LIFE LESSONS

Photonic systems in nature can offer technical insights to designers of optical systems and detectors.

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Just as survival through evolution is important to a species, in today's business climate, technology transfer can be important to the survival of a company. Future advancements may make use of a vast technology base through bio-mimicking. Life has evolved on earth over the last 3.5 to 4 billion years, and the evolution of insects and mammals has perfected many of their features, such as detection mechanisms and optical configurations that have yet to be duplicated by man.

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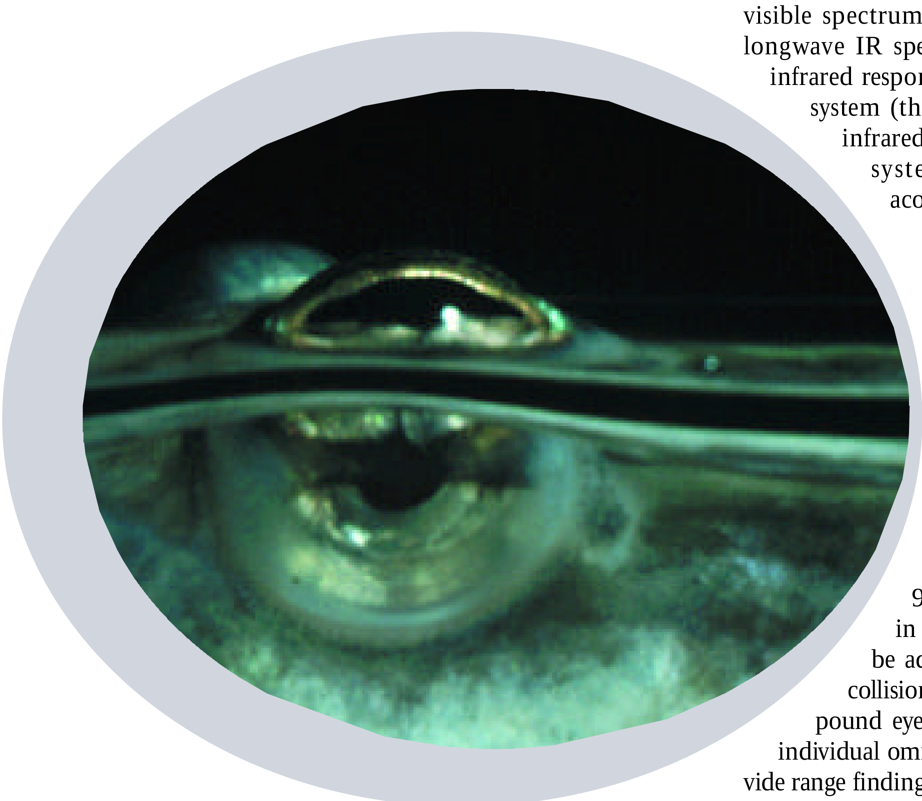
Neural processing borrows from studies of the human retina (detector/frame grabber) prior to sending signals to the central processor (brain). The human eye's wide dynamic range, adaptive gain control, edge enhancement, and clutter rejection along with single-photon detection capability makes bio-mimicking attractive to researchers. Accomplishing some of the signal processing at the detector-chip level, for example, helps reduce readout rates and the number of signal leads from the detector array. Gains from this mimicking are seen in the fields of robotics as well as in the sensor arrays used in the defense/aerospace industry. The eyes of other vertebrates and invertebrates are also being researched for their unique capabilities.

Humans are accustomed to seeing only from the blue to the red spectral regions with three photoreceptor pigments (red, blue, and green). The eyes of some birds, insects, and fish, however, have a spectral response that includes ultraviolet wavelengths. Other animals have a spectral response that extends further in the red or near-infrared spectral region. This deeper red response is helpful in penetrating clouded or murky conditions. The mantis shrimp, for instance, has ten visual pigments that enable it to see fine shades of colors with much greater precision. This enhanced color response may be important to the detection of subtle color, improving the recognition of spectral response differences in dyes and pigments. Such performance would benefit the paint and clothing industries as well as detection of camouflaged targets and counterfeit documents.



Some pit vipers and boid snakes process both visible and infrared response. The unique neural processing in these species makes use of enhanced (visual enhanced by IR, IR enhanced by visual), depressed (visual inhibited by IR, IR inhibited by visual), AND (visual and IR), and OR (visual or IR) processing gates for clutter/false target rejection to enhance the detection of prey. A temperature sensitivity of 0.003°C has been reported without the cryogenic cooling, cold shield, and cold filtering techniques used in many high-sensitivity infrared systems. Understanding this process may be important in fabricating better uncooled IR detectors.

sensor fusion

Some reptiles, bats, and moths have the ability to see the visible spectrum, from blue wavelengths (0.4 µm) to the longwave IR spectral region (8 to 12 µm). Reptiles with infrared response have both a "gimbaled" visual detection system (the eye) and a fixed but moving platform of infrared sensors. Bats and some moths have visual systems and well-developed high-frequency acoustical sensors.

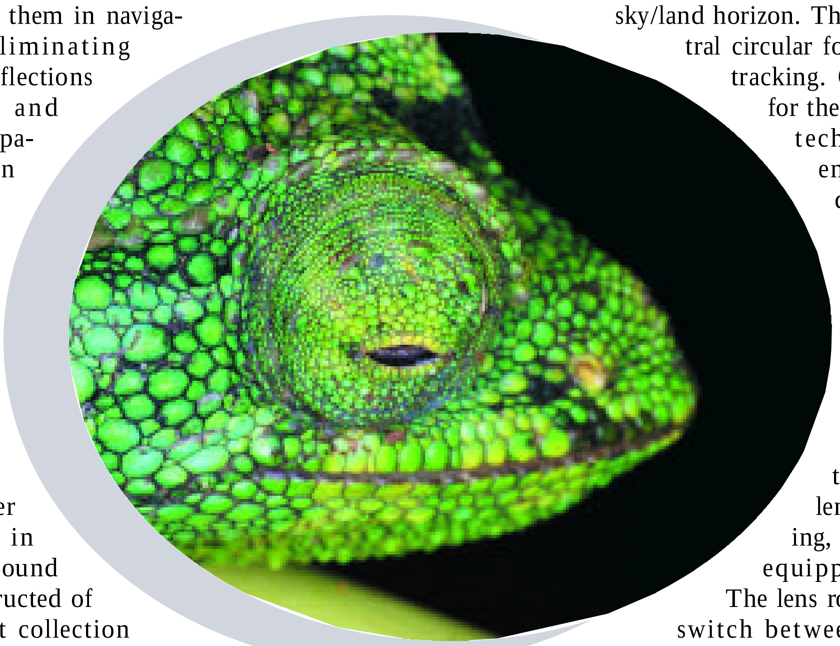
More than 75% of the species in the animal kingdom are equipped with compound eyes. This construction comprises several to thousands of individual eyes, which could encompass individual cornea lenses (ommatidia), crystalline lenses, and photodetectors. The dragonfly has approximately 28,000 ommatidia and is one of the supreme examples of biological micro-optics. The wraparound eye feature of the dragonfly enables it to view approximately 70° horizontally and 90° vertically, up and over the head as well as in the forward direction. Such eye features could be adapted to the design of warning sensors and collision avoidance detectors. In addition, the compound eye's instantaneous field-of-view (IFOV) of the individual ommatidia can vary in angle and overlap to provide range finding in a single eye.

The superposition compound eye can collect light from several ommatidia and focus on a single photoreceptor for low light-level viewing. Under high illumination conditions, a light shield or baffle extends between the ommatidia (photoreceptors) to restrict light collection to a single detector. This process reverses again under low light conditions. This useful feature permits wide dynamic response and the detection under low light-level conditions. The disadvantage is the decreased spatial resolution when light from several ommatidia are integrated on one photoreceptor.

specialized detection

Unlike the human eye, the eyes of some animals and insects permit them to detect polarized light. This capability assists them in navigation, helps in eliminating unwanted specular reflections (clutter rejection), and enhances detection capabilities under certain illumination conditions.

Some eyes are equipped with reflectors in back of the photoreceptor so that light makes a double pass through the sensor to increase the quantum efficiency. Other eyes, such as those in the lobster, are compound eyes, which are constructed of many reflecting light collection cones. The configuration is useful in low light-level detection and as an energy collector concentrating optical radiation into an area where it can be used. The same reflecting optical concept has also been used in x-ray imaging systems.



Diffractive optics exist in nature. The moth eye is an excellent example of a diffractive optical approach to an antireflection coating, exhibiting less than 0.15% reflection (absolute) through the visible spectrum for angles of incidence from zero up to 50°. To reproduce this feat in a multilayer vacuum deposited dielectric coating is exceedingly difficult and would require tens of layers. Advancements in photolithography and ion milling have permitted the small, regular features required for moth-eye diffractive optics to serve as an antireflection coating, however. One application is in high-power laser optics.

fovea variations

The human eye has one area of most distinct vision, also known as the fovea. The fovea measures approximately 400 μm in diameter and has a photoreceptor density of approximately 150,000/mm^2. Compared with examples in the animal kingdom, this figure is not particularly high. Some birds of prey have a density of photoreceptors of up to 1,000,000/mm^2, approximately seven times as great as the human figure. Fabricating detector arrays with greater resolution and developing a means to process the information without exceeding data rates and overloading the processor (brain) is a goal of almost every detector manufacturer, making the study of avian neuro-optical systems worthwhile.

Some creatures have multiple foveae. Shore birds, for example, have one fovea that is rectangular and oriented horizontally to conform to the sky/water and sky/land horizon. They have a second central circular fovea that they use for tracking. Optimizing the fovea for the detection process is a technique that can enhance and augment detection for some applications.

Most birds of prey also have two foveae. Like search and track systems that employ a short focal length optical system for acquisition and a long focal length system for tracking, the eye is oblong and equipped with two fovea. The lens rotates in the socket to switch between search and track modes. It is necessary to understand the "hand off" process between search and track modes that allows a bird to continue the tracking process after target detection without losing its prey. This hand-off process is critical in modern search and track systems.

The anableps fish has an eye with two different focal lengths and two foveae. The long focal length portion of the lens focuses to one fovea for viewing in air; the other short focal length focuses below water. Lens designers can use this technique to develop optics for multiple media applications.

systems

Human eyes tend to move together. The chameleon and many crustaceans are capable of moving their eyes independently of one another. For example one eye can track while the other eye searches. Such a technique could have a distinct advantage in some of today's detection problems.

The human iris is circular and varies from approximately 2 mm to 8 mm diameter to control light intensities. Other animals have vertical or horizontal irises. Some have stenopaic pupils in which one or more pinholes remain open when the iris is fully closed. The slit pupil can close up more effectively and faster than round pupils.

Through the centuries, many insects and marine animals have developed very efficient light sources. These are used for a variety of purposes such as to communicate (i.e., IFF, schooling, mating), to control contrast as a blinding defense, to lure prey, and so on. Bioluminescence efficiencies can range from 88% to 93%. In comparison, the efficiencies of manmade bulbs range from 10% (100 W tungsten bulb) to 25% (fluorescent bulb). The study of bioluminescence systems may provide dividends for commercial lighting development. The enzyme that makes the firefly glow may also prove useful in bacterial detection and detection of biological weapons.

It is said that for every detection system there is a countermeasure system. Some insects can "hear" the ultrasound frequencies emitted by a hunting bat and take evasive action. Others, like the tiger moth, hear the bat and emit a jamming signal in the ultrasonic frequency spectrum. The arctiid moth, which is known by the bat to be distasteful, takes a somewhat different approach. This moth, upon hearing a bat, emits ultrasound pulses at its wing beat rate to identify it to the bat. The bat recognizes this signal and, knowing the moth is distasteful, breaks lock.

In similar fashion, the female glowworm uses the male glowworm light code to signal him. Thinking that it is another male glowworm of the same species, he arrives and is killed by the female and eaten. The deep-sea dragon fish has a light source for illuminating its prey, but unlike other fish with photophores for illumination in the blue-green, this fish has an orange-red source that is covert; in other words, it cannot be seen by other fish that have only blue-green eye sensitivity. How do we approach countermeasures, and can new countermeasures be gleaned from this research?

Some of the techniques and concepts found in the animal kingdom are well understood; others are not. For many concepts, a complete understanding of the biological system is necessary to unlock the mystery of how it works. Much of the understanding involves the neural processing or how the animal combines or makes use of the information. The arguments for bio-mimicking should not be dismissed quickly—three and a half to four billion years of R&D have gone into the process. Nature has the patience to learn in a responsible way. **oe**

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