Paper 3-3 has been designated as a Distinguished Paper at Display Week 2018. The full-length version of this paper appears in a Special Section of the *Journal of the Society for Information Display (JSID)* devoted to Display Week 2018 Distinguished Papers. This Special Section will be freely accessible until December 31, 2018 via:

http://onlinelibrary.wiley.com/page/journal/19383657/homepage/display_week_2018.htm

Authors that wish to refer to this work are advised to cite the full-length version by referring to its DOI:

https://doi.org/10.1002/jsid.665

Resolution Enhanced Light Field Near-to-Eye Display Using E-shifting Method with Birefringent Plate

Kuei-En Peng, Jui-Yi Wu, and Yi-Pai Huang
Department of Photonics & Institute of Electro-Optical Engineering
National Chiao Tung University, Hsinchu, Taiwan, 30010
Hsin-Hsiang Lo, Chuan-Chung Chang, and Fu-Ming Chuang
Coretronic Corporation, Hsinchu, Taiwan, 30010

Abstract

Light field near-to-eye display (LFNED) achieves lightweight device and solves accommodation-convergence conflict. However, low spatial resolution of LFNED brings users bad immersive experience. In this paper, the new method proposed using birefringent plate to enhance image resolution. In results, our method apparently improves resolution in LFNED.

Author Keywords

Near eye display; Light field; Virtual reality; Birefringence; Resolution enhanced.

1. Introduction

As the progress of technology, the display is no longer a flat panel display. Near-to-eye display (NED) with augmented reality (AR) and virtual reality (VR) [1] can give users different novel experience from flat panel display. It is believed that it will be widely applied in many fields, such as entertainment, education, and medicine etc. Most NEDs use binocular parallax method [2] to create 3D images. Binocular parallax method, also called stereoscopic method, separates original image into right eye and left eye image, which contain different angle information of same object. After receiving two images into right eye and left eye of users respectively, users will have depth perception automatically through binocular fusion in human brain. However, this method suffers from accommodation-convergence conflict (A.C. conflict) [3]. Also, bulky devices lead people to uncomfortable feeling. A.C. conflict is caused by difference between accommodation distance and convergence distance shown in Figure. 1 (a). The human brain would be confused when received an unnatural vision. Bulky devices is brought about thickness of main lens in stereoscopic system. To get short lens focal length and wide FOV, main lens needs to be large and thick leading to heavy devices. To solve these problems, light field near-to-eye display (LFNED) was proposed in 2013. As shown in Figure. 1 (b), the micro lens array (MLA) is set in front of the display and different elemental images are shown in panel. The light passing through each micro-lens will converge to the corresponding area on the focal plane. The advantage of LFNED not only reduces thickness but addresses A.C. conflict.

LFNED using micro-lens array [4] has been developed to achieve thin structure and solve the problem of A.C. conflict, but the disadvantages are low spatial resolution which is 4.89 pixels per degree (PPD) per eye and low field of view (FOV) which is 29 degrees in monocular FOV. Though pinhole aperture array based LFNED [5] has been proposed and has better performance in resolution (6.56 PPD) and FOV (60 degrees in monocular FOV), the light efficiency is low and toning effect affects the image quality. Moreover, compare to current commercial stereoscopic VR products, the spatial resolution of both micro-lens array based LFNED and pinhole aperture array based LFNED are much smaller than stereoscopic VR products (>11.87 PPD).

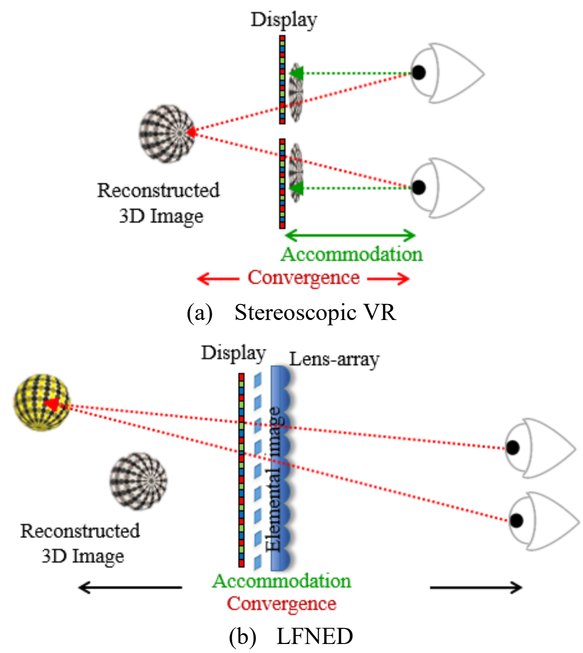


Figure. 1 There is an A.C. conflict issue in (a) stereoscopic VR. In (b) LFNED, the accommodation and convergence distance are same.

In this paper, we proposed a time-multiplexed method with birefringent plate and twisted nematic liquid crystal plate (TN plate) to achieve shifting image with one-half pixel displacement. This idea is similar to wobulation [6], which is proposed by Will Allen. Wobulation is a cost-effective method to increase resolution in digital projection systems. Same of the concept, but we proposed a flat birefringent component that suit for any flat panel display. In application, proposed could easily combine with LFNED and other VR system using flat panel display. We believed our method can make users get better immersive experience in LFNED system, since spatial resolution is important to performance of VR.

2. Light Field Near-to-Eye Display

The system configuration of the LFNED is shown schematically in Figure. 2. A panel of LFNED is a Sony Micro-OLED ECX335A 0.7' panel (3150 pixels per inch) which pixel size p = 7.8 μm. A micro-lens array with N_l (13×7) lenses, each of focal length f = 3.03 mm and lens pitch ω_l = 1 mm, is placed a distance g = 3.01 mm in front of display. Then, it will form virtual image located at distance do = 450 mm from the eye. For an eye relief d_e = 14 mm, this design yields an image with field of view

(FOV) α and spatial resolution Np. The FOV α is given by

$$\alpha = 2\tan^{-1}\left(\frac{(N-1)\times w_l}{2d_e}\right). \quad \text{eq. 1}$$

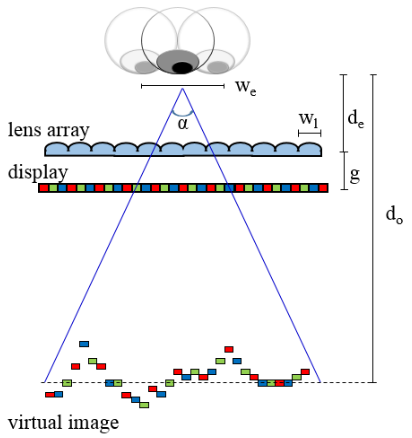


Figure. 2 Design of a near-eye light field display with a micro-lens array and a micro-OLED display.

The spatial resolution N_p can be define as

$$N_p = \frac{1}{2pM}, \text{ such that magnification } M = \frac{d_o - d_e}{g}. \quad \text{eq. 2}$$

The effective panel size h within the FOV is

$$h = N_l \times wl \times \frac{d_e + gap}{d_e}.$$

With the above parameters, we can then calculate the size of the eye box w_e as

$$\boldsymbol{w_e} = \frac{h \times d_e}{N_l \times g}. \quad \text{eq. 3}$$

According to eq. 1, eq. 2 and eq. 3, we can estimates design parameters for monocular system: spatial resolution N_p = 0.4 cy/mm, angular resolution is 7.0 PPD, FOV α = 46×28 degrees and eye box w_e = 5.5 mm.

3. Proposed Method

3.1 Time-Multiplexed Method

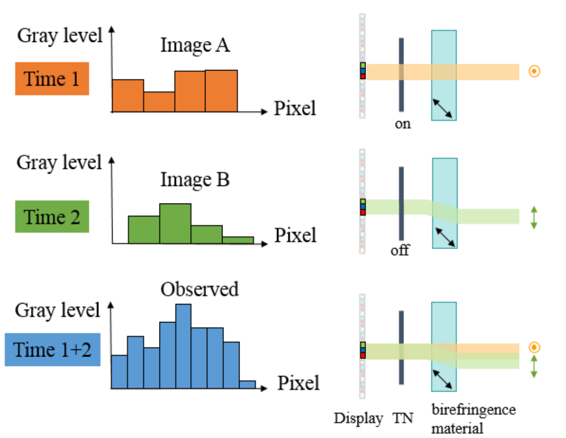


Figure. 3 The concept of using time-multiplexed method to enhance spatial resolution in LFNED. When user perceive image through visual persistence, image resolution is enhanced by superposition of pixel value.

To enhance resolution, we add TN plate and birefringent plate into LFNED system. We have to generate image A and B using sampling algorithm (see section 3.3) in advance. In first moment (time 1), we show image A and turn on the TN, the polarization of light will not change when light pass through the TN plate. Because the polarization of light is vertical to crystal axis of birefringent material, the light will go straight forward. In next moment (time 2), we show image B and turn off the TN, the polarization of light will be switched to another. In this moment, there is an angle between the polarization and crystal axis of birefringent material, so the direction of light will be changed in this material and shifted in a half-pixel distance. By switching TN quickly, we can combine these two images by visual persistence. Then we can observe high resolution image in LFNED. The concept was shown schematically in Figure. 3.

3.2 Hardware

The goal of our proposed LFNED is shifting image a half pixel size distance by using TN plate and birefringent plate with a layout shown in Figure. 4.

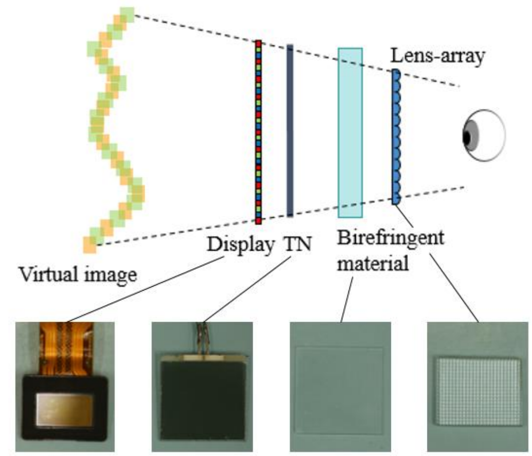


Figure. 4 The structure of resolution enhanced LFNED with display, TN plate, birefringent plate, and lens-array.

In order to apply resolution enhanced method, image has to be shifted. We additionally put TN plate and birefringent plate on original LFNED as we discussed in section 2. The shifting direction is diagonal considering resolution enhanced in horizontal and vertical direction. Also, the shifting distance is half pixel size which is equal to 5.5 um in diagonal direction.

In our structure, we use a TN plate which can quickly switch polarization of light to show 2 frames during the visual persistence (16 msec) of the human eye to achieve shifting image a distance between two polarizations, so each frame can only persist 8 msec. The X-FPM from LC-Tec is a fast single-cell liquid crystal based polarization modulator/rotator that controls the light polarization by an external driving voltage. The response time (T100-T10) and relaxation time (T0-T90) are smaller than 30 μs and 1.8 ms respectively. The total response time is smaller than 8 msec. The thickness of X-FPM is only 1.7 mm that also doesn't take up too much volume. The specification of X-FPM can be used in our system.

To find the birefringent material which can make image diagonally shift 5.5 um, quartz plate is a solution. As shown in Figure. 5, for shifting diagonal direction, the angle between incident light and crystal axis of quartz plate is 45 degrees, and thickness of this plate is 900 um. The refractive index of ordinary light no is 1.54 and the refractive index of extraordinary light ne is 1.55. So, calculate by following formula eq. 4,

$$\emptyset = \theta - \tan^{-1}\left(\frac{n_o^2}{n_e^2}\tan\theta\right), \qquad \text{eq. 4}$$

which θ is an angle between incident light and crystal axis and ∅ is an dispersion angle between two different polarization light. We can get shifting amount is 5.3 um which is similar to half pixel size in diagonal direction.

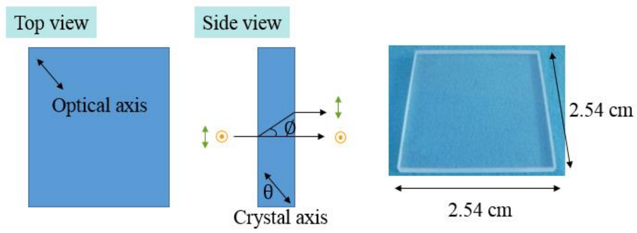


Figure. 5 The size of quartz plate is 2.54×2.54×0.09 cm can cover whole panel and achieve the pixel-shifting effect we expected.

Overall, we shift image without any mechanic element, so there is no vibration issue in our structure. Further, although we put additional optical elements, these elements are flat optical components that would not contribute to aberration issue caused by lens.

3.3 Software

Content of two images showed in different moment is important to get resolution enhanced image. So, we developed an algorithm to generate image A and image B in different moment. The difference between image A and B is diagonal half pixel size. Therefore, we need to do interpolation to get value between pixel and pixel. The flow chart is shown in Figure. 6. First, we input two times of panel resolution image. Then, we double this image to four times of panel resolution using lanczos method. To get different information, we do down sampling to original resolution to generate image A and B by using average of different area. Image A and image B are same resolution of display panel. Image A in time 1 is not shifted, and image B in time 2 is shifted half pixel size diagonally, which is located at center of the nearest four pixels. Finally, the high resolution image from combination of image A, B will be observed when TN plate is switched quickly.

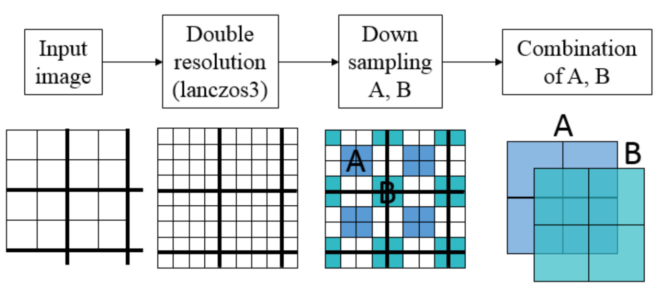


Figure. 6 The flow chart of algorithm in resolution enhanced LFNED. The bold lines represent the original pixel size. In down sampling step, the new pixel value is come from average of 4 pixel values of 4 times of panel resolution.

4. Experimental Results

4.1 Verification of Shifting Effect

Before do resolution enhanced method, we had to verify the shifting amount and direction in advance. To verify it, microscopy system was used to detect the small displacement of 5.5 um. The experiment set up is illustrated in Figure. 7. We set 20x objective lens to observe the image. The CCD is Canon EOS 5D Mark II which pixel size is 6.4 μm. So, the effective resolution is 0.32 μm considering magnifying effect caused by 20x objective lens. The input image is only a green sub-pixel like Figure. 7 shows.

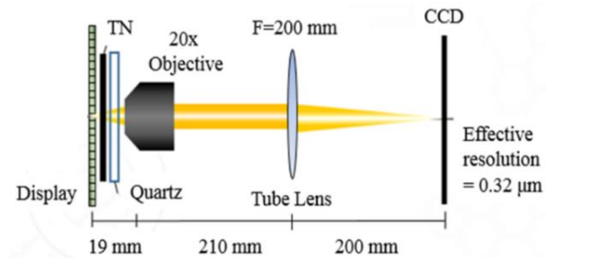


Figure. 7 The experiment set up use microscopy system to verify shifting effect.

In image we captured in Figure. 8, after combination with two images from different polarization, we can observe that one green spot separates into two green spots with horizontal disparity 12 pixels and vertical disparity 11 pixels. The disparity is equal to 5.21 μm diagonally and the direction is 42.5 degrees.

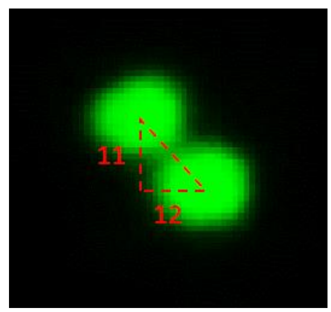


Figure. 8 The experiment result of pixel shifting. Green sub-pixel has 5.21 μm displacement with diagonal direction.

4.2 Resolution Enhanced Light Field Image

The experiment set up is shown in Figure. 9. To record the virtual image at 450 mm of depth, high-sensitivity CCD and vari-focal manual lens (Computar H2Z0414C-MP) are used to capture the LF image.

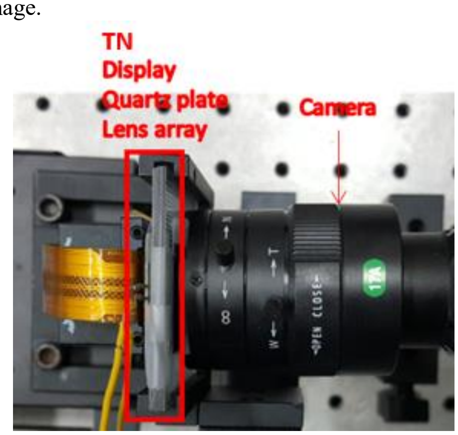


Figure. 9 The experiment set up concludes TN, display, quartz plate, lens-array (in red frame) in resolution enhanced LFNED

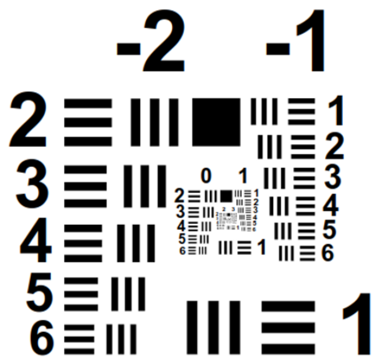


Figure. 10 The USAF 1951 test pattern. It is widely accepted to test the resolution of optical imaging system.

First, we use USAF 1951 (Figure. 10) pattern which is used to test spatial resolution in optical system to quantify our effect of resolution enhanced.

In original LFNED design, element -2-5 is resolvable, which means it could only reach 0.4 lp/mm (6.3 PPD). But in our resolution enhanced LFNED, group -1 element 2 could be distinguished, so the system could actually reach 0.56 lp/mm, which is equal to 8.8 PPD. The result table is list in Table 1.

Table 1 The experiment result are list. The resolution of resolution enhanced LFNED is 0.56 lp/mm, which is better than the original LFNED which is only 0.4 lp/mm.

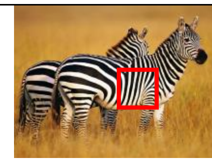
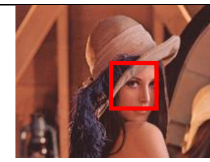
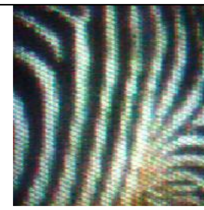
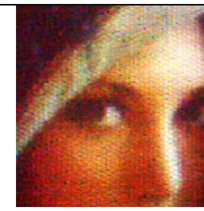
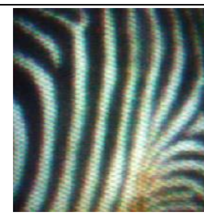
Type / Results	LFNED	Resolution enhanced LFNED
USAF (group-element)	-2 - 5	-1 - 2
Spatial resolution (lp/mm)	0.40	0.56

Next, we use zebra and Lenna picture to do experiment in resolution enhanced LFNED system. After applying time-multiplexed method on the system, we can capture resolution enhanced image from our proposed LFNED shown in Table 2. In picture zebra, the edge of black and white is zigzag and the lines are not clear in red circle in LFNED. After do our time-multiplexed method, the edge become smoother than before. The lines also become distinguishable in red circle in resolution enhanced LFNED. In picture Lenna, the edge of eyebrow and the white of the eye are also become clear and smoother.

5. Conclusion

Current commercial VR products using stereoscopic method have two serious disadvantages. One is visual fatigue caused by A.C. conflict and the other one is heavy devices. The LFNED is addressed to solve these problems, but the spatial resolution is much lower than the former. Therefore, we proposed a novel method by adding TN plate and quartz plate with extra total thickness only 2.6 mm to enhance spatial resolution, as shown in Figure. 11. In result, we use time-multiplexed method by quickly switching polarization of light and shifting image diagonally half pixel size to achieve high resolution light field image during visual persistence. Finally, light field image can reach 8.8 PPD and obtain more detail information than original one (6.3PPD) with our proposed method.

Table 2 Comparison of resolution enhanced LFNED and LFNED in zebra picture.

	Zebra	Lenna
Original image		
LFNED		
Resolution enhanced LFNED		

(a) (b)

Figure. 11 (a) Side view and (b) top view of our proposed LFNED system. We can use coin (10 NTD) as a scale to compare with it. Our proposed method can easily combine with any flat panel display and easily achieve compact device.

6. Acknowledgements

This research is partially supported by Coretronic Corporation. We thank the member in Light Field Technology Division CTO Office for giving great assistance in this research.

7. References

[1] Wu, W., et al., Personal near-eye light field display. SID Information Display, 2014.

[2] Howard, I.P. and B.J. Rogers, Binocular vision and stereopsis. Oxford University Press, 1995

[3]. Hoffman, D.M., et al., Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. Journal of vision,. 8(3): p. 33-33. 2008

[4] Lanman, D. and D. Luebke, Near-eye light field displays. ACM Transactions on Graphics (TOG), 2013. 32(6): p. 220.

[5] Akşit, K., J. Kautz, and D. Luebke, Slim near-eye display using pinhole aperture arrays. Applied optics, 54(11): p. 3422-3427. 2015.

[6] Allen, W. and R. Ulichney. 47.4: Invited paper: Wobulation: Doubling the addressed resolution of projection displays. in SID Symposium Digest of Technical Papers. Wiley Online Library. 2005