A BIOINSPIRED 3D ARTIFICIAL COMPOUND EYE WITH FOCUS-TUNABLE SINGLE LENSES
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ABSTRACT
This paper reports a biologically inspired artificial “compound eye” image acquisition system, which has a wide field-of-view (FOV) and a tunable focal length. The system consists of an array of liquid micro-lenses enclosed in compliant membranes, a flexible base diaphragm, and a smart microfluidic system. Similar to the compound eyes of some insects, the 3D structure allows the individual lenses to orient omni-directionally in the space and thus to obtain a wide FOV. Meanwhile, comparable to a human camera eye, each individual lens has an adaptive working distance, allowing autonomous focusing on objects at different distances. Because of these unique features, the system can be readily used for medical diagnostics such as endoscopy imaging, optical sensing and lab-on-a-chip technologies with improved optical capability.

KEYWORDS: Compound eye; Bioinspiration; Optofluidics

INTRODUCTION
Conventional solid state lenses, the critical component used in optical microscopy, suffer from two major shortcomings: limited field-of-view (FOV) and fixed focal length. The imaging system based on such lenses require multiple cameras and a complicated peripheral control system to achieve a wide FOV and dynamic focusing. These require high manufacturing cost and operation complexity, and restrict the wide applications [1, 2]. In order to address these issues, bioinspired optical components have attracted significant research interests. For instance, Dong et al. reported the development of adaptive liquid microlenses that can tune its focal length using a stimuli-responsive hydrogel, in a similar manner as the way the iris muscle works in a human eye [2]. Jeong et al. reported an array of tiny polymeric lens that reside on a curved surface, which mimics the insect compound eye and exhibits a wide FOV [3]. Despite the advances of these studies, the microlenses systems often accompany complicated fabrication processes and the use of special materials, which, to some extents, inhibits their applications.

In this work, we have developed a 3D artificial compound eye with individually focus-tunable lenses, by combining the strengths of both the human camera eye and insect compound eye. This innovative compound eye structure realizes a wide FOV and adaptive focusing simultaneously in a compact optofluidic microsystem. The system is fabricated with the widely-available PDMS material using a standard softlithographic process, which enables further miniaturization of optical microscopy system with improved imaging performance.

THEORY
The schematics of a human camera eye and an insect compound eye are shown in Figure 1. It is seen that the human eye can see objects at different distances clearly by autonomously adjusting the focal plane [4]. An object image with high resolution is projected through the adaptive lens to the retina surface where the optic nerves sit. Despite of high resolution, human eye suffers from a narrow FOV. In other words, the eye can only observe a small field. In order to view objects out of the field, the eye ball or the head needs to be rotated by the muscles. In contrast, the insects usually have a compound eye which is composed of a large number of focus-fixed ommatidia (small eyes), each of which corresponds to an individual photoreceptor and contributes a single pixel of the entire vision. The image projected by the compound eye thus has relatively lower resolution. The FOV due to the unique configuration, however, can be significantly better than those obtained by the camera eyes. Some insects, e.g. dragonfly, have a FOV of nearly 360° [5, 6]. They can thus have a full view of their environments without turning eyes or heads.

Figure 1: Structures and optical paths of (a) a human camera eye and (b) an insect compound eye, showing how the angle representing the FOV increases from θ to φ.

Figure 2: Schematic of the artificial compound eye in this work. (a) perspective view and (b) cross-section.
Inspired by the natural eyes, we propose an advanced artificial compound eye that integrates the strengths of both a human eye and an insect eye, using an optofluidic method. The schematic design of the system is illustrated in Figure 2. As seen from the perspective and cross-sectional views, the device is composed of two layers of microfluidic networks. In the upper layer, the channel is covered with an array of ultra-thin compliant membranes. When the refractive medium flows into the upper channel by a well-controlled pressure, the ultra-thin membranes deform upon a differential pressure ($P_1$). An array of small lenses with appropriate curvatures is formed. In the lower layer of microfluidic network, the large polymer membrane can be deformed by flowing fluid in the bottom channel and inducing a differential pressure ($P_2$). The array of the ultra-thin membrane sit on the large polymer membrane. As the large membrane deforms, a 3D hemispherical structure forms where each single lens orients in a certain direction to obtain a field. By collecting the fields acquired by all the single lenses, a wide FOV is obtained. The focal plane of each lens can also be independently changed, allowing simultaneous focusing on multiple objects at different directions and on different focal planes.

**FABRICATION**

The fabrication and assembly processes are illustrated in Figure 3a. A double-layer replica molding process is used to fabricate the lenses (Figure 3b). The PDMS membranes are then fabricated by soft lithography. In this work, the ultra-thin membrane on each single lens is 1.5mm in diameter and 10 $\mu$m in thickness. The center-to-center distance between the neighboring lens is 3 mm. The large PDMS membrane is 10mm in diameter and 150 $\mu$m in thickness. The top layer PDMS substrate and the large PDMS membrane are aligned and bonded to form a microfluidic network that delivers refractive medium to each single lens. The stack is then bonded with the bottom layer PDMS substrate to form a microfluidic network that delivers fluid to the large PDMS membrane. During operation, refractive mineral oil (Sigma Aldrich®, refractive index=1.33) is pumped in the upper layer of microfluidic network. Deionized (DI) water is pumped into the lower layer of microfluidic network. Figure 3c shows a prototype of such device while the large PDMS membrane and the small lenses are both pumped.

**EXPERIMENTAL**

The focus tuning characteristics of a single lens is investigated by the fluorescence ray trace method [7]. A parallel beam of light from green laser ($\lambda=532$nm) is shining through a single lens. The focusing behavior of the lens is visualized using an aqueous solution with Rhodamine fluorescent dye (Sigma Aldrich®, USA), which is positioned immediately behind the lens. The concentration of the dye is sufficiently low so that the incident light can propagate through the solution without being significantly attenuated or absorbed. The focusing power of the single lens is controlled by adjusting the pressure driving the refractive medium. To demonstrate the FOV improvement, a list of letters is printed in a row on a planar surface and is used as the object, which is placed at a certain distance from the lens. The object image projected by an array of single lenses is captured using a digital camera (Casio® EX-F1).

**RESULTS AND DISCUSSION**

As the refractive medium flows in the microfluidic channels, the focal length of each individual lens changes. Figure 4a shows that as the pressure increases from zero to 10psi, the focal length of a single lens can be tuned from $+\infty$ to less than 2mm. The relationship between the driving pressure and the focal length (Figure 4b) shows that the focal length is sensitive to the pressure when the pressure is low (less than 4 psi), where a modest pressure change induces a large change in the focal length.

![Figure 3: Experimental demonstration. (a) Fabrication process of the compound eye; (b) Photograph of the lens mold; (c) Optical photograph of a compound eye prototype.](image)

![Figure 4: (a) The ray trace method shows the focus tuning process by adjusting the pumping pressure; (b) The curve shows quantitatively the focal length as a function of the pressure.](image)
As the pressure increases, a substantial pressure change is needed to induce the same amount of focal length change.

Figure 5 illustrates how the FOV improves by using the configuration of artificial compound eye. The large PDMS membrane first keeps flat ($P_2=0$ psi), while the single lenses are tuned to focus on the letter “K”. Afterwards, the fluid flows into the upper layer of microfluidic channel, the curvature of the single lenses are changed in the meantime to focus on the object. It is seen that at $P_2=2$ psi, the lens in the center sees the letter “K”, while the two adjacent lenses see the region between the letters “K” and “L”, and the region between the letters “K” and “J”, respectively. When the pressure $P_2$ increases to 5 psi, the letters “M”, “L”, “J”, and “K” are all brought into the view. Given the geometric configuration of the setup, it is calculated that the FOV increases from 40° to 120° as the pressure increases from 0 psi to 5 psi.

CONCLUSION

In conclusion, an optofluidic system inspired by the insect compound eye is developed, which has a large FOV and focus-tunable single lenses. The fluorescence ray trace study reveals that the adaptive lens can tune its focal length from $+\infty$ to less than 2 mm with a modest pressure less than 10 psi. The FOV of the imaging system increases from 40° to 120° by changing the curvature of the large polymer membrane where an array of single lenses reside. This system combines the strengths of both human camera eye and insect compound eye, and is expected to add capability of current optical microscopy systems.

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REFERENCES


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