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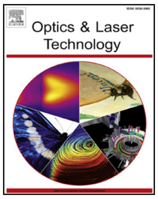

Full length article

Biomimetic photonic structures for optical sensing

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HIGHLIGHTS

- A selection of optical sensors, which have been developed using biomimetic photonic structures is reviewed.
- We discuss how biomimetic-based design strategies have led to the successful fabrication of different sensors.
- Types of sensors: Infrared, chemical, mechanical.
- Sensors for aerospace applications and robotics.

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ABSTRACT

This perspective reviews a selection of optical sensors, which have been developed using biomimetic photonic structures. In particular, we discuss how biomimetic-based design strategies have led to the successful fabrication of infrared, chemical, and mechanical sensors, as well as sensors for aerospace applications and robotics.

1. Introduction

In a broad sense, biomimetic and bio-inspired technologies arise from a flow of ideas from the biological sciences into such disciplines as engineering, chemistry, materials science, physics, and mathematics. Recent advances in understanding the working principles of biological functional materials and systems, achieved by a growing interdisciplinary community of scientists and engineers [1], have spurred an increase in efforts aimed at emulating nature's most impressive design strategies in man-made technology. Being just one of many approaches in technology development, "learning from nature how to build devices with a specific functionality" has the distinct advantage of capitalizing on thoroughly scrutinized, performance-optimized outcomes of millions of years of evolution and natural selection in living systems [2]. This approach is receiving increasing attention given its potential to enable major technological advances that allow artificial devices to approach the sophistication and efficiency of biological systems.

Nature has long inspired the work of inventors and artists; in the last two decades engineers and scientists have embraced the opportunities arising from mimicking natural materials and translating biological design concepts into man-made products. The structural complexity and hierarchical architecture, which frequently enable multiple desirable functions in biological materials is particularly intriguing and still challenging to emulate. Nevertheless, several examples of successful translation of biological material concepts into industrial products exist [2,3].

In this perspective, we will focus on the development of biomimetic and bio-inspired photonic devices for optical sensing, a growing field that has greatly benefitted from deeper insights into nature's light manipulation strategies. Living organisms employ a wide diversity of nano- to macroscale material structures with very specific optical response characteristics to fulfill multiple functional requirements simultaneously [4]. Frequently, these biological materials satisfy needs related to camouflage, aposematic predator deterrence, territorial assertions, and courtship. For these and other purposes, insects in particular have evolved a diverse range of photonic micro- and nanostructures to create conspicuous coloration, which have systematically been studied by scientists for centuries with increased efforts in recent decades [5–9]. Building on the profound understanding of biological light manipulation concepts resulting from such studies, a variety of

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biomimetic optical devices have been devised for various applications [10–15], including solar energy harvesting [16,17] and the fabrication of nanobioreplicated visual decoys for pest control [18].

One aspect of particular interest to scientists emulating nature's light manipulation strategies is the diversity of highly specialized biological optical sensors, which allow organisms to extract information from the environment [19–24]. These systems are a result of evolution over millennia. Biological sensors are generally small, of exceptional sensitivity, and highly energy efficient [20]. In addition, they are often built in a redundant way. The parallel sampling and processing of sensory information improves the signal-to-noise ratio and also reduces the likelihood of errors caused by the malfunctioning or the loss of single sensory elements. Emulating the strategies of biological organisms to sense light levels, assess colors, create images, and otherwise convert light into other stimuli could be beneficial in a wide variety of human devices.

In this context, this perspective reviews a small selection of examples of the current activities in the field of biomimetic optical sensors. This selection is highly representative for the benefits that can result from emulating biological light manipulation concepts in manmade devices.

2. Infrared sensors

Many biological species utilize miniaturized infrared (IR) sensing systems with outstanding performance. Emulating favorable characteristics of these biological systems may help in developing infrared sensing materials and systems for military, medical, space, and industrial applications. Snakes, vampire bats, and some species of fire beetles have IR detecting organs with a similar structural design as those of engineered bolometers [25]. More specifically, the families of boas (*Boidae*), pythons (*Pythonidae*), as well as the subfamily *Crotalinae* of the family of *Viperidae*, possess infrared absorbers to convert IR light into heat, combined with a thermal-sensitive system that directly detects IR radiation-induced temperature changes in the IR sensing organs. Vampire bats are the only animals known to have bolometer-like IR sensing organs to capture the IR signatures of their endothermic preys [26]. The larvae of fire beetles live on freshly burnt woods to avoid the defense reaction of living trees; fire beetles thus need to find these woods to allow their offspring to hatch and grow safely [27–29]. This unique survival strategy is facilitated by their sensitive IR receptors, which have received great attention from the biomimetic IR sensing community. While, as we will see in the next paragraph, some species of fire beetles have photomechanic IR sensing organs, other species such as *Acanthocnemus* and *Merimna*, have bolometer-like IR sensing organs, i.e., organs composed of an IR absorbing area and an associated thermal sensor (Fig. 1).

Melanophila acuminata beetles have infrared sensing organs, which rely on a photomechanic detection mechanism that is also frequently used in engineered photomechanic IR sensors. More specifically, these beetles possess about one-hundred infrared sensing organs (*sensilla*), which are capable of detecting fires from a long distance [30]. Fig. 1 (left) portrays a schematic of a single IR *sensillium*. The receptor cells are based on a pressure chamber made of a hard chitin structure, which is filled with a liquid [31,32]. Incident IR radiation causes an expansion of this liquid and the corresponding pressure rise leads to a deformation of the tip, which induces a response of the mechanoreceptive neuron. Although the detection mechanism has already been established, the actual sensitivity to IR radiation has not yet been determined. Calculations suggest that the beetle can detect IR radiation below 4×10^{-5} $\mathrm{W\,m^{-2}}$, thus outperforming commercial, high-sensitivity pyroelectric detectors [33].

A biomimetic micro-sensor design that emulates the functionality of IR receptors of *Melanophila acuminata* beetles has recently been developed [34–36]. In this design, incident IR radiation heats a liquid, thereby inducing a mechanical deformation of the membrane that is detected by a capacitor. Temperature changes can thus be determined by monitoring changes in capacitance. This photo-mechano-electric device, which is conceptually similar to the beetle's receptor, operates at room temperature without any active cooling, contrary to other infrared photon detectors.

3. Real-time measurement of aircraft wing deflection

Designing longer, thinner, and lighter wings is one of the current strategies for reducing the overall weight of aircrafts. It is expected that this approach would lead to better fuel economics and lower carbon emissions by at least 50% compared to current aircraft technology [37]. However, this approach would result in increased wing flexibility, which can adversely affect aircraft performance with regard to aerodynamic efficiency and safety. Accurate determination of the wing position and shape during flight can help active control methods designed to mitigate potential problems due to increased wing flexibility.

Recently, a biomimetic optical sensor based on the physiological aspects of the eye (and vision-related neural layers) of the common housefly *Musca domestica* has been developed to track wing deflection in real-time [38,39]. Compound eyes exhibit a unique optical scheme for imaging, for instance allowing for wide field-of-view detection [40]. As artificial compound eyes have enormous potential for many different applications, several biomimetic efforts have been devoted to duplicate their functionalities [4], including the bioreplication of the eyes' micro- and nanoscale textured surfaces [41]. For the envisioned application in wing deflection assessment, a biomimetic engineering approach was used to extract the relevant image processing features of the fly's eye without aiming to reproduce all the functionality and appearance of the biological vision system.

Flies use a combination of quasi-Gaussian overlapping photoreceptor responses combined with neural superposition to achieve hyperacuity, i.e., the ability to detect image features to a much higher degree than just the photoreceptor density would imply. Fig. 2 (left) depicts the overlapping Gaussian visual field of three photoreceptors, similar to that exhibited by the fly's vision system, which allows for very precise and accurate measurements of position. This is the basis for the fabrication of the biomimetic sensor platform, which consists of the sensor head and a printed circuit board (PCB). The sensor head has seven light channels connected to seven separate photodiodes located on the sensor PCB. Each photodetector has its own channel on the PCB for current-to-voltage conversion followed by signal conditioning and filtering, taking place in parallel for each channel. A particular emphasis was given to emulating the fly eyes' high sensitivity in low-light and low-contrast environments, its sensitivity to motion, and its compactness.

To test the biomimetic sensor, a target was moved in a horizontal direction in front of the sensor, to simulate the deflection of an aircraft wing. Combined with a hardware-implemented differencing algorithm the sensor showed good target tracking providing a real-time solution to monitoring the deflection of a given aircraft wing. The advantages of this biomimetic sensor over conventional sensor solutions are its low weight and small form factor, fast computation, and low power requirements.

4. Applications in robotics

The new millennium has seen a rapidly growing interest in the development of autonomous robots for applications in industry, health services, medicine, and entertainment. Mobile robots are used to sense information about their surroundings, process the captured data, and in response initiate and effectuate movements to complete specific tasks autonomously. However, implementation of real-time detection and response systems in autonomous robots is challenging, even with the computational power of modern hardware. By contrast, a vast abundancy of biological organisms has mastered the use of sensory-motor