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Image projection in Immersive 3D Visualization Laboratory

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Abstract

In recent years, many centers in the world attempted to build a virtual reality laboratory. The main idea of such laboratory is to allow the user to "immerse" into and move in a computer-generated virtual world. In the paper, the underlying principles of the system of virtual reality (VR) are described. The selected implementations constructed by the research centers of the world are also presented. The cave automatic virtual environment (CAVE) installation is planned to be implemented at the Gdańsk University of Technology. In this solution, the images will be projected on flat screens arranged in the form of a cube. The user will be located inside a transparent sphere freely rotating inside a cube, which allows simulation of free movement without changing the position of the screens. A walking motion of the user will trigger changes in the computer-generated images on screens surrounding the sphere thus creating an illusion of motion. The problems of visualization in the planned installation are outlined and discussed.

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Keywords: virtual reality; CAVE; three-dimensional projection; 3D visualization

1. Introduction

In recent years, the development of visualization systems is largely related to the dynamic growth of entirely new technologies: a projection of three-dimensional (3D) VR or so called augmented reality (AR). Many centers in the world attempted to construct devices (installations), allowing for unlimited territorial walk in a computer-generated virtual world[1-7]. Viewing 3D images, in particular the experience of "immersion" in a 3D environment (virtual

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reality), seems to be the natural direction for development of visualization systems. Basic features and assumptions of virtual reality systems can be summarized as follows:

- The computer reflection of natural reality.
- The obtaining of effect for observer immersion in the surrounding environment or "being in the interior of the data".
- The ability to move in the virtual environment in a natural way.
- The interaction with the computer-simulated environment.

In the literature, the virtual reality is sometimes defined as so-called I^3 (here 3 is a power, not a reference): Interaction + Immersion + Imagination, which well-characterizes the VR nature[8].

An important advantage of VR systems is the ability to generate images, scenes and situations that are beyond the "normal" reality, i.e. the ability to improve the reality for the specific needs of the application as mentioned below:

- Military (training pilots, paratroopers, equipment operators, etc.).
- Scientific and professional – professional workplaces and simulators (medicine, geology, engineering, ship, or helicopter simulators).
- Education.
- Entertainment.

The implementation of VR is a very complex task. Such system combines a number of modules of various types: mechanical, optoelectronics, and informatics. Any assessment of VR system quality ought to consider the properties of the human vision, in particular the spatial vision, perception of color and dynamic images.

2. Selected VR systems

The forerunner of VR systems is the 3D projection system, which dates back to 1838, when the English physicist Sir Charles Wheatstone built the camera for viewing of spatial pictures – the stereoscope. The development of VR systems occurred in the late twentieth century, along with the dynamic development of computer technology and information visualization systems.

The first CAVE installation was built in the University of Illinois at Chicago in 1992[1,9]. The idea of this solution, called the "classic" CAVE, is shown in Fig. 1 a. The projection takes place on a number of flat screens arranged in the form of a cube typically about 3 m × 3 m × 3 m in sizes. In the pioneer installations (including the one in Chicago), the projection was made on four (three walls + floor) or 5 (optional ceiling) screens. On one wall, there was no screen allowing users to freely enter or leave. However, in such implementation of the CAVE the user, who turns back, does not have a screen with an image in front of himself. The first CAVE utilized a two-dimensional (2D) projection, which soon was replaced by the 3D one. Also a continuous increase of resolution and brightness of projectors were observed. One of the most advanced system currently provides the on-screen images with a resolution of 4 k × 4 k pixels with a total luminous flux for each of the screens 11000 lm[7]. The main disadvantage of the "classic" CAVE is the limitation of the user's movement in the created virtual environment due to the finite dimensions of the cube of screens.

In order to provide the ability to move in the VR for the user, a number of solutions have been tested. There are known solutions using a bi-directional conveyor belt[10,11], a conveyor table equipped with an array of bi-directional rollers, or the moving paving slabs placed automatically under the foot while the user walks[12]. All of these systems are rather complicated and thus less reliable. Excessive noise and a lack of image projection on the floor are additional possible disadvantages.

One of the best possibilities providing a "movement without changing location" is using a freely rotating sphere with the user placed inside. This solution is known as Cybersphere (Fig. 1 b)[2] or Virtusphere (Fig. 1 c)[3]. In such installation, freedom of movement is not restricted. The rotating spheres are moved only by the force of the human steps. A sensor system is necessary to monitor the rotational dynamics of the sphere. There is possible to support this movement by a set of servo motors, but in both of these solutions it does not occur.

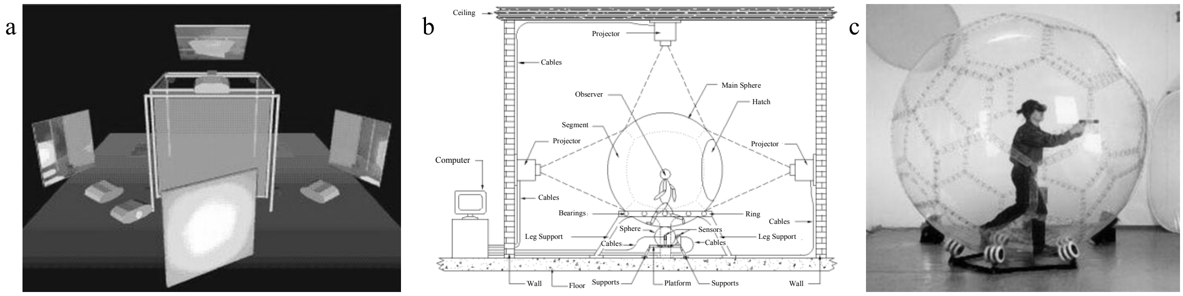

Fig. 1. (a) a classic CAVE[1]; (b) Cybersphere[2]; (c) Virtusphere[3].

In an installation utilizing a rotating sphere to achieve the feeling of audio-visual "immersion" in the surrounding VR, a cybernetic helmet is usually used. This fact results, however, in a discomfort caused by the device of considerable size and weight placed on the user's head. Another key problem is the risk of a delay of the projections in the case of a rapid motion of the user head[5].

Very innovative and interesting solution was developed at the University of Warwick (England) (Fig. 1 b)[2], where a rotating sphere with a user, placed inside, rises in a vertical air stream creating a kind of an air cushion. The sphere is light weight, therefore does not have its own drive, but only sensors to track the movement and is only touched upon the power of the human steps. The sphere consists of two layers, each of which consists of several segments of a specially designed shape[2]. In order to ensure sufficient mechanical stiffness, the segments of individual layer overlap with some offset. The outer layer of the sphere is made of a brushed material, thus becomes a screen, on which the projection of the image is performed.

The inspection of installation by one of the authors of this study also revealed the inadequacies of some applied solutions. First of all, the 2D projection was only used. Matching of projected images of more than two projectors (complex border line of many images for curved screens) on the sphere surface is also a non-trivial task[13], therefore only two projectors (matching of two images), arranged at an angle of 90° to each other were usually used. Moreover, despite the two-layer construction, the sphere did not have sufficient mechanical stiffness.

3. Concept of Immersive 3D Visualization Laboratory

The task of creating a modern VR laboratory, named Immersive 3D Visualization Laboratory, has been undertaken at the Faculty of Electronics, Telecommunications and Informatics at the Gdańsk University of Technology. One of the main assumptions of this laboratory is a desire to ensure the highest possible degree of feelings of "immersion" (not restricted freedom of movement, stereoscopic 3D projection) together with the least amount of the user's worn equipment (e.g. cybernetic helmet) to provide him/her maximum comfort and impression of natural activity.

The laboratory project is partially based on the solutions presented in the previous section. The implementation of a mechanism of the "movement without changing location" will be carried out using a rotary transparent sphere (with a user placed inside). The sphere will rotate on the rollers. It will be placed inside the cubic CAVE with the implemented omni-directional 3D rear projection. The projection will take place onto the set of six flat screens forming the cube structure around the sphere[5]. Two alternative technologies of stereoscopy will be used: spectrum separation and separation in time. This solution requires the projection from six different directions, six pairs of projectors, six sets of projector mounts, etc.

a b

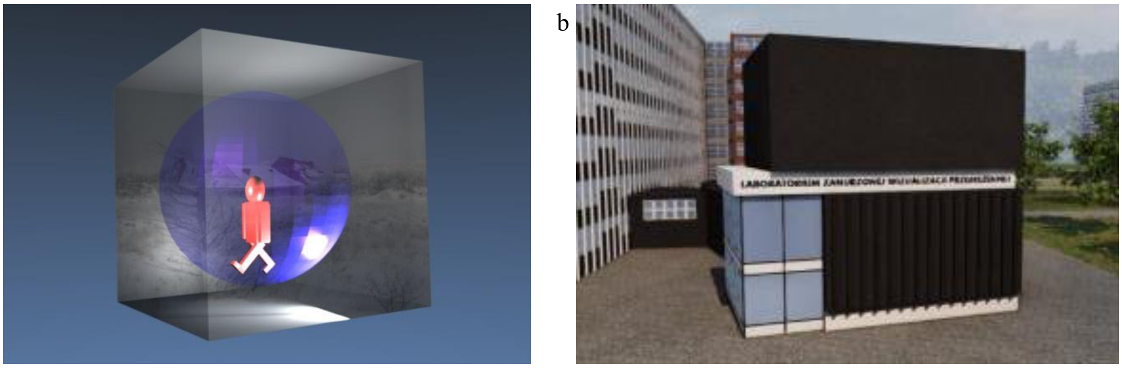

Fig. 2. (a) concept of I3DVL – courtesy of J. Dembski; (b) vision of building – courtesy of M. Wróbel.

The idea of the proposed solution is shown in Fig. 2 a. The basic assumptions can be summarized as follows:

- An application of freely rotating sphere.
- A rear projection into six flat screens (in the form of a cube).
- A stereoscopic projection using the technique of spectrum separation, as it is insensitive to the light depolarization and time synchronization of projectors, and alternatively technique of separation in time.

In the case of rear projection into flat screens surrounding the sphere, a high transparency and a homogeneity of the sphere are required in order to prevent excessive distortion of the observed image. Therefore, the sphere has to be made from a relatively small number of segments (to minimize the length of segment boundaries) and from materials having sufficient mechanical strength (the need to maintain the user inside without a significant deformation of the sphere), resistance to dirt and mechanical damage (scratches) during normal use.

An average observer eye level should coincide with the geometric center of the sphere, which provides the direction of observation perpendicular to the surface of a sphere and a minimization of image distortion in the case of projection on screens surroundings the sphere (on the surface of the sphere there will be no refraction of light rays). Therefore, the diameter of the sphere must be equal to about two height of the average human (up to the eye level) and is estimated at 3–3.2 m. In case of placing the user inside the sphere, it is extremely important (safety reasons) to ensure sufficient air volume in the sphere. For estimated sphere diameter, the above assumption is fulfilled. The estimated sphere diameter provides also sufficiently large radius of curvature. Therefore, an abnormality of movement will be imperceptible or will be at acceptable level[5].

The 3D vision is related to the fact that the eyes of an observer are located at some distance from each other, and, therefore, each eye sees a slightly different picture. The interpretation of these images in the brain of the observer results in the impression of a depth. Although many CAVE systems use the 2D projection, the application of 3D one allows the user the higher impression of “immersion” in virtual environment.

Creating an impression of a depth in the intended manner requires the generation of pairs of images seen from a slightly different perspective, and directing them to the left and right eye of the observer. In this way, the stereoscopic systems operate[14,15]. Few types of stereoscopic systems can be distinguished such as active stereoscopic systems (the projection with separation in time) and passive stereoscopic systems (projection with separation of polarization or projection with spectrum separation).

In active stereoscopy, the images for both eyes are displayed alternately with twice the frequency: one image for the left eye and one for the right eye (Fig. 3). Due to the synchronization with displaying, the shutter glasses pass only every second image to each eye (separation in time). This necessitates power supply of glasses, hence the method is called the active. In the passive stereoscopy, the image consists of two images destined for both eyes. The unpowered glasses with appropriate filters let in only images destined for a given eye. The filtering can be based on different properties of light such as a polarization or a spectrum. The polarization separation may use a linear or a circular polarization (Fig. 4). A projection with a spectrum separation will be presented in details in the next section.

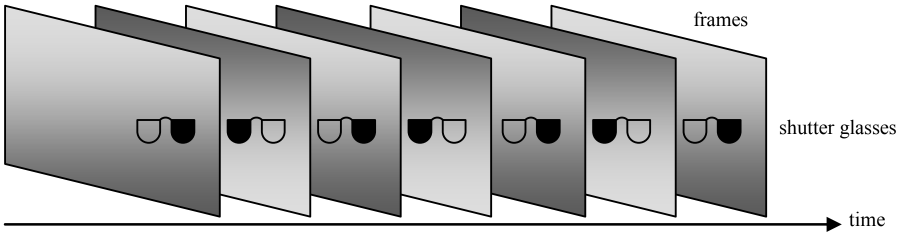

Fig. 3. a principle of active stereoscopy (with separation in time).

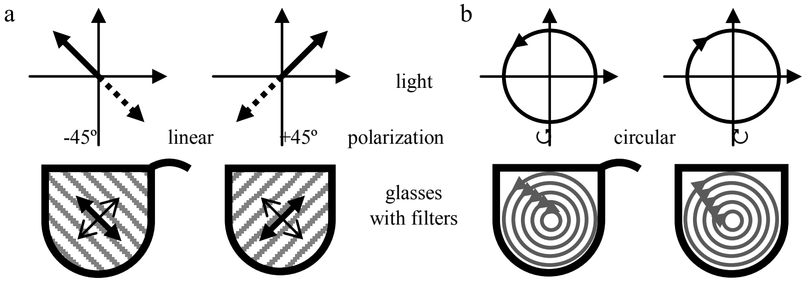

Fig. 4. (a) a linear polarization and (b) a circular polarization.

Because of the possibility of the light depolarization on the rotary sphere material, the projection with a polarization separation may not work properly in the laboratory and has been eliminated. Therefore, the authors have chosen the method utilizing a spectrum separation. Additionally, the technology of separation in time (with active shutter 3D glasses) is applied as alternative way for a stereoscopy. The project of the laboratory requires the construction of the dedicated building (Fig. 2 b). The most important room in this building will be the main hall, where a rotating sphere, the projection screens and a 3D projection system are placed.

The application of a rear projection system strongly affects the overall dimensions of the installation. The six side projection with a screen sizes larger than the diameter of the sphere requires a considerable distance from the projector to the screen. With typical projection throw ratio of 1.1:1, dimensions of the screen side of about 3,5 m and the length of an average high resolution projector of about 0.8 m, the internal space of a building accommodating the system should thus be a cube of 12.5 m × 12.5 m × 12.5 m. It is possible to reduce the dimensions of the room by using the collapsed configuration of the optical system, but it causes the additional complications of installation and greatly increases the cost of projection system.

The additional requirements such as optical (the dark walls to eliminate reflections), mechanical (the projector mounts), and infrastructure (power network, ventilation, service access to projectors) are imposed on the laboratory hall. Neighboring to the main CAVE room, a set of auxiliary rooms is to be built, accommodate the cluster of image-generating computers, other support machinery or control devices, and also a small lecture room.

The freedom of a user walking will be fully perceptible provided by visual and audio synchronization with the user motion. The generation of realistic 3D image modified and synchronized in real time with the user motion is a basis for obtaining a reliable impression of walking in a virtual environment. This effect can be achieved using graphics software ranging from the popular 3DSMax and ending with a special CityEngine. It is also planned to create the own software[5] based on all-purpose OpenGL or designed for game developers Unity 3D. The data for 3D visualization could be also achieved by a dedicated measurement method[16,17].

4. Wavelength multiplex 3D visualization technology

One of the methods of a 3D image generation is a stereoscopic method with separation of the spectrum. The images created for the left and right eye differ in the radiation spectrum. This method is based on technology "wavelength triplet" developed by the Infitec company[18]. In the human vision, the light incoming into the eye stimulates the three groups of color receptors (cones) with different ranges of spectral sensitivity. A color impression is formed in the brain of the observer as a combination of the stimulated different receptors: red (R), green (G) and blue (B). This principle is used in most of the color displays, where a color image is obtained by an additive composition of primary colors. The metamerism phenomenon is applied here[19] – the same color impression can be obtained by various stimulations, and, therefore, also for the different spectral characteristics of the incident light.

The stereoscopic "wavelength triplet" method uses the property mentioned above. The images for the left and right eye are generated based on three primary colors (RGB) but slightly shifted of wavelength λ. The result is two sets of primary colors $R_1G_1B_1$ and $R_2G_2B_2$ for each observer's eye, respectively. The images are generated in such way that each eye receives the same impression of color. Since the shift in the wavelength of both sets of colors is small, the color gamuts for each eye are almost the same. The spectral characteristics of the light flux $\Phi(\lambda)$ of projectors for the left and right eyes are shown in Fig. 5. The spectral characteristics of the radiation forming two complementary images (left and right eye) are not overlapped. Thus, they can be separated using two sets of interference filters. The user (observer) ought to wear a lightweight and inexpensive glasses, whose transmission characteristics are shown in Fig. 5.

In the Infitec technology[18], two projectors are typically used: one of them generates the image for the left eye and one for the right eye. The proper 3D impression precise alignment of both projectors is required so that the spatial distribution of the picture elements overlaps for two projected images. This technique, which uses the passive glasses with interference filter, is called a passive technique. In recent years, however, Barco has developed a special projector (Galaxy Series), which enables the generation of both complementary images (the active Infitec technology). This version continues working with the passive glasses.

The stereoscopic method for separation of the spectrum is the most suitable method to obtain 3D image in the planned CAVE installation. This solution does not introduce any time-dependent elements (there is no sequential switching and synchronization).

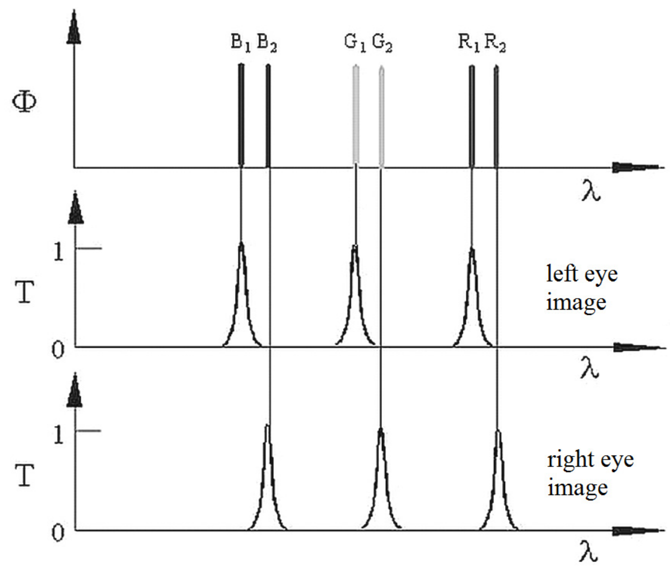

Fig. 5. the characteristics of the light beam projector $\Phi(\lambda)$ and transmission characteristics of filters for left and right eye, respectively[19].

5. Optical system requirements

In the developed VR installation, one of the most important parts is the optical system – a system of 3D rear projection. With the continuous development of VR systems (such as the CAVE-like systems), the optical parameters are changed in order to increase in brightness (luminance) and a resolution of the projected 3D images. These changes are obviously advantageous and in combination with the increasing computational power of computers provide new and better opportunities for the creation of the virtual world. There is, however, the question of the minimum requirements for the optical system, taking into account the characteristics of the human vision as well as the method and conditions (geometry) of projection.

The required resolution is obtained from a normal visual perception threshold of a human vision. It defines the angle, at which one can distinguish object details equal to 5' (angle minutes). An important advantage of the proposed system is that the user's head (and thus his/her eyes) is in a fixed position (distance) relative to the screens (about the center of the sphere). Therefore, this provides much more advantageous than the classic CAVE installations, where the distance to the screen will change, while a participant moves during simulation.

In the case of the proposed system, the most critical situation occurs during the observation for the center of the screen (perpendicular to its surface). The distance of observation will be approximately equal to half of the side of the screen. The density of pixels per a screen is calculated by Eq. 1 or Eq. 2, where N is a number of pixels per screen side, α_t is a visual perception threshold, x is a side length of the screen (Fig. 6 a).

$$\tan\alpha_t = \frac{\frac{x}{N}}{\frac{x}{2}} \quad (1)$$

$$N = \frac{2}{\tan\alpha_t} \quad (2)$$

Substituting α_t with the value of 5', we obtain a minimum number of 1375 pixels. In the case of dynamic images, this value may be smaller but for Immersive 3D Visualization Laboratory 1920 pixels have been assumed. Less than the minimum number of pixels can cause the distinction of individual pixels, therefore, a comfort of viewing images can be reduced. During the observation of points far from the center of the screen (for example, in the corner of the screen), when angular pixel dimensions will be smaller, and the distance of observation – greater, the requirements need not to be so restrictive.

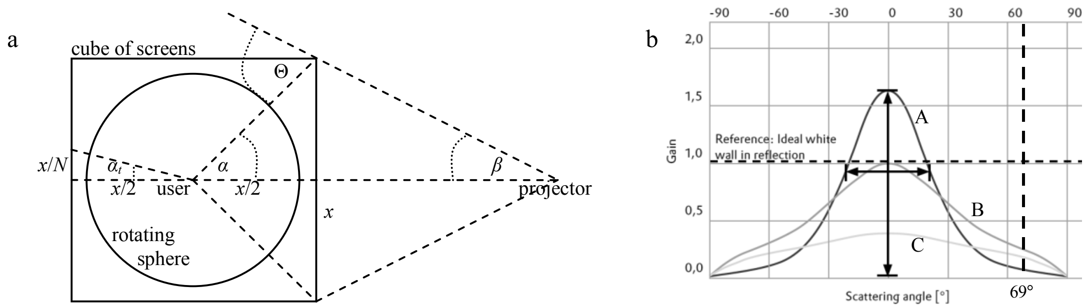

Fig. 6. (a) geometry of observation of single pixel and whole screen from user's point of view (center of sphere); (b) the scattering characteristics for three types of RP screens: A – Daylight 99561 RP, B – Studio 7D006 RP, C – Control 7D009 RP[20].

Another important parameter is the luminance of the projected image. The luminance of the typical monitor is about 300 cd/m². It is difficult to assess the minimum required luminance of the CAVE system because of process of human sight adaptation to the light conditions. In the case, a luminance may not be so large but the luminance of about 30–50 cd/m² would be appropriate. Let us assume a projection on a screen area of 10 m² and effectively (output) light flux of the projector of 1000 lm (homogeneous – ANSI standard). Therefore, luminance on the screen surface will be equal to 100 lumens per square meter, and luminance (from the observer side assuming 100% transmission and the lambertian characteristic of scattering) is estimated by Eq. 3.

$$L = \frac{100}{\pi} = 31.8\,\frac{\mathrm{cd}}{\mathrm{m}^2} \tag{3}$$

In fact, however, the transmission is much less than 100 %, and it should take into account the angular characteristics of scattering of the screen material. Let consider the screen of Plexiglas RP, specially offered by the Evonik Rohm for the rear projection[20]. The scattering characteristics of three types of Plexiglas RP (for a normal angle projection) are shown in Fig. 6 b. In Fig. 6 a, the geometry of the projection and observation of a plane image for the observer eyes is shown. The observation angle α varies from 0° to 45°. However, it should be taken into account that for small values of ratio, the projection angle β will also be important, and for ratio 1.1:1 it will be about 24°. Assuming the maximum angle of scattering Θ (Fig. 6 a) as a simple sum of these two angles, we obtain Eq. 4.

$$\Theta = \alpha + \beta \approx 69° \tag{4}$$

For the Daylight 99561 RP screen (Fig. 6 b – curve A), the luminance of about 50 cd/m² for the normal direction of observation, and of about 4 cd/m² for 69° could be obtained (provided 1000 lm of projector flux). Such significant differences are strongly visible, and will cause some discomfort in the image perception.

A better solution is to apply Studio 7D006 RP (Fig. 6 b – curve B) or Control 7D009 RP (Fig. 6 b – curve C) screens. Although the luminance for the normal angle is lower, its distribution as a function of a scattering angle is more uniform. For the Studio 7D006 RP we obtain a luminance of 32 cd/m² for normal angle and about 10 cd/m² for a scattering angle of 69°, while for the Control 7D009 RP a luminance of 13 cd/m² and about 7 cd/m² is achieved, respectively. The slight differences in luminance can also be corrected by a software. In conclusion, to achieve the desired luminance at the level of 30–50 cd/m² it is required to apply the projector of the output light flux of 4000 lm. The planned pair of Barco Galaxy NW-7 projectors (7000 lm and 1920 × 1200 pixels each) on one screen in Immersive 3D Visualization Laboratory complies with these requirements.

For significant values of a scattering.ng angle Θ, the differences between the scattering of screens for different wavelengths can be noticed. This may lead to differences in color perception (e.g. for shift of white balance point)[21].

6. Summary

The implementation of Immersive 3D Visualization Laboratory is a very complex task. Several problems of different nature such as mechanical, optoelectronics and informatics must be solved. Most of these problems cannot be considered separately, for instance problems related to the projection system cannot be considered in isolation from the problems related to the mechanics or computer generation and synchronization of 3D image. The discussion above concerns mainly the problems related to the visualization of 3D image. A number of problems are still not solved both on technical matters and the subjective user perception of 3D impression as well as the impact on a user health and well-being[22,23]. The technical problems relate mainly to define the minimum required resolution and brightness. The impact of transparent sphere (composed of segments) and the problems concerning dynamic parameters (a proper synchronization user motion with a projected image) on the quality of the image is very difficult to predict.

The number of activities to be implemented in the proposed laboratory seems limitless. It is designed to train programmers, who develop the 3D visualization software. Also this system will be useful in various service activities: the training of public services (virtual battlefield, training for fire brigades, national security), the training of industrial experts (virtual inspection of ships and buildings), scientific visualization (virtual manipulation of complex chemical molecules), virtual tourism, virtual museums (virtual tour of exposure), visiting building projects and facilities (presentation to the customers), the evaluation of the effectiveness of visual advertising, the education (walk in the micro-world or cosmos), the therapy in the treatment of phobia (the method of quenching reactions by immersion), rehabilitation and physiotherapy (analysis of human effort during a march) as well as the entertainment (3D art installations, computer games)[5].

The final result of the program will be a complete VR laboratory. The greatest challenge of this laboratory will be not limited walk through the computer-generated virtual world. The laboratory is scheduled for implementation yet in 2014.

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