Journal of Information Display
Vol. 13, No. 2, June 2012, 83–89

Taylor & Francis
Taylor & Francis Group

Crosstalk evaluation in multiview autostereoscopic three-dimensional displays with an optimized diaphragm applied

Yi-Fan Peng, Hai-Feng Li*, Zhen-Rong Zheng, Xin-Xing Xia, Zhi Yao and Xu Liu

State Key Lab, Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, People's Republic of China

(*Received 22 December 2011; Revised 20 March 2012; Accepted for publication 9 April 2012*)

The crosstalk evaluation of multiview autostereoscopic three-dimensional (3D) displays is discussed, with both the human and technical factors investigated via image quality assessment. In the imaging performance measurements and analysis for a multiview autostereoscopic display prototype equipment, it was inferred that crosstalk would have both a positive and a negative effect on the imaging performance of the equipment. The importance of the attached diaphragm in the crosstalk evaluation was proposed and then experimentally verified, using the developed prototype equipment. The luminance distribution and crosstalk situation were given, with two different diaphragm arrays applied. The analysis results showed that the imaging performance of this 3D display system can be improved with minimum changes to the system structure.

Keywords: autostereoscopic 3D; crosstalk; multiview; optimized diaphragm; LCD

1. Introduction

Three-dimensional (3D) displays have come to have a fascinating research potential due to the intense human pursuit of a visual feast. The conventional 3D display approaches, including the stereoscopic, lenticular lens, and parallax barrier techniques, have been developed to a point where they are already being used in some fields while still having numerous problems [1–3]. An autostereoscopic integral imaging system was recently rapidly developed, thanks to the progress of flat panel displays, and has great prospects in the market of commercial applications due to its great advantages, such as the easy viewing angle control, bright view, and low cost [4]. Most of the temporally or spatially multiplexed equipment already provide a certain 3D display effect but have yet unsatisfactory performances in the crosstalk situation.

Crosstalk is caused by the different origins of the diverse types of 3D display, which may result in different levels of perceived image distortion [5]. The multiview spliced-view-field display is regarded as a light field display providing a smaller crosstalk and a wider viewing area, and it has attracted much attention. Iglesias Guitian [6] developed a large-scale light field display using projectors' array and delivered good-quality 3D visualization. Takaki and Nago [7] have described natural 3D devices that can display 128, even 256, directional images with a small angle interval. Compared with these horizontal-parallax-only 3D display systems, the full-parallax 3D display with both horizontal and vertical parallaxes can more realistically and naturally represent 3D images. In the IMID/ASIA DISPLAY 2010 conference, Zhejiang University also proposed a novel 3D display concept based on spliced images, which can display brighter 3D images with a large number of horizontal and vertical viewpoints [8]. The crosstalk in these spliced-view-field display systems, regardless of whether they are liquid crystal display (LCD)- or projector-based, is mainly caused by the display unit apertures with a certain size. Hence, some unwanted information will be obtained when they perform as the exit pupils to construct a light field. It is manifest that reducing the size of the aperture will certainly decrease the crosstalk while resulting in the brightness rather than the uniformity of the reconstructed image. Therefore, it is necessary to better understand crosstalk visibility and its related impairment level. Far less literatures are available, however, on the crosstalk perception, image uniformity, and aperture parameters for these display types. The precise installation of these projection-style autostereoscopic display systems is almost impossible under most circumstances. Moreover, the lack of knowledge about crosstalk evaluation for practical 3D displays has remained a serious problem to this day [9].

The relation between crosstalk evaluation and diaphragm parameter based on the projection multiview autostereoscopic 3D display is discussed in this paper, and both the human and technical factors were analyzed synthetically in the study via image quality assessment. To evaluate the positive and negative crosstalk, an evaluation method with diaphragms applied was carried out. An analytical formula

---

*Corresponding author. Email: lihaifeng@zju.edu.cn

ISSN 1598-0316 print/ISSN 2158-1606 online

http://dx.doi.org/10.1080/15980316.2012.688881
http://www.tandfonline.com

for predicting the optimum parameter of the diaphragm was proposed and experimentally verified. Measurements were conducted in relation to the related issues, including the crosstalk situation, diaphragm design, and diffuser characteristics. The experiment results demonstrated that the parameters, especially the diaphragm diameter, have a significant influence on the crosstalk. Furthermore, improvement of the display with minimum changes to the system structure was accomplished by optimizing these parameters.

2. Display principle and crosstalk analysis

2.1. Display principle and system

The multiview autostereoscopic display based on a spliced-view field consists of a flat panel LCD monitor, a lens array, and a specially designed orthogonal diffuser [10]. The system schematic is shown in Figure 1. A combination of a flat panel LCD monitor and the related lens was designed to play the role of a mini-projector. All the beams projected by the projectors converge at the center of the directional diffuser screen. On the directional diffuser, each image pixel is composed of numerous overlapping pixels coming from different projectors. Similar to the function of the holographic screen, the diffuser herein is applied to control the diffuse angle so that the emitting projection points would turn out numerous blocked images. Hence, from different viewpoints, the observers can obtain a different view of the 3D scene constituted by many blocked images from different spliced image sources projected by the related projectors.

2.2. Crosstalk analysis

It is obvious that the factors related to the imaging performance of the stereoscopic 3D displays are derived from many aspects. The issues discussed in the measurement field always include the following: the (1) projecting center offset; (2) optimum viewing area; (3) luminance and contrast ratio; (4) 3D point crosstalk and spatial crosstalk; (5) color performance; (6) ortho/pseudostereoscopy angle; and (7) luminance difference ratio [11,12]. Crosstalk is the most important evaluation item of 3D imaging performance because it has a significant influence on the display characteristics, such as the depth range limit, ghost images, and viewing angle limit. The images in the multiview autostereoscopic 3D displays are normally projected onto the diffuser screen by the related projectors, which makes it important to control the impact of the beam from the adjacent projectors or viewpoints, which is the crosstalk effect discussed herein.

For the analysis of crosstalk, a simplified schematic of the imaging process is given in Figure 2, setting a three-view system as an example. Here, the impact of the apertures' size is ignored so as to clearly illustrate the spliced-imaging principle. The term 'negative crosstalk' is given to the unwanted image information that people perceive when they watch autostereoscopic displays. Ideally, the three q image units, which compose a viewpoint's image, are derived from three different p image blocks, which are projected from the three different so-called projectors, as illustrated by the R, G, and B color lines in the schematic. In this case, the observer can view three distinct emitting points, which are the exit pupils of the projectors, only if the diffuse angle of the special diffuser equals zero. Along with the diffuse angle increases, the visible unit on the diffuser screen will expand, enabling the adjacent units to meet. In the actual operation, however, the image units can hardly recombine accurately. Hence, negative crosstalk is thought to exist in this system. The light beam from the adjacent source image and the possible overlapping of the adjacent viewing image units contribute to the viewpoint crosstalk. Besides, the overlapping of the adjacent viewing angles should be considered when evaluating the imaging performance.

Below are the three main factors that may account for the negative crosstalk.

(1) As shown by the illustration of the display principle, the diffuse angle of the diffuser should be equal to the angle between the adjacent projectors from the diffuser. In actual experiments, however, the diffuse angle of the diffuser may be discrepant

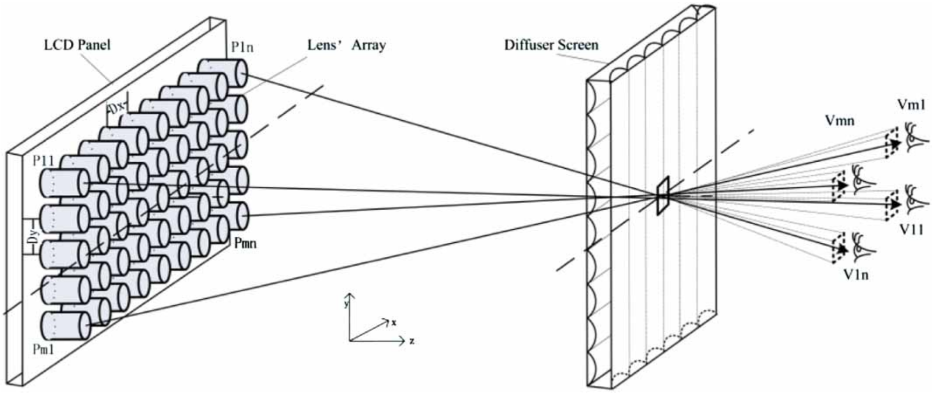

Figure 1. System schematic of the multiview autostereoscopic 3D display.

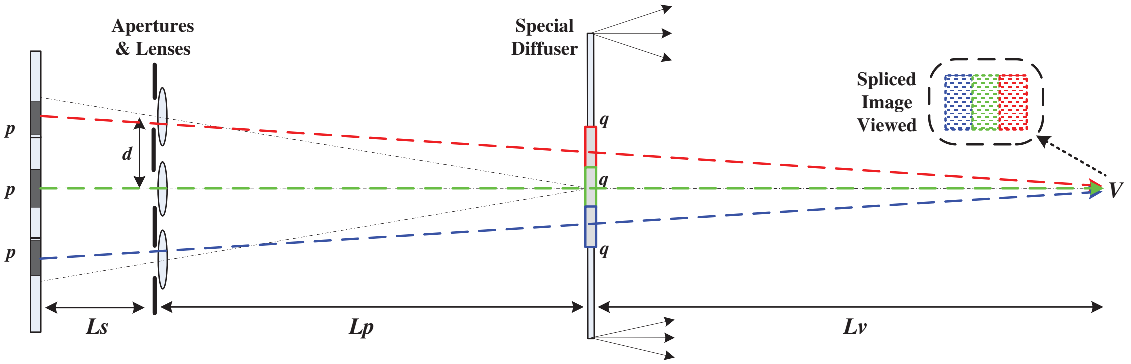

Figure 2. Simplified schematic of the imaging process under ideal conditions.

to the angle interval when the beam is projected obliquely, which suggests that the diffuse angle of oblique viewpoints will probably be enlarged to some degree.

(2) As the LCD panel is utilized to replace the projectors' array, in general, autostereoscopic displays for cost down, the panel is divided into numerous display cells playing the roles of image sources of the special projectors. The projecting relation cannot be exactly adaptable with oblique projecting rays. Although this problem has already been considered to make up for its impact on aberration, it still affects the lens' imaging quality, especially the image distortion, in the edge viewpoints.

(3) If the actual exit pupils of the so-called projectors are larger than the aperture, they may cause the image information of the adjacent viewpoints to be observed on the screen from a certain viewpoint.

Despite the flaws brought about by negative crosstalk, some literatures report that crosstalk may play a positive role in the attainment of a smoother transition between images obtained at different viewing angles, as long as it is controlled to a certain extent [5,13]. Such spliced-view-field systems often suffer from the occurrence of dark slices on the observation screen because a certain viewing image is recombined with numerous image units. From this point of view, to achieve a smoother transition of the image information across different viewpoints during the head movements, an appropriate luminance overlapping of the adjacent perspectives is necessary, which results in the emergence of what may be called 'inherent crosstalk'.

In most multiview autostereoscopic 3D displays based on a spliced-view field, the control of the diffuse-angle distribution of the special diffuser screen is always complicated and largely depends on the manufacturing process as well as on the engineering approximation and the alignment errors of the projectors' array. Assuming that the inherent crosstalk is positive especially for these multiview 3D display systems, to keep a proper inherent crosstalk and to reduce the negative crosstalk of the existing equipment with the least change to the system structure, optimization of the diaphragm attached to each projector is proposed. Based on the results of the above analysis, the control of the diaphragm size can reduce the crosstalk of the rays emitted from the adjacent source image. It significantly affects the accuracy of splicing on the diffuser while playing the role of the exit pupil of the so-called projector, as discussed above. This may also produce a vignetting effect in the imaging process. Thus, the location and size depend on the requirements of the projecting relation, luminance, optical aberration, and system structure. Based on the geometric relation shown in Figure 2, the diffuse angle of the special diffuser is defined by Equation (1) while the optimum size of the image unit is defined by Equation (2), when spliced accurately.

$$\tan\left(\frac{\delta}{2}\right) \approx \frac{d/2}{L_{\mathrm{P}}} \tag{1}$$

and

$$\frac{q}{d} = \frac{L_{\mathrm{V}}}{L_{\mathrm{P}} + L_{\mathrm{V}}}. \tag{2}$$

In the above equations, δ is the diffuse angle of the special diffuser, q is the width of the image unit displayed on the screen, d is the distance between the two adjacent projectors, L_{P} is the projecting distance from the projector to the special diffuser, and L_{V} is the optimum viewing distance.

Figure 3 shows the detailed situation of the diaphragm playing the role of an exit pupil to show the relation between the size of the diaphragm and the size of the image unit on the screen. Here, it is assumed that the lenses perform ideal imaging and the exit pupil emits uniformly. The diffuse half-angle $\delta/2$ can be divided into two parts, α and β, as illustrated, whose parameters can be represented by the length parameters. Thus, the relation between the size of the diaphragm and the size of the image unit on the screen can be derived using the trigonometric formulas shown in Equation (3):

$$\tan\left(\frac{\delta}{2}\right) = \frac{2 \cdot [L_{\mathrm{P}} \cdot q + L_{\mathrm{V}} \cdot (q - D)]}{4 \cdot L_{\mathrm{P}} \cdot L_{\mathrm{V}} - q \cdot (q - D)}, \tag{3}$$

where D is the diameter of the diaphragm.

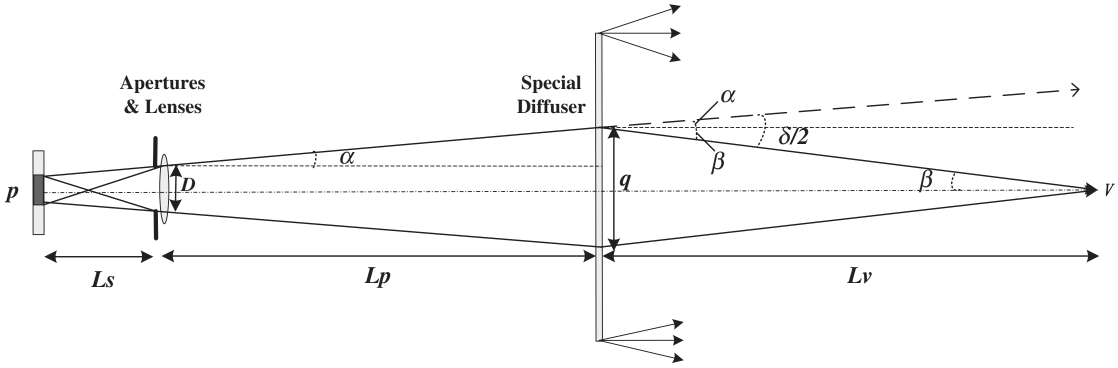

Figure 3. Simplified schematic of the relation between the size of the diaphragm and the size of the image unit on the screen.

For a given 3D display system, L_P, L_V, d, and δ are known. Thus, what needs to be done is to derive the optimum width of the image unit displayed on the screen (q) when a continuous image constituted by many unit images is presented. Therefore, the optimum size of the diaphragm (D) can be finally synthesized.

3. Experiment results

To verify the aforementioned assumption, several experiments were carried out using the proposed multiview 3D display system. Its specifications are listed in Table 1. The 3D scene displayed by the existing system can be observed at different horizontal and vertical viewpoints, with small viewing angle intervals. The obtained 3D images, however, were blurred, especially near the edge of the viewing area. Likewise, some crosstalk of 3D points can be seen when observing the screen at certain angles.

The positive and negative crosstalk should not be considered separately. To keep a proper inherent crosstalk and to reduce the negative crosstalk, it is necessary to demonstrate the predicted effect of the diaphragm. For this, a designed symmetrical color test was operated. The image pattern displayed on the LCD was divided into two colors, with blue representing the area that played the role of the image source corresponding to the central view and red representing the remaining area. The display images were captured with a CCD set on the same height, and vertically toward the screen, and were then analyzed, as shown in Figure 4(a)–(c).

The three groups stand for the different imaging performances with three different-sized diaphragms attached to the front part of the lens' array: large, middle, and small, respectively. The blue strips show the main color while red is the crosstalk color from this viewpoint. As the analysis of the horizontal color yielded the same result as that in the vertical field, a horizontal line can be used to select the image color information distribution. The curve in Figure 4(a)–(c) shows the crosstalk displayed by the normalized brightness distribution. It can be seen that the smaller the diaphragm diameter is, the less the brightness of the image, but the crosstalk, which reduces the width of the peak, is shortened, which indicates that the overlapped angle decreased to a certain degree. Therefore, it is crucial to design a diaphragm with an appropriate size in the engineering field to balance the crosstalk and the brightness.

According to the parameters confirmed by Equations (1) and (2), the optimized parameter of the diaphragm can be easily derived using Equation (3). The developed system with the designed diaphragm array and a smaller one attached to the front part of the lens array were then measured to demonstrate the optimized diaphragm's achievement of a better imaging performance. The typical method of evaluating the crosstalk quantitatively is measuring the light intensity distribution in a horizontal direction across the viewing regions [14]. To measure the crosstalk effect, the horizontal luminance distribution on the screen was first considered. Its effectiveness, however, is hardly addressed in the projection-type multiview equipment. According to the imaging principle of the spliced-view-field 3D displays, the image displayed in any view is composed of numerous

Table 1. Detailed parameters of the prototype.

	Devices and parameters
Number of projectors	45
Image size	30 × 30 cm
Image resolution	225 × 225 pixels (21 central subimages)
Directional diffuser	Special lenticular sheet (orthogonal): approximately 4.7° horizontal and vertical diffuse angles
Projection lens	45 Fresnel lens: focal length, 100 mm; size, 50 × 50 mm^2
LCD display	23 in.; resolution: 1920 × 1080 pixels

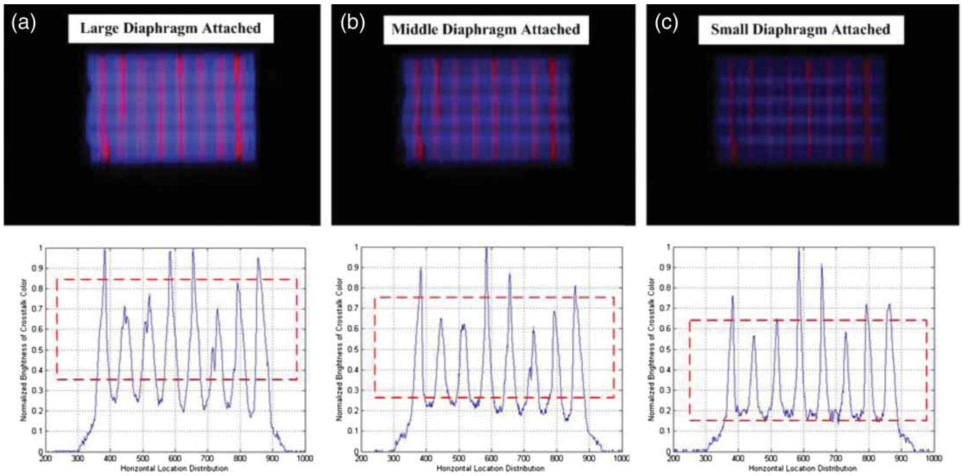

Figure 4. Comparison of the different crosstalk situations from the central viewpoint.

small image cells, herein called 'spliced images'. The luminance distribution on the screen of a given view of the autostereoscopic displays can be obtained with a certain special white block pattern displayed. Only the pixels corresponding to those of such view images are turned on with maximal intensity (i.e. set as white), and all the other pixels are set as black. A measurement setup was thus created to measure the luminance using an imaging photometer moving with small intervals along the horizontal direction of the displays at the optimum viewing distance, as shown in Figure 5. Ten measurement patterns, including nine horizontal-view white blocks with identical central vertical heights and a full-screen black one, were sent into the system to measure the luminance on each point along the screen.

Thus, Figure 6(a) shows the luminance distributions on the screen of nine views of the autostereoscopic displays in the central vertical view. In all the data, the value of FSB, which symbolizes the measured luminance distribution of a full-screen black image, was subtracted. From the luminance distribution, nine separated crests are illustrated. Hence, it can be concluded that the proper images are observed related to certain viewpoints. To demonstrate the positive effect of coherent crosstalk, total luminance $L_{\text{total}}(x)$ from a certain viewpoint is defined by Equation (4):

$$L_{\text{total}}(x) = \sum (L_i(x) - L_{\text{FSB}}(x)). \tag{4}$$

In the above equation, $L_i(x)$ is the non-crosstalk luminance at position x, where view i is the non-crosstalk view in the viewing zone of the concerned view; $L_{\text{FSB}}(x)$ is the luminance of FSB at position x; and above all, x is the horizontal distribution at the optimum viewing distance.

The total luminance distribution of the designed diaphragm 2 was obtained as shown in Figure 6(b) and was compared with that of the attached smaller diaphragm 1. Their crosstalk comparison will be discussed in the following paragraphs. As expected, the smaller diaphragms resulted in a relatively lower luminance and a larger fluctuation. A relatively flat area, fluctuating within 5%, was obtained from the black curve, which was related to the whole image observation area. The transition of the image information when observed across different viewpoints would be smooth, thanks to the positive crosstalk effect of the diaphragm. Thus, it can be inferred that in the reported case, a good uniform 3D quality distribution is expected for the luminance of the adjacent viewpoints overlapping at more than half of the maximum.

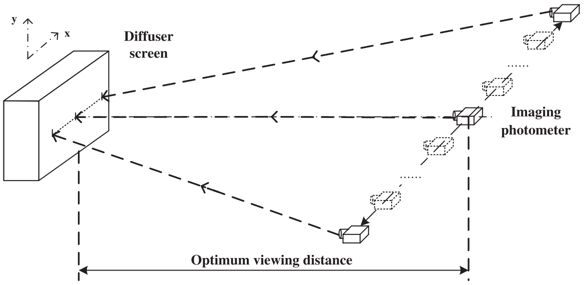

Figure 5. System schematic of the crosstalk measurement process.

The problems of the viewpoints overlapping in the luminance distributions demonstrate the crosstalk's constraints in the system display performance. The crosstalk measurement $C_i(x)$ of these multiview autostereoscopic displays is defined by Equation (5) [15,16]:

$$C_i(x) = \frac{\sum_{j \neq i} (L_j(x) - L_{\text{FSB}}(x))}{L_i(x) - L_{\text{FSB}}(x)}, \tag{5}$$

where $L_i(x)$ is the non-crosstalk luminance at position x, where view i is the non-crosstalk view in the viewing zone of the concerned view; $L_j(x)$ is the crosstalk luminance of view j at position x, where view j is the crosstalk view in the viewing zone of the concerned view; $L_{\text{FSB}}(x)$ is the luminance of FSB at position x; and above all, x is the horizontal distribution at the optimum viewing distance.

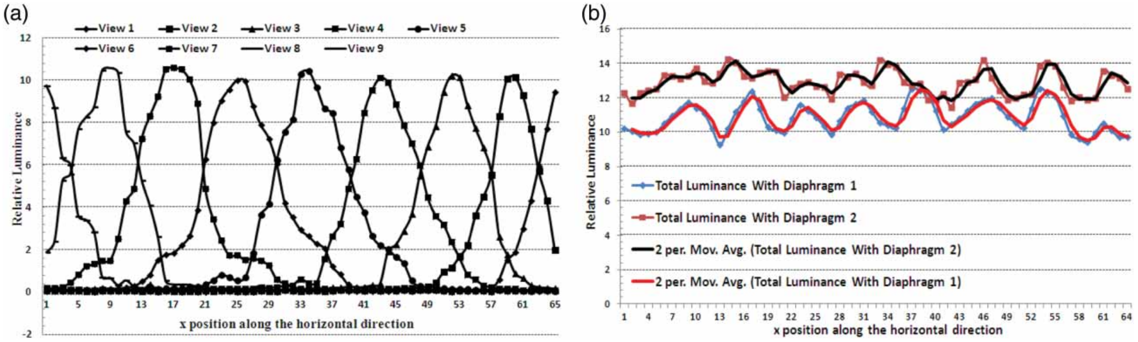

Figure 6. (a) Luminance distribution of all the viewpoints and (b) total luminance distribution under two cases of the developed autostereoscopic display prototype along the horizontal direction on the screen.

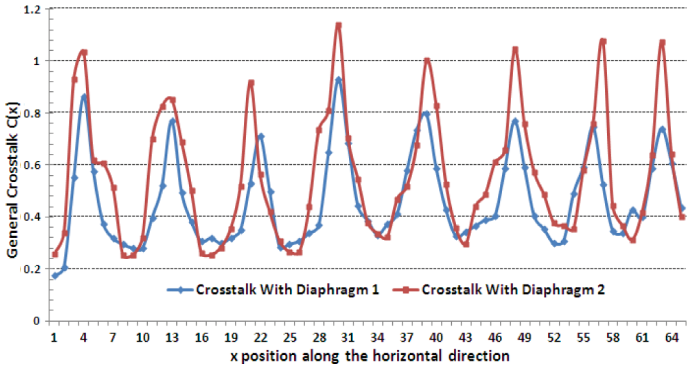

Figure 7. Crosstalk distribution of the developed autostereoscopic display prototype in the optimum viewing distance.

Here, the general $\Sigma C_i(x)$ with the parameter i counted from 1 to 9 was calculated. The general crosstalk distribution was obtained as shown in Figure 7. Eight crests were demonstrated from the curve, which were related to the nine separated views. Further, the degree of the viewpoints' overlapping is demonstrated more instinctively. With the smaller diaphragm attached, the general crosstalk was reduced to some extent, albeit not obvious. For the designed diaphragm, the width between the two consecutive peaks when converted into the parameter on the screen is equal to the viewing image unit width q, consistent with the result of the above analysis. According to Equation (5), the value of the general crosstalk is between 0.2 and 1.0 for the designed diaphragm attached. As its total luminance distribution was regarded as more suitable for viewing, it can be considered a rational crosstalk situation for these multiview-style 3D displays based on a spliced-view field, generating an acceptable imaging performance.

Figure 8(a)–(c) shows the different views' images of the 3D Tiger model displayed by these authors' latest developed prototype equipment with a diaphragm array attached. The obvious 3D effects are presented from the developed prototype equipment. A dynamic video effect was also achieved by playing the image frames through the prototype equipment.

4. Discussions and conclusions

In the present study on multiview autostereoscopic 3D displays, numerous equipment styles were developed, all focusing on the blind pursuit of crosstalk reduction. The crosstalk evaluation methods for parallax barrier

Figure 8. Reconstructed images in the horizontal direction captured from three different viewpoints in the optimum viewing distance.

or lenticular 3D displays may behave differently as no apertures or projecting exit pupils exist there. In fact, the crosstalk in these spliced-view-field-style 3D displays can sometimes play a positive role in the transition of the image information when observed across different viewpoints. Thus, it is significant to keep the positive crosstalk and to reduce the negative crosstalk to accomplish a balanced imaging performance.

The evaluation of the degree of crosstalk reduction in the above method is not sufficiently precise, but it clearly expresses the overlapping lights of the adjacent viewpoints. Moreover, the key parameters of the diaphragm design should be focused on to keep the positive crosstalk and to reduce the negative crosstalk. It is supposed that the ideal parameters of each diaphragm would be different due to the different oblique projections in the display approach. The detailed parameters would be confirmed via the optical software simulation, considering every factor. In addition, the balance between the brightness decline and the crosstalk decline should be further considered. This will not be analyzed deeply here, however, and will be the subject of further research.

In this paper, the crosstalk evaluation of the multiview autostereoscopic 3D displays was demonstrated based on a spliced-view-field full-parallax 3D display system. Both the positive and negative crosstalk effects were analyzed, with the application of a diaphragm, to keep the positive crosstalk and to reduce the negative crosstalk. It was found that the 3D imaging performances of most projection-style light field displays can be improved by controlling the diffuse angle and applying the proper diaphragm.

Acknowledgement

This work was supported by research grants from the National Key Basic Research Program of 973 (2009CB320803) and the National Natural Science Foundation of China (61177015). The authors thank State Key Lab of Modern Optical Instrumentation, Zhejiang University, for providing them with the necessary support.

References

[1] N.S. Holliman, N.A. Dodgson, G.E. Favalora, and L. Pockett, IEEE Trans. **57** (2), 362–370 (2011).

[2] J.H. Park, N. Hong, and B. Lee, Appl. Opt. **48** (34), H77–H94 (2009).

[3] N.A. Dodgson, IEEE Comput. **38** (8), 31–36 (2005).

[4] Y.M. Kim, K.H. Hong, and B. Lee, 3D Res. **1** (1), 17–27 (2010).

[5] L. Wang, Y. Tu, and L. Chen, J. SID **18** (6), 405–413 (2010).

[6] J.A. Iglesias Guitian, E. Gobbetti, and F. Marton, Vis. Comput. **26** (6–8), 1037–1047 (2010).

[7] Y. Takaki and N. Nago, Opt. Express **18** (9), 8824–8835 (2010).

[8] S. Li, H.F. Li, Y.F. Peng, and X. Liu, *IMID International Symposium Digest*, KIDS, Seoul, 2010, pp. 291–292.

[9] L. Wang, K. Teunissen, T. Tu, L. Chen, P.P. Zhang, T.T. Zhang, and I. Heynderickx, J. Display Technol. **7** (4), 208–214 (2011).

[10] S. Li, H.F. Li, Z.R. Zheng, Y.F. Peng, S.C. Wang, and X. Liu, Chin. Opt. Lett. **9** (8), 081202-1–4 (2011).

[11] J. Lee, J. Lee, S. Kim, J. Han, T. Jun, and S. Shin, *SID International Symposium Digest*, SID, Seattle, 2010, pp. 327–330.

[12] L. Chen, Y. Tu, and W. Liu, *SID International Symposium Digest*, SID, Los Angeles, 2008, pp. 1138–1141.

[13] R. Kaptein and I. Heynderickx, *SID International Symposium Digest*, SID, Los Angeles, 2007, pp. 1220–1224.

[14] J.Y. Son, Y. Vashpanov, M.S. Kim, M.C. Park, and J.S. Kim, J. Display Technol. **6** (8), 336–344 (2010).

[15] P. Boher, T. Bignon, and T. Leroux, *Proceedings of Information Display Workshop*, IDW, Niigata, 2008, pp. 2079–2082.

[16] W.X. Zhao, Q.H. Wang, A.H. Wang, and D.H. Li, *Opt. Lett.* **35** (24), 4127–4129 (2010).