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Robustness of an artificially tailored fisheye imaging system with a curvilinear image surface

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ABSTRACT

Curved image sensors inspired by animal and insect eyes have provided a new development direction in next-generation digital cameras. It is known that natural fish eyes afford an extremely wide field of view (FOV) imaging due to the geometrical properties of the spherical lens and hemispherical retina. However, its inherent drawbacks, such as the low off-axis illumination and the fabrication difficulty of a 'dome-like' hemispherical imager, limit the development of bio-inspired wide FOV cameras. Here, a new type of fish-eye imaging system is introduced that has simple lens configurations with a curvilinear image surface, while maintaining high off-axis illumination and a wide FOV. Moreover, through comparisons with commercial conventional fisheye designs, it is determined that the volume and required number of optical elements of the proposed design is practical while capturing the fundamental optical performances. Detailed design guidelines for tailoring the proposed optic system are also discussed.

1. Introduction

In lens design, it is well known that an ideal system can be achieved through overlapping a focal plane, which is usually a Petzval surface, with an image sensor in order to reduce the fundamental aberration. Recently, a curved image sensor was developed [1,2], and this has resulted in a new step being added to optical system design. The advantages, such as the reduced number of optical elements and small package sizes, that result from the curved image sensor have been applied to diverse imaging systems [3–7]. Furthermore, a commercial version of the curved image sensor has already been considered [8]. These sensors have typically been used to design bio-inspired optical systems because there optical devices can provide special features. As a result, research on this topic has been increasing, particularly that mimicking human eyes and insect eyes [1,2,9–11].

However, to date, there has been relatively little research on the ability of these sensors to simplify optical systems. In particular, an imaging system with a wide viewing angle, which is referred to as fisheye camera, has a complex lens configuration comprised of 6–10 lenses (Fig. 1(a)). Although the name of this camera is taken from the visual characteristics of fish eyes, the eye of a fish is composed of only one spherical lens and a curved retina, as depicted in Fig. 1(b) [12]. To date, various fisheye lens systems have been reported and they mimic the wide field of view (FOV) property itself, not the configuration, because realizing a curved image sensor has been almost impossible technically. Now that the research and development of curved image sensors has matured, the simple lens configuration should be considered because it can replace the conventionally complicated optical systems using curvilinear image sensors.

In this paper, a simple fish eye lens system with high performance is reported that utilizes the curved image sensor while exceeding the hemispherical field of view. In this process, three optical systems were designed and evaluated the bioinspired lens structure based on a real fish eye (Fig. 1(c)), hypergon lens-based system (Fig. 1(d)) and Hill sky lens-based system (Fig. 1(e)) previously proposed for wide FOVs [13]. For an optical system inspired by fish eyes (System 1), it is difficult to form a dome-like hemispherical image sensor, and an impractical off-axis brightness characteristic is observed through optical analyses. However, other optical systems such as the hypergon lens system (System 2) and the Hill sky lens-based system (System 3) also exhibit fundamental defects regarding illumination and resolution. Therefore, the proposed system was enhanced through replacing one of the two lenses with a doublet lens (System 4) as illustrated in Fig. 1(f). Through iteratively tailoring the simple fish eye system, the need to reconsider previously proposed optical systems is emphasized because the curved image sensors can offer strategies for old optical systems as simple and high-performance imaging system. Furthermore, in some cases, the combination of natural structures and

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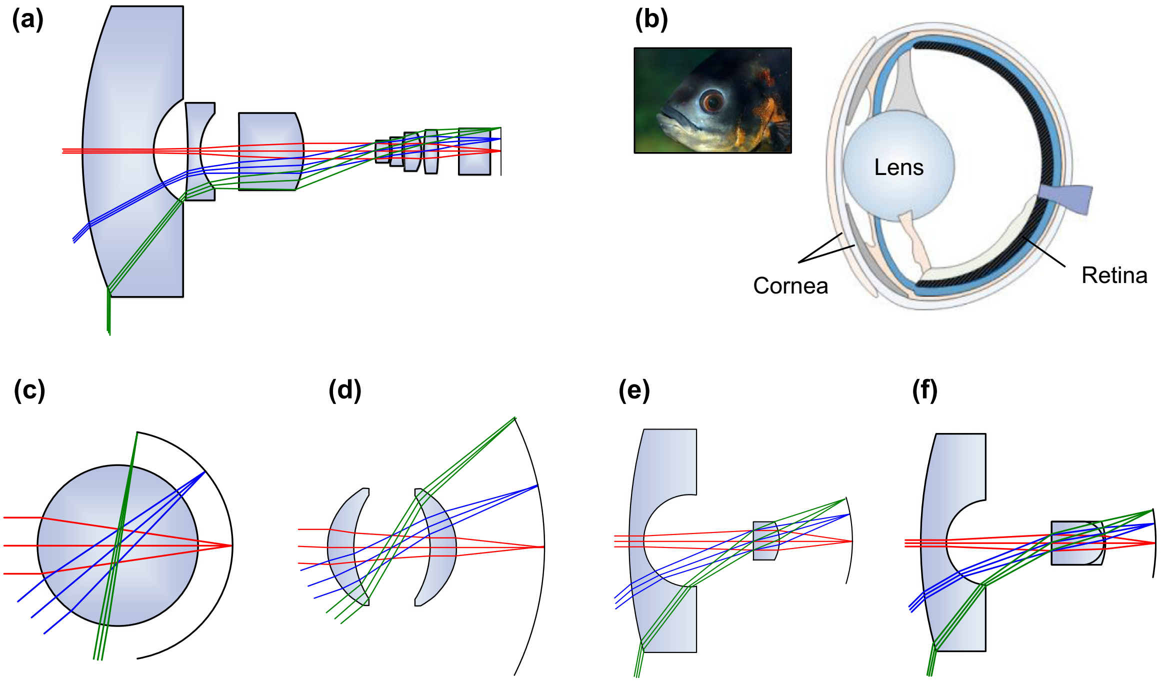

Fig. 1. (a) Conventional fisheye lens optic design with flat image surface [14]. (b) Anatomical image of a teleost eye, which is a representative fish eye in 96% of fish [15]. Inset: image of Astronotus ocellatus [16]. (c) Bio-inspired fisheye lens system (System 1), (d) symmetric optical system (System 2), (e) asymmetric optical system (System 3) with a curved image surface, and (f) Improved asymmetric optical system using a doublet lens (System 4).

artificial design factors (e.g. curved retina and manmade lens configurations) could be more practical and applicable than complete imitation of nature. Details of the design strategies and analysis of the proposed systems are also presented.

2. Simulation methods and optical system design

In order to analyze the lens systems, a sequential ray tracing commercial tool (Zemax, USA) was used to conduct a number of simulations, e.g. spot radius, relative illumination (RI), point spread function (PSF), modulation transfer function (MTF), chromatic focal shift, lateral color, and field curvature. In order to design the proposed optical systems, appropriately constrained merit functions were applied to the overall design process [17].

All optic designs were composed of spherical lens elements only, and a BK7 lens was selected as the base lens. The optical systems were designed in two steps. First, the parameters of the imaging optics, e.g. thickness, lens radii, and distances between each lens, were determined using the local optimization function in the commercial software for wavelengths of 450, 550, and 650 nm. Second, the base lens material (i.e. BK7) was changed to a suitable replacement solution from the library of commercial tool; the parameters were concurrently optimized in order to improve the optical performance using the global optimization function in the software. The information of optimized lens components, such as radii, thicknesses and lens materials for the whole optical systems were listed up in Appendix A.

3. Results and discussion

In order to investigate the resolution characteristics according to the image sensor shapes, i.e. the curved and planar shapes, the spot radius was calculated for each system using the root mean square method as a function of the focus position. The calculated spot radius size for each image sensor type is expressed as a ratio: a_{flat}/a_{curve}, where a_{flat} and a_{curve} are the radius of the spot size on the image plane for the flat and curved image sensors, respectively, for each lens configuration. In order to clearly demonstrate the performance difference depending on the image sensor shape, the values of a_{flat}/a_{curve} were inserted on the focal point (i.e. Focus = 0) with different incident angles as illustrated in Fig. 2(a)–(c). For more accurate comparisons, the radius of curvature (ROC) of the image plane and the F-number of all optical systems were unified to 50 mm and 4, respectively. The ratio of the spot radius means that the larger the ratio of the spot radius, the greater the resolution difference between the planar image sensor and the curved image sensor.

From this perspective, System 1 using a ball lens exhibited the greatest performance improvement when using a curved image sensor compared with the other optical systems because the ratio was more than 1000 at an incident angle of 80°. The size of the spot radius tended to decrease as the incident angle increased, but it is due to the increment of astigmatism, not the resolution grow, as depicted in the inset corresponding to the incident angle of 80° in Fig. 2(a). For the flat image sensor, the spot radius size exponentially increased as the angle increased and became huge with a spot size of approximately 21 mm at an incident angle of 80°. For System 2, the ratio of a_{flat}/a_{curve} increased at a lower rate than System 1. In this system, the astigmatism was more significant at an incident angle of 40° as seen in the inset of Fig. 2(b). Moreover, the illumination converged to 0 due to vignetting at an incident angle of approximately 60°, which can be observed in Fig. 2(d). Therefore, System 2 is not suitable for application in wide FOV imaging systems with curved image sensors. For System 3, the increase in the ratio of a_{flat}/a_{curve} was the smallest among all designs: the performance difference between the flat image sensor and the curved image sensor was not as large as System 1 or System 2. However, in System 3, the increase in astigmatism remained the smallest as the incidence angle increased, as depicted in the inset of Fig. 2(c). These results demonstrate that the curved image sensor provided better optical performance than the flat image sensor in all systems.

Illumination is another critical factor in optical systems; the relative illumination (RI) of each system is compared here. As seen in