Vision-Correcting Near-Eye Light Field Displays by Computationally Controlling Plenoptic Functions

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ABSTRACT

A vision-correcting light field display that can address ametropia, particularly astigmatism, is proposed. Plenoptic functions reconstructing a 3D object are computationally controlled through the genetic algorithm to compensate for eyes' refractive errors with no extra volume and cost. Resolution after the correction negligibly degrades compared with emmetropia.

1 INTRODUCTION

To enable 3D display in near-eye virtual reality (VR) and augmented reality (AR) for military, medical, entertainment, education, and other fields [1], binocular parallax is conventionally used. However, the vergence-accommodation conflict (VAC) and consequent visual fatigue, dizziness, and discomfort after long-term viewing arise due to the lack of adjustable depth information [2].

For achieving true-3D display without the VAC, a variety of methods have been proposed, roughly categorized into light field display [3], holographic display [4], varifocal 3D display [5], etc. Of the methods, the integral imaging (InIm) light field display has become the focus of the next-generation true-3D display due to its feasible hardware, compactness, and continuously adjustable depth.

At present, one of the main challenges of VR/AR devices is adapting to ametropia, including myopia, hyperopia, astigmatism, etc. For this purpose, the most straightforward method is wearing glasses, which is, however, not suitable for near-eye displays. Therefore, many have proposed to add static or dynamic optics into conventional near-eye displays. The static method adopts extra free-form optics or micro-optics that can compensate for eyes' refractive errors. But hardware has to be individually designed and fabricated for specific users [6]. The dynamic method uses additional focus-tunable optics (such as liquid crystal lens), which can be electrically tuned to adapt to different refractive errors [7]. However, the dynamic device is complicated, and maintaining sufficient imaging quality across wide FOV and spectrum is challenging. Using additional optics inevitably increases the total volume and complexity. Therefore, compared with the previous works, we here propose new vision-correction InIm light field displays. Vector light rays (i.e., plenoptic functions) are computationally controlled to compensate for ametropia, particularly astigmatism, with no extra weight and volume.

2 METHOD

Figure 1 shows the principle of a typical near-eye InIm light field display. A microlens array (MLA) is placed in front of a pixelated image source (usually a microdisplay), and each microlens covers a pixel array. An object is reconstructed by several vector light rays corresponding to several pixels on the microdisplay, where the pixel positions determine the rays' directions. The eye's accommodative response coincides with the reconstructed object point's depth. As thus, a computationally tunable accommodation is achieved to mitigate the VAC.

When a user suffers from ametropia, the cornea and crystalline lens may not meet the requirement of converging light at the retina. Compared with an emmetropic eye shown in Fig. 2(a), myopic and hyperopic eyes illustrated in Fig. 2(b) and (c) converge light in front of or behind the retina, respectively. Myopia and hyperopia can be straightforwardly solved using a light field display's intrinsic ability to control the reconstruction depth computationally. Figure. 2(d) presents an astigmatic eye, where sagittal and tangent light rays cannot be simultaneously converged on the retina. Next, we propose to computationally control vector light rays through the genetic algorithm to address astigmatism.

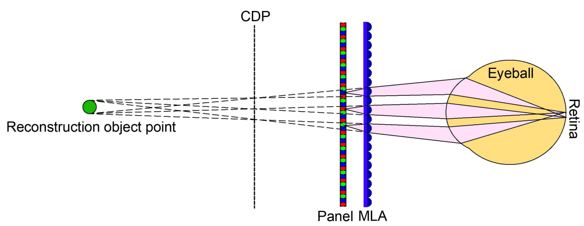

Fig. 1 Principle of a near-eye light field display

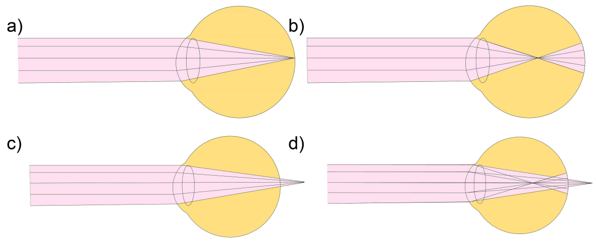

Fig. 2 Light path in different eyes: (a) emmetropia; (b) myopia; (c) hyperopia; (d) astigmatism

The diopter of an astigmatic eye varies with the radial direction. Thus, conventionally, additional optics with no rotational symmetry must be used to introduce complementary diopter, for example, aspheric glasses or freeform lens [6]. Nevertheless, a light field display works quite differently from conventional optics. That is, each 3D object point is reconstructed by several vector light rays, each of which can be controlled by the position of its corresponding pixel. Therefore, this working principle provides the possibility of computational vision correction by fine-tuning pixel positions to control each vector ray's direction.

Two things are needed to put the computational vision correction proposed above into practice. (i) We should know how vector rays are distributed on the retina of an astigmatic eye. (ii) An optimization algorithm is needed to seek a new pixel set reconstructing the 3D object so that vector rays can be converged on the retina.

For the first thing, we previously proposed a highly accurate image formation model of light field displays [8]. The model incorporates diffraction, aberration, defocus, image rendering, and eye model by linking Zemax OpticStudio® and Matlab. It can determine pixels used to reconstruct a 3D object point, as well as output a pupil footprint and a retinal footprint of the pixels' vector rays, and an integrated retinal light field image. For the ametropia of interest in this study, the emmetropic Arizona eye model is replaced by an astigmatic eye model whose cornea surfaces and crystalline lens are represented by biconic polynomials (structural parameters acquired from ophthalmic studies [9]).

Table 1 Specifications of the modeled light field displays

Panel size	0.7 inch
Pixel per inch	3102
Lens curvature	1.50mm
Lens pitch	0.5mm
Panel to MLA	0.725mm
Lens thickness	3.3mm
Eye-relief	14mm

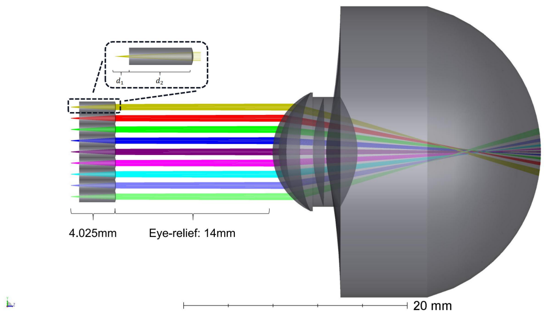

Fig. 3 Schematic model in Zemax OpticStudio®

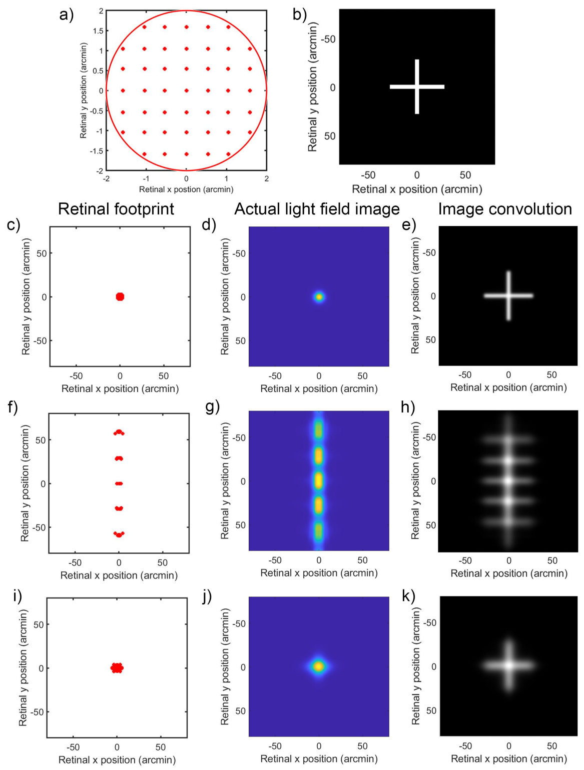

Fig. 4 (a) Pupil footprint of 45 vector rays; (b) a cross symbol to be reconstructed. (c) to (k) Retinal footprints, an object point's retinal light field image, and the symbol's retinal image corresponding to emmetropia (c, d&e), astigmatism without correction (f, g&h), and astigmatism with correction (i, j&k)

We use the specifications in Table 1 to build the image formation model of a typical near-eye light field display, and the corresponding model is shown in Fig. 3. Figure 4(a) shows the pupil footprint of 45 vector rays. Figure 4(b) shows a cross symbol to be reconstructed by the light field display. Next, corresponding to an emmetropic eye, Figs. 4(c), (d), and (e) present the vector rays' retinal footprint, an object point's retinal light field image, and the cross symbol's retinal image, respectively. In comparison, Figs. 4(f), (g), and (h) show the results in an astigmatic eye, where the rays cannot be well converged in the vertical direction and consequently bring about a retinal image highly dispersed in this direction - a typical astigmatic image.

For the second thing, seeking a new pixel set that generates vector rays converged on the astigmatic eye's retina, an optimization algorithm is needed by taking the original pixel set as the initial solution. Next, the genetic algorithm is adopted, whose working flow is shown in Fig. 5. Some matters must be mentioned. (i) To avoid falling into the local minimum, set the population number as large as n×9×10, where n is the pixel number of the initial pixel set, and the solution interval of the problem is one pixel and the circle of pixels around it; that is, each pixel has nine or more possibilities. Binary or Gray code is used to encode the abstract possible states while setting the encoding length based on total computation and enough data sets. To make it possible for various combinations to iterate without falling into a local minimum, take the maximum iteration number as large as several tens of thousands, while it could be modified based on a convergence condition.

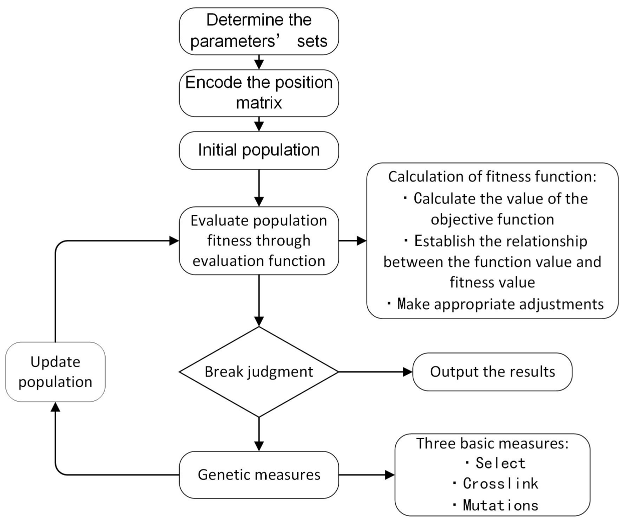

Fig. 5 Working flow of the genetic algorithm

As for the target function, any kinds of them which could achieve the patches of light focusing on the retina can be set. Here, we use the root mean square error (RMSE) as the evaluation function to define the degree of the light spot dispersion, and the solution sets corresponding the minimum value are the optimum results. The definition of RMSE is described by Eq. (1):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n}} \qquad (1)$$

Where x_i is the coordinate of the i^{th} pixel at x direction while $\bar{x}$ is the average location of the whole pixels. The value of n means the total number of selected pixels.

Calculating by numerical simulation software such as MATLAB, we get the optimum result of the pixel set. Furthermore, we build a transformation matrix between the initial pixel positions and the optimum pixel positions to quantify the relationship between the initial pixel set and the optimum set. Applying the matrix in the whole panel before using a light field display for astigmatism, we could obtain an optimum elemental image array.

3 RESULTS

We use the optimization algorithm above, an optimum pixel set generating 45 new vector rays is acquired. Figures 4(i) to (k) show the retinal footprint of the 45 rays, the retinal light field image and a retinal image corresponding to the cross symbol based on optimum results. Compared with Figs. 4(f) to (h) with no vision correction, the vector rays are now considerably converged on the retina in all directions, thereby bringing out a much better retinal light field image. Even compared with Figs. 4(c) and (e) corresponding to emmetropia, the retinal image after the correction is nearly the same converged, suggesting a very slight resolution degradation

4 CONCLUSIONS

While previous studies usually adopted additional optics in near-eye displays to adapt to ametropia at the cost of volume and complexity, this study proposed a vision-correcting light field display by computationally controlling vector rays reconstructing a 3D object with no extra volume and cost. Moreover, the computational correction was implemented through the genetic algorithm to determine an optimum elemental image array that could make vector rays converged on the retina of an ametropic eye.

The proposed vision-correcting display can address all kinds of refractive errors without extra optics. And, the optimization algorithm can be implemented through deep learning for real-time calculation, enabling near-eye VR and AR devices friendly to visually impaired users.

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