Modeling, Algorithm, and Implementation of Resolution-Tripled Near-Eye Light Field Displays

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ABSTRACT

A physical model incorporating all factors affecting the retinal image formation in a near-eye light field display is proposed, based on which, an algorithm recombining subpixels across elemental images to nearly triple the resolution is developed. Finally, an e-shifting method is suggested to further enhance the resolution to 30 pixels-per-degree.

1 INTRODUCTION

To achieve wearable virtual reality (VR) and augmented reality (AR) displays with high resolution, wide field of view (FOV), small form factor, and 3D content with mitigated vergence-accommodation conflict (VAC), there are various technologies such as waveguide optics, optical combiner, digital holography, and near-eye light field display (NE-LFD). Of them, the NE-LFD that typically employs a microdisplay and a microlens array near an eyeball to present 3D plenoptic functions through integral imaging (see Fig. 1), features ultra-thin volume, theoretically unlimited FOV, simple hardware for full-color display, and freedom of the VAC [1-5]. In particular, the VAC is mitigated through retinal blur that mimics real 3D objects, i.e., monocular focus cues [3,4]. However, in an NE-LFD, pixels of the microdisplay have to simultaneously carry positional and angular information, thus current NE-LFDs usually suffer from low resolution [3,4].

To be specific, the factors that limit the resolution are discussed below with the illustration in Fig. 2.

(i) The visual angle of a single pixel after being magnified by a lenslet is determined by the pixel size p and the focal length G, as $\arctan(p/G)$. For example, under a typical configuration (p = 8.5 μm, G = 5 mm), the visual angle is 5.8 arcmin, far beyond the human resolution limit of 1 arcmin. Additionally, considering the requirement of small form factor, the focal length should be kept short.

(ii) In using integral imaging to generate a 3D image point, retinal images of several pixels from several elemental images need to be overlapped (integrated) on the retina. However, due to the finite pixel size, the overlapping is always imperfect, with a misalignment error of at most half a pixel, which may even halve the resolution.

(iii) The small aperture of the lenslets produces non-ignorable diffraction that degrades the image quality.

(iv) The lenslets used for geometric optics-based imaging produce aberration, in particular, when the lens aperture is large or the imaging is off-axis (i.e., large FOV).

(v) If the 3D image point is away from the CDP (see Fig. 1), the retinal image of each pixel will be defocused, which also decreases the resolution.

Due to the above factors, the resolution of current NE-LFDs is usually around only 10 pixels-per-degree (PPD) even for on-axis and on-CDP images, far from the requirement of practical VR/AR devices [6]. In this study, first, an accurate physical model of NE-LFDs will be developed to quantitively analyze the retinal image formation and the resolution. Next, based on the model and currently available hardware, we will propose a resolution enhancement method that recombines subpixels across elemental images to make the resolution limited by the size of a subpixel but not a pixel. In addition, a time-multiplexing e-shifting method from our previous study, which can increase the resolution by at most 50%, will also be simply introduced to be combined with the subpixel recombination method.

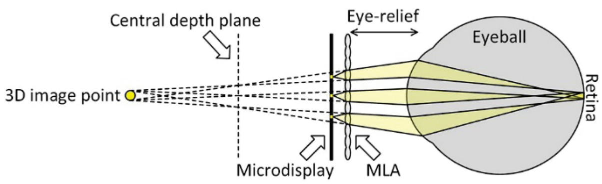

Fig. 1. Working principle of a near-eye light field displays using a microdisplay and a microlens array, where a 3D image point is generated away from the central depth plane (CDP).

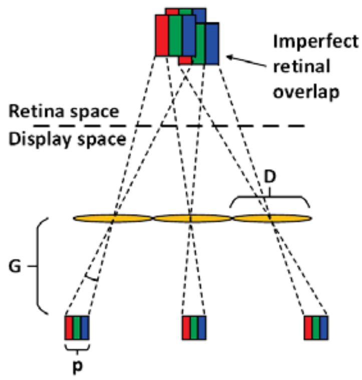

Fig. 2. Simplified retinal image formation in an NE-LFD for resolution analysis.

2 IMAGE FORMATION MODEL

To incorporate all factors affecting the retinal image formation in an NE-LFD, including diffraction, aberration, defocusing, pixel size, subpixel arrangement, and eye accommodation, the fundamental Rayleigh-Sommerfeld diffraction with no simplification for a scalar diffraction system is used. Based on the Arizona eye model [7] that can effectively adjust the eye accommodation, the NE-LFD model is built in Zemax OpticStudio® where the diffraction integral and non-paraxial raytracing are numerically performed, and all calculation data is then transferred to and analyzed in MATLAB through the ZOS-API provided by Zemax.

Panel size	0.7 inch
Pixel size	7.8 µm
Subpixel arrangement	Stripe
MLA material	PMMA
Lenslet aperture	0.5 mm
MLA curvature c	0.67 mm^{-1}
Panel-MLA gap d_1	0.77 mm
MLA thickness d_2	3.30 mm
Central depth plane	4 diopters
Eye accommodation	4 diopters

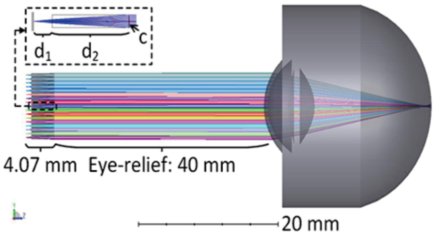

Fig. 3. Specifications of a typical system (left) and its model in Zemax OpticStudio®.

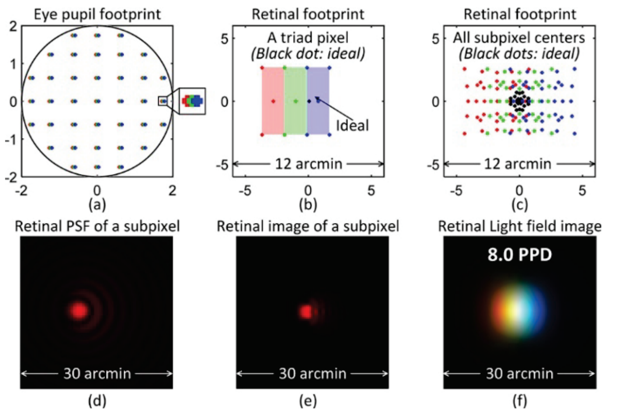

Fig. 4. Formation of a retinal light field image: (a) eye pupil footprint of all subpixels used; (b) retinal footprint of three subpixels from an elemental image; (c) retinal footprint of all subpixels used; (d) retinal point spread function (PSF) of a red subpixel; (e) retinal image of the red subpixel; (f) resultant retinal light field image with its resolution.

Figure 3 shows specifications of a typical system and its model, and Fig. 4 shows how the retinal light field image is formed regarding the microdisplay panel's subpixels. First, through a typical light field algorithm [3], dozens of pixels (37 here) in elemental images are determined to emit light to generate a 3D virtual image point [1,2,5]. Next, pupil footprint and retinal footprint of all subpixels are obtained, which are then combined with point spread functions and retinal image regions of all subpixels. Finally, all retinal images of involved subpixels in elemental images are accumulated to obtain the retinal light field image. In addition, the directional sensitivity of the human retina, expressed by the Stiles-Crawford effect [6], is also considered. As seen in Fig. 4, the resolution derived from the Rayleigh criterion is 8.0 PPD, which is quite low.

3 SUBPIXEL RECOMBINATION METHOD

From Fig. 4, it can be seen that the spreading area of the retinal light field image is mainly determined by the pixel size; that is, the final retinal image is a superposition (integral) of several pixels' retinal image and each pixel simultaneously provides all its three subpixels, as illustrated in Fig. 5(a). In addition, the imperfect alignment of the pixels in the superposition further impairs the resolution.

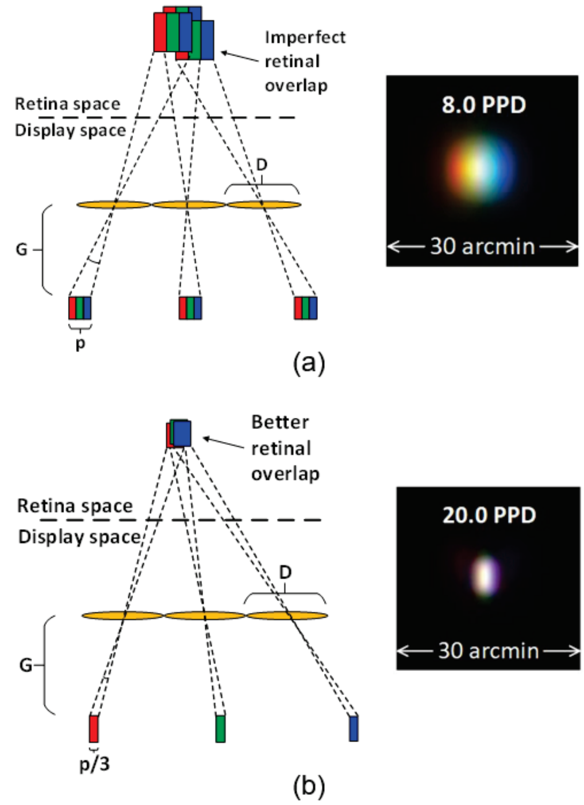

Fig. 5. (a) Conventional and (b) the proposed resolution-tripled elemental image generation algorithms (left: algorithm illustration; right: retinal light field image).

Therefore, we propose that subpixels across different elemental images can be recombined, i.e., each elemental image may provide only one subpixel and by carefully determining the numerical relationship between the lens pitch, lens focal length, and pixel size, the pixels from different elemental images can near-perfectly overlap on the retina, as illustrated in Fig. 5(b) [9]. In this manner, the factor that dominates the system resolution is now the size of a subpixel, so the resolution can be theoretically tripled. By using the same system discussed in the previous section, the retinal light field image is obtained based on the image formation model, as shown in Fig. 5(b), where the resolution is enhanced from 8.0 to 20.0 PPD, namely, a resolution gain of 2.5 times. Certainly, in practice, the resolution is also affected by diffraction and aberration that have little to do with the proposed subpixel recombination method, thus the resolution gain is slightly smaller than the ideal value of three.

4 E-SHIFTING METHOD

If dynamic components are allowed to be used in an NE-LFD, an “e-shifting” method we previously proposed in [8] can be used to further enhance the resolution by at most 50%. The method employs a birefringent plate that allows p-polarized light to keep its propagation direction while shifts s-polarized light for half a pixel. By further using a twisted-nematic liquid crystal (TN-LC) cell to fast switch between the two polarization states, the original light field image and its shifted image can be merged to realize super-resolution through a time-multiplexing schema, as illustrated in Fig. 6(a). By configuring the birefringent plate’s thickness with the consideration of its birefringence, a shift of half a pixel was achieved and experimentally verified, as shown in Fig. 6(b), and the merged light field image exhibited a significant resolution enhancement of nearly 50%, as shown in Fig. 7.

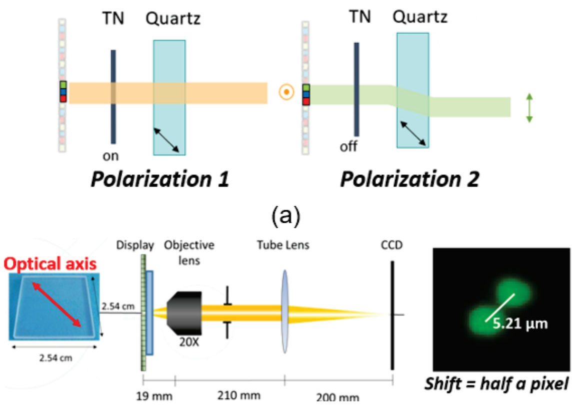

Fig. 6. (a) Schema of the e-shifting method that employs a birefringent plate and a TN-LC cell; (b) photograph of the birefringent plate with its optical axis (left) and a laser beam shifted for half a pixel (5.21 microns on the panel, middle and right).

Fig. 7. The original light field image (left) and the resolution-enhanced image through the e-shifting method (right).

Finally, the e-shifting method can be combined with the subpixel recombination method proposed in Sec. 3 by re-configuring the birefringent plate’s thickness to achieve a shift of half a subpixel. In this manner, the previous resolution enhancement of 2.5 times can be further multiplied with at most 1.5; that is, the resolution of the current NE-LFD, as 8.0 PPD, can be eventually enhanced to 30.0 PPD, which is the general requirement of practical VR and AR devices.

5 CONCLUSIONS

In this study, we sought to quantitively analyze and then enhance the resolution of NE-LFDs. First, a highly accurate physical model of NE-LFDs that could obtain the retinal image was developed. Based on the model, a subpixel recombination method that could make the resolution limited by the size of a subpixel instead of an entire pixel was proposed for a resolution enhancement of 2.5 times. Finally, an e-shifting method was discussed for a further resolution enhancement of at most 1.5 times. As a result, the resolution of an NE-LFD with currently available hardware (3256-ppi-panel and 5-mm-thickness) can eventually reach 30 PPD, a practical level, to achieve VR/AR devices with all-around performance.

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