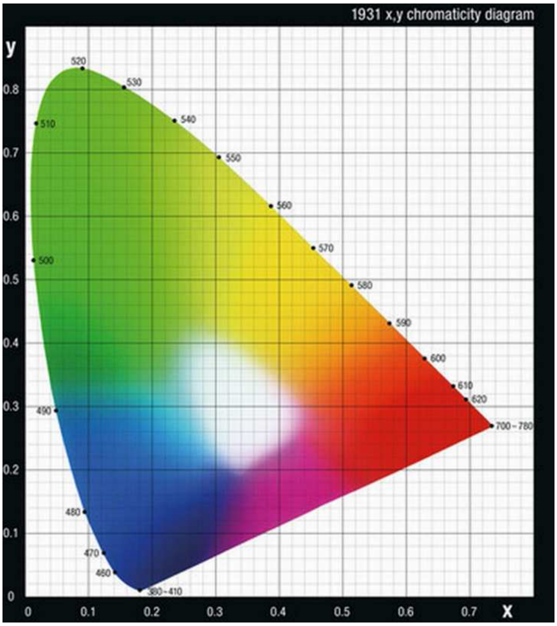


Fig. 7. A colorimetric diagram with marked red, green, blue and white points
for both eye channels for Active Stereo 3D technique.

Besides a slightly narrower colour gamut, Infitec projection technique is characterized by much more differences of colours for the left and the right eyes. It is especially important for the application where the colour reproduction plays the key role. These differences in the colour gamut are caused mainly by interference filters for both eye channels. Theoretically, it should be narrowband and a shift in the wavelength of both sets of colours should be small (Fig. 3). However, due to the optical power budget, the spectral characteristics are much more wide and differ from the ideal case. The characteristics of glasses for both eyes were measured and are presented in Fig. 8.

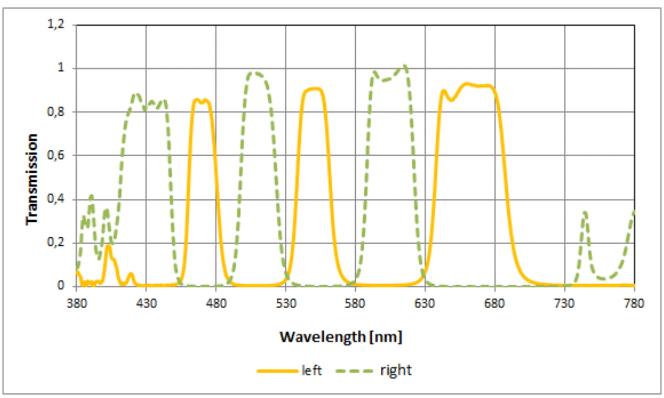


Fig. 8. Spectral characteristics of glasses (Infitec technique) for the left eye and the right eye.

The measured spectral characteristics take into account just only the glasses' filters, but not the spectral characteristics of lamp and built-in filters of projectors.

To estimate the usefulness of the projection technique for I3DVL a possible configuration of the laboratory should be taken into account. A special configuration occurs when the spherical walk simulator is placed in BigCAVE and a scenario is displayed on the screens of BigCAVE.

The main threat to the projection quality is the possibility of light depolarization while passing through or reflecting from the sphere, resulting in an increase of crosstalk. Therefore, the projection with the polarization separation was rejected in the design stage of the laboratory. However, most of the available glasses for the 3D time separation technique (*e.g.* Nvidia active stereo glasses) use LCD shutters, so that they are also polarization-sensitive. Thus, for the special configuration of I3DVL, the 3D projection technique with separation of spectrum (Infitec) seems to be the most suitable.

5. Conclusions

Immersive 3D Visualization Lab is modern and one of the most sophisticated virtual reality laboratories, mainly based on CAVE-type installations. The unique feature of the laboratory is the capability of insertion of a spherical walk simulator in the CAVE that enables unrestricted movement of the user. On the other hand, this solution imposes special requirements on the 3D projection system.

The measurements of stereoscopic parameters and colour gamut were performed for both implemented techniques: Active Stereo (with separation in time) and Infitec (with separation of spectrum). The results obtained for inter-channel crosstalk are satisfactory and comparable for both 3D projection techniques. The crosstalk is relatively small and in practical applications is unnoticeable. The stereoscopic luminance for Active Stereo technique is greater and more uniform for both eye channels than that for Infitec technique. Additionally, Active Stereo technique is characterized by a better and more homogeneous colour reproduction. Thus, based on the measurable technical parameters, Active Stereo technique seems to be the best 3D technique for a "classic" CAVE.

On the other hand, the glasses usually applied in Active Stereo technique are based on an LCD cell and are sensitive to light polarization. While the spherical walk simulator is placed in the CAVE, this may cause non-uniformities of the observed images and decreased values of stereoscopic parameters. Thus, for the special configuration of the laboratory, Infitec technique is recommended.

The above presented conclusions are based on the measurable technical parameters. The subjective parameters, *e.g.*an influence of flickering of active glasses on the user's health and frame of mind were not taken into account in this study and will be examined in the future research.

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References

[1] Lebiedź, J., Mazikowski, A. (2014). Launch of the Immersive 3D Visualization Laboratory. *High-Speed Tracked Vehicles*, 34(1), 49–56.

[2] Cruz-Neira., C., Sandin, D.J., DeFanti, T.A. (1992). The CAVE: A Virtual Reality Theater. HPCCV Publications, 2.

[3] Kuhlen, T., Hentschel, B. (2014). Quo vadis CAVE: does immersive visualization still matter? *IEEE Computer Graphics and Applications*, 34(5), 14–21.

[4] Muhanna, M.A. (2015). Virtual reality and the CAVE: Taxonomy, interaction challenges and research directions. *Journal of King Saud University – Computer and Information Sciences*, 27(3), 344–361.

[5] GBurdea, G., Coiffet, B. (2003). *Virtual Reality Technology*. 2nd Ed., Wiley, New York.

[6] Iowa State University News Service, The most realistic virtual reality room in the world, *http://www.public.iastate.edu/~nscentral/news/06/may/c6update.shtml*, access 02.2017.

[7] DeFanti, T.A., Dave, G., Sandin, D.J., Schulze, J.P., Otto, P., Girado, J., Kuester, F., Smarr, L., Rao, R. (2009). The StarCAVE, a third-generation CAVE and virtual reality OptIPortal. *Future Generation Computer Systems*, 25, 169–178.

[8] Schroder, D., Wafers, F., Pelzer, S., Rausch, D., Vorlander, M., Kuhlen, T. (2010). Virtual Reality System at RWTH Aachen University. *Proc. International Symposium on Room Acoustic*, ISRA 2010, Melbourne.

[9] Lebiedź, J., Mazikowski, M. (2014). Innovative Solutions for Immersive 3D Visualization Laboratory. *Proc. of WSCG2014 Conference on Computer Graphics, Visualization and Computer Vision*, Plzen, Czech Republic, 315–319.

[10] Hereld, M., Judson, I.M., Stevens, R.L. (2002). Introduction to building projection based tiled display systems. *IEEE Computer Graphics and Applications*, 20, 22–28.

[11] Hanel, C., Weyers, B., Hentschel, B., Kuhlen, T. (2016). Visual quality adjustment for volume rendering in head-tracked virtual environment. *IEEE Trans. Vis. Comput. Graph.*, 22(4), 1472–1481.

[12] Szymaniak, M., Mazikowski, A., Meironke, M. (2017). Investigation of tracking systems properties in CAVE-type virtual reality systems. *Conference on Photonics Applications in Astronomy, Communications, Industry and High Energy Physics Experiments, Proc. SPIE 10445*, Wilga.

[13] Mazikowski, A. (2018). Analysis of luminance distribution uniformity in CAVE-type virtual reality systems. *Opto-Electron. Rev.*, 26(2), 116–121.

[14] Lebiedź, J., Szwoch, M. (2016). Virtual Sightseeing in Immersive 3D Visualization Lab. *Proc. of the Federated Conference on Computer Science and Information Systems*, 8, 1641–1645.

[15] Fernandes, K.J., Raja , V., Eyre, J. (2003). Cybersphere: The Fully Immersive Spherical Projection System. *Comm. of the ACM 2003*, 46(9), 141–146.

[16] Medina, E., Fruland, R., Weghorst, S. (2008). Virtusphere – Walking in a Human Size VR Hamster Ball. *Human factors and Ergonomics Society Annual Meeting*, New York, 52(27), 2102–2106.

[17] Gantenberg, J., Schill, K., Zetzsche, C. (2012). Exploring Virtual Worlds in a Computerised Hamster Wheel. *German Research*, 34(1), 24–27.

[18] Garbat, P. Kujawińska, M. (2008). Visualization of 3D variable in time object based on data gathered by active measurement system. *Opto-Electron. Rev.*, 16(1), 97–104.

[19] Flotyński, J., Walczak, K. (2017). Ontology-Based Representation and Modelling of Synthetic 3D Content: A State-of-the-Art Review. *Computer Graphics Forum*, 35(8), The Eurographics Association and John Wiley & Sons Ltd., 329–353

[20] Meironke, M., Mazikowski, A. (2017). Modeling of luminance distribution in CAVE-type virtual reality systems. *Conference on Photonics Applications in Astronomy, Communications, Industry and High Energy Physics Experiments, Proc. SPIE 10445*, Wilga.

[21] Christie CAVE – Cave Automatic Virtual Environment, *http://www.christiedigital.com*, access 10.2016.

[22] Horan, B., *et al.* (2018). Feeling Your Way Around a CAVE-Like Reconfigurable VR Syste. *11th International Conference on Human System Interaction (HSI), Gdańsk, Poland, IEEE Xplore*.

[23] Jorke., H., Fritz, M. (2005). Infitec – a new stereoscopic visualization tool by wavelength multiplex imaging. *Journal of Three Dimensional Images*, 19(3), 50–56.

[24] Barco. Stereoscopic projection. 3D projection Technology, *http://www.vr.barco.com*, access 02.2016.

[25] Mazikowski, A. Trojanowski, M. (2013). Measurement of spectral spatial distribution of scattering materials for rear projections screens used in virtual reality systems. *Metrol. Meas. Syst.*, 20(3), 443–452.

[26] Mazikowski, A., Lebiedź, J. (2014). Image Projection in Immersive 3D Visualization Laboratory. *18^{th} International Conference on Knowledge Based and Intelligent Information &Engineering Systems KES*, *Procedia Computer Science,* 35, 842–850.

[27] International Committee for Display Metrology: Information Display Measurement Standard v1.03, 2012, *https://www.icdm-sid.org/.*

[28] Woods, A.J. (2012). Crosstalk in stereoscopic displays: a review. *Journal of Electronic Imaging*, 21(4), 040902.