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Keywords (separated by '-')	Artificial compound eye - Image reconstruction - Depth estimation - Motion detection - Extended depth of field - Large field-of-view imaging
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Artificial compound eye: a survey of the state-of-the-art

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1 Introduction

Based on the principle of survival of the fittest, introduced by Darwin (2003), living beings on the earth have evolved a lot of features that adapt to their living environments. Different creatures always have different unique features because of their different living environments. Inspired by this, researchers always envisage to imitate the unique features of creatures so as to manufacture various bionic systems. Up to date, bionic systems have been widely researched and applied, for instance, airplane is inspired by birds (Wright and Kelly 1953); a sonar system is inspired by a bat's distance measure system (Barshan and Kuc 1992); helicopter is inspired by dragonfly (Johnson 2012); and so on.

Creatures see the outside world through their eyes, while in imaging devices such as cameras, the images with environment information can also be captured. In the traditional imaging device, the single-aperture principle imitating the mammal eye is utilized to design the optic imaging system. But the factors like image-forming principle and diffraction limit result in the large size of traditional imaging devices and the difficulty to further reduce the size and weight. In some application areas such as intelligent robot vision systems, micro imaging devices and portable devices, the whole imaging system with small size and wide field-of-view (FOV) is always expected. To reach this goal, researchers started to focus on the animals with compound eye system. In comparison with single-aperture eye (also called camera eye), compound eyes have many unique features, such as normally much smaller size, wider FOV, better capability to detecting moving objects and normally much lower spatial resolution. Therefore, the natural compound eye system is imitated to obtain the multi-aperture system so as to break the limitation of the ordinary imaging principle. From the 1970s to 1980s in the twentieth century, not only the biological perspective of compound eyes, but also the optical imaging principles were taken into account, based on the thorough research of natural compound eyes (Snyder 1977; Land 1976; Horridge 1978, 1987; Snyder et al. 1977). Since then, the artificial compound eye system with the merits of natural compound eyes becomes an active and hot research field.

Until now, numerous variants of artificial compound eyes have been proposed and much attention has also been paid to the theoretical investigation and various applications. It is very necessary to summarize systematically, to compare and analyze the work on artificial compound eyes reported in the literature. In this paper, a comprehensive survey of the state-of-the-art work on artificial compound eyes is presented. The survey starts from natural compound eyes to artificial compound eyes, which are reviewed from several aspects such as the system design, theoretical development and applications. The most promising future research developments are also highlighted.

The rest of this paper is arranged as follows. Section 2 introduces natural compound eyes. Section 3 presents the design and analysis of artificial compound eyes. In Sect. 4, the theoretical developments of artificial compound eyes are discussed. Various applications of artificial compound eyes are summarized in Sect. 5. Finally, conclusions and possible further developments are given in Sect. 6.

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2 Natural compound eyes

Compound eyes (Fig. 1a–d) are the most common visual principle in the animal realm, simply because they are typical for arthropods, which comprise the highest number of species, and individuals. Normally associated with insects, eyes which consist of numerous identical visual units are represented likewise in crustaceans, myriapods, chelicerates (such as the horseshoe crab *Limulus*), in some mollusks (ark clams) and annelids (e.g. *Sabellaria*) (Cronin et al. 2014).

There exist two principles after which these individual units can be constructed. The first is represented for example in most myriapoda, and many chelicerates such as scopions. Their visual units consist of small cups, floored by a retina which is covered by a tiny lens—a system which is called ocellus (Fig. 1c). The lens of these ocelli focuses the light, but often deeper than the level of the retina, they underfocus, and thus the image built appears as blurred. These lenses, however, may have a gradient of centrally increasing density, acting as so-called 'gradient index lenses' shortening the focal length. Each of these ocelli is able to perceive the direction of the incident light, to detect movements, and even the formation of images is possible, while the acuity depends among other factors on the number of receptors in the retina, and of course on the focal length of the lens. An example given may be the predatory myriapod *Lithobius*. It has up to 40 separated ocelli, and these have up to 110 receptors each Bähr (1974). Compound eyes, which consist of ocelli, sometimes are called 'aggregate eyes' to distinguish them from the compound eyes of insects and crustaceans. The compound eyes of insects and crustaceans are also composed of identical visual units, here called 'ommatidia'. Ommatidia are different from the visual units composing the eyes of the systematic groups mentioned before. The dioptric apparatus of each ommatidium consists of a translucent cuticular 'corneal lens' (Fig. 1b2-1) and an adjacent 'crystalline cone' (Fig. 1b2-2).

In terrestrial systems the lens focuses the light through the crystalline cone onto a central light guiding structure, the so-called 'rhabdom' (Fig. 1b2-3). The latter is part of the sensory cells (Fig. 1b2-4), and contains the visual pigments. The sterical structure of the pigments is changed by the energy of the incident light, producing an electric signal, which is processed by the nervous system of the arthropod. In aquatic systems the refractive power of the organic lens is not high enough to focus the light sufficiently, because of the low difference of refractive indexes between water and lens. Here the crystalline cone, as a gradient index lens or with other mechanisms, overtakes the function of focusing light. Because all contrasts inside the angle of view of each ommatidium are concentrated on the rhabdom, and thus become melted to one average, there is *no image formation* inside of each ommatidium—the field of view that belongs to one facet is represented by one mean contrast and colour (Fig. 1b4: orange dot). Because the ommatidia are optically isolated against each other by pigment cells acting comparable to a curtain (Fig. 1b2-5), the image seen by the bearer of this compound eye is that of a mosaic, while each ommatidium contributes one tile. The fineness of vision thus depends among other factors on the number of ommatidia, as the number pixels contribute to the acuity of a computer graphic (Fig. 1e). Although each lens of course is capable to perform images by its physical structure, this power is not used—the lens "just" concentrates the light onto the rhabdom. Other parameters contribute also to the acuity of vision in a compound eye. There is the so-called 'interommatidial angle'($\Delta\varphi$), the angle between the optical axes of adjacent facets' lenses, which, as the width of the angle of acceptance of each ommatidium (->rhabdom) should be as small as possible to achieve a high resolution (Fig.1f, g). ($\Delta\varphi$)represents the fineness of scanning inside the field of view. In flat eyes an

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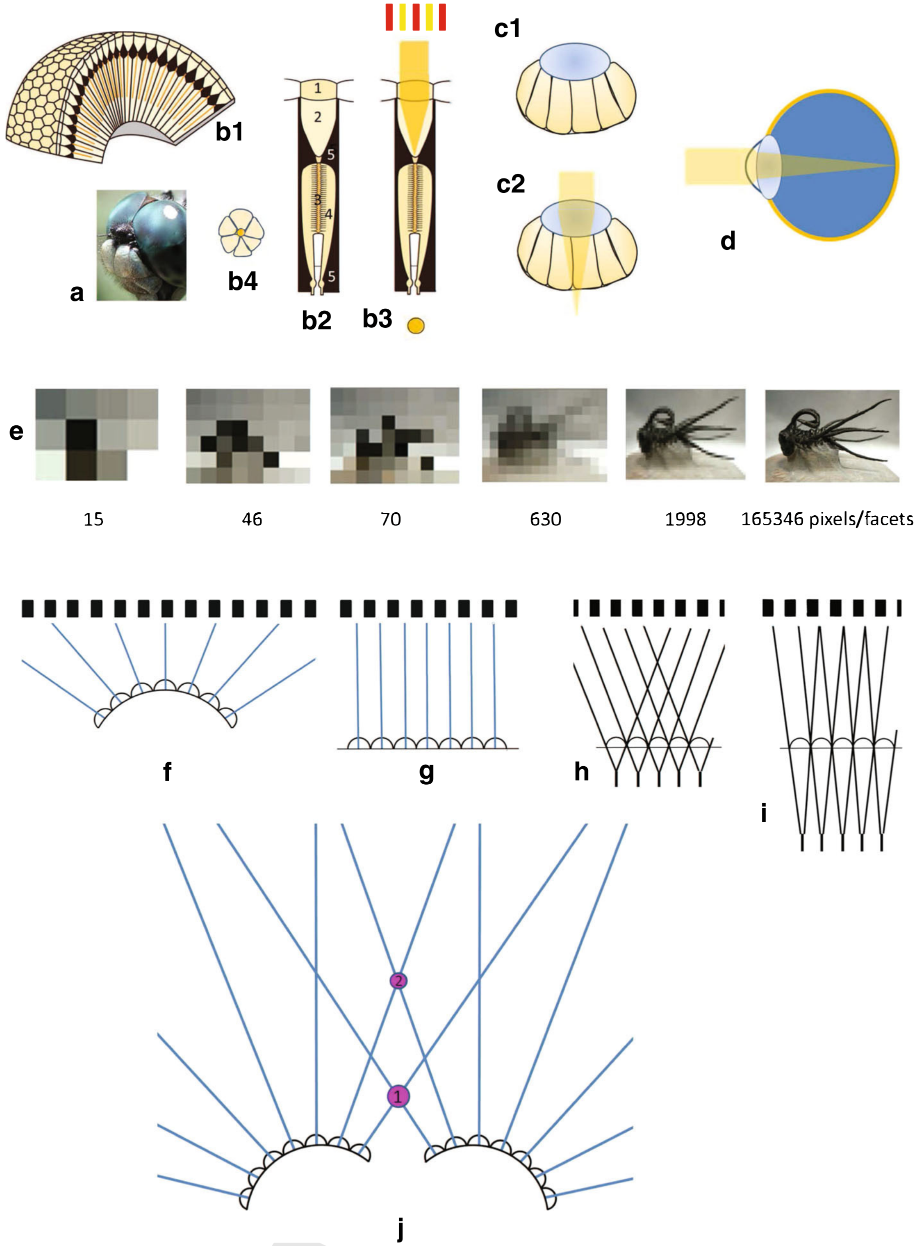

Fig. 1 Structures of focal apposition compound eyes. **a** Compound eye of the dragonfly *Aeschna sp* (*Source*: de.wikipedia.org, David L. Green.) **b1** schematic drawing of a focal apposition compound eye (bee). **b2** Visual cross-section through a visual unit (ommatidium): *1* lens, *2* crystalline cone, *3* rhabdom, *4* receptor cell, sensory cell, *5* screening pigment cells. **b3** Light path and optical signal processing in the ommatidium of a focal apposition eye. **b4** Cross-section of **b2**. **c1** ocellus. **c2** Light path through an ocellus, underfocusing. **d** Vertebrate eye. **e** Acuity of the mosaic-like image formation of an apposition compound eye, depending on the number of ommatidia. **f** resolution with a curved visual surface. **g** Resolution with a flat visual surface. **h** Resolution with a short crystalline cone. **i** Resolution with a long crystalline cone. **j** Distance estimation in a focal apposition compound eye

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optimal, high acute scanning is easier to realise than in eyes with curved surfaces (Fig. 1f, g). Another feature is the overlapping of the angles of acceptance the units cover. The latter depends, among others, on the position of the rhabdom below the crystalline cones (lengths of the crystalline cones). Eyes with long crystalline cones usually supply a less ambiguous information than those with short crystalline cones (Fig. 1h, i).

The mosaic-like vision has consequences for distance estimation, which is possible just in visual systems with overlapping fields of view, represented in many predatory arthropods. Figure 1j shows, that where the optical axes of ommatidia intersect, an estimation of relative positions is possible. For example, beyond intersection 2 in Fig. 1j, no more points of intersection exist, and thus no unambiguous information about relative distances is possible any more beyond this point. From here for the arthropod everything seen is just as "far away" (compare Horridge (1977)).

The number of ommatidia usually varies from some few, as in terrestrial isopods, up to several 10,000 per eye in *Aeschna* (Fig. 1a) or *Anax junius* 28,672 ommatidia in each eye, Sherk (1978), both dragonflies. The number depends on living environments of the respective species, as of its life-style. The effectiveness of a predatory life-style for example, as the success of chasing sexual partners depends on an acute vision. A huge number of facets is installed mainly in daylight adapted arthropods, because dim light conditions demand for a wide aperture, and thus large lenses in a limited space of a compound eye's surface. So the design of any compound eye is a trade-off between optimal acuity (high number of facets) and the necessity to capture photons enough to work sufficiently demanding for a minimum aperture. By optical reasons (diffraction) the lower limit of lens diameters lies at 10 µm (Snyder 1977, 1979), and is nearly realised in certain mitches and diurnal mosquitoes (Collett and Land 1975; Land et al. 1999; Kawada et al. 2006). Arthropods of dark environments often show lens diameters of 200µm and more. The interommatidial angle ($\Delta\varphi$), describing the fineness of scanning of the environment, can vary inside of the visual surface, but especially among species. $\Delta\varphi$ varies from several tens of degrees in Collembola or 7° in *Chlorophanus*, a beetle (Land 1997, 1981) to 0.24° in the acute zone of the visual surface of a dragonfly such as *Anax junus*. For many flying insects, such as bees, flies and butterflies $\Delta\varphi$ lies typically in the range of 1°–3°, less than 1° is valid for many predators such as dragonflies, mantids and specid wasps (Land 1997).

2.1 Classification

The compound eye system explained before is the most common, especially among diurnal insects and crustaceans, and probably the oldest one. Just recently it was described for a 160 million year old crustacean (Vannier et al. 2016). Because the light is focused on the central rhabdom, it is called 'focal apposition eye' Nilsson (1989a). As mentioned, each ommatidium is an independent visual unit, forming one "pixel" to the total mosaic-like image. In arthropods living under dimmer light conditions, adaptive forms of compound eyes evolved, equipped with a higher sensitivity. These are the super-position eyes (optical superposition eyes: refractive superposition eye—e.g. moths; reflecting superposition eyes, working with mirror boxes—e.g. decapod shrimps and crayfish; parabolic superposition eyes—certain amphipod crustaceans; neural superposition eyes—many dipteran flies) (Land and Nilsson 2012). The imaging principles of five different types of compound eyes are shown in Fig. 2 (Nilsson 1989). In superposition eyes the visual units do not work independently. Up to hundreds of adjacent facets support each other in capturing light, enhancing the aperture, but possibly pay with a loss of acuity. Refracting superposition eyes by moving pigment

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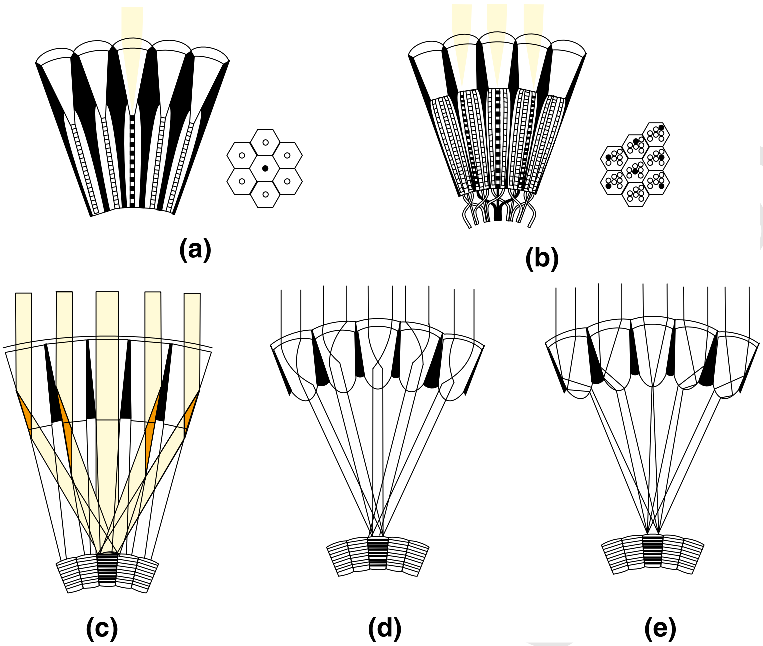

Fig. 2 The imaging principles of different types of compound eyes. **a** The apposition compound eye. **b** The neural superposition compound eye. **c** The reflective superposition compound eye. **d** The refractive superposition compound eye. **e** The parabolic superposition compound eye (Nilsson 1989)

Fig. 3 Trilobite: *Geesops schlotheimi* (BRONN, 1825). Age and location: Middle Devonian Ahrdorf Formation, Flesten Member, Salmerweg bei Gees/Gerolstein, Eifel, Germany

cells can be changed to apposition eyes, and many other intermediate forms between these types of eyes are realised. If the apposition compound eye can be regarded as a *one-to-one* relationship, then the superposition compound eye can be considered as a *many-to-many* relationship.

Some fossil trilobites, extinct arthropods which dominated the faunas of the Palaeozoic, were assumed to possess an ocellar compound eye system. One type of trilobite (*Geesops schlotheimi*) is shown in Fig. 3 (Schoenemann and Clarkson 2013), They possess a sophisticated optic, probably correcting spherical aberrations typical, for thick lenses allowing clear image formation (Clarkson and Levi-Setti 1975). According to these results Schoenemann in 2007 developed a model, where by the processing of information of the individual receptor

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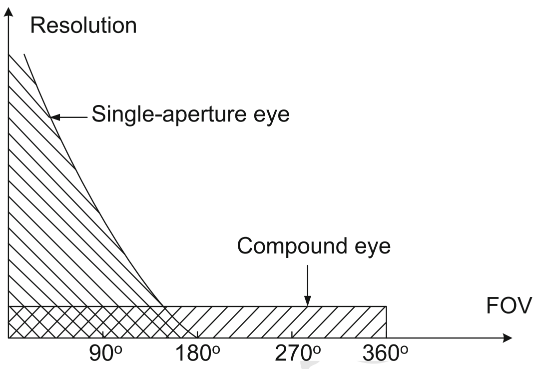

Fig. 4 Comparisons of the compound eye and the single-aperture eye with respect to resolution and FOV (Sanders and Halford 1995)

cells, among the ocelli by means of a neuronal matrix in common, one total image could be produced—optimised in sharpness, acuity and contrasts (Schoenemann 2007).

2.2 Comparative analysis

It becomes obvious that the imaging principle of an ommatidium in an arthropod's apposition compound eye is very different from that of a one lens camera eye, as in vertebrates. In the camera eye through one lens an image is formed onto a retina, which consists in a human being of several millions of receptors that form one image (~6 million cones, ~120 million rods)—while in a compound eye of the apposition type the total image is established by numerous individual units, forming pixels of a mosaic-like image. So, while in a human eye the image is formed by millions of receptors, in arthropods the highest number of receptor units lies at about 30,000 in dragonflies. Thus, in general, a compound eye has a much smaller spatial resolution than a human eye with a single aperture. While a compound eye normally has hardly any modes of accommodation (it is not needed because of their short focal length, some can change their acceptance angle, however that is for capturing more light), a variable or movable lens in a camera eye system brings great advantages in focusing objects at different distances, for those lenses are normally much larger than those of compound eyes. In contrast, due to a curved visual surface in arthropod compound eyes the field of view often is much wider than that of the one lens systems. Figure 4 compares the resolution and FOV between the compound eye and the single-aperture eye. Finally, the temporal resolution of compound eyes (the number of signals distinguished per time unit [signals (ss)/second (s)]) in insects often is higher than in vertebrate eyes. Here the frequencies as most commonly quoted: Because in neural superposition eye the signals are not forwarded but processed directly, this system reaches $\sim 300[ss/s]$, the apposition eye of a honey bee about $\sim 100[ss/s]$, a human's camera eye 20–25 [ss/s]. This temporal resolution depends on the velocity of the nervous structures, furthermore among others on the morphological design of the compound eye (e.g. the width of the acceptance angle of the rhabdom) and the velocity of movement of the arthropod. A comparison of different eyes and their related parameters are shown in Table 1, where human, bee and moth represent a single-aperture eye, apposition compound eye and superposition compound eye, respectively.

3 Design and analysis of artificial compound eye

The study of artificial compound eye was initiated in 1990s. Due to the limitations of processing and manufacturing technologies, most artificial compound eyes are made with a planar

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Table 1 Parameter comparisons of different eyes (Sarkar 2011)

Parameter	Human	Bee (*worker bee*)	Moth (*Ephestia*)
Eye type	Single-aperture eye	Apposition	Superposition
Light habitat	Diurnal	Diurnal	Nocturnal
Lens diameter (mm)	7	0.025	0.4
Focal length (mm)	23	0.06	0.17
Receptor diameter (μm)	2	1.5	8
F-number ($F/\sharp$)	3.3	2.4	0.4
Sensitivity (μm^2)	0.23	0.24	218
Acceptance angle (°)	0.007	1.9	<13
Interreceptor angle (°)	0.005	–	3
Interommatidial angle (°)	–	0.95	–
Resolution ($LP/°$)	100	0.52	>0.08

($LP/°$ means line pair per degree)

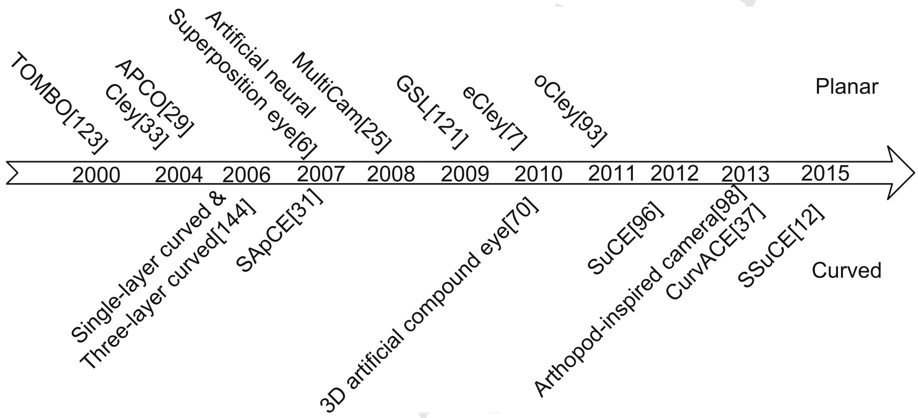

Fig. 5 Start time of different kinds of artificial compound eyes

surface. This structure leads to a large aberration distortion in a large incident angle. It is shown by the research results that curved artificial compound eye has the best structure imitating the functions and features of insect compound eye (Sanders and Halford 1995). With the improvement of micro fabrication technology, curved artificial compound eyes were widely researched in 2000s. Figure 5 shows the advance of several typical planar and curved artificial compound eyes in the twenti-first century. This figure indicates that many curved compound eyes were proposed after the year of 2006 and the research of planar compound eye is still in progress. The main reason is that large overlapped screen information in the ommatidia of planar compound eye can be utilized to enhance resolution and to obtain super-resolution images while keeping the compact structure. Thus, this section reviews the design and analysis of the two kinds of artificial compound eyes, planar and curved, respectively.

3.1 Planar artificial compound eye

In the early research of artificial compound eyes, most researchers focused on planar artificial compound eyes because of the limitation of micro fabrication technology. The prototype of

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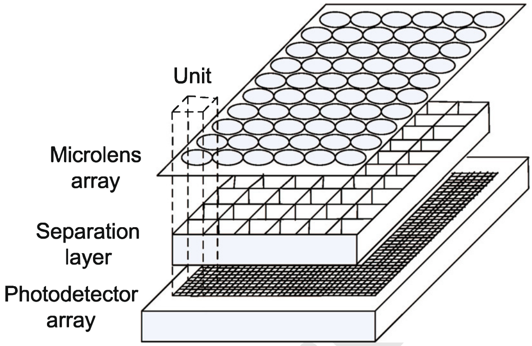

Fig. 6 TOMBO system (Tanida et al. 2000)

planar artificial compound eyes is either apposition compound eye or superposition compound eye. To date, a lot of planar artificial compound eyes have been proposed (Tanida et al. 2000; Duparré et al. 2004b, a; Duparré and Wippermann 2006; Duparré and Völkel 2006; Duparré et al. 2005d, a, 2004c, 2005b, c; Wippermann et al. 2005; Brückner et al. 2007, 2008; Druart et al. 2008; Brückner et al. 2010a, b; Bräuer et al. 2011; Brückner et al. 2011; Meyer et al. 2011; Stollberg et al. 2009; Duparré et al. 2008; Druart et al. 2009; Di et al. 2009; Leitel et al. 2010; Ueno et al. 2013; Brückner et al. 2010c; Ogata et al. 1994; Carr et al. 2004; Hornsey et al. 2004; Kinoshita et al. 2005; Christensen et al. 2006; Wippermann et al. 2006; Yang et al. 2009; Sieler et al. 2010; Fallah and Karimzadeh 2010; Dunkel et al. 2014; Belay et al. 2014). In what follows, several typical planar artificial compound eyes are selected to discuss the design principle.

Inspired by a dragonfly's apposition compound eye, a compact imaging system called TOMBO (Thin Observation Module by Bound Optics) was proposed by Tanida and his research team (Tanida et al. 2000). As shown in Fig. 6, TOMBO is composed of a microlens array, a separation layer and a photodetector array. Each microlens covers multiple photosensitive cells on the photodetector array to form a small imaging system called unit. Specially, adjacent units are separated by separation layers to prevent signal crosstalk. Obviously, this system is thinner than that of traditional cameras. It is noting that the structure can be further improved because each part of TOMBO is separable. However, this separability leads to much bias during the system integration and worsen its images.

A kind of artificial apposition compound eye called APCO (Apposition Compound eye Objective) was proposed by Duparré et al. (2004a, b), Duparré and Wippermann (2006), Duparré and Völkel (2006). In APCO, the overall thickness is only about 300 μm and the FOV about 21° on diagonal is achieved. Generally, the monolithic device is composed of a microlens array, a substrate, a pinhole array in the focal plane and a CMOS sensor array. Moreover, a pitch difference between lens array and pinhole array is designed to obtain wider FOV. In order to prevent crosstalk between adjacent channels, an opaque wall between adjacent channels is added (Duparré et al. 2005a, d). The schematic diagram of APCO is shown in Fig. 7. Subsequently, an imaging system that imitates the superposition compound eye was proposed by this team. As the implementation of each channel is optically isolated, this system is not called superposition compound eye, but cluster eye (Cley) (Duparré and Wippermann 2006; Duparré and Völkel 2006; Duparré et al. 2004c, 2005b, d). Cley is composed of three microlens arrays (MLAs) with different pitches. The working principle of Cley is shown in Fig. 8. Comparing with APCO, the image resolution and distortion in marginal channels of Cley have been greatly improved. However, due to the structure with three MLAs, it is quite complicated in fabrication and the thickness is nearly ten times as much as

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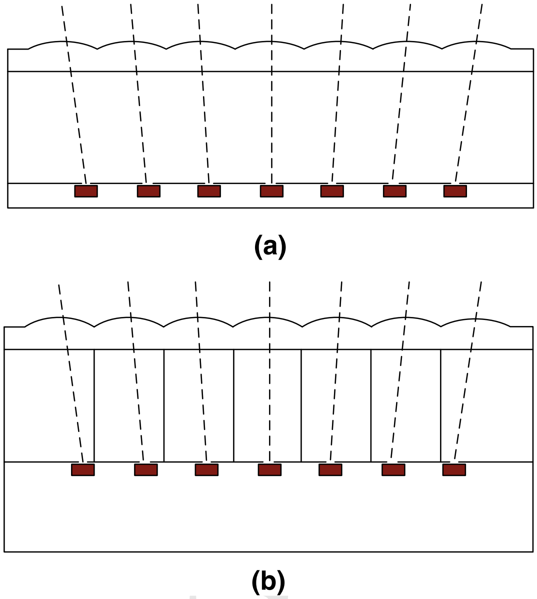

Fig. 7 Schematic diagram of APCO (Duparré et al. 2004b). **a** Without opaque wall. **b** With opaque wall

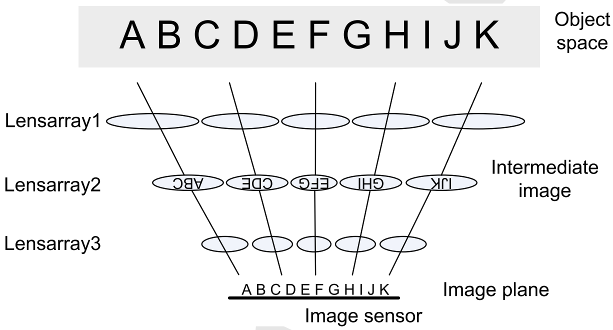

Fig. 8 Working principle of Cley (Duparré et al. 2004c)

that of APCO. The different pitches between MLAs can obtain large FOV, but this structure also suffers obviously by astigmatism in a large incident angle. Since the Cley can be seen as multiple isolated imaging systems, each ommatidium can be designed specifically to correct astigmatism. Inspired by this, Duparré et al. presented chirped arrays, in which ellipsoidal microlenses are used (Duparré et al. 2005c; Wippermann et al. 2005). Each microlens is designed carefully to correct the astigmatism. The related spot diagrams of the circular and ellipsoidal lenses under perpendicular and oblique incidence are shown in Fig. 9, which indicates that it is feasible to use the ellipsoidal lens to correct astigmatism. Thus, the Cley can be further improved by using the ellipsoidal lens. Figure 10 shows the schematic diagram of Cley and two kinds of microlens arrays.

A well-known problem in the area of artificial apposition compound eyes is that the inverse relationship between resolution and sensitivity (Duparré et al. 2005a). The reflective and refractive superposition compound eyes are too complicated to fabricated. Brückner et al. proposed an artificial neural superposition eye Brückner et al. (2007, 2008), just like the

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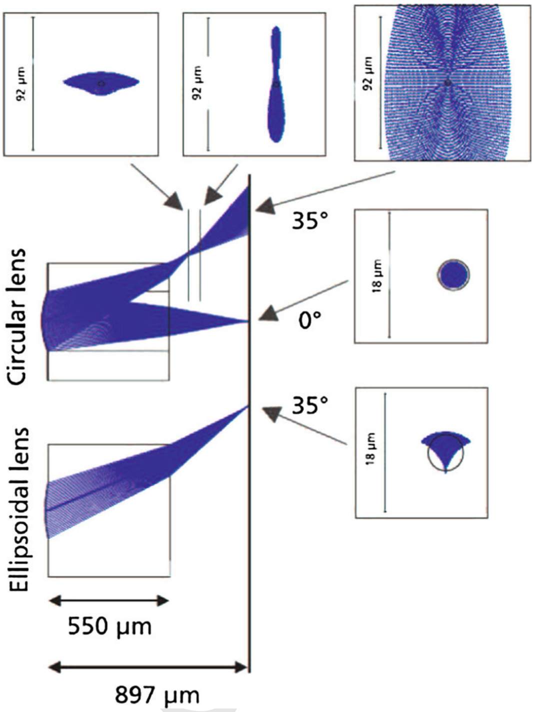

Fig. 9 Circular and ellipsoidal lenses under perpendicular and oblique incidence and related spot diagrams (Duparré et al. 2005c)

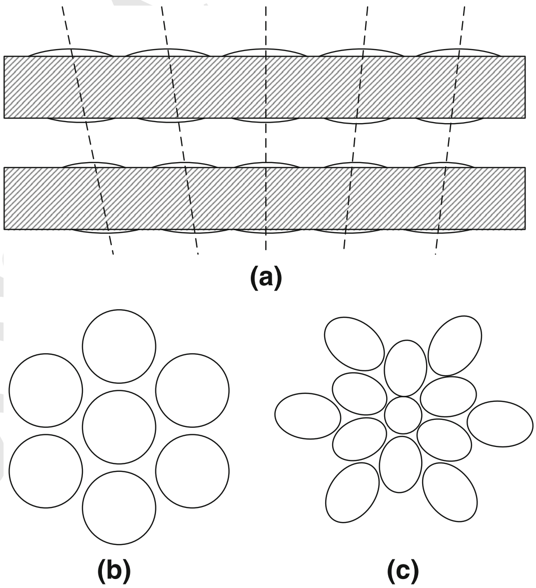

Fig. 10 Cley systems Duparré et al. (2004c). **a** Schematic diagram of Cley. **b** Regular microlens array. **c** Chirped microlens array

neural archetype. In the artificial neural superposition eye, each channel has multiple pixels and each object point is imaged by multiple channels separately; the outputs of the pixels that have parallel optical axes are summed up to increase the sensitivity of the eye under reserving the resolution. The working principles of neural superposition compound eyes in nature and

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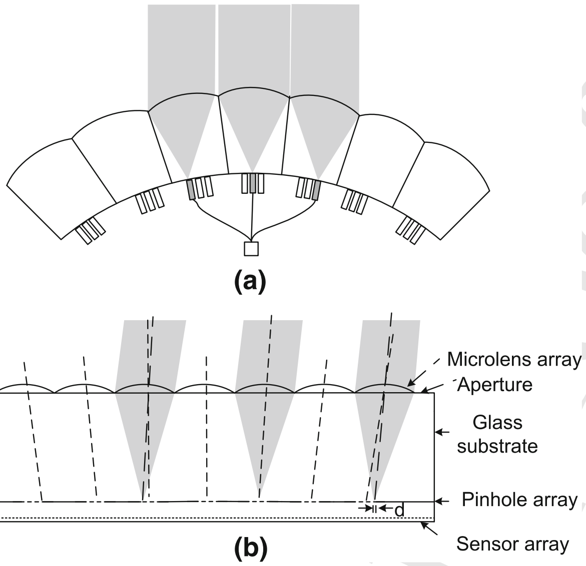

Fig. 11 Working principles of neural superposition compound eye. **a** Neural superposition compound eye in nature. **b** Artificial neural superposition compound eye (Brückner et al. 2007)

the artificial counterparts are shown in Fig. 11, where the working principles of the artificial neural superposition compound eye is just like the prototype found in nature. The artificial neural superposition eye exhibits a set of 3 × 3 pixels underneath each microlens, but the arrangement does not overcome the main disadvantages of the apposition principle. Later, inspired by the compound eye of a parasite of wasps called *Xenos Peckii*, Druart et al. came up with the idea to read out the completely partial image within each imaging channel, and then an imaging pre-processing method is used to form a full high resolution image (Druart et al. 2008). Brückner et al. followed this idea and presented an artificial compound eye system called eCley (Electronic Cluster Eye) (Brückner et al. 2010a, b; Bräuer et al. 2011; Brückner et al. 2011). eCley has an overall thickness only 1.4 mm, but it achieves a VGA resolution with 700 × 550 pixels. Generally, the partial images of the eCley are electronically stitched together to form a final image with high resolution. In contrast to other super-resolution algorithms, the relationship between the viewing directions of adjacent channels is well defined by thoroughly setting up the pitch difference between the optics and each channel, then the partial images are braided together. The principle of braided sampling is shown in Fig. 12. Inevitably, the eCley has a drawback that a customized image sensor in a large active area is needed. In order to overcome the major drawback of eCley, an artificial compound eye with optical stitching of segments called oCley (Optical Cluster Eye) is introduced by Meyer et al. (2011). The oCley is composed of four MLA layers. A special feature is that the second layer acts as field aperture and defines the shape and size of each partial image. The principle of oCley and the aperture shape of each layer are presented in Fig. 13.

The parameters of several typical planar artificial compound eyes are summarized in Table 2. Although the overall size of artificial compound eyes can not be as small as the natural compound eye, the overall thickness can reach 0.2 mm. Even when the VGA resolution is achieved, the overall thickness is only about 1.4 mm.

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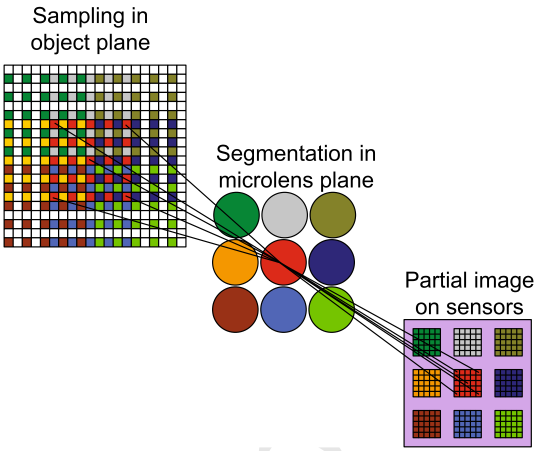

Fig. 12 The principle of braided sampling (Brückner et al. 2011). *Colors* are used for visualization only

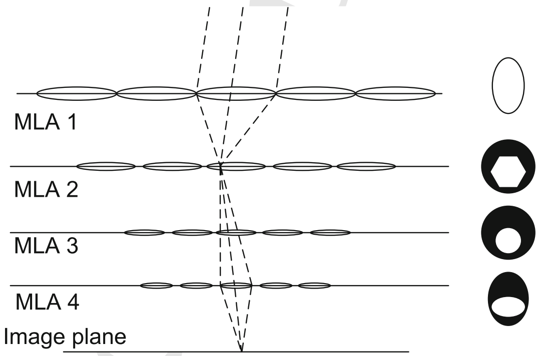

Fig. 13 The principle of oCley (Meyer et al. 2011). The first and the fourth microlens array include toroidal lenses. The second aperture is the hexagonal field aperture, which defines the partial image size

3.2 Curved artificial compound eye

The curved artificial compound eye was first introduced in 2006. Inspired by bees, Jeong et al. (2006) proposed a hemispherical compound eye with 8370 ommatidia. As shown in Fig. 14, each ommatidium is composed of a microlens, a polymer cone, a waveguide core and a photodetector to imitate the natural ommatidium. A comparison between the proposed artificial compound eye and natural compound eye is shown in Table 3. This table indicates that the physical dimensions and the optical characteristics of the proposed artificial compound eye are very comparable to the natural compound eye. Zhang et al. (2006) presented two kinds of curved compound eye: a single-layer and three-layer curved compound eye, in which the curved field lens array was introduced into the compound eye. The FOV of these two kinds of compound eyes are 60° and 88°, respectively. Due to the manufacturing complexity of the curved compound eye, a simplification of the complex natural archetype, called spherical artificial compound eye, was proposed by Radtke et al. (2007), Duparré et al. (2007). This compound eye system is composed of a lens array on a concave bulk lens and a pinhole array on a convex bulk lens. The design principle is shown in Fig. 15, where the designed channels are 112×112 and the FOV is $31^\circ \times 31^\circ$. However, due to the lack of opaque walls, the distortion leads to the usable channels only about 40×40 and the FOV only $10.3^\circ \times 10.3^\circ$. Actually, this is a spherical apposition compound eye (SApCE). Two kinds of spherical superposition compound eyes were proposed by Nakamura et al. (2012)

Table 2 The parameters of planar compound eye ("–" means unknown)

Type	Spatial resolution LP/mm	Angular resolution $LP/°$	FOV	Size $(\text{mm})^2$	Thickness (mm)	$F/\sharp$	Pixels	Channels
TOMBO (Tanida et al. 2000)	–	–	–	6 × 5	–	–	320 × 240	4 × 4 to 32 × 32
APCO (Duparré et al. 2004b)	3.6	1.5	20° × 20°	9 × 9	0.216 ∼ 0.345	2.2	–	130 × 130
Chirped APCO (Duparré et al. 2005c)	24	–	64.3°	9 × 9	0.9	2.6	130 × 130	130 × 130
Cley (Duparré et al. 2004c)	71	3.3	70° × 10°	4.5 × 0.5	2	1.8	700 × 550	21 × 3
Neural superposition eye (Brückner et al. 2007)	–	–	115° × 86°	–	0.65	2.5	60	40 × 30
Zoom compound eye (Duparré et al. 2008)	–	–	49° × 37°	–	6.9	5.6	–	80 × 60
MULTICAM (Druart et al. 2008)	–	8	30°	–	24.8	8	320 × 256	5 × 5
Spherical isolated-islands array (Di et al. 2009)	–	–	–	9 × 9	0.7	–	–	9 × 9
GSL (Stollberg et al. 2009)	49	2	29°	2.8 × 2.8	2	2.8 ± 0.2	156 × 156	15 × 15
eCley (Brückner et al. 2010a)	156	-	58° × 46°	6.8 × 5.2	1.4	3.7	700 × 500	17 × 13
Ultra-thin Array Microscope (Ueno et al. 2013)	115	–	–	36.1 × 24	4	–	4872 × 3248	150 × 90
oCley (Meyer et al. 2011)	155	4.2	53.2° × 39.9°	2.2 × 2.9	1.86	6.7	640 × 480	14 × 13
Close-up imaging system (Brückner et al. 2010c)	150	–	52° × 63°	8.5 × 8.5	6	2.8	3280 × 2464	26,000

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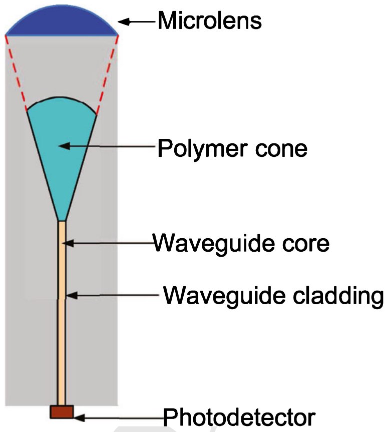

Fig. 14 Structure of artificial ommatidium (Jeong et al. 2006)

Table 3 Comparisons of an artificial compound eye and a natural compound eye (Jeong et al. 2006)

	Artificial compound eye	Natural compound eye
Shape of lens aperture	Hexagon	Hexagon
Maximal lens diameter	25 μm	20–36 μm
F number	1.8–2.9	2.7–3.3
Number of lenses	8370	Few∼30,000
Refractive index of lens	1.584	1.363
Index difference	0.029	0.023
Waveguide shape	Cylindrical	Cylindrical
Waveguide core	5.1–6.3 μm	2–8 μm
Waveguide length	150–300 μm	Appr. 100 μm
Angular sensitivity function	1.1°–4.4°	1.6°–4.7°

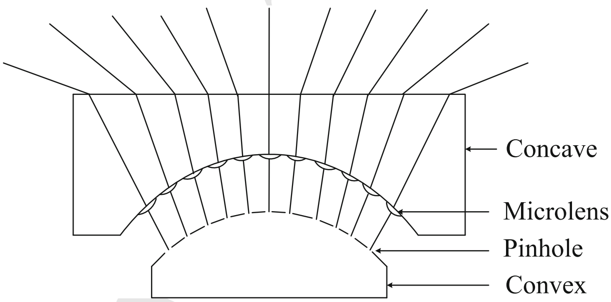

Fig. 15 Design principle of spherical compound eye (Radtke et al. 2007)

and Cao et al. (2015). The superposition compound eye (SuCE) was presented by Nakamura et al. using a spherical array of erect imaging optics to extend the FOV, and the deconvolution processing was introduced to reconstruct a sharp image. Subsequently, a spherical superposition compound eye (SSuCE) with three layers of lens arrays was proposed by Cao et al.. The two kinds of spherical superposition compound eyes have much higher energy efficiency and better resolution than conventional spherical apposition compound eyes. Li and Yi pro-

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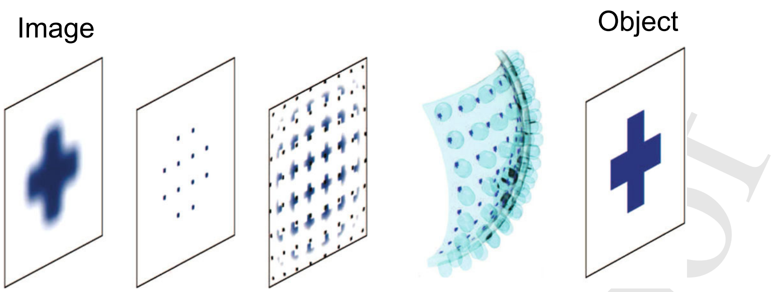
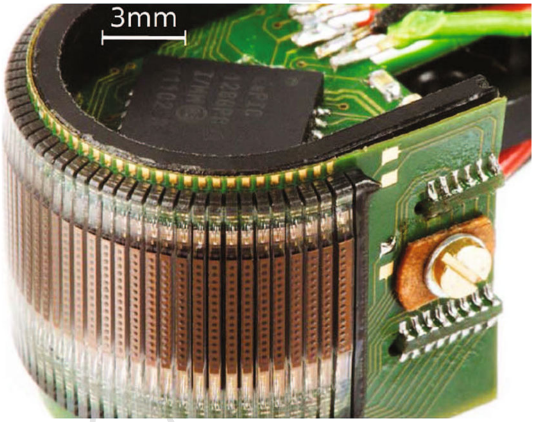


Fig. 16 The imaging principle of arthropod-inspired camera (Song et al. 2013)

Fig. 17 The CurvACE prototype (Viollet et al. 2014)



posed a microfabrication system created on a steep curved substrate. In fact, the fabricated three-dimensional microlens array has very high dimensional accuracy and the profile error is less than 6 μm over the entire surface (Li and Yi 2009, 2010). Based on this structure, the maximum light deviation angle reaches 18.43° and the maximal FOV, in theory, can be as large as 180°, if the entire hemispherical surface is used.

In recent years, various curved artificial compound eyes were proposed (Song et al. 2013; Xiao et al. 2014a, b; Floreano et al. 2013; Viollet et al. 2014; Zhang et al. 2010; Hiura et al. 2011; Moens et al. 2010; Shen and Su 2013; Li et al. 2013; Liu et al. 2012). Their representatives are the arthropod-inspired camera introduced by Song et al. (2013), Xiao et al. (2014b), Xiao et al. (2014a) and the CurvACE (Curved Artificial Compound Eye) presented by Floreano et al. (2013), Viollet et al. (2014). The arthropod-inspired camera is composed of elastometric compound optical elements with deformable array of thin silicon photodetectors, the total FOV up to 160° can be achieved. The imaging principle of the arthropod-inspired camera is shown in Fig. 16. Subsequently, a totally different imaging system, called computational compound eye (COMPU-EYE) (Lee et al. 2016) was proposed for improving the resolution. The CurvACE is inspired by Drosophila and composed of a microlens array, a neuromorphic photodetector array and a flexible PCB. Figure 17 shows the CurvACE prototype, which contains 630 ommatidia. The FOV of CurvACE is 180° × 60°. A comparison between CurvACE and its natural archetype is provided in Table 4.

The parameters of these curved artificial compound eyes are summarized in Table 5.

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Table 4 Comparison of CurvACE and Drosophila eye (Floreano et al. 2013)

	CurvACE	Drosophila eyes
Number of ommatidia	630	600 ∼ 700
Facet diameter (μm)	172	16
Eye diameter (mm)	12.8	0.36
Interommatidial angel	≈4.2°	≈4.7°–5.5°
Acceptance angle	4.2°	∼4.5°
FOV	180° × 60°	160° × 180°
Signal acquisition bandwidth	300 Hz	<100 Hz
Adaptability to illuminance	Yes	Yes
Crosstalk prevention	Yes	Yes

4 Theoretical development of artificial compound eye

This section will discuss the theoretical development of artificial compound eyes including planar and curved compound eyes. The curved compound eye is the best imaging model that imitates insect compound eyes. While the planar compound eye can also imitate natural compound eyes to some extent. Furthermore, some drawbacks of natural compound eyes can also be overcome by using planar compound eyes. For instance, the post-processing technology can be utilized to process large overlapped information in adjacent channels in a planar compound eye, and the final image with high resolution is reconstructed to overcome the low resolution of natural compound eyes.

4.1 Planar compound eye

The theoretical development of planar compound eyes mainly focuses on the image reconstruction, depth estimation and depth of field extension. In what follows, the three aspects will be discussed step by step.

4.1.1 Image reconstruction

In the artificial compound eye, each visual unit can be seen as an independent imaging channel, but in general the imaging channel has only up to several hundred pixels, comparing with traditional camera, which leads to the lower resolution. Due to the small interommatidial angle and large overlapped information between adjacent channels, the reconstruction of the final image with high resolution while keeping the compact structure is very important and also an challenging research topic in the planar artificial compound eye.

In 2001, in order to test the effectiveness of the TOMBO in image retrieval, Tanida et al. used the image sampling and back projection method to fuse and retrieve the final image with high resolution from multiple images with low resolution (Tanida et al. 2001a). In Tanida et al. (2001b), Kitamura et al. (2004), Tanida et al. presented a pixel rearrange method to further overcome the drawbacks that the sampling method can not increase the resolution in principle and the back projection method is difficult to suppress undesired noises. The principle of the pixel rearrange method is that the geometrical parameters of each unit image are first estimated to determine the position of the pixels, and then the pixels in all unit images are rearranged onto a virtual image plane with high resolution, and finally the interpolation is applied to compensate the pixels which are not assigned values. In 2003, the pixel rearrange

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Table 5 Parameters of curved artificial compound eye

Type	Angular resolution $LP/°$	FOV	Size (mm)	Thickness (mm)	$F/\sharp$	Pixels	Channels
Hemispherical compound eye (Jeong et al. 2006)	–	–	–	–	1.8–2.9	–	8370
Convex solid substrate based compound eye (Zhang et al. 2010)	–	60°	1.435	–	–	–	11 × 11
Krill-eye (Hiura et al. 2011)	–	≈180°	D = 1.8	–	–	–	10 × 10
Single-layer (Zhang et al. 2006)	–	60°	0.9 × 0.9	0.5	–	–	–
Three-layer (Zhang et al. 2006)	–	88°	0.9 × 0.9	0.5	–	–	–
Spherical compound eye (Radtke et al. 2007)	–	10.3° × 10.3°	D = 40	–	–	40 × 40	40 × 40
3D compound eye (Li and Yi 2009)	–	18.43°	D = 20	2.03	–	–	601
Two-layer lenses compound eye (Moens et al. 2010)	0.3	124°	–	–	–	–	25
Parabolic cluster eye (Shen and Su 2013)	–	102° × 90°	6.12 × 4.62	2.74	2.26	2053 × 1540	59
Arthropod-inspired camera (Song et al. 2013)	–	160°	R = 6.96	–	–	–	16 × 16
CurvACE (Floreano et al. 2013)	–	180° × 60°	R = 12.8	–	–	–	630

The symbols –, D and R means unknown, diameter and radius

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method was extended to color imaging; and two configurations, color separation by pixels and color separation by units, were discussed (Tanida et al. 2003). The result shows that the first configuration has a better performance than the second and is more complicated than the second in integration. As the pixel rearrange method used the interpolation method to compensate the invalid pixels, it cannot solve the problem caused by undersampling. In Nitta et al. (2006), to further improvement of the method, Nitta et al. introduced an iterative back projection method (IBP), where the pixel rearrange method was first applied to obtain the initial image and the back projection method was iteratively applied to refine the image.

Except for the pixel rearrange method, lots of image reconstruct methods were also discussed in planar artificial compound eye (Kanaev et al. 2007; El-Sallam and Boussaid 2008, 2009; Horisaki et al. 2009; Oberdörster et al. 2011; Mendelowitz et al. 2013; Wood et al. 2004, 2005, 2006; Li et al. 2007, 2009; Chan et al. 2006b; Choi and Schulz 2008; Tudela et al. 2008b, a). Kanaev et al. (2007) presented a scene-independent method, in which the final image with high resolution could be reconstructed only based on the accurate relative pixel shifts. In El-Sallam and Boussaid (2008), El-Sallam et al. introduced a spectral-based blind image restoration method, which neither requires the prior information about the imaging system nor the original scene. This method was extended to color imaging later El-Sallam and Boussaid (2009). Horisaki et al. (2009) proposed to divide the compound-eye imaging into the low and high frequency components to suppress the effect of the color shift. The low-frequency component was utilized to generate the final smooth image and the high-frequency component was used in the depth estimation. Based on eCley system, a braiding algorithm to restore the final image was discussed in Oberdörster et al. (2011). Various image reconstruct methods for planar artificial compound eye are summarized in Table 6, where the advantages and limitations of different methods are compared.

4.1.2 Depth estimation

In stereo vision, in order to obtain depth information of the environment, in generally, two cameras or multiple cameras are required to capture the same object in different directions. Thus, the stereo matching algorithms for obtaining the accurate depth information are very important and a hot area of research in computer vision. A survey on the stereo correspondence algorithms was made in Scharstein and Szeliski (2002). An artificial compound eye is a multi-aperture camera, where each ommatidium lies in the different view direction. In generally, an object can be seen by multiple ommatidia. So the structure of artificial compound eyes has a potential function for 3D information extraction.

Based on the multi-aperture structure, the multiple base-lines method was first used in TOMBO system to retrieve the 3D image, and the outlines of objects were obtained in the early research of the depth estimation in artificial compound eyes (Yamada et al. 2006). As the high-resolution image was reconstructed by the pixel rearrange method, which assumes that the object is located at specific distance, different object distances between the actual and the assumed positions will result in the poor reconstruction performance. Inspired by this, several candidate object distances were used to estimate the depth information and the final depth was obtained by evaluating the SSD (Sum of Squared Difference) between the reconstructed image and the back-projected image (Horisaki et al. 2007). In Miyazaki et al. (2008), the pixel rearrange method was further improved by using the parallax images and directly mapping the pixel value onto a 3D surface, and then a high-resolution 3D image was retrieved by using the ray tracing. In Kagawa et al. (2010), a high-speed multispectral 3D imaging system was discussed by introducing time delay and multiple wavelength decomposition. The depth map was obtained by comparing the images for different wavelengths in the same time. Gao et al.

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Table 6 Comparisons of different image reconstruct methods for planar artificial compound eye

Methods	Systems	Advantages	Limitations
Image sampling (Tanida et al. 2001a)	TOMBO	Simple principle and easy implementation	Cannot increse resolution
Backprojection (Tanida et al. 2001a)	TOMBO	Simple principle and easy implementation	Difficult to suppress undesired noise
Pixel rearrange based on correlation method (Tanida et al. 2001b)	TOMBO	Simple principle, easy implementation, need not to know the shift between units	Geometry parameter is not accurate enough; inaccuracy of measurement
Pixel rearrange based on ML method (Kitamura et al. 2004)	TOMBO	More accurate than in Tanida et al. (2001b)	High spatial resolution information cannot efficiently restore
IBP (Nitta et al. 2006)	TOMBO	Useful to restore high spatial resolution information	Time consuming
Scene-independent method (Kanaev et al. 2007)	TOMBO	Scene-independent;robust; stable and efficient	Have to first know relative subimage shift
Spectral-based blind method (El-Sallam and Boussaid 2008)	TOMBO	Do not require prior information; robust to additive noise	PSF of subimages needs to be known
IBP+depth estimated method (Horisaki et al. 2009)	TOMBO	Depth information is introduced to sharpen image	Computational error due to correlation method
Braiding algorithm (Oberdörster et al. 2011)	eCley	Near real-time	Imaging accuracy effected by estimated depth
MVE algorithm using lens diversity (Wood et al. 2005)	–	Multiple lenses provide more information	High cost due to multiple lenses
Shift & add algorithm (Li et al. 2007	–	Have clearer edges	System PSF needs to be known
Signal-processing based method (Choi and Schulz 2008)	TOMBO	Very accurate if no noise exists	Margin oscillation effects; sensitive to noise
Wiener filter method (Tudela et al. 2008a, b)	APCO	Simple principle and easy implementation	PSF needs to be known; sensitive to noise

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(2012a) proposed a method, which combines segmentation-based adaptive support-weight approach with scale invariant feature transform, to estimate depth for TOMBO. In Gao et al. (2012b), the investigation indicates that the compound images could be treated as 4-D light field data and a Fourier slice algorithm was introduced for digital refocusing. In Jiang et al. (2014), a new method for eCley, which is based on the property of the intensity transitional area, was presented by Jiang et al. to measure the depth information.

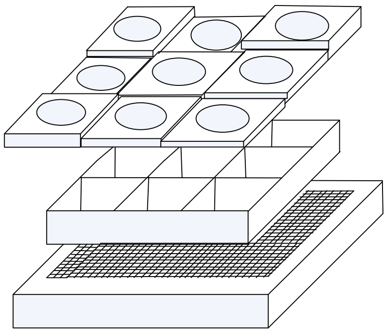
4.1.3 Depth of field extension

Generally, the compact structure of artificial compound eyes leads to short focal length. To improve the performance of artificial compound images, the extension of the depth of field is also an important research topic in planar compound eye.

To extend the depth of field, Chan et al. proposed to incorporate TOMBO with a phase mask and they introduced a conjugate gradient method to obtain the final image (Chan et al. 2006a, 2007). The final images obtained from two kinds of system structures, without phase mask and with phase mask, are shown in Fig. 18. On the other hand, in a conventional TOMBO system, lenses are placed on a flat surface, so this structure will result in the degradation of rays for far objects. This problem is solved by the irregular lens-array arrangement and the depth of field is extended in Horisaki et al. (2008, 2010). Figure 19 shows the irregular lens-array of TOMBO.

Fig. 18 The reconstructed images in Chan et al. (2006a)

Fig. 19 Irregular lens-array arrangement of TOMBO (Horisaki et al. 2008)



4.2 Curved compound eye

4.2.1 Large FOV imaging

The theoretical research of curved compound eyes mainly focuses on the large FOV imaging because curved compound eyes have the intrinsic features such as large FOV and less distortion in large incident angle. In Huang and Xu (2006), a seven-cameras model was proposed to imitate curved compound eyes. In this model, the position of each camera is pre-determined; adjacent images have small overlapped areas; the final large FOV image is obtained by directly splicing the adjacent images; the connecting mark is eliminated by combining the pixel values of adjacent images in the transition area. But this is just a multi-camera model imitating the principle of the compound eye. A direct method splicing the ommatidia images of artificial compound eyes was proposed by Cao et al. (2012). The excellent image quality is achieved when the FOV is over 166°.

4.2.2 Performance analysis

In order to further improve the performance of the curved compound eye, some researchers also devote to the performance analysis of the curved compound eyes. In Cheng and Lin (2007), Lin and Cheng (2007, 2008), a novel spherical compound-like eye of a superposition type was presented, based on two different configurations; and how the number of eyelets impacts on the performance of the compound-like eye was tested and analyzed. In Liu et al. (2009a, b), a generalized compound eye detector array was proposed to detect and localize the particle emitting sources, in addition, the statistical analysis about the performance of the compound eye array was analytically and numerically derived by computing Cramér-Rao bounds on the errors in estimating the direction of the incident particles. Many impact factor, such as Signal-to-Noise Ratio, the number of eyelets in the array, the number of detectors in each eyelet, were analyzed to illustrate the properties and performance of the array.

5 Applications of artificial compound eyes

Due to the fast advance of the fabrication and imaging techniques of artificial compound eyes, much attention has been increasingly paid to their various applications. In what follows, we review the applications from planar artificial compound eye to curved compound eye, like in Sect. 4.

5.1 Applications of planar artificial compound eyes

The compact structure and the good capacity of depth estimation are very useful in tiny equipments, so the planar artificial compound eye have been successfully applied to various fields, such as security systems, medical instruments, tiny scanners and projectors.

1. Security systems: Shogenji et al. (2004) presented a fingerprint capturing system, which combines TOMBO system with a light-guide plate. Each unit of TOMBO captures a partial fingerprint and the final fingerprint image is obtained by combining all the unit images. The resolution 1727 dpi of the fingerprint image can be obtained.
2. Medical instruments: In medical devices, endoscopes-based surgical techniques are widely used. Conventional endoscopes have great difficulty in the estimation of the exact

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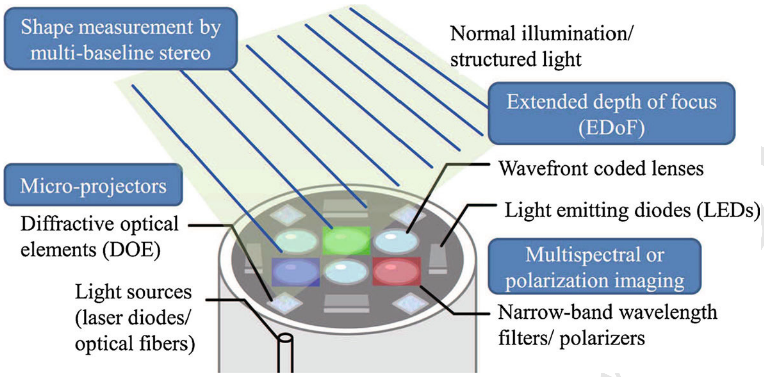

Fig. 20 Architecture and functions of TOMBO endoscope Kagawa et al. (2012c)

size of a lesion due to the lack of depth information. Applying the capacity of TOMBO in depth estimation, Yamada and Kagawa et al. invented a 3D endoscope system with the functions of extended depth of focus (EDoF), depth estimation, multispectral or polarization imaging (Yamada et al. 2005; Kagawa et al. 2012a, b, c). The architecture and functions of the TOMBO endoscope are shown in Fig. 20. As the intraoral diagnosis is very important to keep one's teeth healthy, Kagawa et al. created an active 3D shape measurement system with TOMBO (Kagawa et al. 2009a, b), which can be put into a narrow intraoral space. A horizontal stripe was introduced into the 3D shape measurement system as a structure pattern because the large textureless intraoral regions will lead to incorrect depth estimation. In Lai and Meng (2013), a MRI compatible SPECT system called MRC-SPECT-II was introduced based on an artificial compound eye gamma camera. This SPECT system is very compact and could obtain peak geometry efficiency about 1.5 %, while modern pre-clinical SPECT systems can gain the typical level of 0.1–0.01 %. This SPECT system could potentially take simultaneous MRI/SPECT imaging.

3. Tiny scanners and projectors: The conventional front-projection systems for free-form screens always require a trade-off between the system complexity and achievable performance, the compound eye structures could potentially use to handle this problem. A microoptical array projector was proposed by Sieler et al. (2012, 2013), and a novel slide pre-processing algorithm was presented to get the final projected image. A high-speed 3D array projector was proposed by Heist et al. (2013), and a combination of Gray code and phase-shifted sinusoidal fringes was used for depth estimation. A compact and large FOV image scanner was proposed by Kawano et al. (2013), which has the optical track length with 32 mm and the track width with 40 mm.

5.2 Applications of curved compound eyes

The large FOV of curved compound eyes is very useful for autonomous navigation and motion detection.

1. Autonomous navigation: In Leitel et al. (2014), Pericet-Camara et al. (2014), the CurvACE system was reported to directly applied in the autonomous navigation system. In this system, the optical flow method was used for navigation.
2. Motion detection: Neumann et al. (2003, 2004), a polydioptic camera, which is able to estimate its 3D motion by using an independently linear algorithm of scene, was invented. Krishnasamy et al. (2004a, b), a compound-eye image sensor, named "DragonflEYE",

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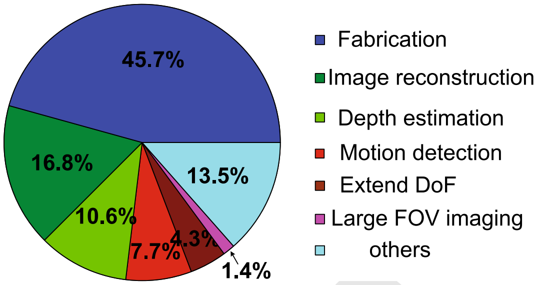
Fig. 21 Statistical pie chart of artificial compound eye researches from 1994 to 2014



was designed for target tracking, and an extension of the vanishing-point calibration method was also presented and evaluated.

In addition, a comprehensive survey about insect-like robots that navigate and control their motion using biologically inspired visual strategies can be referred in Franceschini (2014).

6 Conclusions and future research lines

This paper provides a comprehensive survey on the bionic system, the artificial compound eyes and the natural compound eyes. We review and analyze the system design, theoretical development and applications of artificial compound eye in terms of their two main types: planar and curved artificial compound eyes.

Artificial compound eyes are regarded as *the promising next generation compact imaging system*, due to their compact system structure, wide FOV and sensitivity to motion objects. A pie chart shown in Fig. 21 indicates the statistical values (%) with respect to the numbers of publications reported from 1994 to 2014. Among 210 papers, almost a half of researches are concentrating on the fabrication of artificial compound eye; the percentage 16.8 % implies that the image reconstruction is the most concern in the theoretical development of artificial compound eye. Given the current increasing research interest in artificial compound eye, we think it is worth discussing some future research directions in this area that the researchers envisage to further develop. In what follows, we list the future research lines from the design and fabrication, theoretical development and applications of artificial compound eye, respectively.

1. Design and fabrication of artificial compound eyes: Due to the compact structure, a very small assembly error will result in huge quality deterioration in the manufacturing process of artificial compound eye. So the fabrication technology and the design parameters need to be further improved.

   (a) How to treat the trade-off between field of view, resolution and sensitivity is a challenging issue to enhance the imaging performance of artificial compound eyes.
   (b) Now the imaging performance of artificial compound eye is comparable to its natural archetype, but compared with traditional cameras, the imaging performance of artificial compound eye needs to be greatly enhanced. A possible solution is to design a new artificial compound eye with advanced imaging techniques.
   (c) Now the image sensors are still placed in flat surface in the fabrication of a curved compound eye, which results in much complexity of fabricating techniques for cor-

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recting distortion. How to overcome this limitation is also an important research issue.

2. Theoretical development: The theoretical study of artificial compound eye mainly focuses on how to obtain the final high quality images by using various good and efficient methods and algorithms so as to well mimic the natural compound eye.

   (a) The quality of image, which is reconstructed by the artificial compound eye, mainly depends on the accuracy of interommatidial angles and the shift estimation of adjacent images. So it is very important to develop high-accuracy methods to estimate the adjacent images shift.
   (b) Interpolation methods are widely used in image reconstruction of artificial compound eyes, but they always bring the edge blur effect. So the research of edge contour enhancement methods needs to be further pushed. At the meantime, the PSFs of the channels are available. This information could be used to regain some sharpness with PSF deconvolution.
   (c) The image reconstruction has to consider the parallax between the ommatidia of artificial compound eye. This parallax depends on object depth. In fact, conventional depth estimation methods in compound eye are quite time-consuming and also result in estimation errors due to the short base line. The depth estimation could be determined either by correlating neighboring subimages, as the principle of light field (Wanner and Goldluecke 2014), or by using the defocus measure (Tao et al. 2013). So new and better depth estimation methods are required.
   (d) Other features of natural compound eyes are also worth further researching. For example, motion detection is one of the most important feature of natural compound eyes, but only a very limited number of investigations related to motion detection are reported in the community of artificial compound eyes. Therefore, any methods or algorithms for better imitating insect compound eyes' functions are also worth discussing.

3. Applications: The compact imaging structure and the wide field of view of artificial compound eye are very attractive in downsizing the imaging devices, especially are very necessary in the fields requiring tiny imaging instruments.

   (a) Application in security systems: Nowadays, more and more attention is paid to property security such as credit card safety. As usual, the thickness of the credit card is less than 1 mm, how to well embed an artificial compound eye into ID cards or credit cards to capture the users' fingerprints as an identification is a promising technique.
   (b) Application in biomedicine area: Now internal examination is much straightforward to check the symptom of a patient. The micro capsule robot is widely researched to hope to be used in internal examination. Due to the compact structure and short range imaging feature, artificial compound eye can be integrated into micro capsule robots as the imaging system. This will greatly improve the diagnosis reliability of the patients' symptoms.

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References

Bähr R (1974) Contribution to the morphology of chilopod eyes. In: Proceedings of the symposium held at the Zoological Society of London, vol 32, pp 388–404

Barshan B, Kuc R (1992) A bat-like sonar system for obstacle localization. IEEE Trans Syst Man Cybern 22(4):636–646

Belay GY, Ottevaere H, Meuret Y, Vervaeke M, Van EJ, Thienpont H (2014) Proof-of-concept demonstration of a miniaturized three-channel multiresolution imaging system. In: Proceeding of the SPIE, vol 9138, p 91380B

Bräuer A, Brückner A, Wippermann F, Dannberg P, Leitel R (2011) High resolution multichannel imaging systems. In: Proceedings of the IEEE microopics conference, pp 1–2

Brückner A, Duparré J, Dannberg P, Bräuer A, Tünnermann A (2007) Artificial neural superposition eye. Opt Express 15(19):11922–11933

Brückner A, Duparré J, Bräuer A (2008) Advanced artificial compound-eye imaging systems. In: Proceedings of the SPIE, vol 6887, p 688709

Brückner A, Duparré J, Dannberg P, Leitel R, Bräuer A (2010a) Driving micro-optical imaging systems towards miniature camera applications. In: Proceedings of the SPIE, vol 7716, p 77160J

Brückner A, Duparré J, Leitel R, Dannberg P, Bräuer A, Tünnermann A (2010b) Thin wafer-level camera lenses inspired by insect compound eyes. Opt Express 18(24):24379–24394

Brückner A, Duparré J, Wippermann F, Leitel R, Dannberg P, Bräuer A (2010c) Ultra-compact close-up microoptical imaging system. In: Proceedings of the SPIE, vol 7786, p 77860A

Brückner A, Leitel R, Oberdörster A, Dannberg P, Wippermann F, Bräuer A (2011) Multi-aperture optics for wafer-level cameras. J Micro Nanolithogr MEMS MOEMS 10(4):043,010

Cao A, Shi L, Shi R, Deng Q, Du C (2012) Image process technique used in a large fov compound eye imaging system. In: Proceedings of the SPIE, vol 8558, p 85581K

Cao Z, Zhai C, Wang K (2015) Design of artificial spherical superposition compound eye. Opt Commun 356:218–222

Carr PK, Ara F, Thomas PJ, Hornsey RI (2004) Distributed imaging using compound eye sensors. In: Proceedings of the SPIE, vol 5578, pp 454–464

Chan WS, Lam EY, Ng MK (2006a) Extending the depth of field in a compound-eye imaging system with super-resolution reconstruction. In: 18th international conference on pattern recognition, vol 3, pp 623–626

Chan WS, Lam EY, Ng MK (2006b) Investigation of computational compound-eye imaging system with super-resolution reconstruction. In: IEEE international conference on acoustics speech and signal processing proceedings, vol 4, pp 1177–1180

Chan WS, Lam EY, Ng MK, Mak GY (2007) Super-resolution reconstruction in a computational compound-eye imaging system. Multidimens Syst Signal Process 18(2–3):83–101

Cheng CC, Lin GL (2007) Motion estimation using the single-row superposition-type planar compound-like eye. Sensors 7(7):1047–1068

Choi K, Schulz TJ (2008) Signal-processing approaches for image-resolution restoration for tombo imagery. Appl Opt 47(10):B104–B116

Christensen MP, Bhakta V, Rajan D, Mirani T, Douglas SC, Wood SL, Haney MW (2006) Adaptive flat multiresolution multiplexed computational imaging architecture utilizing micromirror arrays to steer subimager fields of view. Appl Opt 45(13):2884–2892

Clarkson E, Levi-Setti R (1975) Trilobite eyes and the optics of des cartes and huygens. Nature 254(5502):663–667

Collett TS, Land MF (1975) Visual control of flight behaviour in the hoverflysyritta pipiens l. J Comp Physiol 99(1):1–66

Cronin TW, Johnsen S, Marshall NJ, Warrant EJ (2014) Visual ecology. Princeton University Press, Princeton

Darwin C (2003) On the origin of species. Broadview Press, Peterborough

Di S, Lin H, Du R (2009) An artificial compound eyes imaging system based on mems technology. In: Proceedings of the IEEE international conference on robotics and biomimetics, pp 13–18

Druart G, Guérineau N, Haïdar R, Lambert E, Tauvy M, Thétas S, Rommeluère S, Primot J, Deschamps J (2008) Multicam: a miniature cryogenic camera for infrared detection. In: Proceedings of the SPIE, vol 6992, p 69920G

Druart G, Guérineau N, Haïdar R, Thétas S, Taboury J, Rommeluère S, Primot J, Fendler M (2009) Demonstration of an infrared microcamera inspired by Xenos peckii vision. Appl Opt 48(18):3368–3374

Journal: 10462-AIRE Article No.: 9513 TYPESET DISK LE CP Disp.:2016/8/26 Pages: 31 Layout: Small

Dunkel J, Wippermann F, Brückner A, Reimann A, Müller M, Bräuer A (2014) Fabrication of refractive freeform array masters for artificial compound eye cameras. In: Proceedings of the SPIE, vol 9130, p 91300P

Duparré J, Völkel R (2006) Novel optics/micro-optics for miniature imaging systems. In: Proceedings of the SPIE, vol 6196, p 619607

Duparré J, Wippermann F (2006) Micro-optical artificial compound eyes. Bioinspir Biomim 1(1):R1–R16

Duparré J, Dannberg P, Schreiber P, Bräuer A, Tünnermann A (2004a) Artificial apposition compound eye fabricated by micro-optics technology. Appl Opt 43(22):4303–4310

Duparré J, Dannberg P, Schreiber P, Bräuer A, Tünnermann A (2004b) Micro-optically fabricated artificial apposition compound eye. In: Proceedings of the SPIE, vol 5301, pp 25–33

Duparré J, Schreiber P, Volkel R (2004c) Theoretical analysis of an artificial superposition compound eye for application in ultra flat digital image acquisition devices. In: Proceedings of the SPIE, vol 5249, pp 408–418

Duparré J, Dannberg P, Schreiber P, Bräuer A, Tünnermann A (2005a) Thin compound-eye camera. Appl Opt 44(15):2949–2956

Duparré J, Schreiber P, Matthes A, Bräuer A, Tünnermann A, Völkel R, Eisner M, Scharf T et al (2005b) Microoptical telescope compound eye. Opt Express 13(3):889–903

Duparré J, Wippermann F, Dannberg P, Reimann A (2005c) Chirped arrays of refractive ellipsoidal microlenses for aberration correction under oblique incidence. Opt Express 13(26):10539–10551

Duparré J, Wippermann F, Dannberg P, Schreiber P, Bräuer A, Völkel R, Scharf T (2005d) Microoptical artificial compound eyes: from design to experimental verification of two different concepts. In: Proceedings of the SPIE, vol 5962, p 59622A

Duparré J, Radtke D, Tünnermann A (2007) Spherical artificial compound eye captures real images. In: Proceedings of the SPIE, vol 6466, p 64660K

Duparré J, Wippermann F, Dannberg P, Bräuer A (2008) Artificial compound eye zoom camera. Bioinspir Biomim 3(4):0460,08

El-Sallam AA, Boussaid F (2008) Spectral-based blind image restoration method for thin TOMBO imagers. Sensors 8(9):6108–6124

El-Sallam AA, Boussaid F (2009) A high resolution color image restoration algorithm for thin TOMBO imaging systems. Sensors 9(6):4649–4668

Fallah HR, Karimzadeh A (2010) MTF of compound eye. Opt Express 18(12):12304–12310

Floreano D, Pericet-Camara R, Viollet S, Ruffier F, Brückner A, Leitel R, Buss W, Menouni M, Expert F, Juston R et al (2013) Miniature curved artificial compound eyes. Proc Natl Acad Sci USA 110(23):9267–9272

Franceschini N (2014) Small brains, smart machines: from fly vision to robot vision and back again. Proc IEEE 102(5):751–781

Gao Y, Liu W, Yang P, Xu B (2012a) Depth estimation based on adaptive support weight and sift for multi-lenslet cameras. In: Proceeding of the SPIE, vol 8419, p 84190C

Gao Y, Yang P, Yan H, Xu B (2012b) Digital refocusing of compound images using fourier slice algorithm for thin observation module by bound optics. In: Proceedings of the international congress on image and signal processing, pp 1686–1690

Heist S, Sieler M, Breitbarth A, Kühmstedt P, Notni G (2013) High-speed 3D shape measurement using array projection. In: Proceedings of the SPIE, vol 8788, p 878815

Hiura S, Mohan A, Raskar R (2011) Krill-eye: Superposition compound eye for wide-angle imaging via GRIN lenses. Inf Media Technol 6(1):144–157

Hornsey R, Thomas P, Wong W, Pepic S, Yip K, Krishnasamy R (2004) Electronic compound-eye image sensor: construction and calibration. In: Proceedings of the SPIE, vol 5301, pp 13–24

Horisaki R, Irie S, Nakao Y, Ogura Y, Toyoda T, Masaki Y, Tanida J (2007) 3D information acquisition using a compound imaging system. In: Proceedings of the SPIE, vol 6695, p 66950F

Horisaki R, Nakao Y, Toyoda T, Kagawa K, Masaki Y, Tanida J (2008) A compound-eye imaging system with irregular lens-array arrangement. In: Proceedings of the SPIE, vol 7072, p 70720G

Horisaki R, Nakao Y, Toyoda T, Kagawa K, Masaki Y, Tanida J (2009) A thin and compact compound-eye imaging system incorporated with an image restoration considering color shift, brightness variation, and defocus. Opt Rev 16(3):241–246

Horisaki R, Kagawa K, Nakao Y, Toyoda T, Masaki Y, Tanida J (2010) Irregular lens arrangement design to improve imaging performance of compound-eye imaging systems. Appl Phys Express 3(2):022,501

Horridge GA (1977) Insects which turn and look. Endeavour 1(1):7–17

Horridge GA (1978) The separation of visual axes in apposition compound eyes. Philos Trans R Soc B 285(1003):1–59

Horridge GA (1987) The evolution of visual processing and the construction of seeing systems. Proc R Soc Lond B Biol Sci 230(1260):279–292

Journal: 10462-AIRE Article No.: 9513 TYPESET DISK LE CP Disp.:2016/8/26 Pages: 31 Layout: Small

Huang Z, Xu G (2006) Research on panorama picture formation in bionic compound eye measuring system. Metrol Measur Technol 26(1):17–26
Jeong KH, Kim J, Lee LP (2006) Biologically inspired artificial compound eyes. Science 312(5773):557–561
Jiang T, Zhu M, Kuhnert KD, Kuhnert L (2014) Distance measuring using calibrating subpixel distances of stereo pixel pairs in artificial compound eye. In: Proceedings of the IEEE international conference on informative and cybernetics for computational social systems, pp 118–122
Johnson W (2012) Helicopter theory. Courier Corporation, North Chelmsford
Kagawa K, Tanabe H, Ogata C, Horisaki R, Ogura Y, Nakao Y, Toyoda T, Masaki Y, Ueda M, Tanida J (2009a) A compact shape-measurement module based on a thin compound-eye camera with multiwavelength diffractive pattern projection for intraoral diagnosis. In: Proceedings of the SPIE, vol 7442, p 74420U
Kagawa K, Tanabe H, Ogata C, Ogura Y, Nakao Y, Toyoda T, Masaki Y, Ueda M, Tanida J (2009b) An active intraoral shape measurement scheme using a compact compound-eye camera with integrated pattern projectors. Jpn J Appl Phys 48(9S2):09LB04
Kagawa K, Fukata N, Tanida J (2010) High-speed multispectral three-dimensional imaging with a compound-eye camera tombo. In: Proceedings of the SPIE, vol 7797, p 77970N
Kagawa K, Yamada K, Tanaka E, Tanida J (2012a) A three-dimensional multifunctional compound-eye endoscopic system with extended depth of field. Electron Commun Jpn 95(11):14–27
Kagawa K, Shogenji R, Tanaka E, Yamada K, Kawahito S, Tanida J (2012b) Variable field-of-view visible and near-infrared polarization compound-eye endoscope. In: Annual international conference of the IEEE engineering in medicine and biology society, pp 3720–3723
Kagawa K, Tanaka E, Yamada K, Kawahito S, Tanida J (2012c) Deep-focus compound-eye camera with polarization filters for 3D endoscopes. In: Proceedings of the SPIE, vol 8227, p 822714
Kanaev AV, Ackerman JR, Fleet EF, Scribner DA (2007) TOMBO sensor with scene-independent superresolution processing. Opt Lett 32(19):2855–2857
Kawada H, Tatsuta H, Arikawa K, Takagi M (2006) Comparative study on the relationship between photoperiodic host-seeking behavioral patterns and the eye parameters of mosquitoes. J Insect Physiol 52(1):67–75
Kawano H, Okamoto T, Matsuzawa T, Nakajima H, Makita J, Toyoda Y, Funakura T, Nakanishi T, Kunieda T, Minobe T (2013) Compact and large depth of field image scanner for auto document feeder with compound eye system. Opt Rev 20(2):254–258
Kinoshita H, Hoshino K, Matsumoto K, Shimoyama I (2005) Thin compound eye camera with a zooming function by reflective optics. In: Proceedings of the IEEE conference on micro electro mechanical systems, pp 235–238
Kitamura Y, Shogenji R, Yamada K, Miyatake S, Miyamoto M, Morimoto T, Masaki Y, Kondou N, Miyazaki D, Tanida J et al (2004) Reconstruction of a high-resolution image on a compound-eye image-capturing system. Appl Opt 43(8):1719–1727
Krishnasamy R, Thomas P, Pepic S, Wong W, Hornsey RI (2004a) Calibration techniques for object tracking using a compound eye image sensor. In: Proceedings of the SPIE, vol 5611, pp 42–52
Krishnasamy R, Wong W, Shen E, Pepic S, Hornsey R, Thomas PJ (2004b) High precision target tracking with a compound-eye image sensor. In: Canadian conference on electrical and computer engineering, vol 4, pp 2319–2323
Lai XC, Meng LJ (2013) Artificial compound-eye gamma camera for mri compatible spect imaging. In: Proceedings of the IEEE nuclear science symposium and medical imaging conference, pp 1–7
Land MF (1976) Superposition images are formed by reflection in the eyes of some oceanic decapod Crustacea. Nature 263:764–765
Land MF (1981) Optics and vision in invertebrates. Handb Sens Physiol 7(6b):471–593
Land MF (1997) Visual acuity in insects. Annu Rev Entomol 42(1):147–177
Land MF, Nilsson DE (2012) Animal eyes. Oxford University Press, Oxford
Land MF, Gibson G, Horwood J, Zeil J (1999) Fundamental differences in the optical structure of the eyes of nocturnal and diurnal mosquitoes. J Comp Physiol A 185(1):91–103
Lee WB, Jang H, Park S, Song YM, Lee HN (2016) COMPU-EYE: a high resolution computational compound eye. Opt Express 24(3):2013–2026
Leitel R, Brückner A, Buß W, Viollet S, Pericet-Camara R, Mallot H, Bräuer A (2014) Curved artificial compound-eyes for autonomous navigation. In: Proceedings of the SPIE, vol 9130, p 91300H
Leitel R, Stollberg K, Brückner A, Duparré J, Dannberg P, Bräuer A (2010) A wafer-level camera approach based on the Gabor superlens. In: Proceedings of the SPIE, vol 7716, p 77160L
Li L, Yi AY (2009) Microfabrication on a curved surface using 3D microlens array projection. J Micromech Microeng 19(10):105,010
Li L, Yi AY (2010) Development of a 3D artificial compound eye. Opt Express 18(17):18125–18137

Journal: 10462-AIRE Article No.: 9513 TYPESET DISK LE CP Disp.:2016/8/26 Pages: 31 Layout: Small

Li M, Xu L, Huang F, Tang M, Wang H (2007) Reconstruction of bionic compound eye images based on super-resolution algorithm. In: Proceedings of the IEEE international conference on integration technology, pp 706–710

Li M, Xu L, Shi A, Huang F (2009) Image reconstruction algorithm inspired by a bionic compound eye system. CAAI Trans Intell Syst 4(2):180–187

Li F, Chen S, Luo H, Gao Y (2013) Curved micro lens array for bionic compound eye. Opt Int J Light Electron Opt 124(12):1346–1349

Lin GL, Cheng CC (2007) Single-row superposition-type spherical compound-like eye for pan-tilt motion recovery. In: Proceedings of the IEEE symposium on computational intelligence in image and signal processing, pp 24–29

Lin GL, Cheng CC (2008) An artificial compound eye tracking pan-tilt motion. IAENG Int J Comput Sci 35(2):242–248

Liu Z, Nehorai A, Paldi E (2009a) A biologically inspired compound-eye detector array—part I: modeling and fundamental limits. IEEE Trans Signal Process 57(5):1839–1857

Liu Z, Nehorai A, Paldi E (2009b) A biologically inspired compound-eye detector array—part II: statistical performance analysis. IEEE Trans Signal Process 57(5):1858–1876

Liu Y, Shi L, Shi R, Dong X, Deng Q, Du C (2012) An artificial compound eye system for large field imaging. In: Proceedings of the SPIE, vol 8558, p 85581L

Mendelowitz S, Klapp I, Mendlovic D (2013) Design of an image restoration algorithm for the TOMBO imaging system. J Opt Soc Am A 30(6):1193–1204

Meyer J, Brückner A, Leitel R, Dannberg P, Bräuer A, Tünnermann A (2011) Optical cluster eye fabricated on wafer-level. Opt Express 19(18):17506–17519

Miyazaki D, Ito K, Nakao Y, Toyoda T, Masaki Y (2008) Retrieval of three-dimensional image from compound-eye imaging with defocus using ray tracing. In: Proceedings of the IEEE international conference on innovative computing information and control, pp 51–51

Moens E, Meuret Y, Ottevaere H, Sarkar M, Bello DSS, Merken P, Thienpont H (2010) An insect eye-based image sensor with very large field of view. In: Proceedings of the SPIE, vol 7716, p 77162D

Nakamura T, Horisaki R, Tanida J (2012) Computational superposition compound eye imaging for extended depth-of-field and field-of-view. Opt Express 20(25):27482–27495

Neumann J, Fermüller C, Aloimonos Y (2003) Polydioptric camera design and 3D motion estimation. In: Proceedings of the CVPR IEEE, vol 2, pp II–294

Neumann J, Fermüller C, Aloimonos Y, Brajovic V (2004) Compound eye sensor for 3D ego motion estimation. In: Proceedings of the IEEE international conf on intelligent robots and systems, vol 4, pp 3712–3717

Nilsson DE (1989a) Optics and evolution of the compound eye. In: Facets of vision. Springer, Berlin, pp 30–73 5

Nilsson DE (1989b) Vision optics and evolution. Bioscience 39(5):298–307

Nitta K, Shogenji R, Miyatake S, Tanida J (2006) Image reconstruction for thin observation module by bound optics by using the iterative backprojection method. Appl Opt 45(13):2893–2900

Oberdörster A, Brückner A, Wippermann FC, Bräuer A (2011) Correcting distortion and braiding of micro-images from multi-aperture imaging systems. In: Proceedings of the SPIE, vol 7875, p 78750B

Ogata S, Ishida J, Sasano T (1994) Optical sensor array in an artificial compound eye. Opt Eng 33(11):3649–3655

Pericet-Camara R, Bahi-Vila G, Lecoeur J, Floreano D (2014) Miniature artificial compound eyes for optic-flow-based robotic navigation. In: Proceedings of the workshop on information optics, pp 1–3

Radtke D, Duparré J, Zeitner UD, Tünnermann A (2007) Laser lithographic fabrication and characterization of a spherical artificial compound eye. Opt Express 15(6):3067–3077

Sanders JS, Halford CE (1995) Design and analysis of apposition compound eye optical sensors. Opt Eng 34(1):222–235

Sarkar M (2011) A biologically inspired CMOS image sensor. Delft University of Technology, Delft

Scharstein D, Szeliski R (2002) A taxonomy and evaluation of dense two-frame stereo correspondence algorithms. Int J Comput Vis 47(1–3):7–42

Schoenemann B (2007) Trilobite eyes and a new type of neural superposition eye in an ancient system. Palaeontogr Abt A 281(1–3):63–91

Schoenemann B, Clarkson EN (2013) Discovery of some 400 million year-old sensory structures in the compound eyes of trilobites. Sci Rep 3 6

Shen HK, Su GDJ (2013) Cluster eye camera using microlenses on parabolic surface. In: Proceedings of the SPIE, vol 8842, p 884202D

Sherk TE (1978) Development of the compound eyes of dragonflies (Odonata). III. Adult compound eyes. J Exp Zool 203(1):61–79

Journal: 10462-AIRE Article No.: 9513 TYPESET ✓ DISK LE CP Disp.:2016/8/26 Pages: 31 Layout: Small

Shogenji R, Kitamura Y, Yamada K, Miyatake S, Tanida J (2004) Bimodal fingerprint capturing system based on compound-eye imaging module. Appl Opt 43(6):1355–1359

Sieler M, Schreiber P, Dannberg P, Bräuer A (2010) Array projection optics: multi-channel design for ultra slim projectors. In: Proceedings of the SPIE, vol 7716, p 77161A

Sieler M, Schreiber P, Dannberg P, Bräuer A, Tünnermann A (2012) Ultraslim fixed pattern projectors with inherent homogenization of illumination. Appl Opt 51(1):64–74

Sieler M, Fischer S, Schreiber P, Dannberg P, Bräuer A (2013) Microoptical array projectors for free-form screen applications. Opt Express 21(23):28702–28709

Snyder AW (1977) Acuity of compound eyes: physical limitations and design. J Comp Physiol 116(2):161–182

Snyder AW (1979) Physics of vision in compound eyes. In: Comparative physiology and evolution of vision in invertebrates. Springer, Berlin, pp 225–313

Snyder AW, Stavenga DG, Laughlin SB (1977) Spatial information capacity of compound eyes. J Comp Physiol 116(2):183–207

Song YM, Xie Y, Malyarchuk V, Xiao J, Jung I, Choi KJ, Liu Z, Park H, Lu C, Kim RH et al (2013) Digital cameras with designs inspired by the arthropod eye. Nature 497(7447):95–99

Stollberg K, Brückner A, Duparré J, Dannberg P, Bräuer A, Tünnermann A (2009) The gabor superlens as an alternative wafer-level camera approach inspired by superposition compound eyes of nocturnal insects. Opt Express 17(18):15747–15759

Tanida J, Kumagai T, Yamada K, Miyatake S, Ishida K, Morimoto T, Kondou N, Miyazaki D, Ichioka Y (2000) Thin observation module by bound optics (TOMBO): an optoelectronic image capturing system. In: Proceedings of the SPIE, vol 4089, pp 1030–1036

Tanida J, Kumagai T, Yamada K, Miyatake S, Ishida K, Morimoto T, Kondou N, Miyazaki D, Ichioka Y (2001a) Thin observation module by bound optics (TOMBO): concept and experimental verification. Appl Opt 40(11):1806–1813

Tanida J, Kitamura Y, Yamada K, Miyatake S, Miyamoto M, Morimoto T, Masaki Y, Kondou N, Miyazaki D, Ichioka Y (2001b) Compact image capturing system based on compound imaging and digital reconstruction. In: Proceedings of the SPIE, vol 4455, pp 34–41

Tanida J, Shogenji R, Kitamura Y, Yamada K, Miyamoto M, Miyatake S (2003) Color imaging with an integrated compound imaging system. Opt Express 11(18):2109–2117

Tao MW, Hadap S, Malik J, Ramamoorthi R (2013) Depth from combining defocus and correspondence using light-field cameras. In: Proceedings of the IEEE inernational conference on computer vision, pp 673–680

Tudela R, Brückner A, Duparré J, Bräuer A (2008a) Image capture and processing for a microoptical compound-eye sensor. In: Proceedings of the SPIE, vol 7000, p 700019

Tudela R, Brückner A, Duparré J, Bräuer A (2008b) An image restoration approach for artificial compound eyes. In: Proceedings of the SPIE, vol 6812, p 68120O

Ueno R, Suzuki K, Kobayashi M, Kwon H, Honda H, Funaki H (2013) Compound-eye camera module as small as 8.5 8.5 6.0 mm for 26 k-resolution depth map and 2-Mpix 2D imaging. IEEE Photonics J 5(4):6801,212

Vannier J, Schoenemann B, Gillot T, Charbonnier S, Clarkson E (2016) Exceptional preservation of eye structure in arthropod visual predators from the middle jurassic. Nat Commun 7

Viollet S, Godiot S, Leitel R, Buss W, Breugnon P, Menouni M, Juston R, Expert F, Colonnier F, L'Eplattenier G et al (2014) Hardware architecture and cutting-edge assembly process of a tiny curved compound eye. Sensors 14(11):21702–21721

Wanner S, Goldluecke B (2014) Variational light field analysis for disparity estimation and super-resolution. IEEE Trans Pattern Anal 36(3):606–619

Wippermann F, Duparré J, Schreiber P, Dannberg P (2005) Design and fabrication of a chirped array of refractive ellipsoidal micro-lenses for an apposition eye camera objective. In: Proceedings of the SPIE, vol 5962, p 59622C

Wippermann F, Duparré J, Schreiber P (2006) Applications of chirped microlens arrays for aberration compensation and improved system integration. In: Proceedings of the SPIE, vol 6289, p 628915

Wood SL, Rajan D, Christensen M, Douglas S, Smithson B (2004) Resolution improvement for compound eye images through lens diversity. In: Proceedings of the digital signal processing workshop and IEEE signal processing education workshop, pp 151–155

Wood SL, Smithson BJ, Rajan D, Christensen MP (2005) Performance of a MVE algorithm for compound eye image reconstruction using lens diversity. In: International conference on acoustics, speech, and signal processing, vol 2, pp 593–596

Wood SL, Lan H, Rajan D, Christensen MP (2006) Improved multiplexed image reconstruction performance through optical system diversity design. In: Proceedings of the IEEE image processing, pp 2717–2720

Wright O, Kelly FC (1953) How we invented the airplane. McKay, Philadelphia

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Xiao J, Song YM, Xie Y, Malyarchuk V, Jung I, Choi KJ, Liu Z, Park H, Lu C, Kim RH et al (2014a) Arthropod eye-inspired digital camera with unique imaging characteristics. In: Proceedings of the SPIE, vol 9083, p 90831L

Xiao J, Song YM, Xie Y, Malyarchuk V, Jung I, Choi KJ, Liu Z, Park H, Lu C, Kim RH et al (2014b) Bio-inspired hemispherical compound eye camera. In: Proceedings of the SPIE, vol 8958, p 89580A

Yamada K, Asano T, Tanida J, Shougenji R, Nagakura T (2005) Development of three dimensional endoscope by compound optics. In: Proceedings of the SPIE, vol 5864, p 586405

Yamada K, Mitsui H, Asano T, Tanida J, Takahashi H (2006) Development of ultrathin three-dimensional image capturing system. In: Proceedings of the SPIE, vol 6056, p 60560V

Yang F, Chang H, Dong L, Wang A, Ming H (2009) Study on far-field image using microlens array integrated with LCD. In: Proceedings of the SPIE, vol 7509, p 750904

Zhang H, Lu Z, Wang R, Li F, Liu H, Sun Q (2006) Study on curved compound eye imaging system. Opt Precis Eng 14(3):346–350

Zhang Y, Du J, Shi L, Dong X, Wei X, Du C (2010) Artificial compound-eye imaging system with a large field of view based on a convex solid substrate. In: Proceedings of the SPIE, vol 7848, p 78480U

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