# Multiuser Stereoscopic Projection Techniques for CAVE-Type Virtual Reality Systems

Jacek Lebiedź and Adam Mazikowski

***Abstract*—Despite the development of increasingly popular head mounted displays, CAVE-type systems may still be considered one of the most immersive virtual reality systems with many advantages. However, a serious limitation of most CAVE-type systems is the generation of a three-dimensional (3-D) image from the perspective of only one person. This problem is significant because in some applications, the participants must cooperate with each other in the virtual world. This paper presents the adaptation of a one-user Cave Automatic Virtual Environment (CAVE) installation in the Immersive 3-D Visualization Lab at the Gdańsk University of Technology to a two-user stereoscopy system. Simultaneous use of two alternative one-user stereoscopies available in the I3DVL (a technique with spectrum separation—Infitec, and active stereo) and a simple electronic circuit have allowed us to transform the one-user stereoscopy CAVE installation to a two-user stereoscopic system. The experiments performed concentrated on several objective measurable parameters. The calculated crosstalk value was low, approximately 1%, which can be considered negligible and shows the proper operation of the proposed technique. Additionally, initial experiments based on the tested two-user application and related to user comfort in the developed two-user stereoscopy are discussed in this paper. However, this topic still needs further research. The proposed solutions are a cheap alternative to adapt the existing one-user CAVE-type systems which support two projection techniques to a two-user system.**

***Index Terms*—CAVE-type systems, multiuser stereoscopy, multiviewer systems, virtual reality (VR).**

## I. Introduction

OVER the last several years, the improvement of computational power, display technology and tracking systems has allowed for the development of an entirely new technology: virtual reality (VR). Many scientists, theorists and engineers have created many installations and applications in which users can manipulate and explore the surrounding, computer-generated, three-dimensional virtual world. To achieve the best quality and experience of VR, a combination of two basic elements is needed: interaction through input devices and immersion provided by output devices [1]–[4].

As mentioned above, interaction with the virtual world is one of the key factors which determines the quality of VR systems. Additionally, interaction can be an essential element for investigating human behavior under controlled conditions [5]–[12]. We may assess how a user cooperates with a virtual environment to perform a specific task, a task which quite often requires not only cooperation with a virtual environment but also with other users [13]. As most every-day behavior occurs in a social environment, detailed investigation of human behavior also has to take into account the inclusion of social context [12]. The task is therefore to immerse multiple persons into a single virtual environment.

Some authors distinguish between a nonimmersive multiuser environment and an immersive multiuser environment for social interaction. The former comprises online multiuser two-dimensional (2-D) environments, such as social networks, chat programs, auction websites and computer games, including massive multiplayer online role-playing games [12]. The huge number of users and advanced interaction possibilities make multiuser 2-D environments an interesting tool for analyzing complex social behavior.

An immersive multiuser environment is specified as a 3-D virtual world where several humans can interact, communicate and cooperate. Similar to standard (one-user) VR installations, it requires a standard technical setup that is extended by the tracking of multiple bodies, rendering one virtual world from different perspectives and usage of avatars as a representation of the other participants [12], [14].

Currently, VR headsets are gaining increasing popularity. Occasional users of VR solutions may find VR headsets the ultimate source of simulating immersive experiences. However, except for the cost, CAVE-type installations have several undeniable advantages over their lightweight alternatives. First, using the CAVE-type system is much more convenient and natural for the user, who does not need to burden their head and neck with additional optoelectronic devices restricting freedom of movement. Second, the use of headsets is often associated with cybersickness, while this problem is relatively rare for CAVE users. This is because when the user's head is turned, the VR headset generates a new image with a certain delay, contrary to the CAVE-type systems that are capable of simultaneously displaying multiple images on their walls. Therefore, images always "wait" for the user instead of lagging behind, as in the case of VR headsets.

Manuscript received February 17, 2021; revised May 12, 2021; accepted July 3, 2021. Date of publication August 24, 2021; date of current version September 15, 2021. This work was supported by the Ministry Subsidy for Local Research and the Special Research Infrastructure Support under Grant 86/E-359/SPUB/SP/2019. This article was recommended by Associate Editor G. Serra. *(Corresponding author: Jacek Lebiedź.)*

Jacek Lebiedź is with the Department of Intelligent Interactive Systems, Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology, 80-233 Gdańsk, Poland (e-mail: jacekl@eti.pg.edu.pl).

Adam Mazikowski is with the Department of Metrology and Optoelectronics, Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology, 80-233 Gdańsk, Poland (e-mail: adamazik@eti.pg.edu.pl).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/THMS.2021.3102520.

Digital Object Identifier 10.1109/THMS.2021.3102520

Finally, the most important advantage of CAVE-type installations is that the user is aware of the physical presence of their entire body, not just their avatar, in the generated virtual world. Such "consistency of being" is crucial for many simulation scenarios, especially when the mental and emotional states of users are studied or exercised. This becomes even more important when there are several participants in the CAVE–they can talk freely with each other, touch each other or use real devices (e.g., tools or weapons).

CAVE-type installations should be considered the most immersive installations of VR [15]–[18]. They are essentially one-person installations or quasi multiperson installations, where the corresponding images are displayed for one user only [19]–[21]. This limitation results from their construction which usually consists of one-person stereoscopic displays (projectors or monitors) that can simultaneously present only two offset images separately to the left and right eyes of the user. Active and passive stereoscopy encountered in this type of solution is discussed in Section III. Adding the possibility of interaction between two users would certainly be a significant improvement to the concept of physical immersion in a virtual world—specific only for CAVE-type installations. Such modification, however, requires simultaneous generation of separate images for each eye of each user.

The correct perspective view for several users is especially important when each person performs their tasks independently. If only one user is interacting and the others only observe the virtual environment (e.g., architect demonstrates the design of the new building to investors), then they are usually close to the host of the virtual show, and the degree of distortion between the head-tracked viewpoint and an untracked viewer's perspective is not glaring. However, when multiple participants perform their individual tasks by independently interacting with the shared virtual environment (e.g., as in distributed mission training scenarios [22]), then the correct perspective for every user is indispensable. It allows for correct 3-D perception of the virtual world and natural spatial manipulation of its objects.

Such multiperson simulations apply to all types of training of human groups working in close proximity, such as tank or fire crews, medical teams performing an operation, nuclear plant security management staff, etc. These types of simulations usually require quite complex manual interaction by each participant. We tested our concept of the independent viewpoint for each user on a simplified model of mechanics of playing a game of virtual beach ball with two people. Each player must be able to see the virtual ball in the same 3-D location to bounce it properly. Therefore, each of them must receive their own stereoscopic image from their own perspective. The preliminary tests confirmed the usefulness of the proposed solution, which is described later in the paper.

## II. Immersive Multiuser VR Installations

During the last few decades, a few VR multiuser installations have been developed. These installations differ in the applied solutions [23]–[25]. An example is the distributed interactive virtual environment [14]. As it is a distributed environment, information of the displayed scene is propagated and exchanged between the users using internet networking protocols. Other systems are designed as a multiuser workbench [26] or bottom-lit projection surface [27]. Still other systems (destined, e.g., for human interaction investigation) are arranged as a large, e.g., 12 by 15 m [12], fully tracked, free walking space. Similarly, large systems for training military forces or members of the public service have also been designed [28].

Generally, users navigate in a 3-D space and may see, meet and collaborate with other users and the application. These actions require using a visual interface (specialized views for all participants) and a wide range of input/output devices, such as wands, flysticks, data gloves, or a mouse interface. The effectiveness of interaction and thus the effectiveness of cooperation between users are influenced both by the design of the application and task as well as by the technical aspects of the whole installation. Another important subsystem in a VR system is the visual interface. All users need to see a different, personalized image. To support spatial perception, a stereoscopic view is commonly chosen.

Immersive environments can be achieved by several methods. One is the use of a head mounted display (HMD) [29], [30]. This is currently one of the most popular methods. Each user can see their own, stereoscopic image and is protected from seeing the images of the other users. The assignment to the user's point of view depends only on the master application. On one hand, this allows the creation of an application with multiple users. On the other hand, other users are represented only by a graphical virtual object, called an avatar (user embodiment, body icon). The user also does not see their own body. The quality of a user's body mapping (as an avatar) can introduce significant restrictions in the cooperation of the simulation participants, as they may not feel free and behave in an unnatural way.

Another configuration is having two separate displays (monitors or projection screens), with one display for one user. The problem with this configuration is that the screens block the view of the partner and, consequently, reduce interpersonal interaction. With modification of this solution, called the split-screen configuration, the user can see the content of the second user's screen, which is not an option for many applications.

It seems that a better solution is to apply a projection-based VR system, with the same set of screens for all participants and specialized views for each of them. In this case, different information can be shown to the users similar to the image splitting when a stereoscopy image is displayed, which means that each eye obtains a different image. This image splitting can also be used to separate information between users [13], [26].

A few installations operating on the same set of screens for all participants have been developed [13], [26], [27], [31]–[35]. These solutions usually utilize only one projecting screen, designed as a workbench or bottom-lit projection surface. Thus, these installations significantly limit the user's field of view and do not provide an omnidirectional projection. However, there are also multiuser stereoscopic CAVE-type installations intended for two or more people [36]–[38]. We address this approach later in this article.

An alternative solution to multiuser stereoscopy in CAVE-type installations is pseudo multiuser stereoscopy. In such installations, each pixel of the stereoscopic image is generated only from the perspective of one person, but for different parts of the image, the location of the point of view may change. If some part of the image is only seen by one user, it is rendered from that user's perspective. If more users look at the same part of the screen, the point of view for its pixels is calculated as the midpoint between the positions of the users [39], [40]. In comparison to the standard one-person stereoscopic installation, this approach does not force an extension of the hardware of the projection system. All you need to do is to modify the rendering software, adapting it to a "floating" perspective and to track multiple users. The challenge is to ensure the continuity of the image generated.

The need for correct-perspective image generation for several people also occurs for autostereoscopic monitors [41]–[43]. The main difference is the lack of tracking of viewers' heads and the constant distribution of viewpoints. The short distances between the users allow the use of certain elements of one view during the generation of other views from the adjacent perspective. Unfortunately, we cannot use such optimization for simple stereoscopy.

## III. Stereoscopic Techniques for Multiuser Projection-based VR Systems

For standard one-user 3-D VR installations, a few types of stereoscopic techniques can be distinguished: active stereo (image display with separation in time, active shutter glasses), passive projection with separation of polarization (linear horizontal/vertical or circular left-hand/right-hand polarization, passive polarization glasses), passive projection with spectrum separation (anaglyph, passive red-cyan glasses) or advanced passive projection with spectrum separation (Infitec, based on wavelength triplet technique, passive glasses with interference filters [44], [45]). Based on the abovementioned standard techniques, it is possible to obtain a 2-D image for two users. However, the 2-D image significantly reduces the sense of immersion in the virtual world, so the aim is to provide stereoscopic projection for many (a minimum of 2) users.

Two-user stereoscopic projection techniques may be used for many applications [13], [33]–[38], [46]. Generally, they are an extension or combination of one-user stereoscopic projection techniques.

### A. Active Stereo

Active stereo implementation requires a specially designed, synchronized pair of shutter glasses (four eye channels) where at the same time only one image is passed to the appropriate eye and the other three are blocked [26], [47]. Two-user active stereo can be supported by new increased frequency projectors such as Barco UDX-4K22 (from the specifications: "active eye wear (optional), passive circular (optional); 2 flash up to 200 Hz" [48]) or Christie D4K40-RGB (from the specifications: "frame rates: 24–60 Hz standard, optional 96–120 Hz 4K, 240–480 Hz 2K scaled" [49]). The two projectors mentioned above are among the first of their type. The offerings of various producers are becoming richer in this matter. Such projectors provide high comfort of use, but their price is still prohibitive, which is especially important in the case of multiprojector CAVE-type installations.

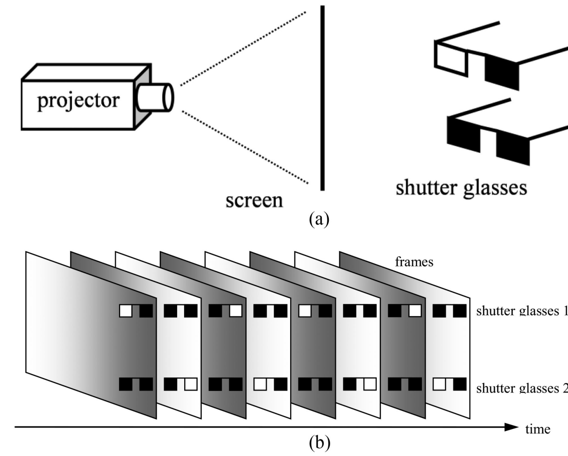



Fig. 1. (a) Block diagram of a two-user active stereo technique. (b) Sequence of frames and shutter glass states.

Unfortunately, time-honored active stereo glasses do not support such functionality. Due to their embedded electronics, it is quite difficult to adapt them to appropriate image splitting. An advantage is the fact that apart from special glasses, this technique does not require additional equipment, and the generation of four different images may take place on the software path (an appropriate refresh rate is required). A block diagram of this technique is presented in Fig. 1(a), with the sequence of frames and shutter glass states in Fig. 1(b). Further extension of this technique for more than two users is possible, but the frequency of projection needs to be increased accordingly.

### B. Passive Stereo

Passive stereo implementation requires four well-separated wavelength channels where each eye of both users observes an image through a filter that passes only light corresponding to its own channels. Infitec is a passive technique with spectrum separation based on wavelength triplets. Theoretically, it would be possible to multiply wavelength triplets to four (two stereo pairs). However, for practical reasons, such a solution would be extremely difficult to obtain. Apart from special glasses, this technique requires projection in four wavelength channels (four projectors with stable filters or one projector with a rotating filter). Further extension of this solution for more than two users is also theoretically possible, but the increasing number of well-separated wavelength channels poses a major technical problem.

Exclusively using the separation of polarization technique for a multiuser stereo VR installation is not possible because only two independent polarization states exist (two linear orthogonal or two left-handed and right-handed circular). Separation by polarization allows for separation into only two images (for two eyes). Therefore, it cannot be applied without being combined with another method for more than one user [13].

### C. Hybrid Technique—Combination of Active and Passive Stereo

Another solution is to combine both passive (e.g., Infitec) and active stereo techniques (see Fig. 2). It requires wearing double

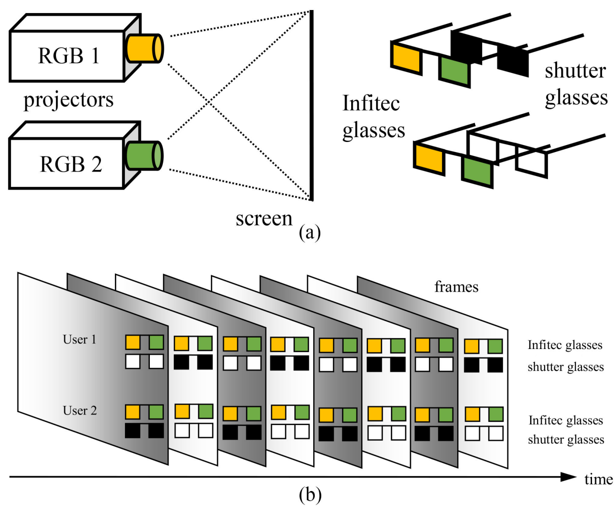



Fig. 2. (a) Block diagram of the two-user combined Infitec—active stereo technique. (b) Sequence of frames and corresponding Infitec glass and shutter glass states.

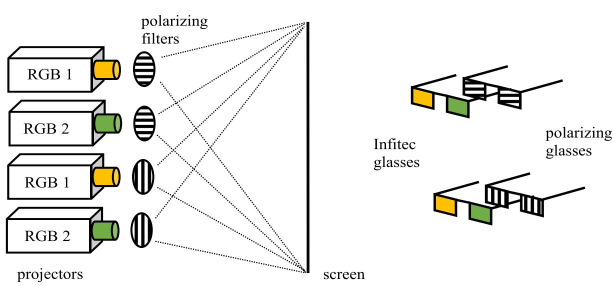



Fig. 3. Block diagram of a two-user combined Infitec—polarization technique.

glasses, active stereo shutter glasses and, for example, Infitec glasses with interference filters. A key advantage, these glasses are the typical glasses used for one-user stereo projection. The images for the left and right eyes are displayed at the same time, simultaneously, based on the Infitec technique, and the distinction between users is implemented with the use of active stereo shutter glasses. The reverse solution is also possible.

Similarly, the separation of the polarization technique combined with the active stereo technique can be applied. The configuration of the apparatus of this technique is analogous to the previous one. In this case, interference filters and glasses are replaced by polarizing elements. However, this method requires polarization (linear or circular)-preserving projection screens. Such a solution was implemented at Bauhaus University Weimar [13], [33], [50], where a display for up to six correct-perspective viewers was available [34].

### D. Hybrid Technique—Combination of Two Passive Methods

A combination of spectrum and polarization separation techniques leads us to a fully passive two-user stereo technique. A block diagram of this technique is shown in Fig. 3. Each projector generates only one image, directed to the appropriate user's eye using a set of passive glasses. In the case presented in Fig. 3, the images displayed for the left and right user's eyes are separated using interference glasses (Infitec), while the distinction between users is obtained with the use of polarization glasses. The reverse solution is also possible.

This method allows flickering of the images to be avoided (compared to the standard mono projection for one user). Unfortunately, this technique requires multiple pieces of equipment, e.g., as many as four projectors. Extension of both hybrid techniques for more than two users is possible by adapting one of the "pure" methods (excluding polarization separation) to a larger number of people, as mentioned in the description of the first two solutions in Section III-A and III-B.

### E. Combination of Anaglyph With Other Techniques

The predecessor of the modern technique with spectrum separation is the anaglyph technique, which allows the separation of images in red-cyan colors. This technique has also been proposed in the context of a multiuser VR installation. For example, Agrawala *et al.* [26] mentioned the use of this technique in combination with a two-user active stereo technique to multiply the number of users to four.

This technique can also be used in combination with the Infitec technique, although both techniques assume filtration of the spectrum. Glasses with interference filters (based on the wavelength triplet principle) are applied to colored anaglyph glasses (whereby user 1 wears glasses in a red-cyan configuration and user 2 wears glasses in inverse cyan-red configuration). For proper operation, this technique requires the appropriate preparation of images on the software side, e.g., coding in red and cyan colors. It is also a fully passive technique and relatively cheap to implement (inexpensive anaglyph glasses). The disadvantage is the image quality, in particular the color reproduction, e.g., the typical imperfections of the anaglyph technique.

This technique seems to be acceptable in the case of monochrome visualization (e.g., radiological medical data such as MRI or CT). By applying red-pass filters for stereoscopic glasses, 3-D visualization only in the red channel can be obtained. Similarly, separate 3-D visualization in the blue and green channels is possible. Each basic one-user stereoscopic projection technique can be simply adapted to the three-user monochrome stereoscopic method by applying three additional filters corresponding to the RGB components—one filter for a pair of glasses. This approach allows three people to watch the scene from their own perspective, but only in one applied channel: red; green; or blue. Of course, image generation should be independent in each channel (from different points of view).

## IV. Immersive 3-D Visualization Lab

Experiments with adaptation of the one-user stereoscopy system (more specifically, the system with two built-in parallel methods of one-user stereoscopy) to the two-user stereoscopy system were performed in our Immersive 3-D Visualization Lab. The main part of the lab is a CAVE-type installation consisting of six rigid square projection screens, one of which is an automatic sliding door arranged in the form of a cube with edges of approximately 3.4 meters each [51]–[53].

An omnidirectional view is achieved by stereoscopic rear projection onto all six screens. The whole image is displayed by 12 digital three-chip DLP 120 Hz Barco Galaxy NW-7 projectors with two projectors per screen. The final resolution of an image on a single screen, taking into account the edge blending technique, is 1920×1920 pixels.

Two techniques for 3-D projection were implemented: active stereo and spectrum separation (active Infitec). The applied projectors have a built-in (and removable, when possible) color filter wheel with two sets of interference filters (wavelength triplet technique, $R_1, G_1, B_1$ for the left eye and $R_2, G_2, B_2$ for the right eye). Finally, one projector simultaneously supports both 3-D projection techniques and provides two complementary images for the left and right eyes. The mentioned parallelized techniques allow the user to alternatively wear glasses with LCD shutters or with interference filters.

Each of the twelve WUXGA projectors is controlled by a separate computer equipped with a professional graphics card using the NVIDIA Kepler architecture. Two parallel networks, Ethernet 1 Gb/s and InfiniBand 40 Gb/s, alternatively connect all computers. Two additional computers synchronize the operation of all the computers, generate 8.1-channel surround sound, and supervise the precise ART tracking system [54] and the navigation controllers, including the spherical walk simulator [9]. The tracking system is based on four infrared TRACKPACK/C cameras placed in the upper corners of the CAVE. It can track many objects, including several people. Therefore, to obtain multiuser stereoscopy, we needed to only separate the images for more than two eyes according to the perspective from which they were generated.

## V. Hardware Adaptation

This article was carried out based on the CAVE-type VR environment described in Section IV. As mentioned, in this installation, two techniques of stereo projection were applied: Infitec (a technique with spectrum separation) and active stereo. Therefore, when designing a new two-user stereo projection, a combination of these two techniques was used. Because active Infitec is used (Infitec technique based on only one projector, with a color filter wheel for eye-channel separation), the sequence of frames is different than in the case of two separate projectors, as the images in the Infitec technology are also displayed alternately. A block diagram of the developed technique and corresponding sequences of both glasses is shown in Fig. 4.

As shown in Fig. 4(b), to ensure proper operation, the active glasses must be controlled by a signal with twice the lower frequency. Therefore, an electronic divider device (and, if necessary, a synchronizer) was introduced. Barco glasses with interference Infitec filters were used for spectrum separation, while a Volfoni EDGE shutter glasses VPEG-05010 model was used as the active glasses. In a standard configuration of the CAVE in I3DVL, the glasses are controlled by a reference signal of 60 Hz. However, the reference signal frequency can be reduced to 25 Hz.

In the case of one-user stereoscopy, a 120 Hz projection provides a 60 Hz image to each eye. For two-user stereoscopy based on 120 Hz projection, the frequency per eye must be half: 30 Hz. As mentioned, Volfoni shutter glasses can be controlled by such a reference signal.

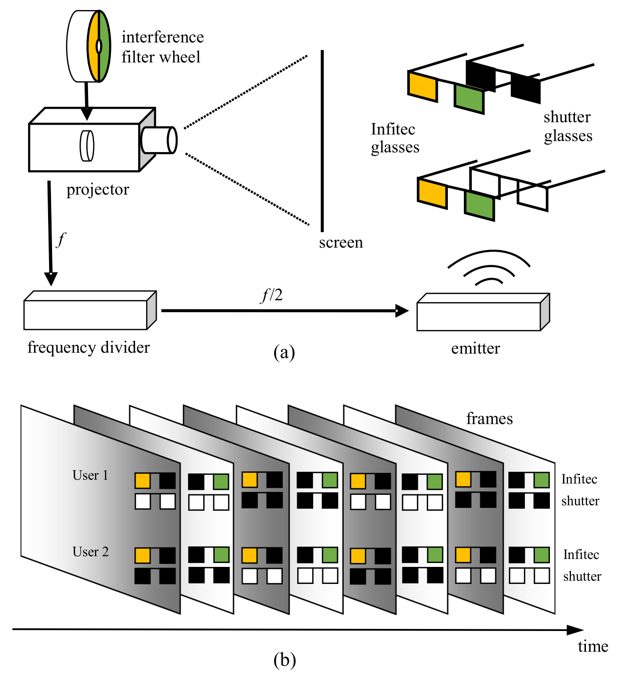



Fig. 4. (a) Block diagram of two-user stereo projection technique, applied in I3DVL. (b) Sequence of frames and corresponding Infitec glass and shutter glass states.

In addition to alternating work (left channel open, right closed and vice versa), these glasses can work in such a way that both channels (glasses) are open or closed (at the same time) and alternately change. A previously determined and saved configuration (when the glasses are connected to a system) can be later selected using an embedded switch; such functionality makes it much easier to set up the system for two-user stereo projection.

The advantage of implementing two-user stereoscopy is the use of existing Barco Galaxy NW-7 projectors already installed in our one-user CAVE system. This means that for a single screen (half of our CAVE screen), only one projector generates all four images for each of the four eyes. Until now, this was possible only for pure active stereoscopy. Of course, one disadvantage is frequency reduction to 30 Hz per eye, as higher frequencies would require the purchase of new expensive projectors. The frequency of 30 Hz is considered too low today for comfortable use in VR devices. This, however, mainly applies to HMDs and monitors used in daylight where high luminance is required to obtain adequate contrast. However, in the case of a CAVE such as ours, isolated from external lighting, the projection luminance for two-user stereoscopy is relatively low, approximately 1 cd/m²; note that each method of stereoscopy reduces the light efficiency individually [55]; hence, the double stereoscopy gives relatively low luminance. For such luminance, the critical flicker frequency is lower than 30 Hz [56], so lowering the frequency of image delivery to the eye in a CAVE to 30 Hz seems acceptable. Initial experiments with users using the software described in the following section confirm the validity of this assumption. However, further research is required to assess user comfort, as in the article, we focus only on the technical feasibility of our solution.

Although each user must use two pairs of glasses at the same time, two glasses may be integrated into one frame. Any 3-D printer can be used to prepare a common frame for both pairs of glasses. The user would then have the impression of wearing a single pair of ordinary light 3D glasses.

## VI. Developed Software

For the experiment using two-user stereoscopy, we developed a specific application in which it is very important for both users to observe objects exactly from their own perspectives. This application is a two-user simulator of a beach ball (volleyball), where both players should have the impression that the ball and net are in the same 3-D position in the scene. Therefore, each player needs their own stereoscopic view, i.e., their own pair of two images dedicated to their two eyes. The virtual beach ball shows the effectiveness of the applied solution.

The beach ball simulator was developed using the Unity game engine. The virtual camera generating the image is alternately shifted into the positions of both players, but the standard stereoscopy mechanism offered by the engine is used for rendering images for a single player. The virtual net is placed in the middle of the CAVE, and the players can bounce the ball over the net (contacting the ball) using a standard hand-held CAVE controller (flystick) as a virtual bat (in the shape of a paddle). Each player can see only their own image of the ball, the net, and the bats, but of course, both images place every one of these virtual objects in the same virtual 3D position relative to the real location of the players (see Fig. 5).

## VII. Measurements

Two optical properties of multiuser stereoscopic techniques are considered. The first aspect is related to the subjective feeling of the user (e.g., readability of the projected content or the well-being of the user). The second is the measurable parameters that can be determined experimentally. In this article, only objective measurable parameters are presented and discussed.

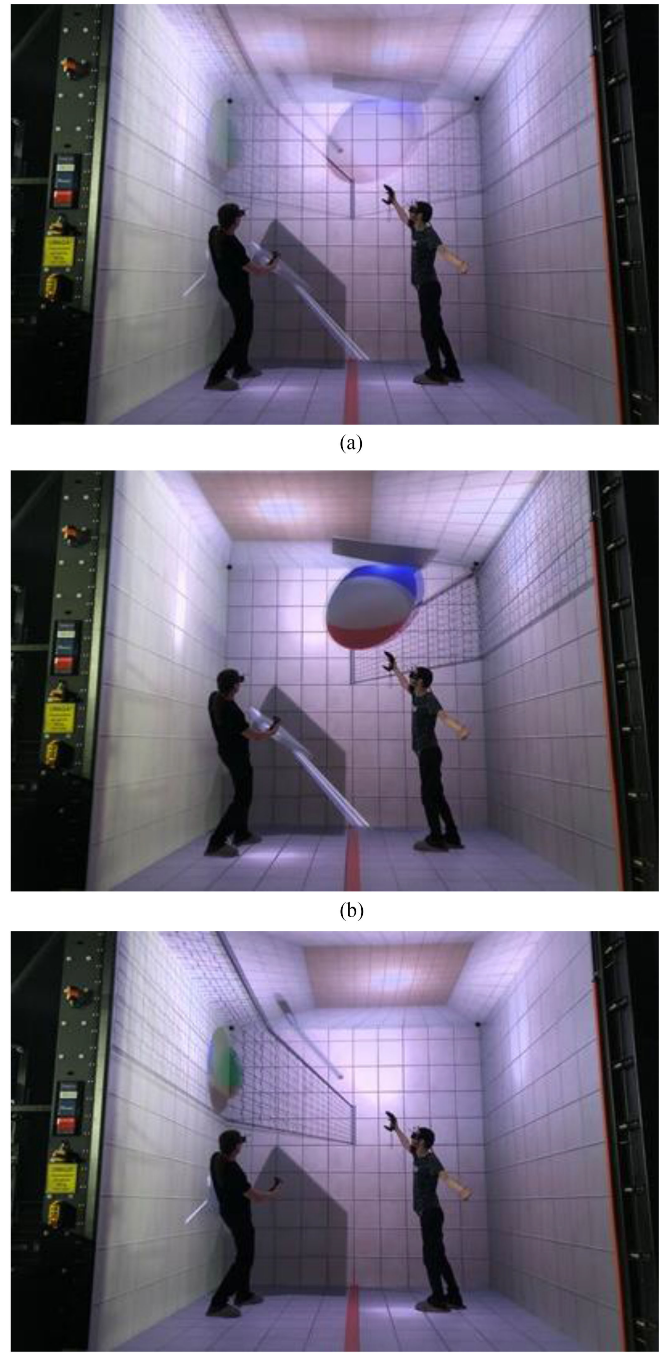
For 3-D projection system characterization, the most important and common parameter is stereoscopic crosstalk [57], [58]. Additionally, for characterization of color reproduction, a color gamut can be determined for each eye separately.

Interchannel crosstalk is a phenomenon of obtaining information intended for one eye by another eye. Crosstalk for standard (one-user) projection, as well as the measurement procedure and apparatus, are specified by measurement standards (Information Display Measurement Standard IDMS [57]). The black-white crosstalk $X_L$ for the left eye and $X_R$ for the right eye is defined as follows [57]:

$$X_L = \frac{L_{LKW} - L_{LKK}}{L_{LWK} - L_{LKK}},$$

$$X_R = \frac{L_{RWK} - L_{RKK}}{L_{RKW} - L_{RKK}} \quad (1)$$

where $L_{LKW}$, $L_{LKK}$, $L_{LWK}$, $L_{RKW}$, $L_{RKK}$, and $L_{RWK}$ are the measured luminance; indexes *L* and *R* refer to the left and right eyes, respectively, while *W* and *K* denote the measured white and black patterns for the left (middle index) and right eyes (right index), respectively.



(a) (b) (c)

Fig. 5. (a) Two-user stereoscopic beach ball simulation (photos by Paweł Tarnowski)—combined view (without glasses) for both players with two different stereoscopic dual images of the net and two different stereoscopic dual images of the ball. (b) Separate view seen only by the left player (wearing his glasses) with only his own stereoscopic dual image of the ball and his own stereoscopic dual image of the net. (c) Separate view seen only by the right player (wearing his glasses) with only his own stereoscopic dual image of the ball and his own stereoscopic dual image of the net.

However, the aforementioned measurement standard does not take into account the multiuser stereoscopic system. Thus, by analogy to the one-user system, determining stereoscopic crosstalk as the average crosstalk value for all possible combinations of the two channels for the multiuser system, has been proposed. For a two-user system, crosstalk can be determined

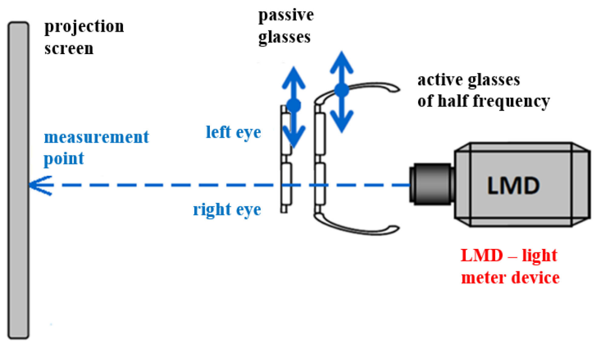



Fig. 6. Modified measurement setup for determination of crosstalk for two-user stereoscopic projection system.

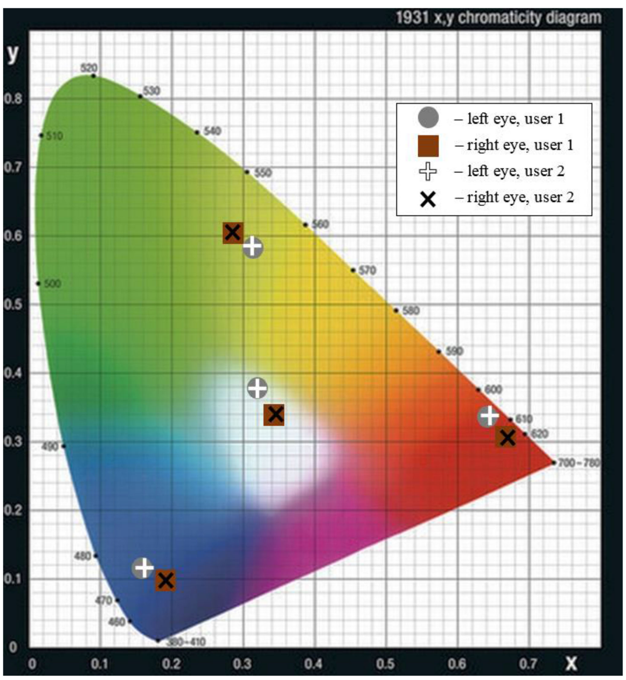



Fig. 7. Color gamuts for the left and right eyes for the both users in examined two-user stereoscopic projection system.

using the following formulas:

$$X_{s,d} = \frac{L_s - L_{\text{amb}}}{L_d - L_{\text{amb}}},$$

$$X_{\text{AVG}} = \frac{\sum X_{s,\,d}}{N} \tag{2}$$

where $L_s$ and $L_d$ denote the respective luminance for the source and destination channels of crosstalk, $s$ and $d \in \{L_1, R_1, L_2, R_2\}$, where $s \neq d$ and $L_i$ and $R_i$ denote the left and right eyes of the $i$th user, $L_{\text{amb}}$ denotes ambient luminance (black reference patterns), $X_{\text{AVG}}$ is the average crosstalk value for all possible combinations and $N$ is the number of possible combinations.

Based on the modified measurement setup (see Fig. 6), crosstalk for the developed two-user stereoscopic system was determined. Luminance measurements were carried out for white, red, green, and blue reference patterns. This allowed us to determine crosstalk for the entire visible range (white) as well as for individual components of the spectrum and gave additional knowledge about the possible reasons for crosstalk of the examined system. The results of our calculated crosstalks are given in Table I.

TABLE I
INTERCHANNEL CROSSTALK FOR WHITE, RED, GREEN, AND BLUE PATTERNS

| | crosstalk from eye-channel | crosstalk to eye-channel $L_1$ | $R_1$ | $L_2$ | $R_2$ |
|---|---|---|---|---|---|
| white patterns | $L_1$ | – | 0.50% | 0.94% | 0.00% |
| | $R_1$ | 0.93% | – | 0.00% | 0.02% |
| | $L_2$ | 0.25% | 0.00% | – | 0.53% |
| | $R_2$ | 0.00% | 0.00% | 0.92% | – |
| red patterns | $L_1$ | – | 0.00% | 0.24% | 0.00% |
| | $R_1$ | 2.72% | – | 0.00% | 0.00% |
| | $L_2$ | 0.00% | 0.00% | – | 0.06% |
| | $R_2$ | 0.00% | 0.00% | 2.64% | – |
| green patterns | $L_1$ | – | 0.54% | 0.23% | 0.00% |
| | $R_1$ | 0.49% | – | 0.00% | 0.02% |
| | $L_2$ | 0.26% | 0.00% | – | 0.56% |
| | $R_2$ | 0.00% | 0.00% | 0.49% | – |
| blue patterns | $L_1$ | – | 0.09% | 1.19% | 0.00% |
| | $R_1$ | 0.53% | – | 0.00% | 0.00% |
| | $L_2$ | 0.00% | 0.00% | – | 0.37% |
| | $R_2$ | 0.00% | 0.00% | 0.53% | – |

The average crosstalk value, calculated for all two-channel crosstalks, is 0.32%. This result is very good and comparable with results obtained for the one-user stereoscopic system applying both Infitec and active stereo techniques [58]. A few individual values exceed the calculated average. This may be caused by a luminance measurement error, additional light sources (e.g., the examined screen itself, or the computer screen which although dimmed and obscured could have influenced measurements anyway) and measuring accuracy of geometry settings (quite important for glasses with interference filters). However, as reported, these errors are very small.

The assessment of the crosstalk visibility threshold is a complex task. According to [59], this threshold depends not only on the determined crosstalk value but also on the presented depth of the dynamic scene (the binocular parallax) and contrast. It should be noted, however, that as far as visualization in CAVE-type systems is concerned, the obtained contrast values are relatively small due to the mutual influence of individual screens. Considering the determined crosstalk values (on average below 1%), based on [59], it can be estimated that the visibility threshold of the crosstalk will not be exceeded in a wide range of displayed scenes.

The above statement was also confirmed based on the experience of the authors and approximately 30 other people taking part in the developed scene. The respondents included both casual and frequent users of CAVE-type systems. None of them complained of any major inconvenience. Practically, the only problem was wearing two pairs of glasses at the same time. The crosstalk was found as invisible or negligible. This confirms that the flicker and crosstalk are rather imperceptible and that the brightness of the scene is sufficient. We expect that additional experiments with a larger representative group of users will confirm these observations. It would be useful to draw up a detailed description of the validation stage and the obtained results in terms of user satisfaction and, in particular, cybersickness effects. Such research should include participant recruitment, prestudy training, study procedure, study tasks, measurements, analysis, the results, etc. In this paper, only a technical evaluation measurement supplemented with preliminary verification on users is considered.

For the examined two-user stereoscopic projection system, color gamuts for all four eye channels were measured. The obtained results are presented in the CIE 1931 chromaticity diagram (see Fig. 7). The color gamuts for both users are almost the same. However, they differ for the left and right eyes of both users due to applying Infitec stereoscopic glasses.

## VIII. Conclusion

Multiuser CAVE-type installations are limited by one-user stereoscopic projection. Multiuser stereoscopy breaks this limitation as every user receives their own view from the correct perspective. By simultaneously using two alternative one-user stereoscopic systems available in the described CAVE and a simple electronic circuit, we achieved a two-user stereoscopic immersive CAVE-type system. Technical analysis and initial experiments carried out on a suitably-prepared application have shown that simple and inexpensive adaptation of two one-user stereoscopic systems based on the same set of projectors to two-user stereoscopy is fruitful. Nevertheless, if further experiments can confirm that there is no deterioration in the user's comfort, then the only disadvantage of our solution will be the necessity of wearing two pairs of glasses. More practically, a common frame design can be further researched.

Currently, there are projectors on the market that provide the correct perspective with active stereoscopy for two people and a frequency of 60 Hz for each eye at the same time [48], [49]. However, their price is still very high; in the case of advanced CAVE installations, more than a dozen such projectors would be needed (e.g., 24 [60]). Therefore, the solution proposed in the paper is an attractive alternative to convert an existing one-perspective CAVE-type system into two-user stereoscopy if using projectors simultaneously supporting active and passive stereoscopy, such as Barco Galaxy NW series projectors (e.g., [61]–[63]).

## Acknowledgment

The authors would like to thank Robert Trzosowski for developing the two-user stereoscopic beach ball simulator in the Unity game engine according to their instructions.

## References

[1] G. Burdea and P. Coiffet, *Virtual Reality Technology*, 2nd ed., Hoboken, NJ, USA: Wiley, 2003.

[2] D. Checa and A. Bustillo, "A review of immersive virtual reality serious games to enhance learning and training," *Multimedia Tools Appl.*, vol. 79, no. 9, pp. 5501–5527, 2020, doi: 10.1007/s11042-019-08348-9.

[3] S. Hudson, S. Matson-Barkat, N. Pallamin, and G. Jegou, "With or without you? Interaction and immersion in a virtual reality experience," *J. Bus. Res.*, vol. 100, pp. 459–468, 2019.

[4] Y.-J. Lan, "Immersion, interaction and experience-oriented learning: Bringing virtual reality into FL learning," *Lang. Learn. Technol.*, vol. 24, no. 1, pp. 1–15, 2020, [Online]. Available: http://hdl.handle.net/10125/44704

[5] H. Adams, G. Narasimham, J. Rieser, S. Creem-Regehr, J. Stefanucci, and B. Bodenheimer, "Locomotive recalibration and prism adaptation of children and teens in immersive virtual environments," *IEEE Trans. Visualization Comput. Graph.*, vol. 24, no. 4, pp. 1408–1417, Apr. 2018.

[6] D. Checa and A. Bustillo, "Advantages and limits of virtual reality in learning processes: Briviesca in the fifteenth century," *Virtual Reality London*, vol. 24, no. 1, pp. 151–161, 2020.

[7] T. Y. Grechkin, J. M. Plumert, and J. K. Kearney, "Dynamic affordances in embodied interactive systems: The role of display and mode of locomotion," *IEEE Trans. Visualization Comput. Graph.*, vol. 20, no. 4, pp. 595–605, Apr. 2014.

[8] M. Gzik, P. Wodarski, J. Jurkojć, R. Michnik, and A. Bieniek, "Interactive systems of engineering support of upper limb diagnosis," in *Proc. Innov. Biomed. Eng.*, 2016, pp. 115–123.

[9] Z. Kowalczuk and M. Tatara, "Sphere drive and control system for haptic interaction with physical, virtual, and augmented reality," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 2, pp. 588–602, Mar. 2019.

[10] P. Monteiro, M. Melo, A. Valente, J. Vasconcelos-Raposo, and M. Bessa, "Delivering critical stimuli for decision making in VR training: Evaluation study of a firefighter training scenario," *IEEE Trans. Hum.-Mach. Syst.*, vol. 51, no. 2, pp. 65–74, Apr. 2021, doi:10.1109/THMS.2020.3030746.

[11] R. Serrano Vergel, P. Morillo Tena, S. Casas Yrurzum, and C. Cruz-Neira, "A comparative evaluation of a virtual reality table and a hololens-Based augmented reality system for anatomy training," *IEEE Trans. Hum.-Mach. Syst.*, vol. 50, no. 4, pp. 337–348, Aug. 2020, doi: 10.1109/THMS.2020.2984746.

[12] S. Streuber and A. Chatziastros, "Human interaction in multi-user virtual reality," in *Proc. 10th Int. Conf. Humans Comput.*, 2007, pp. 1–6.

[13] B. Fröhlich *et al.*, "Implementing multi-viewer stereo displays," in *Proc. 13th Int. Conf. Central Europe Comput. Graph., Visualization Comput. Vis.*, 2005, pp. 139–146.

[14] C. Carlsson and O. Hagsand, "DIVE – a Multi-user virtual reality system," in *Proc. IEEE Virtual Reality Annu. Int. Symp.*, 1993, pp. 399–400, doi: 10.1109/VRAIS.1993.380753.

[15] T. A. DeFanti *et al.*, "The future of the CAVE," *Central Eur. J. Eng.*, vol. 1, no. 1, pp. 16–37, 2011.

[16] "The most realistic virtual reality room in the world," Iowa State Univ., Ames, IA, USA, 2006. [Online]. Available: https://www.news.iastate.edu/news/2006/may/c6update.shtml

[17] A. Mazikowski, "Analysis of luminance distribution uniformity in CAVE-type virtual reality systems," *Opto-Electron. Rev*, vol. 26, no. 2, pp. 116–121, 2018.

[18] J. Mütterlein and T. Hess, "Immersion, presence, interactivity: Towards a joint understanding of factors influencing virtual reality acceptance and use," in *Proc. 23rd Americas Conf. Inf. Syst.*, 2017, pp. 1–10.

[19] B. Pollock, M. Burton, J. W. Kelly, S. Gilbert, and E. Winer, "The right view from the wrong location: Depth perception in stereoscopic multi-user virtual environments," *IEEE Trans. Visualization Comput. Graph.*, vol. 18, no. 4, pp. 581–588, Apr. 2012.

[20] S. Coburn, L. Rebenitsch, and C. Owen, "Passive viewpoints in a collaborative immersive environment," in *Proc. Int. Conf. Virtual, Augmented Mixed Reality*,2013, pp. 3–12.

[21] J. G. Estrada, J. P. Springer, and H. Wright, "Simplifying collaboration in co-located virtual environments using the active-passive approach," in *Proc. IEEE 2nd VR Int. Workshop Collaborative Virtual Environ.*, 2015, pp. 1–7..

[22] H. H. Bell, "The effectiveness of distributed mission training," *Commun. ACM*, vol. 42, no. 9, pp. 72–78, Sep. 1999.

[23] M. Bolas, I. McDowall, and D. Corr, "New research and explorations into multiuser immersive display systems," *IEEE Comput. Graph. Appl.*, vol. 24, no. 1, pp. 18–21, Jan./Feb. 2004.

[24] V. Bayon, G. Griffiths, and J. R. Wilson, "Multiple decoupled interaction: An interaction design approach for groupware interaction in co-located virtual environments". *Int. J. Hum.-Comput. Stud.*, vol. 64, no. 3, pp. 192–206, 2006.

[25] R. M. S. Clifford, S. Jung, S. Hoermann, M. Billinghurst, and R. W. Lindeman, "Creating a stressful decision making environment for aerial firefighter training in virtual reality," in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces*, 2019, pp. 181–189.

[26] M. Agrawala, A. Beers, I. McDowall, B. Frohlich, M. Bolas, and P. Hanrahan, "The two-user responsive workbench: Support for collaboration trough individual views of a shared space," in *Proc. 24th Annu. Conf. Comput. Graph. Interactive Techn.*, 1997, pp. 327–332.

[27] V. Küszter, G. Brunnett, and D. Pietschmann, "Exploring stereoscopic Multi-user interaction with individual views," in *Proc. Int. Conf. Cyberworlds*, 2014, pp. 1–6.

[28] A. Mossel, A. Peer, J. Goellner, and H. Kaufmann, "Towards an immersive virtual reality training system for CBRN disaster preparedness," in *Proc. Int. Defense Homeland Secur. Simul. Workshop*, 2015, pp. 23–32.

[29] S. Mallaro, P. Rahimian, E. E. O'Neal, J. M. Plumert, and J. K. Kearney, "A comparison of head-mounted displays vs. Large-screen displays for an interactive pedestrian simulator," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, Nov. 2017, pp. 1–4.

[30] E. Medina, R. Fruland, and S. Weghorst, "Virtusphere – walking in a human size VR hamster ball," *Hum. Factors Ergonom. Soc. Annu. Meeting, Proc.*, vol. 52, no. 27, pp. 2102–2106, 2008.

[31] "Virtual surgery table," Barco, Kortrijk, Belgium, 2000. [Online]. Available: https://www.barco.com/en/product/virtual-surgery-table

[32] R. Lissermann, J. Huber, M. Schmitz, J. Steimle, and M. Mühlhäuser, "Permulin: Mixed-focus collaboration on multi-view tabletops," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, 2014, pp. 3191–3200.

[33] H. Salzmann, M. Moehring, and B. Froehlich, "Virtual vs. Real-world pointing in two-user scenarios," in *Proc. IEEE Virtual Reality Conf.*, 2009, pp. 127–130.

[34] A. Kulik *et al.*, "C1x6: A stereoscopic six-user display for co-located collaboration in shared virtual environments," *ACM Trans. Graph.*, vol. 30, no. 6, 2011, Art. No. 188.

[35] S. Beck, A. Kunert, A. Kulik, and B. Froehlich, "Immersive group-to-group telepresence," *IEEE Trans. Visualization Comput. Graph.*, vol. 19, no. 4, pp. 616–625, Apr. 2013, doi: 10.1109/TVCG.2013.33.

[36] W. Chen, C. Clavel, N. Ferey, and P. Bourdot, "Perceptual conflicts in a multi-stereoscopic immersive virtual environment: Case study on face-to-face interaction through an avatar," *Presence Teleoper. Virtual Environ.*, vol. 23, no. 4, pp. 410–429, 2014.

[37] W. Chen, N. Ladeveze, C. Clavel, D. Mestre, and P. Bourdot, "User cohabitation in multi-stereoscopic immersive virtual environment for individual navigation tasks," in *Proc. IEEE Virtual Reality Conf.*, 2015, pp. 47–54.

[38] W. Chen, N. Ladeveze, C. Clavel, and P. Bourdot, "Refined experiment of the altered human joystick for user cohabitation in multi-stereocopic immersive CVEs," in *Proc. IEEE 3rd VR Int. Workshop Collaborative Virtual Environ.*, 2016, pp. 1–8.

[39] J. P. Schulze, D. Acevedo, J. Mangan, A. Prudhomme, P. X. Nguyen, and P. P. Weber, "Democratizing rendering for multiple viewers in surround VR systems," in *Proc. IEEE Symp. 3D User Interfaces*, 2012, pp. 77–80.

[40] P. Tripicchio, C. Loconsole, A. Piarulli, E. Ruffaldi, and F. Tecchia, and M. Bergamasco, "On multiuser perspectives in passive stereographic virtual environments," *Comput. Animation Virtual Words*, vol. 25, pp. 69–81, 2014.

[41] F. de Sorbier, V. Nozick, and V. Biri, "GPU rendering for autostereoscopic displays," in *Proc. 4th Int. Symp. 3D Data Process., Visualization Transmiss.*, 2008.

[42] F. de Sorbier, V. Nozick, and H. Saito, "GPU-based multi-view rendering," in *Proc. Comp. Games, Multimedia Allied Technol*., 2010, pp. 7–13.

[43] J. Luo, K. Qin, Y. Zhou, M. Mao, and R. Li, "GPU-based multi-view rendering for spatial-multiplex autostereoscopic displays," in *Proc. 3rd Int. Conf. Comput. Sci. Inf. Technol.*, 2010, pp. 28–32.

[44] H. Jorke. and M. Fritz, "Infitec—A new stereoscopic visualization tool by wavelength multiplex imaging," *J. Three Dimensional Images*, vol. 19, no. 3, pp. 50–56, 2005.

[45] "Stereoscopic projection. –3D projection technology," Barco, Kortrijk, Belgium. Accessed: Feb. 2014. [Online]. Available: http://www.vr.barco.com

[46] A. Simon, "Usability of multiviewpoint images for spatial interaction in projection-based display systems," *IEEE Trans. Visualization Comput. Graph.*, vol. 13, no. 1, pp. 26–33, Jan./Feb. 2007.

[47] K. Blom, G. Lindahl, and C. Cruz-Neira, "Multiple active viewers in projection-based immersive environments," in *Proc. Immersive Projection Technol. Workshop*, Mar. 2002, pp. 1–5.

[48] Barco, UDX-4K22, Accessed: Aug. 2021. [Online]. Available: https://www.barco.com/en/product/udx-4k22#specs

[49] Christie, Christie D4K40-RGB, Accessed: Aug. 2021. [Online]. Available: https://www.christiedigital.com/products/projectors/all-projectors/4K40-RGB-series/christie-d4k40-rgb/overview

[50] R. Blach, M. Bues, J. Hochstrate, J. Springer, and B. Fröhlich, "Experiences with multi-viewer stereo displays based on LC-Shutters and polarization," in *Proc. IEEE VR Conf. Emerg. Display Technol. Workshop*, 2005, pp. 1–2.

[51] A. Mazikowski and J. Lebiedź, "Image projection in immersive 3D visualization laboratory," *Procedia Comput. Sci.*, vol. 35, pp. 842–850, 2014.

[52] J. Lebiedź and J. Redlarski, "Applications of immersive 3D visualization lab," in *Proc. 24th Int. Conf. Comput. Graph., Visualization Comput. Vis.*, 2016, pp. 69–74.

[53] J. Lebiedź and M. Szwoch, "Virtual sightseeing in immersive 3D visualization lab," in *Proc. Federated Conf. Comput. Sci. Inf. Syst.*, 2016, vol. 8, pp. 1641–1645.

[54] M. Szymaniak, A. Mazikowski, and M. Meironke, "Investigation of tracking systems properties in CAVE-type virtual reality systems," *Proc. SPIE*, vol. 10445, 2017, Art. no. 104451T.

[55] Barco: Barco's complete range of stereoscopic technologies, 2005. [Online]. Available: https://www.barco.com/projection_systems/downloads/stereoscopic_technologies_overview.pdf

[56] R. A. J. M. Bierings, M. H. de Boer, and N. M. Jansonius, "Visual performance as a function of luminance in glaucoma: The de Vries-Rose, Weber's, and Ferry-Porter's law," *Invest. Ophthalmol. Vis. Sci.*, vol. 59, no. 8, pp. 3416–3423, 2018.

[57] Information Display Measurements Standard 1.03, 2012, [Online]. Available:http://icdm-sid.org/

[58] A. Mazikowski, "Investigation of optical properties of infitec and active stereo stereoscopic techniques for CAVE-type virtual reality systems," *Metrol. Meas. Syst.*, vol. 26, no. 1, pp. 139–151, 2019.

[59] A. J. Woods, "Crosstalk in stereoscopic displays: A review," *J. Electron. Imag.*, vol. 21, no. 4, Oct.–Dec. 2012, Art. no. 040902.

[60] T. W. Kuhlen and B. Hentschel, "Quo vadis CAVE: Does immersive visualization still matter?," *IEEE Comput. Graph. Appl.*, vol. 34, no. 5, pp. 14–21, 2014, doi:10.1109/MCG.2014.97.

[61] aixCAVE, Aachen, Germany, 2019. [Online]. Available: https://www.itc.rwth-aachen.de/cms/IT-Center/Forschung-Projekte/Virtuelle-Realitaet/Infrastruktur/∼fgqa/aixCAVE/lidx/1/

[62] "CLARTE creates a virtual environment with Barco," Barco, Kortrijk, Belgium, 2017. Accessed: Apr. 2018. [Online]. Available: https://www.barco.com/en/news/2011-04-22-clarte-creates-a-virtual-environment-with-barco

[63] "3D Lab geosciences," Univ. Potsdam – Inst. Geosci., Potsdam, Germany, 2020. Accessed: Apr. 2018. [Online]. Available: https://www.uni-potsdam.de/3d-lab/