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Microfluidic-assisted 3D-printed eye (MAP-eye): a biomimetic ommatidium array with direct full-colour 3D to 2D panoramic imaging and position tracking

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ABSTRACT

After half a billion years of evolution, arthropods have developed sophisticated compound eyes with extraordinary visual capabilities that have inspired the development of artificial compound eyes. However, the limited 2D nature of most traditional fabrication techniques makes it challenging to directly replicate these natural systems. This work demonstrates a microfluidic-assisted 3D-printing technique that can be used to replicate a 3D compound eye. The microfluidic-assisted 3D-printed eye (MAP-eye) consists of 522 microlenses on a 5 mm-diameter hemisphere to mimic the 522 ommatidia of a natural compound eye. Each microlens is connected to the bottom planar surface of the MAP-eye *via* intracorporal refractive-index matched waveguides to mimic the rhabdoms of a natural eye. Full-colour 170° wide-angle panoramic views and position tracking of a point source have been realized by placing the MAP-eye directly on top of a commercial planar imaging sensor; the ability to use the MAP-eye with any commercially available imaging sensors presents numerous advantages including improved scalability, high sensitivity, and high-speed imaging. As a biomimetic analogue to naturally occurring compound eyes, the MAP-eye's full-colour 3D to 2D mapping capability has the potential to enable a wide variety of applications from improving endoscopic imaging to enhancing machine vision for facilitating human–robot interactions and improving 3D displays.

Introduction

Survival of the fittest has continuously driven the evolution and improvement of compound eyes [1,2]. Even early examples of arthropods dating back to the Cambrian era had evolved faceted compound eyes [3,4] which enabled them to perceive their environment based on visual phototaxis [5]. A compound eye consists of a group of ommatidia which are oriented in different directions to provide arthropods with panoramic vision accompanied with low-aberration detection of their surroundings and high-sensitivity motion tracking. Each ommatidium includes a corneal facet lens for light collection, a crystalline cone and a rhabdom for light transmission, and pigment cells for optical isolation to minimize crosstalk [6,7]. The resulting outstanding visual performance enabled by this compound design has been widely exploited for a diverse range of applications such as endoscopic examination [8], robot navigation [9,10], and surveillance [11]. Natural compound eyes have inspired various optical systems with artificial microlens arrays [12-18], and a significant amount of research has been devoted to improving the fabrication and design of these systems.

Most artificial compound eyes that have been previously demonstrated rely on conventional 2D fabrication methods. For example, some compound eyes are fabricated by transferring planar microlens arrays (or moulds) to the surface of a hemisphere [19-21]. Although these planar microlens arrays are relatively easy to prepare by using thermal reflow [22,23], laser-induced forward transfer [24,25], jet printing [26,27], or microfluidic manipulation [28-30] techniques, transferring the pattern to a spherical surface can decrease the uniformity of the lens and negatively affect the performance of the system. Even though these problems can be resolved by applying advanced microfabrication techniques, such as 3D laser writing, laser lithography, or chemical etching [31-35], a fundamental problem still exists. Namely, the images produced from these 3D compound eyes do not match with current commercial planar imaging sensor technology. Automatic matching of the image from a compound eye to a planar imaging sensor can significantly reduce the complexity of the image-processing algorithm and also will reduce the number of sensors required for the system. Deformable optoelectronics, in which an array of photodetectors are curved to match to a compound eye [36-39], provide a potential solution for the aforementioned matching problem; however, the entire system relies on complex optical-to-electrical conversion and tedious signal readout strategies which are incapable of producing full-colour imaging. Moreover, the deformable curvature and the density of the electrical contacts limits the size and the imaging quality of the compound eye [17].

In order to overcome all these shortcomings, we have developed a unique fabrication method that combines 3D-printing with microfluidic-assisted moulding to pattern 522 microlenses, in an omnidirectional manner, across the surface of a hemisphere. Each microlens of the microfluidic-assisted 3D-printed eye (MAP-eye) is optically connected to the flat base of the hemisphere with an optical pipe that consists of a refractive-index matched waveguide. The flat base of the compound lens can be directly attached to any planar image sensor to enable full-colour, wide-field-of-view imaging. This effectively makes the MAP-eye an accurate recreation of a natural compound eye, yielding a compact form factor (5 mm in diameter vs. 4 mm for the compound eyes of a dragonfly) and a large viewing angle (170° vs. 150° to 180° in most natural compound eyes). As a proof-of-concept demonstration, we captured full-colour, wide-angle panoramic images, and demonstrated accurate position tracking of a point source.

The unique fabrication method presented herein enables the fabrication of highly adaptable biomimetic compound eyes that are compatible with any existing planar imaging sensors and greatly simplifies the optics and electronics required for obtaining a digital 3D panoramic view. With its unique 3D to 2D mapping capability, the 3D MAP-eye presented here opens up many applications in photonics, sensing, and imaging.

Results

Fabrication of the 3D MAP-eye

The design of the 3D MAP-eye follows the anatomical structure of an apposition compound eye (Fig. 1a). Each microlens on the MAP-eye has the same function as the corneal facet lens of a natural eye. The cylindrical post and the silicone-elastomer waveguide function as a crystalline cone and a rhabdom, respectively (Fig. 1b). The internal structure of the artificial eye mimics the function of pigment cells to reduce optical crosstalk. The number of ommatidia in the MAP-eye (522) is comparable with that of bark beetles (*Dendroctonus rufipennis*, average count: 272; *Dendroctonus valens*, average count: 372), ants (*Temnothorax albipennis*, average count: 300 (male) and 171 (queens); *Brachyponera chinensis*, average count: 168 (worker) (Fig. 1c)) and fruit flies (*Drosophila melanogaster*, average count: 730) [40-42]. Fig. 1d shows a top-view SEM image of the MAP-eye. It has a radius of 2.5 mm and its microlenses are hexagonally and omnidirectionally distributed across the hemispherical dome. The most peripheral ommatidia are oriented at $\pm 85^\circ$ with respect to the vertical axis, extending the viewing angle of the MAP-eye to 170° .

The fabrication process and the components used in the fabrication are illustrated in Fig. 1e-i (additional details provided in Supplementary Figs. 1-4). First, a mould with an open hemispherical pit is 3D-printed using a projection micro-stereolithography 3D printer [43,44]. The surface of the hemispherical mould is patterned with 522 cylindrical microholes, each with a diameter of 180 μm , that are arranged omnidirectionally along the surface of the hemisphere (Fig. 1f and Supplementary Fig. 2). The process of forming a convex lens mould within these cylindrical holes, however, requires precision handling; due to the small size of the microholes and current limitations in the resolution of 3D printing technology, the curvature cannot be encoded into the mould directly. Therefore, a microfluidic-assisted moulding technique, which leverages surface tension, was used to form a proper concave shape within each microcavity.

The procedure of the microfluidic-assisted moulding is illustrated in Fig. 2a. First, the hemispherical pit with cylindrical microholes is filled with acrylate resin. The mould is then spun around its central axis at a spin rate of Ω rpm. A detailed explanation of the microfluidic-assisted moulding process and the optimization and determination of parameters used for fabrication of the desired lens shape within the mould is given in the Methods section and the Supplementary Information. As the mould is spun, a portion of the acrylate resin is ejected from the microholes due to the centrifugal force generated by the spinning process. The amount of resin that remains within each hole is a function of the spin parameters and the location of the hole within the mould. Fig. 2b and Supplementary Fig. 5 presents results from numerical simulations that were performed to study the surface profile of the acrylate resin in the microholes at different orientations (α) within both a spinning mould and after the spinning has stopped.

When the spinning stops, the surface tension dominates and deforms the surface of the acrylate resin into a concave shape within the microholes. More specifically, the radius of

curvature of the concave surface can be described by the contact angle, θ_e , between the three phases under thermodynamic equilibrium, *i.e.*, $R = d/(2\cos(\theta_e))$ (Fig. 2c). The equilibrium contact angle is 13.2° , as measured in Fig. 2d for the system used in these experiments. With a uniform curvature achieved within each microhole, the liquid-state acrylate resin within each chamber is then UV cured for 15 minutes. The convex surface of each ommatidium can be obtained as the complimentary mould of the acrylate resin in the microholes using microfluidic-assisted moulding. To analyse this performance of this replication process, two moulds, each of which consisted of a single row of microholes on the bottom of the hemispherical pit, were prepared by spinning the acrylate resin with speeds of 1,500 rpm and 4,500 rpm, respectively. Fig. 2e shows side-view optical images of the replicated microlenses at different orientations and spinning speeds. The profiles of the microlenses are nearly identical, demonstrating that their shape is independent of their orientation and the rotational speed, which is consistent with the assumption that the surface tension dominates the formation of the concave lenses. The radius of curvature of each microlens is $91.9 \pm 0.8 \mu\text{m}$, which is in good agreement with the theoretical prediction, $R = 92 \mu\text{m}$ (Eq. 6 in Supplementary Note). As expected, the height of the cylindrical post (h_{post}) depends on both the rotational speed (Ω) and the orientation of the microholes (α) in the mould as shown in Fig. 2f. This is because a larger spin speed removes more of the acrylate resin, resulting in a deeper microhole, and subsequently a larger complementary lens. Fig. 2g shows the height of the post as a function of α at different rotational speeds Ω . The experimental data (markers) agrees well with the calculations (solid curves). Even though the height of each post is different for each ommatidium in the MAP-eye, the curvature of the microlens on each post is the same. This means that all the ommatidia have an identical relative aperture.

After the concave lens mould surfaces are fabricated, a hemisphere that is complementary to the patterned mould is 3D-printed using a UV curable diacrylate polymer (refractive index $n_{\text{Polymer}} = 1.46$) that is mixed with Sudan Black 3 solvent dye (Fig. 1g). The hemisphere consists of 522 hollow pipelines, or tapered channels, which connect the hemispherical surface to the flat base. Additional details about the design and the 3D model of this complementary substrate can be found in the Supplementary Note, as illustrated in Supplementary Fig. 3 and Supplementary Fig. 4. The hemisphere is then inserted into the mould and the hollow pipelines in the substrate are aligned with the cylindrical microholes in the mould. The empty pipelines and the concave microholes are filled with silicone by immersing the combined system in a room-temperature-vulcanizing (RTV) silicone in a liquid state. After curing for 4-hours, the RTV silicone solidifies into an elastomer. Separating the hemisphere from the mould yields a complete MAP-eye, as shown in Fig. 1h. Each ommatidium consists of a microlens with a radius of $90 \mu\text{m}$ capped on a cylindrical polymer post. These ommatidia are optically connected to the bottom of the MAP-eye through the pathway formed by the silicone-elastomer waveguide (refractive index $n_{\text{Silicone}} = 1.50$) which was formed in the hollow pipeline. The diameters of the silicone-elastomer waveguides gradually narrow down from the ommatidia ($d_T = 157 \mu\text{m}$) to the bottom of the MAP-eye ($d_B = 100 \mu\text{m}$). This design serves to increase the separation between individual sources. The outputs of the waveguides are hexagonally arranged at the flat bottom of the MAP-eye (Fig. 1i). Since the bottom of the MAP-eye is physically flat and the 3D array of the surface microlenses has been mapped to a regular hexagonal 2D array *via* these waveguides, this system can be directly matched to any commercial planar image sensor.

Optical characterization of the MAP-eye

In order to ensure that the MAP-eye maintains a high optical fidelity comparable to a natural compound eye, we optimized the performance of the waveguides and hemispherical substrate of the device. The hemispherical element, which serves as the supporting body of the MAP-eye, is comprised of a photosensitive polymer dyed with Sudan Black 3 solvent dye. The optical waveguides that connect the cylindrical posts of the artificial ommatidia and the bottom surface of the MAP-eye are patterned within this photosensitive polymer. The dye is used to absorb any stray light that escapes from the waveguides and hence acts to eliminate optical crosstalk between adjacent waveguides. Fig. 3a shows a slice of the photosensitive polymer before adding the solvent dye. Fig. 3b-d show slices of the photosensitive polymer mixed with solvent dye at concentrations of 900 $\mu\text{g/mL}$, 1200 $\mu\text{g/mL}$, and 1500 $\mu\text{g/mL}$, respectively. The polymer, which is usually yellow without the solvent dye, transitions to black as the concentration of the dye increases. Each slice shown in the figures has a thickness of 100 μm to mimic the smallest separation distance between two adjacent waveguides within the MAP-eye. Fig. 3e shows the optical density of the polymer over the entire visible spectrum as the concentration of the dye increases. When the concentration is 1,500 $\mu\text{g/mL}$, the material can efficiently absorb the light that leaks out of the waveguides with a high optical extinction ratio above 7.3 dB. The RTV silicone used for ommatidia and waveguides is transparent in the range of 400 nm to 1100 nm (Supplementary Fig. 6).

To further test the transmission properties and optical crosstalk between the waveguides of each ommatidium of the MAP-eye, three curved silicone waveguides were fabricated within the photosensitive polymer and mixed with 1,500 $\mu\text{g/mL}$ solvent dye, as shown in Fig. 3f. The diameter of each silicone waveguide and the separation distance between each optical pathway are each 100 μm , consistent with the dimensions of the MAP-eye. The bend radius and angle of the waveguides are 600 μm and 90°, respectively. A multi-mode fibre with a 532 nm light source was connected to the middle waveguide (Channel 2). Fig. 3g shows an image from the outputs of the three waveguides when only Channel 2 is illuminated. We could not visibly detect any light from Channel 1 or Channel 3, which was consistent with the light distribution measured from the proximal ends of the waveguides (Fig. 3h). The extinction ratios between Channel 2 and Channel 1 and between Channel 2 and Channel 3 are 16.1 dB and 15.2 dB, respectively. These results are consistent with the absorbance measurements from Fig. 3e, and confirm that the photosensitive polymer mixed with the solvent dye can eliminate any optical crosstalk between the waveguides.

We also analysed the coupling and propagation of light within each ommatidium of the MAP-eye using a ray tracing method (Fig. 3i). In this simulation collimated light, which is incident on the microlens of the ommatidium, is coupled into the waveguide. We performed these simulations with both a straight waveguide and a waveguide that was curved at an angle of 36 ° to mimic the curvature of the optical pathways within the MAP-eye. Since the refractive index of the substrate is lower than that of the waveguide, light propagates inside the waveguide due to total internal reflection. This further confirmed that the waveguides within the MAP-eye efficiently transmitted light from the lenses to the base of the eye without crosstalk between adjacent pathways.

In addition to the curvature of the waveguides within the MAP-eye, the 3D nature of this system means that light enters each ommatidium at different angles; therefore, the angular sensitivity function of two ommatidia at two different orientations ($\alpha=0^\circ$ and $\alpha=36^\circ$) were investigated. Fig. 3j schematically shows this experimental setup, where a collimated light beam illuminates the surface of the MAP-eye, and the angular sensitivity function of each ommatidium is obtained by measuring the transmitted light intensity from each ommatidium (either $\alpha=0^\circ$ or $\alpha=36^\circ$) as a function of the incident angle of the collimated light beam (polar angle α' and azimuthal angle β' , as defined in Fig. 3j and Supplementary Fig. 7). The incident collimated light beam can be rotated around the MAP-eye at any angle (α' or β') as defined in Fig. 3j. Fig. 3k and 3l show the angular sensitivity function of two ommatidia with an orientation of $\alpha=0^\circ$ or $\alpha=36^\circ$, respectively. The light intensity is normalized to the maximum value measured at the centre ommatidium ($\alpha=0^\circ$). The plotted points are obtained from experimental data, while the curve is a Gaussian fit of the experimental data. The ommatidia with orientations of $\alpha=0^\circ$ and $\alpha=36^\circ$ have the highest transmission at incident angles of ($\alpha'=0^\circ$, $\beta'=0^\circ$) and ($\alpha'=12^\circ$, $\beta'=270^\circ$), respectively. The acceptance angle of each ommatidium, which is defined as the full width at half maximum of the ASF, is about 44° . The wide acceptance angle is attributed to the large diameter of the waveguide, where a large number of propagating modes are allowed [45]. These experiments suggest that light collected by each ommatidium is efficiently transmitted to the bottom surface of the MAP-eye and can be directly detected by a planar image sensor regardless of the incident angle relative to the artificial eye.

Panoramic imaging using the MAP-eye

In contrast to conventional macro imaging lenses, the MAP-eye is capable of forming wide-angle panoramic images. Fig. 4a shows the working principle for capturing panoramic images by coupling a MAP-eye to a planar charge-coupled device (CCD). Light emitted or reflected from an object, such as the red or blue regular tetrahedron in Fig. 4a, is captured by each ommatidium and guided to the bottom of the MAP-eye where its speckle pattern is recorded by a colour CCD. The speckle pattern on the CCD that corresponds to the light from each ommatidium is then homogenized by taking the average value of the light from each ommatidium. This averaging is needed because each ommatidium projects its light across approximately 80×80 pixels of the planar imaging sensor. Finally, a panoramic image of the object is generated on a hemisphere by digitally stitching the images from each ommatidium together while accounting for the orientation of each ommatidium on the outer surface of the MAP-eye (details in Methods and Supplementary Fig. 8). The resolution of the MAP-eye is dependent upon the total number of ommatidia.

Fig. 4b shows the panoramic imaging of a square as visualized through the MAP-eye. A mask with a square slot which is $300 \mu\text{m}$ in width (Fig. 4c) was placed in front of the MAP-eye to project a square onto the MAP-eye. Fig. 4d shows a side-view optical image of the projected light on the MAP-eye, as taken using another digital single-lens reflex camera equipped with a macro lens at an angle of $\alpha=15^\circ$ and $\beta=0^\circ$. A telecentric lens was used to magnify the image at the flat bottom surface of the MAP-eye and project it onto the CCD. The telecentric lens is not necessary in practical applications, and the MAP-eye can be directly attached to an image sensor; the telecentric lens was used in this experiment solely to magnify the image and

improve spatial sampling. Fig. 4e shows the image of the square slot on the CCD. The corresponding panoramic 3D image of the square slot is shown in Fig. 4f.

We also demonstrated that the MAP-eye can image objects at different angular positions with a visible angle ranging from -85° to 85° . Fig. 4g schematically shows the experimental setup for imaging of two objects at different angular positions. A red cross with a line width of $300\ \mu\text{m}$ is placed at a fixed angular position of $\alpha=60^\circ$ (the centre position of the cross), while a blue triangle with a line width of $200\ \mu\text{m}$ is moved from the side toward the red cross. The corresponding panoramic views for the centre position of the blue triangle at $\alpha=-60^\circ$ (Fig. 4h), $\alpha=-40^\circ$ (Fig. 4i), and $\alpha=-20^\circ$ (Fig. 4j) are reconstructed. The patterns are clearly recognized and the triangle at different angular positions is imaged with a high uniformity in size and shape.

In nature, arthropods can quickly detect and escape from predators and track prey, all based on the information, e.g., position, direction, and speed of motion, provided by their peripheral vision. The advantages of wide-angled, motion-based sensing in applications range from macro surveillance functions to navigational functions in endoscopic surgeries. Hence, researchers have sought to create artificial systems that mimic the panoramic imaging of natural arthropods. In the next section, we detail a proof-of-concept experiment that demonstrates the capabilities of the MAP-eye for 3D point-source tracking.

3D point-source tracking with the MAP-eye

The natural compound eyes of fruit flies and worker bees have poor resolution with respect to static images, but they are highly sensitive to motion detection. Similarly, the MAP-eye can be used to track the position of objects in three dimensions. In this section, we demonstrate the 3D position tracking of a green light point source with a MAP-eye, as shown in Fig. 5a. The diverging green light emitted from an optical fibre is captured by a MAP-eye and projected onto a CCD camera. The light spots projected onto the CCD camera through the MAP-eye (Fig. 5c-h) change in position and diameter depending on the angular position of the point source and the distance between the point source and the centre point of the MAP-eye. The light spot on the CCD camera can be fitted neatly with a Gaussian function (Fig. 5c-e). Fig. 5f-h show the corresponding panoramic views of the point source at three angular positions. When the angular position of the point light source is changed, the light spot detected on the CCD camera is displaced laterally. When the point light source moves away from the MAP-eye, the diameter of the light spot imaged on the CCD increases, and vice versa. Therefore, the centre position and the width of the imaged light spot on the CCD camera can be calibrated to obtain the 3D position of the point source as it moves. Fig. 5i shows the calibration curve between the distance and the width of the light spot on the CCD. The angular position of the point light source can be determined from the centre position of the light spot on the CCD (Methods). Fig. 5b shows the 3D positioning of the point light source at different positions. For the calibration process, the yellow and green solid data points show the actual position and measured position of the light point source, respectively. The yellow and green circles show the actual position and measured position of a point source which had an unknown position *a priori*. The light distribution and the reconstructed images from the nominally-unknown point source are shown in Fig. 5j,k and Supplementary Fig. 9. The measured positions are consistent with the actual positions of the point source with a root-mean-square deviation of less than 0.16. The precision of the position tracking can be further improved by increasing the number of ommatidia of the

MAP-eye and the bit depth of the CCD camera. This 3D position tracking feature of the MAP-eye allows it to quantitatively locate a moving light source, which could be potentially implemented for advanced 3D phototaxis navigation and search applications, *e.g.*, as a sensor to guide a robotic capsule endoscope to locate fluorophore-labelled lesions.

Discussion

We have demonstrated a hybrid fabrication method that combines 3D printing and microfluidic-assisted moulding in order to generate a 3D MAP-eye that closely mimics the panoramic imaging capabilities of a natural compound eye. In contrast to conventional 2D fabrication techniques, microfluidic-assisted 3D printing produced precise curved microstructures inside of complex 3D micro-geometries. The MAP-eye was designed to both acquire full-colour 3D panoramic views and to subsequently seamlessly map the omnidirectional images to a planar imaging sensor, avoiding complex 3D photodetection techniques and bulky signal readout strategies. The imaging properties of the MAP-eye were characterized in detail to investigate the device's capability to acquire panoramic views of surroundings and to track a point light source in 3D space. Wide-angle and full-colour panoramic images without aberrations were successfully reconstructed from the 2D images detected by the CCD. Furthermore, precise 3D position tracking of a point light source was demonstrated without the need for complicated algorithms.

Because of the MAP-eye's ability to seamlessly match to any 2D planar imaging sensor without the requirement of additional matching optics, increasing the resolution can be improved simply by increasing the number of ommatidia. The image from each ommatidium effectively contributes one pixel to the entire panoramic image, thus increasing the number of ommatidia present in the MAP-eye will proportionally increase the number of pixels in the resulting 2D image. In contrast, increasing the number of ommatidia in a compound eye that is manufactured by a less adaptable method such as deformable optoelectronics or nanowires requires a complete redesign of the entire imaging system, including complex matching optics and photodetectors. In principle, a full image can be formed independently from each ommatidium; therefore, 522 independent images with different view angles can be obtained simultaneously on one single planar image sensor. In the future, using imaging over fibre technology [46,47], the speckle pattern obtained from each ommatidium could be reconstructed into an independent image, and an ultra-high-resolution panoramic image could be created. Additionally, the MAP-eye normally functions in a receiving mode for panoramic imaging, *i.e.*, collecting light from the top surface and transmitting the light to the bottom to form an image on a planar image sensor. However, the MAP-eye could also function in an emitting mode by replacing the image sensor with a 2D display, *e.g.*, with a liquid crystal display, for potential applications in planetarium projection systems [48] and volumetric 3D displays [49]. On a fundamental level, the MAP-eye may also be useful as a biomimetic model for natural compound eyes, allowing scientists to study and test the mechanisms behind insect vision and perception. Additionally, due to the miniaturized design and scalability of the MAP-eye, it could be adopted by fields such as micro-robotics where it can be utilized for applications including 3D endoscopic vision in industrial and medical inspections; the MAP-eye may also be useful for machine vision for functional human–robot interactions, and improving 3D displays.

Methods

Fabrication process for the MAP-eye

Supplementary Fig. 1 shows the fabrication process for the MAP-eye, as follows: (1) A mould consisting of an open hemispherical pit and 522 cylindrical microholes arranged omnidirectionally on the bottom of the pit was designed by computer-aided design (CAD) software and 3D printed with a 3D printer (BMF Precision Technology Co.). (2) Acrylate resin (Aroh Alona) was added to the pit of the mould. The mould was placed in vacuum at -0.1 MPa for 10 minutes to remove any microbubbles from the acrylate resin. (3) The mould was then spun at 1,500 rpm for 4 minutes. (4) The mould was exposed with UV light for 15 minutes to cure the acrylate resin. (5) A hemispherical substrate consisting of 522 hollow pipelines was designed and 3D printed using a photosensitive polymer dyed with Sudan Black 3 (Sigma-Aldrich) at a concentration of $1,500 \mu\text{g/mL}$ with the same 3D printer (BMF Precision Technology Co.). The design of the pipeline structure, which act as optical waveguides, is discussed in Supplementary Fig. 3. (6) The hemispherical substrate was inserted into the pit of the mould. The six auxiliary supports around the hemisphere of the substrate (Fig. 1g) and the six slots on the surface of the mould (Supplementary Fig. 2) were used to align the microholes in the substrate with the pipelines in the mould. (7) The entire mould plus hemispherical substrate structure was immersed into liquid-state RTV silicone (Part A: phenyl(chlorophenyl)siloxane-dimethylsiloxane copolymer, vinyl dimethylsiloxane terminated and Part B: methylhydrosiloxane-phenylmethylsiloxane copolymer, hydride terminated; the weight ratio of Part A and Part B is 1:1) (Gelest, Inc.) and evacuated at -0.1 MPa for 20 minutes to ensure that the RTV silicone completely filled in the pipelines and the microholes. (8) The RTV silicone was then cured at 55°C for 4 hours. (9) The fully formed MAP-eye was separated from the mould.

Characterization of the materials

In order to reduce the optical crosstalk due to light leakage between the waveguides of the MAP-eye, the photosensitive polymer used for the supporting structures of the MAP-eye was mixed with Sudan Black 3 solvent dye. Four $100 \mu\text{m}$ slices were 3D printed using the prepared photosensitive polymer. The absorbance of the slices was measured using a spectrophotometer (LAMBDA 1050, PerkinElmer). When the dye concentration was $1500 \mu\text{g/mL}$, the optical density, in the wavelength range from 400 nm to 800 nm , was above 3.3. The contact angle, θ_e , of an acrylate resin droplet on the flat photosensitive polymer substrate and the curvature of the microlenses were measured by an optical contact angle meter (SL200B, Kino).

Reconstruction of a panoramic image

A panoramic image was directly mapped from the flat bottom of the MAP-eye onto a CCD. Each image from the flat bottom of the waveguide is a speckle pattern, which is homogenized by taking the averaging value of the image. A block of $N \times N$ pixels projected from the flat bottom waveguide/pipeline array onto the CCD was used to represent a sub-view of a particular ommatidium, that is oriented with the polar angle, α , and azimuthal angle, β . The proximal end of the waveguide was centered at the position of $(x_{\text{Bottom}}, y_{\text{Bottom}})$ in the plane $\mathbb{R}^2$ (Supplementary

Fig. 8). The relation between the orientation of the ommatidium and the center of the proximal end of the waveguide can be written as

$$\alpha = \frac{2\sqrt{x_{Bottom}^2 + y_{Bottom}^2}}{D} \times 90^\circ \quad (1)$$

$$\beta = \begin{cases} \arctan\left(\frac{y_{Bottom}}{x_{Bottom}}\right), & x \geq 0 \\ \arctan\left(\frac{y_{Bottom}}{x_{Bottom}}\right) + 180^\circ, & x < 0 \end{cases} \quad (2)$$

The sub-view is then used as a part of the panoramic view. The corresponding center position of the sub-view in the 3D Euclidean space $\mathbb{R}^3$ is (x_{3D}, y_{3D}, z_{3D}) , which can be expressed as

$$x_{3D} = \frac{L \tan(\alpha) \cos(\beta)}{\sqrt{1 + \tan^2(\alpha)}} \quad (3)$$

$$y_{3D} = \frac{L \tan(\alpha) \sin(\beta)}{\sqrt{1 + \tan^2(\alpha)}} \quad (4)$$

$$z_{3D} = \frac{L}{\sqrt{1 + \tan^2(\alpha)}} \quad (5)$$

where L is the nominal viewing distance assuming an observer is located at the origin of the MAP-eye. Since the panoramic image is a virtual image of the real object, the nominal viewing distance L is defined as a dimensionless parameter as:

$$L = \frac{N}{2 \tan\left(\frac{\Delta\alpha}{2}\right)} \quad (6)$$

where N is the pixel number of the sub-view, $\Delta\alpha$ is the difference in polar angle of the orientation between the two adjacent ommatidia (with the orientation at the same azimuthal angle).

Positioning of a point light source

When a point light source illuminates a MAP-eye, the proximal ends of the corresponding ommatidia also become illuminated. The intensity of the light output from each ommatidium was homogenized and the light spot on the CCD was fitted with a Gaussian function as follows

$$G(x, y) = I_{max} \left(e^{-\frac{(x-x_{max})^2}{2\sigma^2}} + e^{-\frac{(y-y_{max})^2}{2\sigma^2}} \right) \quad (7)$$

where I_{max} is the peak intensity of the distribution, x_{max} and y_{max} are the position of the peak and σ is the width of the Gaussian distribution. The distance between the point light source and the origin of the MAP-eye (L_P) is related to the width of the Gaussian distribution and can be calibrated with a point light source with a known distance L_P . In this experiment, a logarithmic calibration function was obtained as:

$$\sigma = \frac{p_1}{1 + e^{-p_2(L_P - p_3)}} + p_4 \quad (8)$$

where p_1 , p_2 , p_3 and p_4 are the fitting parameters. The measured distance L_P can be readily obtained by measuring the width of the Gaussian distribution of the light spot on the CCD as:

$$L_P = p_3 - \frac{1}{p_2} \ln\left(\frac{p_1}{\sigma - p_4} - 1\right) \quad (9)$$

The peak position of the Gaussian distribution reveals the orientation of the point light source, which can be calculated by using Eq. 1 and Eq. 2. Finally, the position of the spotlight source can be determined using Eq. 3-5.

Data availability

The data in support of the reported findings are available from the corresponding author upon request.

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Author contributions

B.D., L.Z., C.Z., L.Z., and D.Z., initiated the project. T.J.H., S.Z., and D.Z. supervised the project. B.D., L.Z., X.W., and D.Z., fabricated the compound eyes. L.Z., Z.J., and W.L., characterized the compound eyes. B.D., L.Z., L.Z., C.Z., and D.Z., designed and conducted the hemispherical imaging experiments. B.D., L.Z., C.Z., H.B., and J.M., analysed the experimental data. B.D., L.Z., C.Z., L.Z., H.B., R.B., J.M., T.J.H., and D.Z., wrote the paper. ALL authors contributed to discussing, editing, and revising the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information accompanies this paper.

Figures

Figure 1 | Illustrations of the fabrication procedure and images of the MAP-eye. **a**, Anatomical structure of an arthropod compound eye. **b**, Labelled cross section of a MAP-eye. **c**, SEM image of a compound eye of the Asian needle ant, *Brachyponera chinensis*. **d**, SEM image of a MAP-eye. **e**, Illustration of the main steps of the fabrication procedure. The MAP-eye is produced in a hemispherical substrate by casting it in a prepared mould. **f**, Image of the 3D printed mould. **g**, The 3D printed substrate and a quarter sectional slice of the substrate. **h**, Image of a MAP-eye after release from the mould. **i**, A view showing the flat bottom of the MAP-eye.

Figure 2 | Design of the mould and morphologic characterization of the MAP-eye. **a**, Illustration showing the fabrication of the mould. **b**, The surface profiles of the acrylate resin in the microholes in different orientations during dynamic (while spinning) and static (after spinning) equilibrium. **c**, A comparison between the surface profiles of the acrylate resin on the (top) flat polymer substrate, (middle) in the microhole, and (bottom) after the microlens is demoulded from the microhole. **d**, Contact angle measurements for the acrylate resin on the photosensitive polymer. **e**, Microscope images of the artificial ommatidia. The microlenses in the different orientations and as produced under different spin rates have a uniform curvature. **f**, Images of a single row of the ommatidia along the curved surface of the MAP-eye. Different heights are produced based on the location of the posts and the balance of forces during the fabrication process. **g**, Experimentally measured (data point markers) and simulation results (solid curves) of the post height distribution across the surface of the hemisphere, with respect to rotational rate.

Figure 3 | Optical performance of the artificial ommatidia. **a**, A cured, 100 μm thick polymer slice without any solvent dye. **b-d**, Cured, 100 μm thick polymer slices mixed with 900 $\mu\text{g/mL}$, 1200 $\mu\text{g/mL}$, and 1500 $\mu\text{g/mL}$ solvent dye, respectively. **e**, The optical absorbance of the photosensitive polymer and the Sudan Black 3 solvent dye mixture at different concentrations. **f**, A three-channel model to measure the crosstalk among the curved silicone waveguides. **g**, Image captured at the output panel showing the light intensity at the proximal ends of the three silicone waveguides. **h**, The measured light distribution at the output panel. **i**, Ray tracing simulation in the ommatidia with waveguide orientations of 0° and 36° , respectively. **j**, The experimental setup for measuring the angular sensitivity function. **k** and **l**, The angular sensitivity function of the ommatidia with orientations of 0° and 36° , respectively. Red dots: the normalized intensity obtained from experimental measurements.

Figure 4 | Imaging using the MAP-eye. **a**, Workflow for image acquisition and processing by the MAP-eye. **b**, Schematic diagram of the experimental setup of the imaging system. **c**, The square mask used for image detection experiments. **d**, The illuminated square pattern as detected by the MAP-eye. The image of the illuminated pattern on the artificial ommatidia is captured by a single lens reflex (SLR) camera equipped with a macro lens. **e**, The square pattern image captured from the bottom of MAP-eye. **f**, The digitally reconstructed hemispherical image. **g**, Illustration of the hemispherical imaging for a red cross pattern whose centre is fixed at an angular position of $\alpha = 60^\circ$ and a blue triangular pattern moving from the side ($\alpha = -85^\circ$) toward the red cross. **h-j**, The reconstructed images showing the triangle as it travels from $\alpha = -60^\circ$, $\alpha = -40^\circ$, and $\alpha = -20^\circ$. The digitally generated callouts provide stereoscopic vision (for a human observer) of the hemispherical images.

Figure 5 | Tracking the position of a light point source using the MAP-eye. **a**, Schematic diagram of the light point source tracking experiments. **b**, The positions of the light spots. The yellow and green solid dots are the target and measured positions used for calibration, respectively. The yellow and green circles are the target and measured positions from experiments where the light location is not known a priori. **c-e**, The light distribution collected by the MAP-eye and **f-h**, the corresponding hemispherical images of the light spots at a radial distance 5 mm, 7 mm, and 9 mm away from the original point. Yellow dots are the average grayscale measured from the proximal ends of the waveguides. **i**, The relation between the full width at half maximum (FWHM) of the light distribution obtained by the MAP-eye and the distance from the original point to the light spot. **j**, The light distribution obtained for the light spot at a nominally-unknown position and **k**, the corresponding hemispherical images of the light spot.

Figures

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