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Symmetrical optical imaging system with bionic variable-focus lens for off-axis aberration correction

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ABSTRACT

A bionic variable-focus lens with symmetrical layered structure was designed to mimic the crystalline lens. An optical imaging system based on this lens and with a symmetrical structure that mimics the human eye structure was proposed. The refractive index of the bionic variable-focus lens increases from outside to inside. The two PDMS lenses with a certain thickness were designed to improve the optical performance of the optical imaging system and minimise the gravity effect of liquid. The paper presents the overall structure of the optical imaging system and the detailed description of the bionic variable-focus lens. By pumping liquid in or out of the cavity, the surface curvatures of the rear PDMS lens were varied, resulting in a change in the focal length. The focal length range of the optical imaging system was 20.71–24.87 mm. The optical performance of the optical imaging system was evaluated by imaging experiments and analysed by ray tracing simulations. On the basis of test and simulation results, the optical performance of the system was quite satisfactory. Off-axis aberrations were well corrected, and the image quality was greatly improved.

1. Introduction

The variable-focus lens without moving parts has received much attention because of its advantage that it can dynamically control the focal length by changing the curvature of the refractive surface or its refractive index. Many prototypes based on different physical principles have been reported, and a number of potential applications have been proposed [1–5].

In recent years, researchers have paid increasing attention to the optical properties of the variable-focus lens and the optical imaging system based on this lens [6]. Antonin Miks et al.[7–9] focused on theoretical aberrations of the variable-focus lens and the possible designs of zoom systems based on variable-focus lenses and analysed the surface shape of the variable-focus membrane lens. Dan Liang et al. [10–14] designed optical imaging systems based on variable-focus lens to mimic the human eye structure. Fuh et al. [15–18] proposed variable-focus fluidic lenses with the function of aberration correction and studied the optical properties in experiments. In 2015, Latifi et al. [19] presented a tunable electrowetting-based lens with a wedge-shaped PDMS layer, and analysed the optical properties and visibility of images numerically and experimentally. In 2014, Wang et al. [20] designed an adaptive achromatic doublet composed of double variable-focus lenses. Choi et al. fabricated an array of variable-focus liquid-filled microlenses with a transparent elastomer membrane and electro-active polymer actuators in 2011 [21] and analysed the nonlinear large deformation of the transparent elastomer membrane under hydraulic pressure to investigate its optical performance in 2014 [22].

In previous research, we developed the first prototype of a bionic optical imaging system based on a solid-liquid mixed variable-focus lens according to the Gullstrand's exact eye, called ZJU SY-I [23]. We found that coma, astigmatism, field curvature and distortion in the large field of view were significant. Therefore, we continued further study on this basis and designed a novel optical imaging system, called ZJU SY-II, a new version with better optical properties, better image quality, and well-corrected off-axis aberrations.

On the basis of the optical theory, the symmetrical optical structure can be used to eliminate the off-axis aberrations. Moreover, the crystalline lens of the human eye is a layered structure with increased refractive index from the edge to the centre. Therefore, we proposed a bionic variable-focus lens with symmetrical layered structure to mimic the crystalline lens, and like the human eye lens, the refractive index of the proposed lens increases from outside to inside. On the basis of the proposed lens, we designed an optical imaging system with symmetrical structure, called ZJU SY-II, which mimics the human eye structure. Each of the two PDMS lenses in the proposed lens has a certain thickness to improve the optical performance and minimise the gravity effect of liquid. The rear PDMS lens can be deformed by pumping liquid in or out of the cavity, leading to the variation in the

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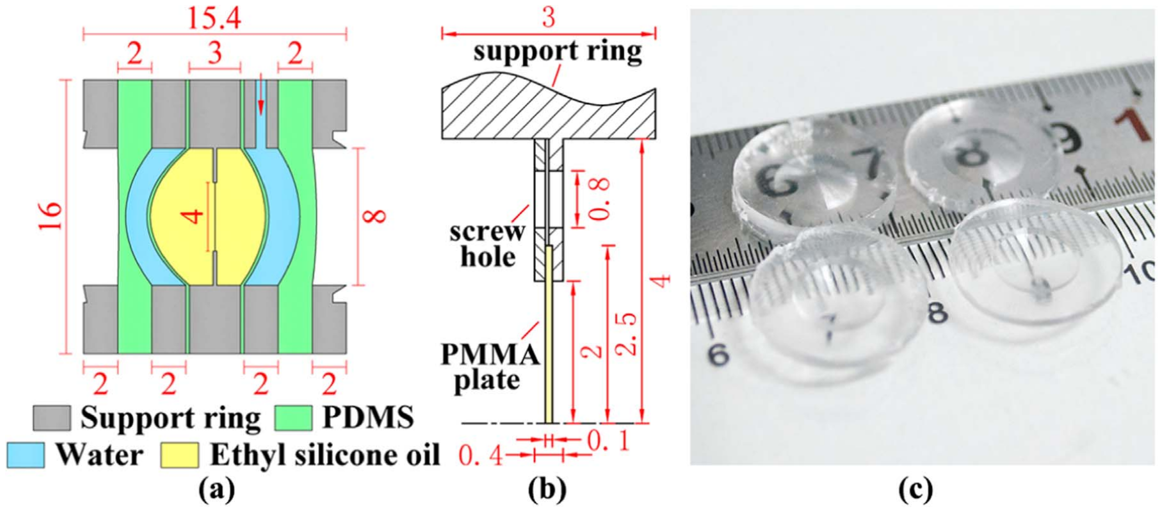

Fig. 1. (a) The structure of the bionic variable-focus lens. (b) The sectional view of the support ring with the thickness of 3 mm. (c) The fabricated PDMS lenses and membranes. The unit in the figure is millimetre.

focal length. The present paper describes the design of the bionic variable-focus lens and ZJU SY-II as well as the analysis of the optical performance through experiments and simulations. The off-axis aberrations were corrected very well, and the imaging quality was greatly improved.

2. Structure design

2.1. Bionic variable-focus lens

To eliminate the off-axis aberrations, we employed symmetrical structure to design the variable-focus lens and the optical imaging system. Through the further research study of the human eye structure, we found that the crystalline lens is a layered structure with increasing refractive index. The structural schematic diagram of the Gullstrand's exact eye is well described in literature [24]. Therefore, we designed a bionic variable-focus lens with symmetrical layered structure to mimic the structure of the crystalline lens.

The structure of the bionic variable-focus lens is shown in Fig. 1(a). In addition to the support rings and the two kinds of liquids, the lens includes from left to right the front polydimethylsiloxane (PDMS) lens, the front PDMS membrane, the rear PDMS membrane and the rear PDMS lens. The diameter of the proposed lens is 16 mm and the thickness is 15.4 mm. The support ring is composed of the polyformaldehyde (POM) material. The PDMS lenses and membranes are composed of the PDMS material. The two kinds of liquids are water and ethyl silicone oil. The closed cavity formed by the two PDMS membranes and the support ring with a thickness of 3 mm is filled with ethyl silicone oil. Two other closed cavities on the two sides of this cavity are filled with water. The support ring with the thickness of 3 mm in the middle of the proposed lens also functions as an aperture. The sectional view of the support ring with the thickness of 3 mm is shown in Fig. 1(b). The aperture is a PMMA plate with the thickness of 0.1 mm fastened in the middle of this support ring with screws. The diameter of the PMMA plate is 5 mm and the aperture diameter is 4 mm. The edges of the PDMS membranes and lenses are flat for mounting. The thickness of the two PDMS membranes is 200 μm, and the thickness of the edge of the two PDMS lenses is 2 mm. For the water and ethyl silicone oil, the thickness of the edge is determined by the height of the corresponding support rings. From left to right, the height of the support rings is 2, 2, 3, 2 and 2 mm. The diameter of the central area with certain curvatures in the PDMS lenses and membranes is 8 mm.

The shape of the front and rear surfaces is different for each of the two PDMS lenses in the initial state. The parabolic surface shape had been employed in ZJU SY-I and had been verified to be suitable for the design and fabrication of the PDMS lens. Therefore, each surface of the PDMS lenses and membranes in the proposed lens is processed into a parabolic surface with specified curvature. The surface curvatures of the PDMS lenses and membranes are the result of the optical optimization design, which is presented in detail below. By pumping water in or out of the cavity through the slim hole, the curvature of each surface of the rear PDMS lens changes, leading to a variable focal length.

Fig. 1(b) presents the two PDMS lenses and membranes fabricated by us. The PDMS product of Dow Coming, Sylgard 184, was selected. As each surface of the PDMS lenses and membranes is designed to be parabolic with specified curvature, we employed the moulding method and machined special moulds for the fabrication of the PDMS lenses and membranes. The fabrication process is shown in Fig. 2(a). The PDMS mixture with the ratio of 20:1 (PDMS/curing agent) was poured into the cavity formed by assembling the upper and lower moulds in the sleeve to carry out the crosslinking reaction. By replacing the corresponding upper and lower moulds and repeating the fabrication process, we could obtain the needed PDMS lenses and membranes. Fig. 2(b) is the special moulds machined by us for the fabrication of the PDMS lenses and membranes.

2.2. Optical imaging system

On the basis of the bionic variable-focus lens, we proposed ZJU SY-II, an optical imaging system with symmetrical structure that mimics the human eye structure. ZJU SY-II consists of a shell, two glass lenses, the bionic variable-focus lens, a plug, a connecting part and a CCD imaging device, as shown in Fig. 3(a). The two glass lenses and the bionic variable-focus lens are mounted in the shell according to a certain order and fastened by the plug. The front glass lens (the left one) plays the role of the cornea. To eliminate the off-axis aberrations,