A rapid precision fabrication method for artificial compound eyes

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ABSTRACT
A bionic artificial compound eye manufactured on a concave mold with precision engraving method for imaging, which allows for the rapid fabrication of large-scale compound eyes at a low cost. Thousands of concave structures are accurately machined and positioned omnidirectionally in concentric rings with a minimum diameter of 100 μm on a hemisphere. The PDMS ommatidia can be obtained once replicated, which can greatly improve preparation efficiency, and the peel-off process can also be optimized by alcohol ultrasonic without edge damage. The optical performance and field of view of the artificial compound eye are also investigated, and the experimental results are around 120°. Furthermore, the combination of the prepared compound eye and the commercial CMOS camera successfully captures images of different shapes.

KEYWORDS
Compound eyes; precision engraving; imaging system; microlens array

1. Introduction
Curved microlens arrays inspired by the compound eyes of insects in nature are extensively applied in three-dimensional imaging, pinhole cameras, as well as unmanned aerial navigation, and medical endoscope.\(^1\)–\(^6\) Compared with the previous planar lens arrays, curved compound eyes are attracting more and more attention due to their advantages, such as a larger field of view (FOV) and higher sensitivity for fast-tracking and detection of moving targets.\(^7\)–\(^10\) In general, microlens arrays are made up of thousands of micron-sized lenses, known as ommatidia in insect compound eyes, that have minimal surface roughness, good homogeneity, and are sensitive to external optical information, imposing significant demands on processing accuracy.\(^11\)–\(^14\)

In the last decade, there has been tremendous improvement in the fabrication technologies of artificial compound eyes. Several approaches have been proposed, such as direct laser writing, thermal reflow of photoresist, self-assembly, microdroplet jetting and femtosecond laser aided wet or dry etching.\(^15\)–\(^18\) Despite considerable advances, these techniques still have certain drawbacks, such as high time consumption, high process complexity, lack of fabrication flexibility, and difficulties in consistence. Femtosecond lasers and precision machining are the two major ways for constructing concave structures directly on curved substrates currently available. Bian et al. proposed employing femtosecond laser-assisted wet etching directly on a curved glass substrate to construct 3000 ommatidia in 2016.\(^19\) Femtosecond laser needs expensive experimental equipment and requires point-to-point scanning, which is time-consuming and labor-intensive.
Moreover, the introduction of corrosive liquids, such as hydrofluoric acid into wet etching increases the danger of the experiment, and the corrosion rate and time cannot be precisely controlled. In 2019, Jin et al. used a two-photon polymerized femtosecond laser direct writing method to fabricate a curved SU-8 template that can be reused more than 50 times without deformation.\textsuperscript{[20]} They prepared only 7 and 19 ommatidia in a much shorter time, verified the optical microscope imaging, but did not integrate it into a commercial complementary metal-oxide-semiconductor (CMOS) camera to form a miniature imaging system. And the number of compound eyes prepared is much lower than that of insects in nature. Compared to the compound eyes prepared by femtosecond laser processing, with the modernization of equipment, five-axis precision machining equipment can now efficiently and rapidly produce a wide variety of structures on flat, spherical, and aspheric surfaces.

In this paper, a bionic artificial compound eye based on a concave mold manufactured by precision engraving methods for imaging is described and investigated, which has the potential to be combined with a commercial CMOS sensor to acquire target position information. This method saves time and labor, and one-time fabrication of templates can be reused more times, which greatly improves the efficiency of preparing artificial compound eyes. The compound eye prepared by this method has a roughness of about 40 nm and is capable of clear imaging observation. The focal length is adjusted by an optical microscope test platform to obtain a clear image, and the FOV is also measured at $\sim$120°. The complete morphology of the compound eye can be obtained by replicating the structure once, avoiding the deviation of the morphological dimensions caused by multiple replications. The method can achieve low-cost and low-consumption mass preparation of artificial compound eyes, which is meant for practical applications. Furthermore, the combination of the prepared compound eye and the commercial CMOS camera successfully captures images of different shapes.

2. Experimental methods

2.1. Design and fabrication of the curved concave mold

Different from the method mostly related to replications from a planar concave membrane, we directly fabricated the hemispherical groove structures on the curved surface.\textsuperscript{[21–25]} With the continuous updating of precision machining equipment, the accuracy of machinable microstructures is also increasing. Here, we utilize the precision equipment (JDGR 200), which adopts fully closed-loop control technology combining with multi-axis positioning and five-axis simultaneous machining to fabricate curved polymethylmethacrylate (PMMA) molds. The X–Y–Z axes, which regulate three-dimensional (3D) movement, and the B–C axes, which control rotational motion, are among the five axes. This machine has “0.1 μm feeding and 1 μm cutting” capability, strong vibration suppression, and low tool wear. Adopting on-machine measurement and intelligent correction technology, it can also realize the functions of automatic workpiece alignment and reconstruction of the coordinate system of machining surface features, which can improve the accuracy and efficiency of product machining, simplify the five-axis machining operation, reduce the time of machine setting and reduce the requirement of tooling for products.

Considering the minimum accuracy of the precision machining, Figure 1(a) shows that a concentric circle construction was designed with customized the tapered ball cutter with a diameter of 100 μm, satisfying the minimum accuracy specifications in the diameter and interval of the small concaves. The surface groove structure was directly drawn with the 3D design software Creo, and the file was then loaded into the precision machining equipment to begin the milling operation. The large diameter ball cutter was used to rough out the required profile, followed by the small diameter tapered ball cutter to complete the microstructure, and eventually, the resultant chips were discarded. The curved concave mold, which measured with an internal diameter of 10 mm and an external diameter
of 12 mm was obtained as shown in Figure 1(b) after precision engraving. A total of 7734 groove structures with a diameter of 100 μm were finally fabricated on the curved PMMA substrate.

2.2. Replication process from PMMA mold

To obtain a curved microlens array (MLAs) with convex structure, polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning, USA) mixture composed of PDMS precursor and curing agent with the weight ratio of 10:1 was poured into the concave mold as illustrated in Figures 2(a) and (b). To avoid thermal deformation of the mold, the PDMS was cured at room temperature for 24 h, since the curing temperature of PDMS is similar to the glass conversion temperature of PMMA.\cite{15} The cured device was immersed in a petri dish with anhydrous ethanol and sonicated for 5 min, which will make it easier to separate the PDMS from the PMMA mold as illustrated in Figure 2(c). Figure 2(d) shows the compound eye with a completed convex structure that was demolded from the PMMA concave mold.

If the cured PDMS was peeled out with tweezers directly from PMMA mold, different degrees of damage to the inside and edges of the device will occur. Figure 3(a) depicted the inside of the damaged structure. When trying to separate it with tweezers, the tip of the tweezer tends to stick into the structure and resulting in severe damage. Of course, if the demolding is done only at the edges, although the breakage in the middle part is relatively insignificant, the structure will easily fall off at the edges as shown in Figure 2(b) and the inset picture. Therefore, it is not feasible to separate PDMS directly from the PMMA mold. The whole device was put into a petri dish filled with alcohol and sonicate for 5 min. The reason for choosing alcohol is that PMMA molds are soluble in organic solvents, such as acetone, and the ultrasonic temperature is set to room temperature, which will lead to deformation of the PMMA mold if the temperature is high. After sonicating, the whole PDMS with integral edges was obtained as illustrated in Figure 3(c).

3. Results and discussion

3.1. Characterizations of precision machined eyes

Three concentric circles at different positions in the mold were selected for observation with a super-depth-of-field microscope (VHX-5000) as depicted in Figures 4(a)–(c). Each component in
the mold can be manufactured into a concave configuration and has an average diameter of ~100 μm, suggesting that precision engraving equipment is capable of achieving aspheric machining with minimal accuracy. The concave structures of each circle are virtually on the same horizontal plane as the cross-sections depicted in Figure 4(d). However, the machining error and the knife cutting fault resulted in the phenomenon of a slight unevenness in the image.

The contour of the entire mold was characterized by VHX-5000. The recessed structures are equally distributed over a hemispherical concave surface as shown in Figures 5(a) and (b) illustrate its cross-sectional profile. The convex structures conforming to the groove structure were generated with great replication accuracy during the PDMS replication process as depicted in
Figure 5(c). The profile of the convex structures in Figure 5(d) shows that the replication process is complete and there are no missing structures.

The high-resolution scanning electron microscope (SEM) was employed to observe the convex structures on the hemisphere as shown in Figure 6(a), demonstrating that each concave structure can be replicated in its entirety. The roughness of the processed mold is 64 nm. The surface roughness measured by Atomic Force Microscope (AFM) was about 40 nm in the area of $5 \times 5 \mu m$ as depicted in Figure 6(b). Lower PDMS surface roughness indicates greater optical imaging ability and improved light transmission, which is required to ensure that every ommatidium can be imaged.

### 3.2. Optical performance

To evaluate the imaging quality of the compound eye, an optical microscope imaging test platform with a CCD camera, an objective lens, the constructed compound eye, and an imaging mask labeled “SJTU” was established, as shown in Figure 7(a). Firstly, the objective lens was aligned directly above the dome of the compound eye, and the distance between the compound eye and the objective lens was adjusted so that the focused spot can be observed. Then the mask was placed under the compound eye, and the clear imaging letter “SJTU” on the screen was found by continuously adjusting the distance between the compound eye and the mask as illustrated in Figure 7(b). The focusing spots are not on the same plane since all the ommatidia are consistently and uniformly scattered along the top of a hemisphere. Therefore, when adjusting the distance between the objective lens and the MLA, there is a difference in the imaging of the letters at different positions captured by the CCD. As the objective lens moves downward, the
focus position of the spot gradually moves toward the outer circle. Figure 7(c) focused on the inner few turns, showing the imaging of “S” and when the objective lens moving down, the focusing position changed, and the “S” of the outer few turns gradually shows clear as depicted in Figure 7(d). When concentrating on different areas, four letters were caught indicating that the compound eye has good optical performance with each ommatidium having the potential to generate clear pictures due to the excellent quality and uniformity of each unit.
3.2.1. FOV measurement

He-Ne laser with a wavelength of 632.8 nm, a beam expander, a filter, a rotating platform and sliding stages, 4× objective lens, CMOS camera, and a computer screen for receiving images were used to set up the optical test platform for measuring FOV as shown in Figure 8(a). Figure 8(b) shows the spot diagram obtained when focusing at the center of the compound eye. The information of the light spot at different angles is collected and captured by rotating the rotary table. Figure 8(c) depicts light spots created by rotating 20°, 40°, and 60° to the left, respectively, whereas Figure 8(d) illustrates light spots rotated the same degrees to the right. It can be demonstrated that each small eye can form a corresponding spot and that the FOV angles are symmetrical. The ultimate FOV of the precisely machined compound eye was measured to be 120°. The FOV could theoretically reach 180° if the designed radius and height were identical, however owing to the rotary table’s limitations, the spot information at the edge was not fully exhibited.

3.2.2. Imaging system

As demonstrated in Figure 9(a), the compound eye is integrated with a commercial CMOS camera to form a compact imaging system. The optimal focal length for capturing good images is obtained by shifting the lens sleeve up and down and changing the base of various diameters. Figure 9(b) is the captured heart imaging in the center and Figures 9(c) and (d) are the imaging of the plus sign and triangle captured in different positions, respectively. Each small eye can be individually imaged, although the imaging looks a little blurred, that may be because of the incomplete bump structure during the precision machining process.
4. Conclusion

In this paper, we proposed a bionic artificial compound eye for imaging that is based on a concave mold fabricated by advanced precision engraving technologies, allowing for the rapid preparation of large-scale microlens arrays at a low cost and with less labor. The artificial compound eye imaging system can provide a large field of view as well as a large amount of surrounding environmental information for microlight devices with small size, lightweight, and high-resolution target monitoring capability. Thousands of concave structures are accurately machined and positioned omnidirectionally in concentric rings with a minimum diameter of 100 μm on a hemisphere. Precision machined molds can be reused multiple times without deformation, and the
alcohol ultrasound optimized demolding process also allows for efficient and rapid preparation of artificial compound eyes. Furthermore, the compound eye's FOV is measured to be around 120°. The prepared compound eye can be combined with the commercial CMOS camera successfully to capture images of different shapes, but also the quality and resolution of the images are anticipated to improve. The artificial compound eye imaging system will provide a visual navigation device for robotic drones and other robots, which can correctly determine the location, direction, and distance between the robot and the target objects in the surrounding environment, to smoothly pass through the obstructed environment and make the robot’s movement more flexible and freer in the future.

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Disclosure statement
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