An Autostereoscopic 3D Projection Display Based on a Lenticular Sheet and a Parallax Barrier

Lin Qi, Qiong-Hua Wang, Jiang-Yong Luo, Wu-Xiang Zhao, and Cheng-Qun Song

***Abstract*—Three-dimensional (3D) projection display is an effective approach to realize large size 3D images with high resolution. An autostereoscopic 3D projection display is proposed. It consists of four projectors, a projection screen, a lenticular sheet and a parallax barrier. Operation principle and calculation equations are described in details and the parallax images are corrected by the means of homography. A 50-inch autostereoscopic 3D projection display prototype is developed and it presents good stereoscopic images. The normalized luminance distributions of the viewing zones are measured, and the results agree well with the designed values. Compared with the conventional autostereoscopic 3D projection display based on two parallax barriers, the proposed prototype has much higher brightness.**

***Index Terms*—Autostereoscopic display, homography, 3D projection display.**

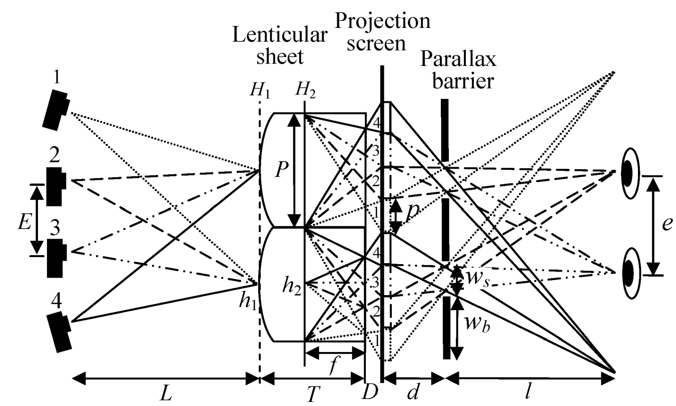


Fig. 1. Configuration of the proposed autostereoscopic 3D projection. Dotted line, dashed line, dot–dashed line, and solid line denote projection light from projectors 1, 2, 3, and 4, respectively.

I. Introduction

THREE-DIMENSIONAL (3D) displays, which expand viewer's sensation beyond what is offered by traditional 2D displays, are candidates for the next generation image media [1]. Currently, the stereoscopic displays using aids, such as glasses or helmet are mature and have been applied widely. Nevertheless, autostereoscopic display [2], [3], volumetric display [4], integral imaging [5] and holographic display [6] which present 3D images without aids are the developing trend.

Among these 3D displays, the autostereoscopic display is popular, because it has advantages such as easy realization, low cost, and easy commercialization. The autostereoscopic display consists of a flat panel display (FPD) and a lenticular sheet or a parallax barrier. For an N-view autostereoscopic display, N different parallax images are displayed on the FPD at the same time. The resolution of an observed parallax image is inversely proportional to N. For instance, for a 9-view autostereoscopic display having a FPD with an available resolution 1920×1080, the 3D resolution is only 640×360. Therefore, the autostereoscopic display based on FPD is not the most effective method for high resolution 3D images. In contrast, 3D projection display is a simple and effective approach to realize large size 3D image with high resolution. A high-quality integral videography is proposed using long-focal-length projection technique to create a high resolution image onto the screen [7]. A practical integral imaging projector, which displays elemental images with a large number of pixels using spatio-temporal multiplexing, is proposed [8]. The spatio–temporal multiplexing results in an increase in the number of pixels in a display panel. An autostereoscopic 3D projector display based on two parallax barriers is presented to realize large size 3D image with high resolution [9].

Although the 3D projection display based on two parallax barriers realized large and high resolution, most light from the projectors is blocked by the parallax barrier facing the projectors, which lowers the brightness of the 3D projection display. In this paper, we propose an autostereoscopic 3D projection display based on a lenticular sheet and a parallax barrier. The proposed prototype presents high resolution 3D images as the conventional prototype based on two parallax barriers. Moreover, it has much higher brightness and efficiency of light utilization.

II. Principle and Calculations

The proposed autostereoscopic 3D projection display consists of four projectors, a projection screen, a lenticular sheet and a parallax barrier, as shown in Fig. 1. Four projectors are arranged in a horizontal array, and they project four parallax images onto the lenticular sheet. The projected parallax images pass through the lenticular sheet and form a synthetic image on the projection screen. The synthetic image includes four parallax images which are vertically interlaced. The parallax barrier between the projection screen and the viewers ensures correct parallax image separation for the viewers' left and right eyes.

Manuscript received March 07, 2011; revised July 24, 2011; accepted March 20, 2012. Date of publication June 12, 2012; date of current version June 25, 2012. This work is supported by the National Natural Science Foundation of China under Grants 60877004 and 61036008.

The authors are with School of Electronics and Information Engineering, Sichuan University, Chengdu 610065, China, and also with State Key Laboratory of Fundamental Science on Synthetic Vision, Sichuan University, Chengdu 610065, China (e-mail: qhwang@scu.edu.cn).

Color versions of one or more of the figures are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JDT.2012.2192097

As shown in Fig. 1, the pitch, the thickness and the focal length of the lenticular sheet are denoted by P, T and f, respectively. The focal plane locates at the back surface of the lenticular sheet. H_1 and H_2 are the principal planes of the lenticular sheet. L is the projection distance. The distance between every two adjacent projectors is E. Assume that the incident rays passing through each lenticular lens are parallel, because the pitch of the lenticular sheet P is far less than the projection distance L. h_1 and h_2 are two principal points of the lens optical system. The projection screen is placed at D behind the focal plane. Dotted line, dashed line, dot dashed line and solid line denotes projection light from projectors 1, 2, 3 and 4, respectively. Image stripes 1, 2, 3 and 4 on the projection screen are projected from projectors 1, 2, 3, and 4, respectively. The pixel pitch of the synthetic image is denoted by p. The parallax barrier with slit width w_s and black strip width w_b places at d from the projection screen. e is the interpupillary distance and l is the optimum viewing distance. According to the geometric analysis, the following relations are satisfied:

$$\frac{D}{D+f} = \frac{1}{5}\left(1+\frac{f}{L}\right) \tag{1}$$

$$p = \frac{DP}{f} \tag{2}$$

$$E = \frac{(L+f)}{5f}P \tag{3}$$

$$d = \frac{l \cdot p}{e+p} \tag{4}$$

$$w_s = \frac{e \cdot p}{e+p} \tag{5}$$

$$w_b = 3w_s. \tag{6}$$

The parameters of the autostereoscopic 3D projection display are obtained from (1) to (6).

III. Correction of the Parallax Images

The four projectors in the autostereoscopic 3D projection display are placed at four places in the horizontal direction with horizontal shift. Four projectors are arranged in a horizontal array in the academic design, however, the distance between every two adjacent projectors E should be limited according to (3). If the width of each projector is larger than the value, the four projectors can not be placed on one layer, which cause vertical shift. The phenomena lead to horizontal distortion and vertical parallax of the parallax images presented by the projectors. According to the researches in [10], the mismatches in binocular parallax image pairs can cause serious viewing discomfort, and even can make viewers lose stereoscopic effect. The threshold values for horizontal shift and vertical shift should be less than about 2–3 PD ($1\mathrm{PD} = 1$ prismatic diopter) and 1 PD, respectively. So the correction of the parallax images is necessary to have a better stereoscopic effect.

We correct the parallax images by the means of homography. The homography is an invertible transformation from one projective plane to another which maps straight lines to straight lines [11]. It is projective transformation, which describes the transformation relation between two planes. Set a coordinate system of the projection screen, parallax image and its target image shown in Fig. 2. Origin of the coordinate system is located at the upper left corner of the projection screen, and the point at the lower right corner is defined as (1, 1). The transformation relation between the parallax image and its target image are represented as follows:

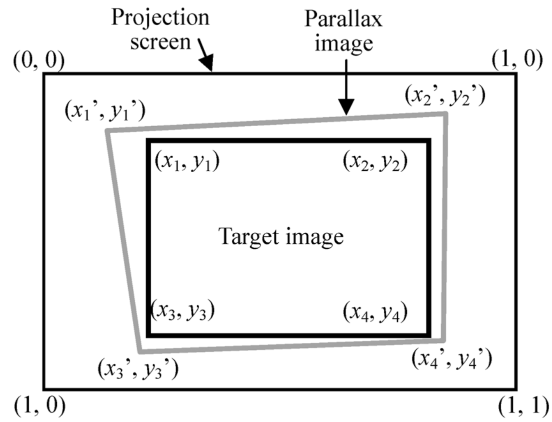
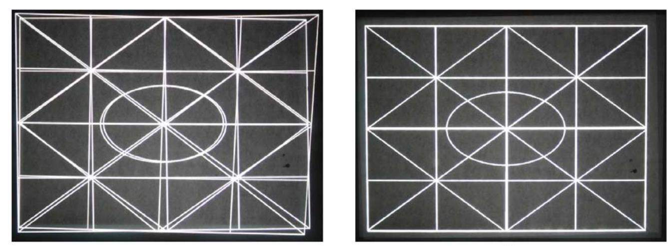


Fig. 2. Relative coordinates of the projection screen, parallax image and its target image.



a b

Fig. 3. Correction of the parallax images. (a) Uncorrected parallax image. (b) Corrected parallax image.

$$x' = \frac{ax+by+e}{ux+vy+1} \tag{7}$$

$$y' = \frac{cx+dy+f}{ux+vy+1} \tag{8}$$

where x', y' are the coordinates of a point on a parallax image to be corrected, x, y are the coordinates of a point on the rectangular target image, and a, b, c, d, e, f, u, v are the factors which can be obtained by four pairs of measurable vertices: $(x'_1, y'_1), (x_1, y_1)$; $(x'_2, y'_2), (x_2, y_2)$; $(x'_3, y'_3), (x_3, y_3)$; $(x'_4, y'_4), (x_4, y_4)$. Then all points on the parallax image are transformed to the rectangular target image according to (7) and (8). When the transformed parallax images are projected onto the projection screen, they overlap completely and do not have vertical parallax and image deformation. Fig. 3(a) and (b) shows the rectangle parallax images projected from two projectors before and after they are corrected using the above method, respectively. We can see that the parallax images in Fig. 3(a) are distorted seriously, especially on the marginal areas. However, the parallax images in Fig. 3(b) overlap very well and do not have vertical parallax and image deformation.

IV. Experiments

A 50-inch prototype of the proposed autostereoscopic 3D projection display is developed, as shown in Fig. 4. Specifica-

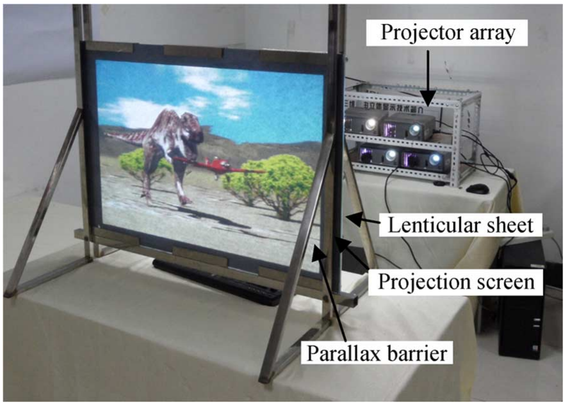


Fig. 4. A 50-in autostereoscopic 3D projection display prototype.

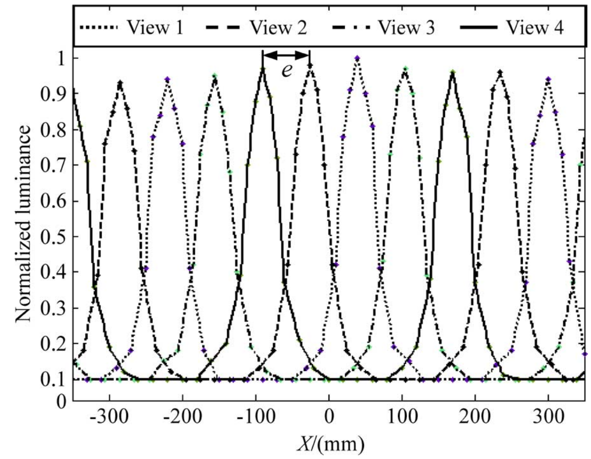


Fig. 5. The normalized luminance distribution of each viewing zone along the horizontal direction at the optimum viewing distance for the prototype.

TABLE I
SPECIFICATIONS OF THE PROPOSED 3D PROJECTION DISPLAY PROTOTYPE

Parameter	Value (*mm*)
L	1700
P	0.976
T	4.336
f	2.914
E	114
D	0.730
l	2600
e	60
d	10.553
w_s	0.244
w_b	0.732

TABLE II
PERFORMANCES OF THE TWO AUTOSTEREOSCOPIC 3D PROJECTION DISPLAY PROTOTYPES

Performances	Proposed prototype	Conventional prototype
Screen size (*inch*)	50	50
Brightness (cd/m^2)	336	152
Resolution of parallax image	1024×768	1024×768
Resolution of 3D image	1024×768	1024×768
Optimum viewing distance (*mm*)	2600	2600

tions of the prototype are listed in Table I. Four parallax images with a resolution of 1024×768 pass through the lenticular sheet and form a synthetic image with a resolution of 4096×768. And the resolution of the 3D image is the same as that of the parallax image, i.e., 1024×768.

The validity and rationality of 3D display can be evaluated by the luminance distribution characteristics [3], [12]. In the proposed prototype, the measured luminance distribution of one viewing zone can be obtained by turning on the corresponding projector with white image and turning off the others. And the luminance is measured by moving an imaging photometer along the horizontal direction at the optimum 3D view distance, as shown in Fig. 5. Horizontal axis X represents horizontal position at the optimum viewing distance. The viewing position corresponds to the display center when X is equal to 0. We can see that the horizontal distance between peak positions of two adjacent viewing zones is 65 mm, which agrees well with the designed value of e.

A coequal conventional autostereoscopic 3D display prototype based on two parallax barriers is developed for comparison. The parameters of the two prototypes are identical. The performances of the two prototypes are shown in Table II. It can be seen from Table II that the proposed prototype has brightness twice higher than the conventional prototype.

V. CONCLUSION

In order to realize a large size 3D image with high resolution, an autostereoscopic 3D projection display is proposed. It consists of four projectors, a projection screen, a lenticular sheet and a parallax barrier. Operation principle and calculation equations are described in details. A 50-inch autostereoscopic 3D projection display prototype is developed and it presents good stereoscopic images with high resolution. Compared with the conventional autostereoscopic 3D projection display based on two parallax barriers, the proposed prototype has achieved higher brightness. The autostereoscopic 3D projection display has potential application because it has many advantages such as large size, high resolution and high brightness.

REFERENCES

[1] A. Smolic, K. Mueller, P. Merkle, C. Fehn, P. Kauff, P. Eisert, and T. Wiegand, "3D video and free view-point video—Technologies, applications and MPEG standards," in *Proc. IEEE Conf. on Multimedia Expo.*, 2006, pp. 2161–2164.

[2] J. Y. Son, V. V. Saveljev, J. S. Kim, S. S. Kim, and B. Javidi, "View zones in three-dimensional imaging systems based on cylindrical, parallax-barrier, and microlens-array plates," *Appl. Opt.*, vol. 43, pp. 4985–4992, 2004.

[3] W. X. Zhao, Q. H. Wang, A. H. Wang, and D. H. Li, "An autostereoscopic display based on two-layer lenticular lens," *Opt. Lett.*, vol. 35, pp. 4127–4129, 2010.

[4] M. Lasher, P. Soltan, W. J. Dahlke, N. P. Acantilads, and M. McDonald, "Laser-projected 3D volumetric display," *Proc. SPIE.*, vol. 2650, pp. 285–295, 1996.

[5] S. W. Min, M. Hahn, J. Kim, and B. Lee, "Three-dimensional electro-floating display system using an integral imaging method," *Opt. Express*, vol. 13, pp. 4358–4369, 2005.

[6] K. Maeno, N. Fukaya, O. Nishikawa, K. Sato, and T. Honda, "Electro-holographic display using 15 mega pixels LCD," *Proc. SPIE.*, vol. 2652, pp. 15–23, 1996.

[7] H. Liao, M. Iwahara, N. H. , and T. Dohi, "High-quality integral videography using amultiprojector," *Opt. Express*, vol. 12, pp. 1067–1076, 2004.

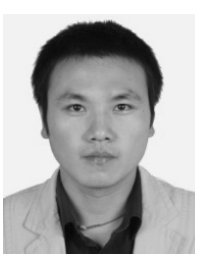
[8] J. S. Jang and Y. S. Oh, "Spatiotemporally multiplexed integral imaging projector for large-scale high-resolution three dimensional display," *Opt. Express*, vol. 12, pp. 557–563, 2004.

[9] Y. H. Tao, Q. H. Wang, J. Gu, W. X. Zhao, and D. H. Li, "Autostereoscopic three-dimensional projector based on two parallax barriers," *Opt. Lett.*, vol. 34, pp. 3220–3222, 2009.

[10] F. L. Kooi and A. Toet, "Visual comfort of binocular and 3D displays," *Disp.*, vol. 25, pp. 99–108, 2004.

[11] B. Zhang and Y. Li, "Homography-based method for calibrating an omnidirectional vision system," *J. Opt. Soc. Amer. A*, vol. 25, pp. 1389–1394, 2008.

[12] H. K. Hong, J. Park, S. C. Lee, and H. H. Shin, "Autostereoscopic multi-view 3D display with pivot function, using the image display of the square subpixel structure," *Displays*, vol. 29, pp. 512–520, 2008.



Lin Qi is working toward the Ph.D. degree in optical engineering from the School of Electronic and Information Engineering, Sichuan University, Chengdu, China.

His recent research interest is information display technologies.

Qiong-Hua Wang received the M.S. and Ph.D. degrees from the University of Electronic Science and Technology of China (UESTC) in 1995 and 2001, respectively.

She is a Professor of Optics at the School of Electronics and Information Engineering, Sichuan University, Chengdu, China. She was a post-doctoral research fellow in the School of Optics/CREOL, University of Central Florida, Orlanda, in 2001–2004. She worked at UESTC in 1995–2001, and at Philips Mobile Display Systems, Philips Shanghai, in 2004. She has published 150 papers on display devices and systems. Her recent research interests include optics and optoelectronics, especial display technologies. She holds 5 U.S. patents and 16 Chinese patents.

Dr. Wang is a senior member of the Society for Information Display (SID).

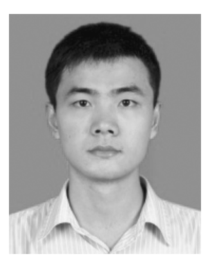
Jiang-Yong Luo is working toward the graduate degree in optical engineering from the School of Electronics and Information Engineering, Sichuan University, Chengdu, China.

His recent research interest is information display technologies.

Wu-Xiang Zhao received the M.S. degree from the Sichuan University, Chengdu, China, in 2010.

He is a lecturer of optics at the School of Electronics and Information Engineering, Sichuan University, Chengdu, China. He has published more than 10 papers. His recent research interests include optics and optoelectronics, especial display technologies and optical measurements.

Mr. Zhao is a member of the Society for Information (SID).



Cheng-Qun Song is working toward the Ph.D. degree in optical engineering from the School of Electronic and Information Engineering, Sichuan University, Chengdu, China.

His recent research interest is information display technologies.