Journal of Micromechanics and Microengineering

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To cite this article before publication: Yuanyuan Wang *et al* 2019 *J. Micromech. Microeng.* in press https://doi.org/10.1088/1361-6439/ab0e9f

IOP Publishing Journal Title
Journal **XX** (XXXX) XXXXXX https://doi.org/XXXX/XXXX

Fabrication and characterization of a polymeric curved compound eye

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Abstract

Curved compound eyes, i.e. microlens arrays on curved surfaces, are highly desirable for their unique optical properties including wide field of view, tracking of fast moving objects and so on. However, it is technically challenging to fabricate biomimetic gapless microlens arrays. In this work, we report a simple method for fabricating close-packed microlenses in a kind of stretchable polymeric material PDMS on curved surfaces inspired by the vertebrate eyes. The successfully fabricated polymeric curved compound eye consists of more than 6000 close-packed ommatidia with an average diameter of 600 µm for each ommatidium. The ommatidia are located on a convex surface with a diameter of 40 mm and thus a total field of view of about 180° has been obtained. The optical test on ommatidia shows that the NA for each ommatidium is about 0.21 and the imaging result of the whole compound eye is also given. Furthermore, an optical relay system is introduced to integrate with the compound eye to form a biomimetic compound eye camera. The formed camera is shown to have a great potential for a broad range of optical imaging applications, such as surveillance imaging, target detection and tracking, surveying and mapping, collision-free navigation of terrestrial and aerospace vehicles.

Keywords: compound eye, optical relay system, microlens arrays

1. Introduction

The eye is one of the most important sensory organs of animals, it can sense the light and provide the vision of the outside world [1-3]. Compound eyes are a type of animal visual system commonly found in arthropods. Insect compound eyes can be seen as a smart optical imaging system and the angle of view of which is quite large in that their unique curved surface structures. At the same time, the multiple eyes of the compound eye of an insect can simultaneously image the same object and have a highly concentrated central nervous system. Therefore, it can also identify and locate the moving object with a high sensitivity [4-5].

With the development of imaging technology, the single aperture optical system has the limitation on achieving high quality image at a large field of view (normally larger than 90^o) with a miniaturized size. Inspired by insect compound eyes, bionic composite eyes have been developed by copying the structure of biological compound eyes and its imaging principle [6-11]. Since the insect compound eye has multiple imaging apertures, i.e. ommatidia, it can obtain the image of the same object from different view angles at the same time [12-13], and the whole field of view of the compound eye is formed by integrating every sub-field of view from each ommatidium together so that an ultra large field of view for compound eyes can be achieved. It is because its larger field of view that the compound eye has found applications in many fields including radar systems, medical monitoring and sport robots [14-18].

Microlens array on curved surfaces as a key element of compound eyes so far is still challenging to fabricate. For the past few years, many methods have been developed to fabricate the microlens arrays on curved surfaces. In 2012, Liu et al reported a femtosecond-laser-based microfabrication and thermomechanical bending method to fabricate gapless micro-lens array on curved surfaces [7]. In 2015, soft lithography and thermopressing was used by Wang et al for the fabrication of microlens array [8]. In 2016, Deng et al reported a method of fabricating a hemispherical microlens array based on femtosecond laser and thermal embossing [9]. In 2017, Wen-Kai Kuo et al. made curved lens array by soft lithography and thermopressing [10]. However, above mentioned methods have their own limitations or shortcomings such as they are not cost-effective, complex or requiring a long processing time. Whereas the mask based photolithography technique has a relatively lower cost and higher production rate. In this work, we have developed a new process for making bionic compound eyes based on the traditional photolithography technology. By using our method, a large-scale, compact and uniform curved microlens array in PDMS has been fabricated successfully. The fabricated PDMS curved microlens array consists of more than 6000 ommatidia and each ommatidium has a size of 600 μm. The optical properties of curved microlens arrays are then characterized to show its optical imaging capabilities.

There are also other special ways to make compound eye camera [19-23]. For instance, H. Afshari et al designed a new bio-inspired vision sensor (named the Panoptic camera) made of one hundred classical CMOS imagers, which is suitable for real-time acquisition and processing of 3-D image sequences [24]. However, this kind of compound eye imaging system is basically a simply integration of many simple single aperture cameras and therefore it is quite complicated [14,25]. In this paper, we demonstrated a more compact and integrated compound eye imaging system. The new system consists of a curved microlens array, an optical relay system and a CMOS imaging sensor. The optical relay system projects the curved focal plane formed by the curved microlens array onto the focal plane of the CMOS imaging sensor for image receiving. With this simple and smart design, the more compact compound eye camera has been realized.

2. Experimental section

Figure 1 shows the details of the new fabrication process for the fabrication of polymeric hemispherical compound eye. The fabrication begins with a flat microlens array, which was fabricated by a traditional photolithographic and thermal reflow process as is shown in Figs. 1(a)-(d). The photomask has a pattern of circular pad array in chromium with each circle has a diameter of 600 μm and the gap between neighboring circles is about 10 μm. A positive photoresist AZ9260 (AZ Electronic Materials) film with a thickness 50 μm was obtained by applying a two-layer spin-coating process. After exposure and development, a photoresist cylinder array with a period of 610 μm was obtained. The sample was then put onto a hotplate to conduct thermal reflow process as shown in Fig. 1(d). Basically, it was heated at different temperatures from 95^{o}C to 140^{o}C with 10^{o}C as a step and the time duration at each step is 10 minutes. With such a temperature setting, the photoresist cylinder melts and forms a spherical microlens. But it should be noted that the microlens array formed at this stage is on the flat substrate and thus should be called the planar microlens array.

Once the planar photoresist microlens array is formed, a 10 wt% PMMA solution was cast onto the photoresist microlens array and left at room temperature for enough long time to allow PMMA to solidify as shown in Fig.1(e). In this way, a negative microlens array can be replicated into PMMA which could be peeled off readily from the planar photoresist microlens array as shown in Fig.1(f).

In the meantime, a glass hemisphere was used as a mold to replicate the hemispheric surface shape into the polydimethylsiloxane (PDMS) film. The hemisphere has a diameter of 40 mm. The PDMS film was prepared by uniformly mixing the base material and the curing agent (10:1 wt ratio). The gas bubbles generated in the mixing process were removed in a vacuum bubble remover. The mixed PDMS solution was then casted onto the hemispherical mold and placed on a hot plate to solidify. The fully cured PDMS was then peel off from the mold so that a PDMS based spherical curved surface was formed as shown in Fig.1(g). Next, the PDMS spherical surface was stretched to form a flat surface as shown in Fig.1(h). The process was achieved by using a ring metal frame. Firstly, the curved PDMS film was embedded in the metal frame and then fixed to the circular frame by gluing. Then, the bracket was placed in the inner frame and the support frame was finally pressed by the ring to support and stretch the film. As a result, ideal flatness of the PDMS film can be achieved. Fig.2. shows the PDMS film before and after flattening. This step can be easily accomplished due to the unique tensile property of the PDMS material.

Once the stretched and flat PDMS film was obtained, it was then pressed onto the PMMA film whose surface was dispensed with a thin layer of liquid PDMS in advance as shown in Fig.1(i). As the liquid PDMS solution dispensed onto the PMMA surface filled up the negative microlens structure, the positive microlens structure can be replicated into the PDMS film after it is solidified. It should be noted that the mechanical tool had always been applied onto the stretched and flat PDMS film to maintain its flat shape during the solidification process. Once the liquid PDMS was fully cured, the stretched and flat PDMS film had been successfully bonded onto the planar PMMA film. At this time, when the PDMS layer was peeled off from the PMMA layer and was released from the mechanical ring, the PDMS film recovered back to the original hemispherical surface shape. As a result, a hemispherical microlens array in PDMS had been successfully obtained as shown in Fig.1 (j).

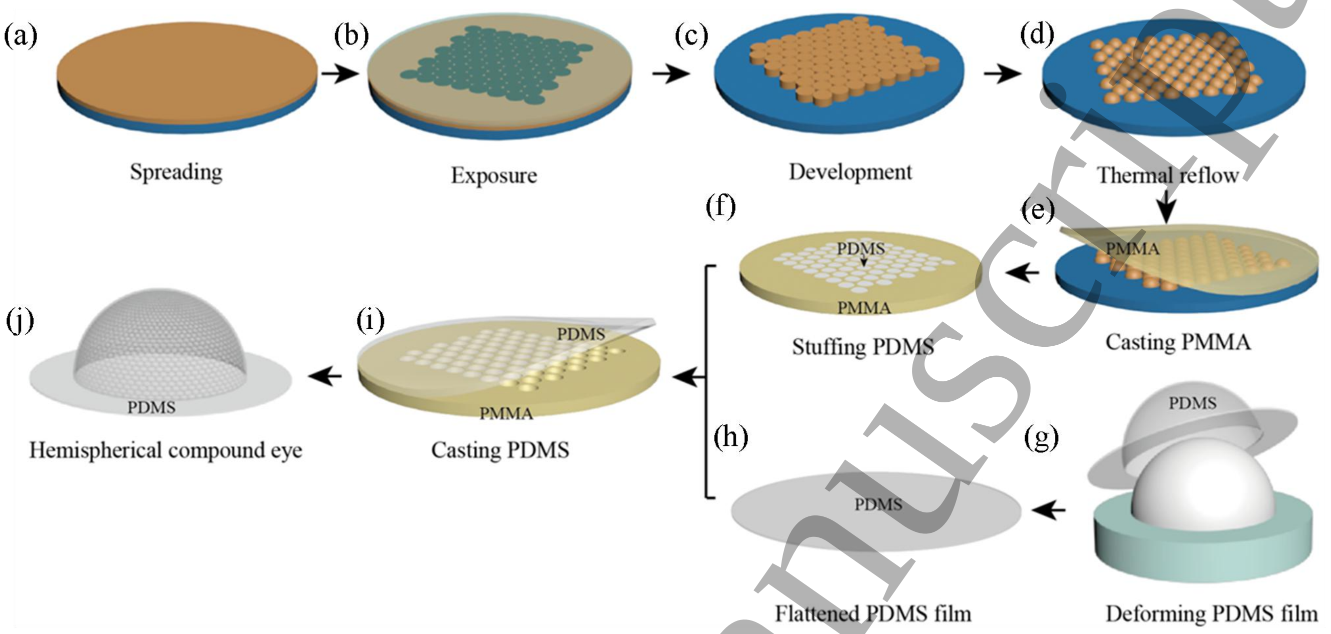

Fig.1. Fabrication process for polymeric hemispherical compound eye.

Fig.2. PDMS film with a curved surface (a) and flat surface (b).

3. Results and discussions

Figure 3 shows the images of the PDMS compound eye structure taken by optical microscope and SEM respectively. As can be seen, the microlens array is quite uniform. The diameter and the sag height for a single microlens was measured to be 600 ± 7.6 μm and 50 ± 2.1 μm respectively. With the refractive index of the microlens material PDMS is n=1.43, it is not difficult to calculate the focal length and numerical aperture of the microlens, which is f =2.09 mm and NA=0.125 respectively. As the microlens array is located on the surface of a hemisphere, the field of view of the compound eye structure is as large as about 180°.

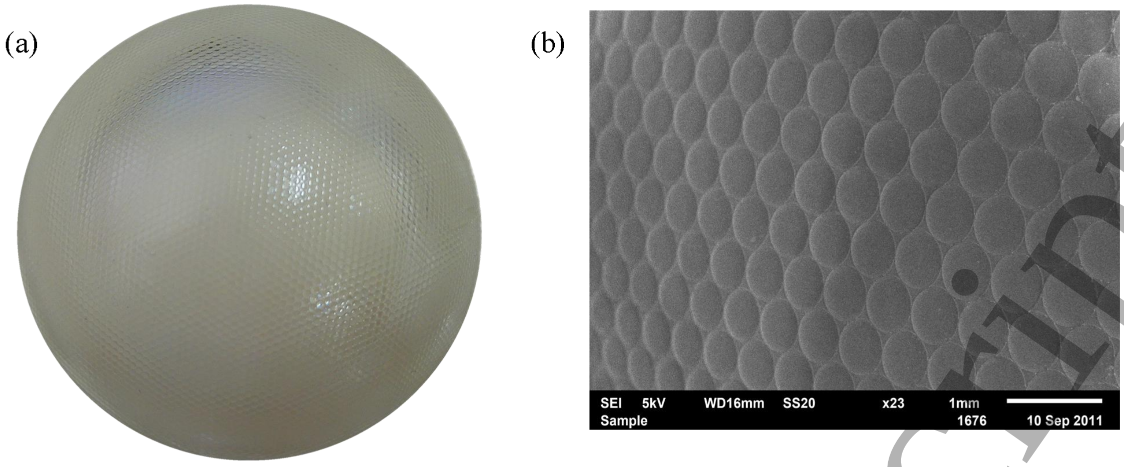

Fig.3. Images of the PDMS compound eye structure taken by optical microscope (a) and SEM (b) respectively.

To test the imaging performance of the fabricated artificial compound eye, an optical imaging system was set up as shown in Fig.4. As can be seen in Fig.4(a), the microlens array is used to image the letter "a" displayed on the screen of an mobile phone. As the microlens array is distributed on the curved surface, the focal plane of the hemispheric compound eye is actually not on a planar surface but a curved surface, which apparently does not match with the planar focal plane of the CMOS image sensor. Microlens arrays viewed from top to bottom from different fields of view of 0°, +40° and +80°, respectively. As can be seen in Fig.4(b), the image formed by the compound eye on the CMOS image sensor becomes blurred from the center to the edge, which is caused by the mismatch between the curved focal plane of the compound eye and the planar focal plane of the imaging sensor. The angular sensitivity function is one of the most important parameters affecting the microlens array imaging capability， it can be characterized by measuring the point spread function (PSF) in different field of view of the curved microlens array. Fig.5(a) shows the optical setup for PSF testing. Where, a 532-nm laser beam was firstly collimated before it incidents onto the curved microlens array. A microscope with a high magnification objective lens and a CCD camera was used to capture the formed focal spot array by the curved microlens array. Fig. 5 (b) shows the captured Airy patterns in different FOVs. Fig.5 (c) shows a comparison of the 2D profile of Airy spot between the measured ones with that of the ideal one. As can be seen, the measurement results are close to the ideal one. The minute discrepancy might be attributed to the non-perpendicular incidence of the laser beam on the microlens, which could be improved further by carefully modified experiment setup.

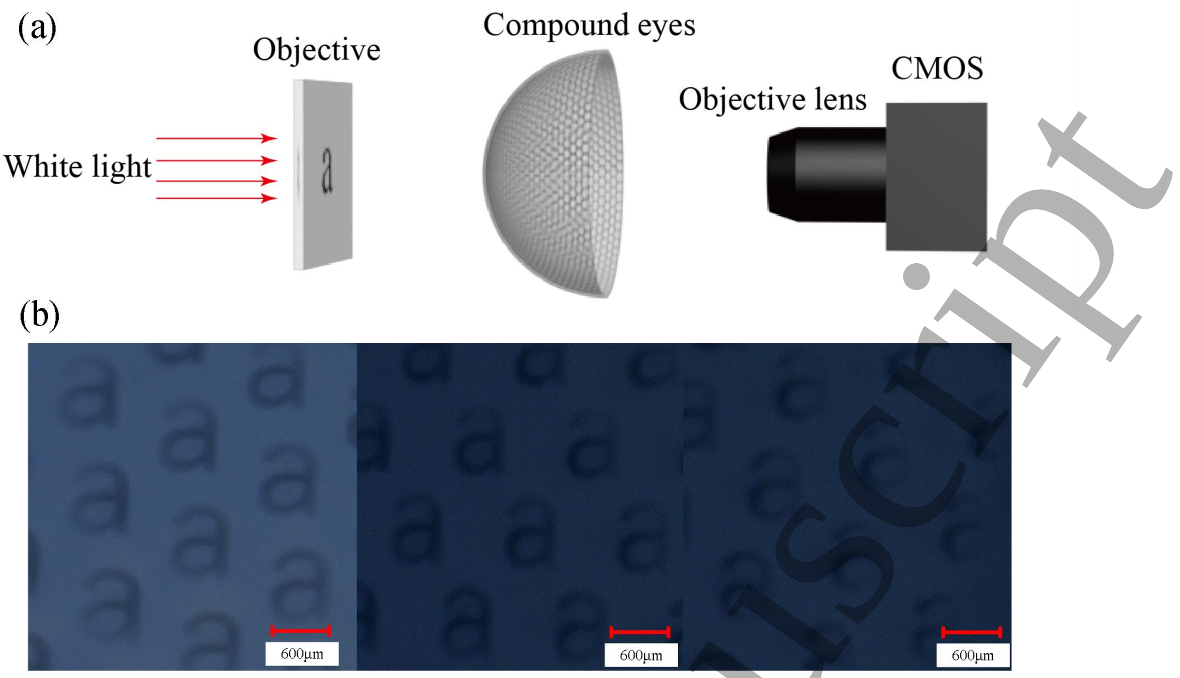

Fig.4.(a) Optical setup used for testing of the imaging ability of the curved microlens array. (b) Image of the letter 'a' formed by the hemispherical micro-lens array viewed from different FOVs of 0°, +40° and +80° respectively.

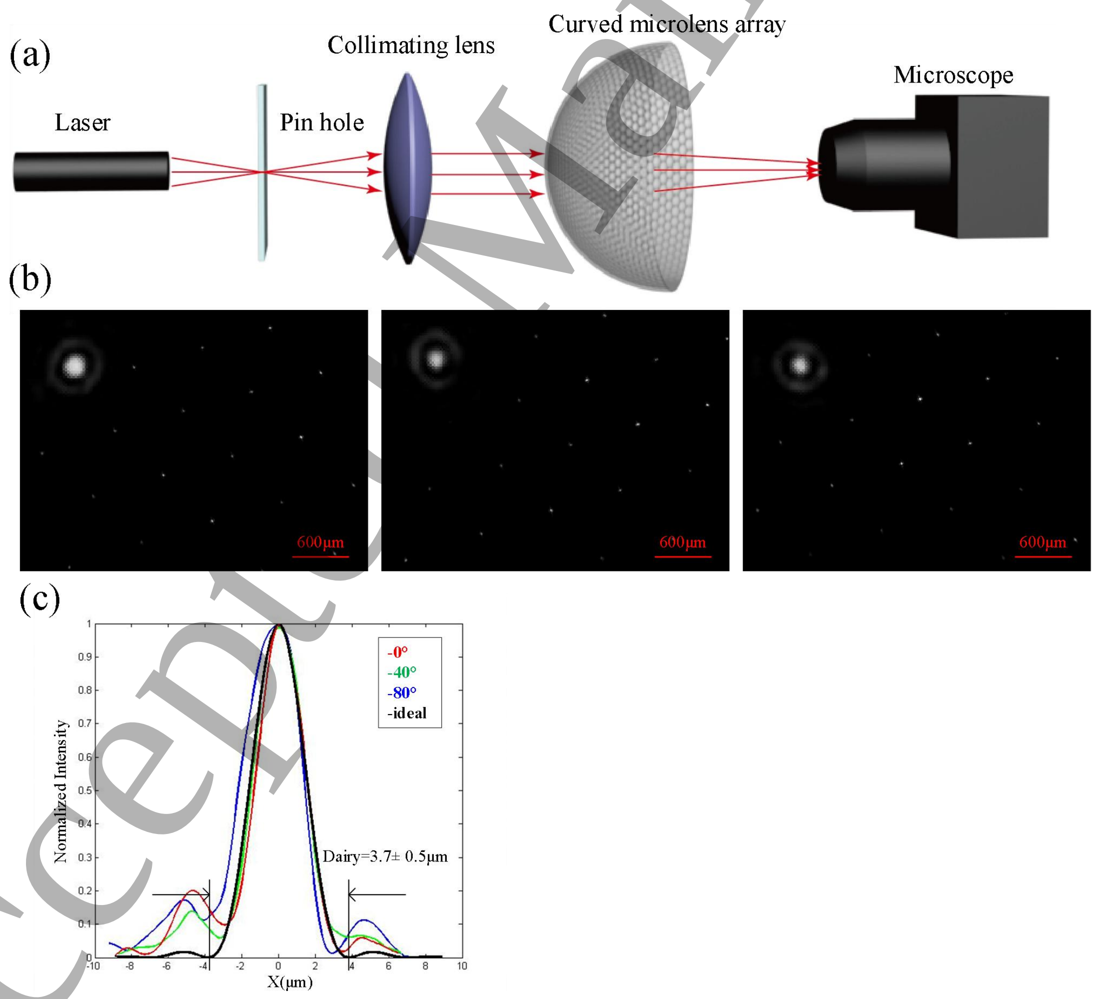

Fig.5(a) Experimental setup for measuring the PSF of the curved microlens array, (b) PSF measurement results in different FOVs of 0°, 40°and 80°. (c) Comparison between the measured PSFs with that of the ideal ones.

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Fig 6. The optical relay system. (a) 3D optical path model, (b) The prototype.

In order to overcome the mismatch problem between the curved focal plane of the hemisphere compound eye and the planar focal plane of the CMOS imaging sensor, we have introduced an optical relay system in between of them as shown in Fig.6. The focal length of the optical relay system is 5 mm, the maximum field of view is 120º, the relative aperture is about 1/3, the maximum aperture is less than 22 mm and the total optical length is 48.6 mm. The design results are shown in Fig.7. As is shown in Fig.7(b), the MTF value is larger than 0.38 at the Nyquist frequency and larger than 0.7 at half of the Nyquist frequency. The RMS of the radius of the spot diagram is close to or smaller than Airy's disc represented by blue cross as shown in Fig.7(c). In general, the aberrations of the optical system are well controlled except that the distortion is relatively large due to the ultra-large field of view. However, it could be corrected by using proper image processing algorithms.

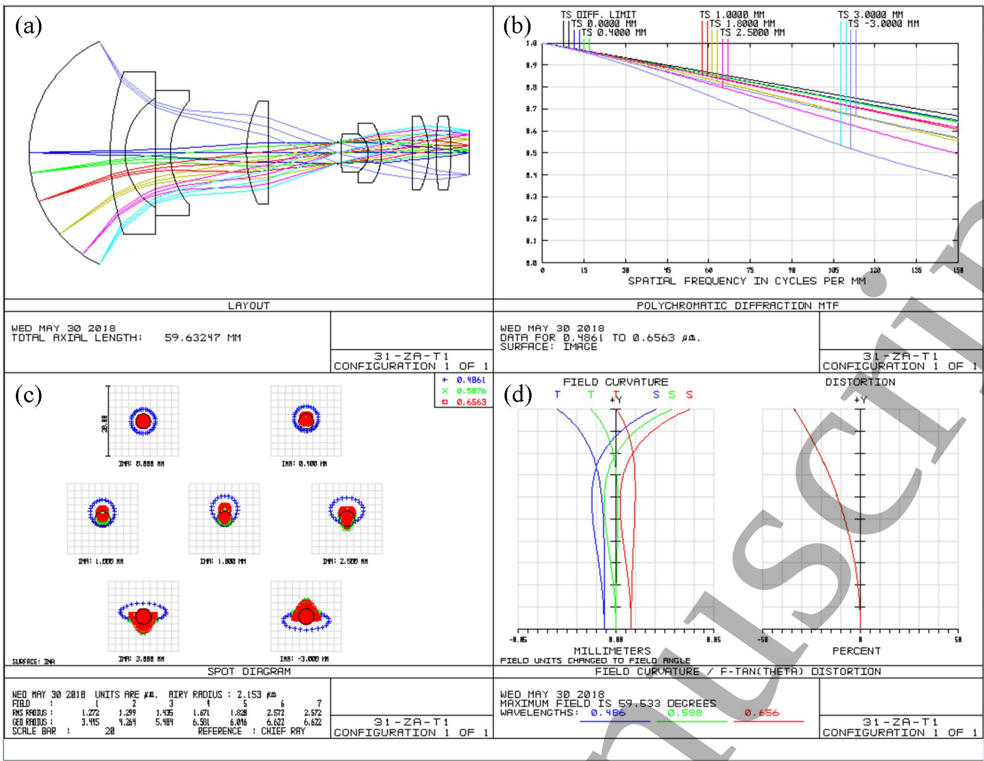

Fig 7. The light path and image formation simulation. (a) Layout, (b) MTF, (c) Spot diagram, (d) Field curvature.

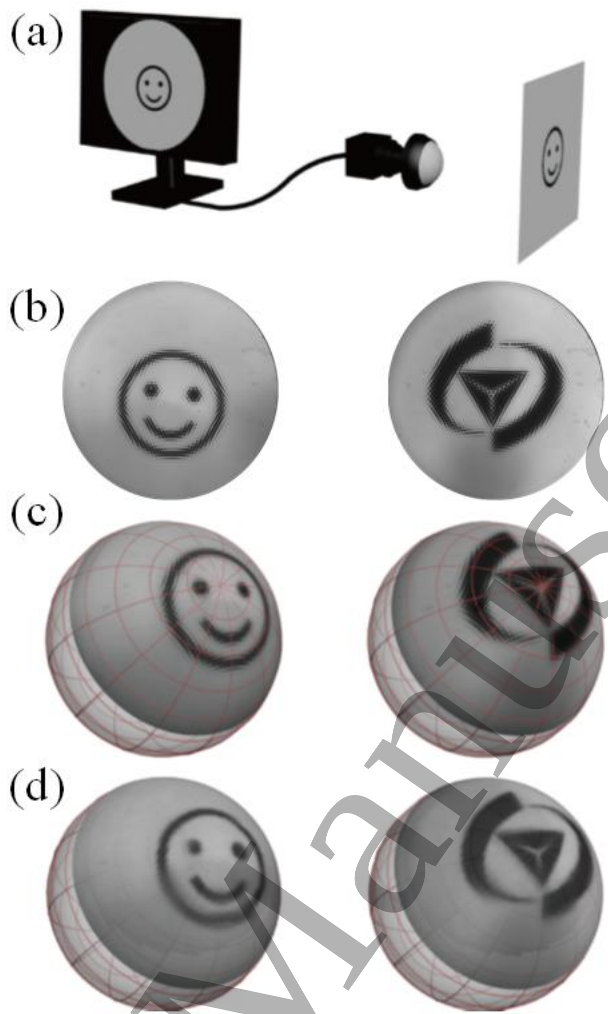

Fig 8. Compound eye imaging setup and results: (a). Imaging schematic, (b). Original image, (c). Mapped image, (d). Reconstructed image.

The designed optical relay system was fabricated and integrated with the polymeric curved compound eye to form the final compound eye imaging system. Fig.8 shows the optical imaging setup and the corresponding experimental results. The imaging process of the compound eye imaging system is as follows. Firstly, the object placed in front of the compound eye imaging system is imaged by the curved microlens array to form an image on the curved focal plane of it. Next, the optical relay system transforms the image on the curved focal plane onto the planar focal plane of the CMOS imaging sensor and the obtained original images are shown in Fig. 8(b). Since the image formed on the CMOS imaging sensor is composed of thousands of sub-images, and each sub-image only corresponds to a small portion of the object due to the large object and small field of view of each ommatidium. To restore the full information captured by the compound eye imaging system, a flat-to-spherical mapping process was made and the result is shown in Fig. 8(c). Since there is some image overlap between adjacent sub-images, appropriate pixels were extracted from each sub-image and then stitched together to form a final reconstructed image as shown in Fig. 8(d). As can be seen, the final image is quite clear and has no obvious distortion. In our prototype, a commercial CMOS imaging sensor, Sony IMX264 is adopted as the photoreceptor. The data signal-processing module is used to image acquisition and pre-processing, and then transmitted the image signal to the computer though a USB interface. Further image processing is done on the computer. The image obtained consists of about 4400 sub-images and each sub-image covers about 20×20 pixels.

Table 1. a comparison of our work with others.

	FOV	Whether to join the relay image conversion system or not	Solve the problem of detector incompatibility	Composition of optical systems	Number of cameras

2013 Digital cameras[22]	About 160°	no	yes	yes	many
2014 compound eye[8]	About 60°	no	no	no	
2016 Artificial compound[9]	About 140°	no	no	no	
2017 a multi-focusing artificial compound eyes[26]	over 140°	no	no	no	
This paper	About 160°	yes	yes	yes	one

4. Conclusions

In summary, we have developed a novel fabrication process for realization of polymeric curved microlens arrays. A hemispherical polymeric compound eye element has been successfully fabricated by using the developed process in PDMS. There are more than 6000 microlenses in compound eye and each microlens has a diameter of 600 μm and NA of 0.125. The Result of compares my present work with others are listed in Table 1. The fabricated polymeric compound eye was then optically characterized by introducing an optical relay system between it and the CMOS imaging sensor. By integrating the polymeric compound eye, optical relay system and the CMOS imaging sensor together, a curved compound eye imaging system was formed. The optical imaging experiment shows that it has a relatively good imaging performance. Since the developed fabrication process is quite simple and cost-effective, it is expected to have great potential to be applied in the fields including medical catheters, endoscopic imaging and machine vision for ultra-large field imaging purpose.

Acknowledgements

The financial support from Natural Science Foundation of China under grant number 61475156 is acknowledged.

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