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APPLICATION OF BIOMIMETICS PRINCIPLES IN SPACE OPTICS

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INTRODUCTION

The principles of biomimetics have been successfully applied in space optics, e.g. in Lobster-Eye X-ray optical systems. However, the recent increase in knowledge on vision of sea animals, especially on mirror eyes of scallops, crustaceans, and deep sea fishes, makes possible to consider other such applications. Especially the discoveries of mirror eyes of the deep sea fishes *Dolichopteryx longipes* and *Rhynchohyalus natalensis* are promising because of their unique arrangements and likely active optics.

We report on ongoing study with focus on understanding of very specific animal mirror eyes and how they may help us to design and develop special optics for scientific applications. We study the ways these mirror eyes work, what are the advantages of these eye arrangements, and whether these optics can be used in advanced devices, e. g. space optics. We will briefly present and discuss the preliminary results.

ANIMAL EYES

Vision is one of the most important animal senses. All animal phyla have developed various optical systems for light detection and processing of the visual information, which may be modified in many ways. One of the most unique adaptations of the animal optic systems is the so-called mirror eyes. The mirror eye type is an image-forming arrangement based on reflection of a biological mirror, which is very unique since the majority of the eye systems utilise refraction of lenses. The mirror eye arrangement can be found mostly in animals living in the dim or deep water, such as scallops, shrimps, prawns or even some fishes [1].

LONG-BODIED DECAPOD MIRROR EYES

The long-bodied decapod crustaceans, e.g. prawns and lobsters (however, not hermit and true crabs), possess superposition eyes utilising reflective optics [1]. Their compound eye consists of thousands of ommatidia. Each ommatidium compounds of a corneal facet, a crystallin cone surrounded by pigment cells and a rhabdom of retinular cells (Fig. 1) [2,3]. The corneal facet has a squared shape and homogenous refractive index. It works as a weak lens to pre-focus light [1]. The distal part of the crystallin cone is shaped as a regular four-sided pyramid where the sides form approximately right angles [3,4]. The refractive index is homogeneous in the distal part of the cone. However, it decreases axially onwards the rhabdom in the proximal tail of the cone. The sides of the distal part of the cone work as multilayer biological mirrors [3]. Thanks to the special orthogonal arrangement, this system works for any incident light beam; hence, the ray reflects once or twice in the cone. The combination of the multilayered reflective tissue of the distal part of the cone and the refractive index gradient in the proximal part of the cone allows the superposition image formation further in the eye – in the rhabdom [4]. Image created in the decapod eye is bright with good spatial resolution [3]. The retinular cells in the rhabdom are specially arranged so they can determine even the polarization of light [5].

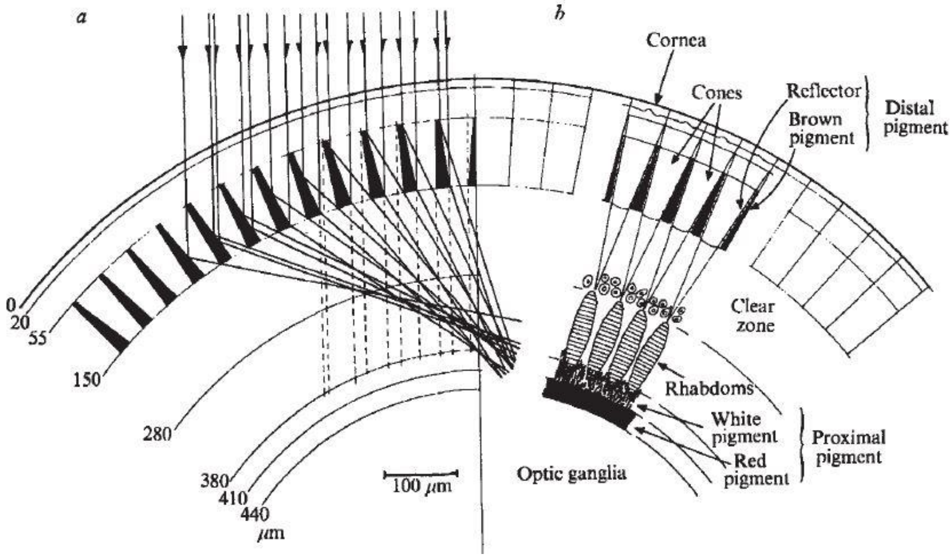

Fig. 1. Optical (a) and Anatomical (b) Structure of Part of the Eye of the Shrimp *Oplophorus*.
In (a) it is assumed that the only optical components in the eye are the reflector-lined faces of the cones. Solid lines show how reflected light is brought to a focus; dashed lines indicate pencils of rays that pass through directly. The numerals on the left show the depth of each layer from the surface.
(b) shows the parts of the eye as visible in a hemisected eye seen through a dissecting microscope [6].

FISH MIRROR EYES

In 2009, D*olichopteryx longipes* was described by Wagner et al. as the first vertebrate possessing mirror eyes. In 2014, Partridge et al. described another fish, *Rhynchohyalus natalensis*, with reflective optics that belongs to the same family of fish – Opisthoproctidae (also known as barreleyes or spook fishes) as *Dolichopteryx longipes*. Although the mirror eyes of these two species are similar, they vary in two important attributes – the origin of the reflective tissue and the orientation of their reflective plates [8].

Dolichopteryx longipes, the Brownsnout spookfish

Dolichopteryx longipes is a cylindrical elongated fish living in the mesopelagic zones of warm-water areas of the northern Atlantic and the northern Pacific ocean [1,9–11]. It has two eyes, each divided into two parts separated by a septum – a bigger upwards oriented tubular eye and a smaller lateral diverticulum (Fig. 2). The upper part of the eye works as a proper lens tubular eye processing the visual world dorsally; however, the lateral part of the eye forms images of the lateroventral visual world based on the reflective optics [7].

In the diverticulum, the retina lies on the side of it. The reflective layer lies on the surface of the diverticulum – in the septum dividing the eye parts. The mirror consists of organized small plates of high refractive index probably made of guanine. The plates are not oriented parallel to the surface of the septum, instead their angles gradually change as their position from the geometric centre increases. This arrangement together with the fact that the mirror is parabolic and off-axis provide the eye with a well-focused image high in brightness and contrast over most of the retina. However, when the light beams are close to the vertical, only a part of the mirror is utilized so the image is less bright at the dorsal part of the retina. Whereas the tubercular part of the eye probably serves to capture dark objects against the residual sunlight, the diverticulum is supposed to detect primarily bioluminescent flashes coming from the deeper water layers, i.e. from the ventral side of the fish [7].

To accommodate the mirror eye for closer objects, the mirror would have to be moved away from the retina. Since the *retractor lentis* – a muscle of the tubular part of the eye – is attached to the septum, there might be a possibility of accommodation of the *Dolichopteryx longipes* diverticulum [7].

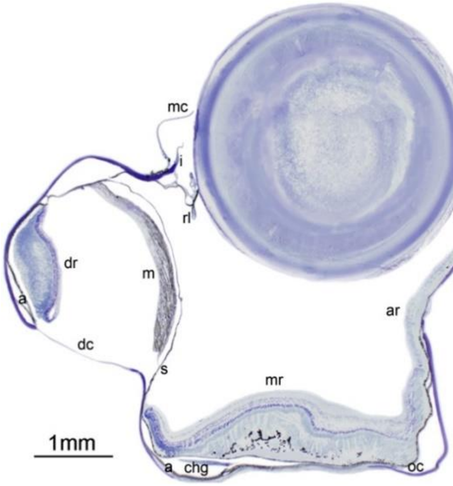

Fig. 2. Transverse Section of the Entire Right Eye of *Dolichopteryx longipes*. It is showing both a main, upwardly directed tubular portion and a lateroventrally directed diverticulum. The section was taken 522 mm from the rostral edge of the eye.
a, argentea; ar, accessory retina; ce, ciliary epithelium; chg, choroid gland; dc, diverticular cornea; dr, diverticular retina; I, iris; m, mirror; mc, main cornea (partially removed for facilitating the impregnation of tissue with resin); mr, main retina; oc, outer coats of the eye, consisting of sclera, argentea, and choroid; rl, retractor lentis muscle (ventral part); s, septum between the main tubular eye and the diverticulum [7].

Rhynchohyalus natalensis, the Glasshead barreleye

Rhynchohyalus natalensis is a mesopelagic, probably circumtropical, fish species of the Opisthoproctidae family [8,12]. The eyes of *Rhynchohyalus natalensis* consist of two parts separated by a septum – a dorsal tubular eye and a ventro-lateral diverticulum dividing the visual space in similar way as in *Dolichopteryx longipes* (Fig. 3) [8].

The retina of the diverticulum is similar to the tubular eye retina and lies on the lateral wall. The biological mirror lies on the opposite side of the diverticulum, on the septum. It contains few layers of probably guanine crystals orientated parallel to the basal membrane of the septum separated by cytoplasm. The crystals vary in their thickness. The mirror probably works as “chaotic” reflector. Hence the diverticulum can form an image by reflection (though the reflectance is approximately only 20–30%), with probably good preservation of spatial information [8].

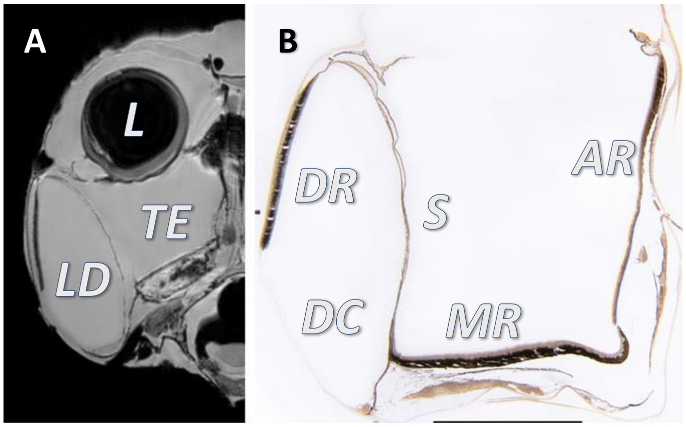

Fig 3. Gross Morphology of the Eyes of Rhynchohyalus natalensis.
(A) MRI section of the right half of the head showing the tubular eye (TE) including the lens (L) and the lensless diverticulum (LD); (B) 25 mm thick resin-embedded histological section of the eye with the lens removed. Scale bar = 10 mm.
DR, diverticular retina; DC, diverticular cornea; S, septum with mirror on the lateral side; MR, main retina of tubular eye; AR, acessory retina of tubular eye [8].

BIOMIMETICS OF MIRROR EYES

The term “biomimetics” refers to technological application of the concepts known from nature. The biomimetics is an interdisciplinary field whose innovations are used in many other fields, such as engineering, electronics, nanotechnology, robotics, artificial intelligence, biosynthesis, bioengineering etc. [13].

The reflective superposition eyes of decapods served as an inspiration for innovation in the field of astrophysics – the lobster-eye X-ray telescopes. While the decapod eyes work in the visible spectrum, the technical applications of the lobster-eye telescope work in the field of X-ray imaging at energies from 0.1 to 10 keV [14].

In future, there might be a potential of biomimetic application of some other principles of the mirror eyes, such as the light and dark adaptation in the superposition eyes of crustaceans or the tilting of mirror plates in the recently described eyes of the spookfish (*Dolichopteryx longipes*).

LOBSTER-EYE TELESCOPES AS AN EXAMPLE OF BIOMIMETICS APPLICATION

The Lobster-eye telescopes are based on the optical arrangement of the lobster eye. The main difference from classical X-ray space telescopes in wide use is the very large field of view while the use of optics results in higher efficiency if compared with detectors without optics. Recent innovative technologies have enabled to design, to develop and to test first prototypes. They will provide deep sensitive survey of the sky in X-rays for the first time which is essential for both long-term monitoring of celestial high-energy sources as well as in understanding transient phenomena. The technology is now ready for applications in space.

Schmidt objectives

One dimensional lobster-eye geometry was originally suggested by Schmidt [15], based upon flat reflectors arranged in a uniform radial pattern around the perimeter of a cylinder of radius R. X-rays from a given direction are focused to a line on the surface of a cylinder of radius R/2. The azimuthal angle is determined directly from the centroid of the focused image. At glancing angle of X-rays of wavelength 1 nm and longer, this device can be used for the focusing of a sizable portion of an intercepted beam of X-ray incident in parallel. Focusing is not perfect and the image size is finite. On the other hand, this type of focusing device offers a wide field of view, up to maximum of 2° with the coded aperture. It appears practically possible to achieve an angular resolution of the order of one tenth of a degree or better. Two such systems in sequence, with orthogonal stacks of reflectors, form a double-focusing device. Such device offers a field of view up to 1000 square degrees at a moderate angular resolution.

It is obvious that this type of X-ray wide field telescopes will play an important role in future X-ray astrophysics. The innovative very wide field X-ray telescopes have been suggested based on these optical elements but have not been flown in space so far. One of the early proposals was the All Sky Supernova and Transient Explorer (ASTRE) [16]. The Lobster Eye Optics in Microchannel Plate (MCP) design was considered for the LOBSTER ISS space experiment. There is also potential for possible extending the wide field imaging system to higher energy by the use of multilayer or other coatings in analogy to those described for flat reflectors in the Kirkpatrick-Baez geometry. Experimental designs of LE X ay telescopes were reported many times over last years [17-22]. Miniature LE objectives were developed and tested allowing applications on nano and cubesatellites (Figs. 4, 5).

The very recent application of LE X ray optics is on Czech VZLUSAT nanosatellite (Fig. 6) [23].

Angel objectives

There is also an alternative based on slightly different arrangement, sometimes referred as two-dimensional lobster eye optics. The idea of two dimensional lobster-eye type wide-field X-ray optics was first mentioned by Angel [14]. The full lobster-eye optical grazing incidence X-ray objective consists of numerous tiny square cells located on the sphere and is similar to the reflective eyes of decapod crustaceans such as lobsters. The field of view can be made as large as desired and good efficiency can be obtained for photon energies up to 10 keV. Spatial resolution of a few seconds of arc over the full field is possible, in principle, if very small reflecting cells can be fabricated.

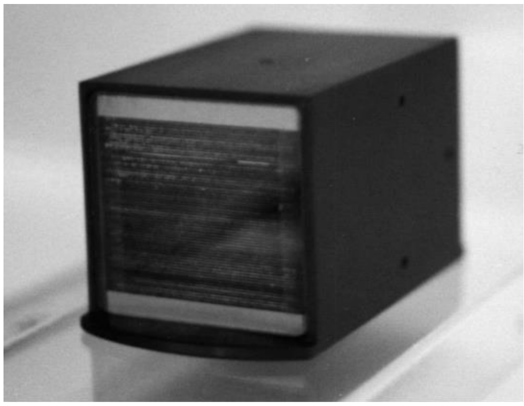

Fig. 4. The mini (24 x 24 mm, 0.1 mm thick foils spaced at 0.3 mm) Schmidt LE module illuminated by the laser beam.

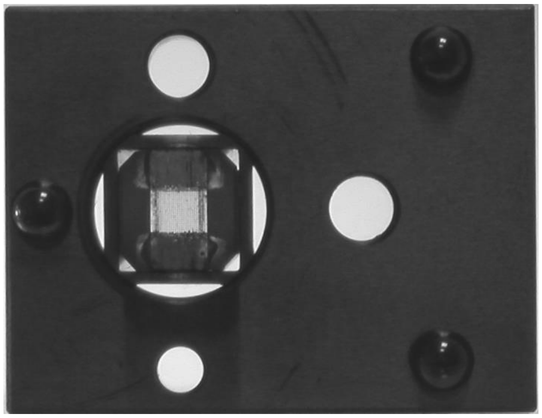

Fig. 5. The micro LE Schmidt module (3 x 3 mm, 0.03 mm thick glass foils) in the holder.

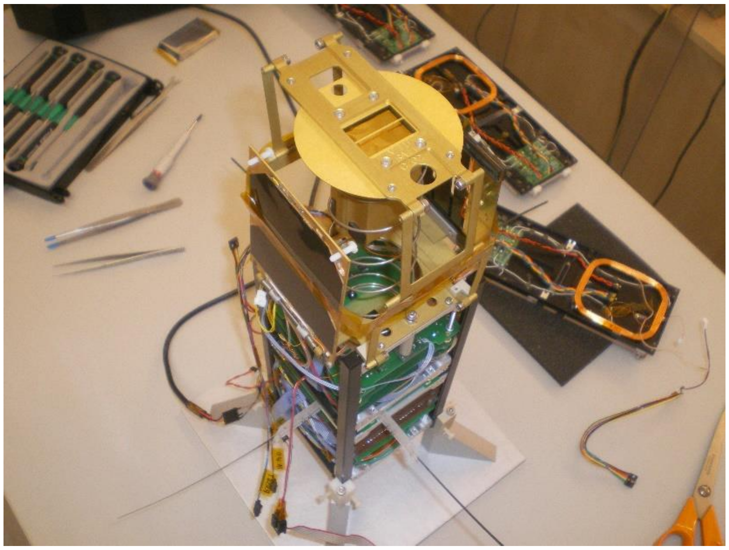

Fig. 6. The mini 1 dimensional LE optics is used on the Czech nanosatellite VZLUSAT.

CONCLUSION

As confirmed by very successful application of Lobster Eye optics design in space optics, the biomimetics may play an important role in space optics in general. While the LE application was extensively studied over the last 20 years, other animal mirror eyes are still awaiting technical and scientific application. But even the LE applied was used in a limited way, as the real LE show features we still cannot apply in technics, such as switching the various modes (with pigment), deconvolution in brain, and ability to recognize polarized light. We believe there is still large potential in scientific and technical applications of animal mirrors eyes.

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