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Fish eye optics

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Abstract. We report on small student (high–school) project of the Czech Academy of Sciences dealing with animal (fish) eyes and possible application in science and technology. Albeit most fishes have refractive eyes, the recent discoveries confirm that some fishes have reflective eyes with strange arrangements as well.

Key words: Fish–Eye Optics – Animal Eyes – Lobster eye optics – X-ray monitoring– Biomimetics

1. Introduction

Principles of some animal eyes were succesfully applied in space optics in the past and recently, e.g. in Lobster-Eye optical systems, e.g. (Hudec et al., 2015; Pína et al., 2016). However, the recent growing knowledge of sea vision, especially deep sea fishes, makes possible to consider other such applications.

Albeit most fishes have refractive eyes with spherical lens, there are new discoveries e.g. is deep sea fish *Rhynchohyalus natalensis* with mirror eyes based on very large numbers of very small mirrors developed from the choroidal argentea with crystals orienteted almost parallel to the mirrors surface. This arrangement may even include principles of multi–mirror active optics (Hudec & Remisova, 2016; Remisova, 2016).

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

The mirror optics in these special eyes might be also applicable in technical and scientific area, including astronomy and astrophysics. Already in past century, Angel Angel (1979) came up with an idea of technical application of the lobster mirror eye arrangement. He proposed to imitate principle of decapod eye imaging to construct a high-energy responsive telescope with wide field of view. Eventually, this so-called lobster-eye X-ray telescope was assembled and it is nowadays used in astronomical satellites, such as VZLUSAT-1 (Pina et al., 2014, 2015; Urban et al., 2016; Baca et al., 2016).

2. Refractive fish eyes

Recent biomimetical applications of lobster eye in space telescopes raise up the question about understanding of often strange animal eyes in general. For example, how the fish eye work and what are its optical parameters?

In the 1st part of the study performed within the framework of the Open Science IV and V projects of the Czech Academy of Sciences, we investigated animal mirror eyes, including fish mirror eyes (Hudec & Remisova, 2016; Remisova, 2016). We have shown that in addition to widely discussed mirror eyes of decapods (lobsters, crayfish, etc.) there are more recent discoveries of strange mirror eyes in very specific fishes which even resemble multi–layer, multi–mirror optics in (possibly) active arrangement. This field is however very little investigated and understood, including possible technical and scientific applications.

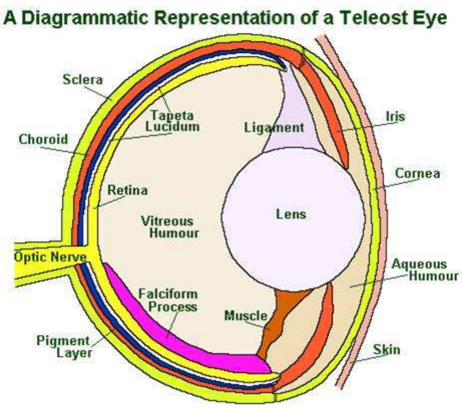

Figure 1. Refractive fish eye. The fish eye lenses tend to refract light resulting in a significant amount of light at the retina. Spherical lens = good picture in the centre. http://animals.mom.me/structure-fishs-eye-10517.htm.

In this contribution, we discuss fish (animal) optics in general, i.e. refractive as well as reflective arrangements. These very preliminary results were obtained in small student (high–school) project within Open Science V program.

Many fish, even when unmoving have a greater monocular field of vision than man, but much less binocular vision: While the FOV of human eye is typically 154/150 deg horizontal and vertical with binocular FOV of 25 deg, for the fish lens (refractive eye) it is typically 165/134 deg and 12 deg [1].

As the lens of fish eye is an almost spherical lens (and hence different optical arrangement as used in our developed and manufactured fish–eye lenses, which consist of numerous pieces of glass), the fish vision is clearest in the middle of the picture, and to focus, they must point directly at something [2]. Iris (Fig. 1) adjusts the light and it takes between 15 and 20 minutes to change light levels.

Interesting feature is the fish UV view [3]. Fish vision is mediated by four visual pigments. A mutation of the opsin on one of these pigments allows some vertebrates to absorb UV light. UV light can be detected for example by Rainbow Trout and Goldfish. It may be related to foraging, communication or mate selection. Sometimes its used during only part of the life cycle. For example, brown trout uses UV vision only as a juvenile, to detect zooplankton, because of living in a shallow water. When they get older, they move to deeper waters.

Literature research performed within the student project revealed that optical parameteres such as field of view (FOV), angular resolution (on–axis/off-axis), image distorsion, f/ratio, spectral sensitivity, etc., are only very rarely mentioned in the literature.

3. Reflective fish eyes

In the past, all animal eyes were expected to work with light refraction, i.e. based on either single, or numerous, lenses. This picture changed when first animal mirror eyes were described (in decapods) Land (1965, 1972, 1976). Then the picture changed again more recently: in 2009, fish *Dolichopteryx longipes* was described by Wagner et al. (Wagner et al., 2014) as the first vertebrate possessing mirror eyes (Hudec & Remisova, 2016; Remisova, 2016). In 2014, Partridge et al. (Partidge, 2014) 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 (diverticula) 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 (Partidge, 2014).

Figure 2 illustrates the 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. In the diverticulum, the retina lies on the lateral, caudal and rostral surfaces. The retina is thick and composed of layers of photoreceptor cells in the centre; however, it contains

[1] `http://en.wikipedia.org/wiki/Vision_in_fishes`

[2] `http://www.earthlife.net/fish/sight.html`

[3] `http://en.wikipedia.org/wiki/Brown_trout`

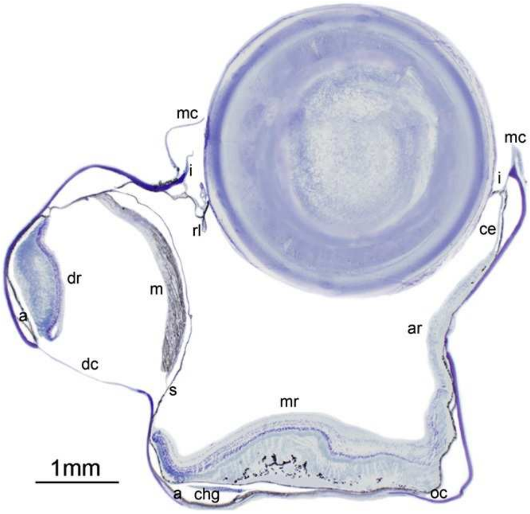

Figure 2. Transverse Section of the Entire Right Eye of *Dolichopteryx longipes*. It is showing both a main, upwardly directed tubular portion and a lateroventrally directed diverticulum. The section was taken 522 mm from the rostral edge of the eyea, argentea; ar, accessory retina; ce, ciliary epithelium; 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 (figure and legend adapted from (Wagner et al., 2014).

thin single-cell layer in the edges. The retina of the diverticulum is continuously connected with the retina of the tubular eye. The reflective layer (a biological mirror) lies on the medial surface of the diverticulum in the septum dividing the eye parts. The mirror is approximately 0,2 mm thick and it is surprisingly derived from the retina and not from the argentea. It 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 (Wagner et al., 2014). To accommodate the 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 (Wagner et al., 2014;

Hudec & Remisova, 2016). 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 (Wagner et al., 2014).

4. Biomimetics of fish–eye optics

The biomimetics of fish–eye optics is, in our oppinion, little understood. Albeit most common fish eye is based on refraction and is represented by a sphere which is moved along the eye optical axis, in specific fishes mentioned above were in addition to refractive eyes also eyes based on mirrors found. The animal fish eye (based on refraction) arrangement is not quite identical with classical "fish eye" lenses we know from optics and it is obvious that the optical performance and properties are also different. In contrast to technical solution of fish–eye lenses (which usually consists of numerous lenses), the animal fish–eye arrangement is quite simple.

Even much more complicated is the picture of specific mirror eyes found in some fishes described above and which are completely different from any optical system we know from optics but may represent peculiar multi–layer, multi–mirror, and even active optics. The optical performance and arrangements of these eyes are far from to be investigated and understood, and this includes possible technical and scientific applications as well. We plan to focus on this area in the 2nd part of our high–school student project. The main goal is the understanding the way the strange fish mirror eyes work and finding out whether the mirror eye optics could be used in advanced optical devices, for example in astronomy.

Since the light conditions in the space are in some cases similar to those in the deep sea, the optical needs of deep sea organisms and astronomers might be similar. Therefore, some principles of the mirror eyes might be utilised as biomimetic application in astronomical optical technology, as demonstrated in case of the lobster-eye X-ray telescopes (Angel, 1979; Schmidt, 1975; Hudec et al., 2015).

5. Conclusion

The physical (optical) parameters were rarely measured in live organisms; most of them come from the ray tracing of the eye models instead. However, there are very few such results so far. Therefore, the information about the strange animal, especially mirror eyes is very limited and in many cases even unavailable. For better understanding, more detailed anatomical examination is needed (e.g. of the ultrastructure of multilayer reflectors) as well as molecular and genetic analyses together with advanced mathematical modelling of the ocular performance and investigating the image created in live specimens. In future, there is an enormous potential of further studies, especially of biomimetic application of some 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*).

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