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Editor's Note: PIREP *is aviation shorthand for* pilot report. *It's a means for one pilot to pass on current, potentially useful information to other pilots. In the same fashion, we intend to use this department to let readers know about air and space power items of interest.*

Electromagnetic Applications of Biomimetic Research

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For the past several years, the Air Force Research Laboratory (AFRL) has been developing sensors capable of detecting electromagnetic radiation across the spectrum—from the infrared (IR), through the visible, and into the ultraviolet regions. These sensors have become integral parts of military weapons systems as well as intelligence, surveillance, and reconnaissance systems—and, undoubtedly, the capabilities we have developed are technologically sophisticated. However, many biological systems possess sensing capabilities unmatched by current technologies. For example, the IR-sensitive beetle (*Melanophila acuminata*) is attracted to fires and smoke 50 kilometers away.[1] These insects are attracted to forest fires because burned trees provide the ideal environment for larvae to develop and hatch into adults. The forest fires emit IR radiation that the beetle detects via a specialized IR sensor known as the IR pit organ or IR sensilla. By understanding the mechanism and the biological processes involved in this IR sensor, one could develop new and improved materials and sensors for Air Force applications.

Literally, the term *biomimetics* means to imitate life. In a more practical sense, biomimetics is an interdisciplinary effort aimed at understanding biological principles and then applying them to improve existing technology. This process can mean changing a design to match a biological pattern or actually using biological materials, such as proteins, to improve performance.[2]

Biomimetics, which had its earliest and strongest footholds in materials science, is rapidly spreading to the arenas of electromagnetic sensors and computer science. This article addresses electromagnetic radiation on either side of the visible, ultraviolet, and IR regions, providing a general overview of recent advancements in biomimetics research as it relates to the Air Force and national defense.

When examining the landscape of biomimetics, one finds the application obvious in a number of areas, many of which are defense related. The study of fish swimming, for example, has obvious tie-ins to underwater locomotion and naval interests, and much of the work in structural biomimetics (how biology builds structures) is of interest to the Army due to the potential for producing next-generation, lightweight armor based on naturally occurring biological composite materials.[3] From a commercial standpoint, few biomimetic results have proved as exciting as the recent successes in biologically derived silica and silica polymerization.[4] After all, a significant portion of the economy—especially the technology sector—is based on manipulating silicon. It is easy to understand why the ability to manipulate this element under benign, ambient conditions using biomolecules has many people excited.

Sensing electromagnetic radiation is of particular interest in aviation because of the increasing distances over which sensors need to operate. The ability to detect such radiation in the IR without cryogenics—the science of low-temperature phenomena—has been an important technology driver because of increased sensor reliability and reduced payloads. The latter are becoming even more important as space migration dominates defense and commercial interests. Against this backdrop, it is easy to see why several funding agencies have expanded the area of research in biomimetics—in particular, biomimetic electromagnetic sensing. In short, biomimetics should allow for smaller, lighter, less complicated, and easier-to-maintain sensor systems.

The Materials and Manufacturing Directorate's Critical Research Role

Scientists at the AFRL's Materials and Manufacturing Directorate (ML) at Wright-Patterson AFB, Ohio, working with the Air Force Office of Scientific Research near Washington, DC, and prominent research scientists at universities, have made significant strides in biomimetic research. Their efforts support the Air Force's goal of producing hybrid materials with properties superior to those made entirely of either synthetic or biological alternatives. They also increase our understanding of living creatures that possess unique properties and abilities that we could someday use to enhance the performance and affordability of critical defense technologies.

In fact, biomimetic technologies could have a *profound* impact on materials science and national defense, the principal objective being to use the best biology has to offer to enhance Air Force systems—particularly sensor and detection systems. To achieve this goal, scientists in the directorate's Survivability and Sensor Materials Division (MLP) are drawing upon biology's ability to sense electromagnetic radiation outside the visible-light region. This is important to the Air Force due to the proliferation of and reliance upon sensors and detection systems that operate in the IR region of the electromagnetic spectrum. The quest for understanding this phenomenon has escalated even further as a result of the extreme sensitivity reported in biological IR/thermal detection and because biology, unlike most synthetic systems, can achieve this sensing without cryogenics.

MLP researchers continue to be intrigued by various organisms' ability to sense IR radiation through using the readily available elements of carbon, hydrogen, oxygen, and nitrogen, whereas science's sole option has been a reliance on toxic formulations of inorganic alloys. At various universities around the world, ML supports studies that examine a variety of specimens with unique properties and abilities, including the IR-sensitive beetle; snakes from the boa, python, and pit-viper families; and bacterial-based systems of thermal detection. These investigations have yielded critical insights and have helped ML scientists and others progress toward the development of bio-inspired and bio-derived technologies—the principal research paths in the rapidly growing field of biomimetics.

The resourcefulness of nature in detecting electromagnetic radiation is evident. Less clear is the means of engineering these traits in order to enhance vital technologies and lower their costs. The process of signal processing in biological systems, for example, is very complicated and well beyond the scope of current biomimetics. Instead, researchers are focusing on isolating biological “triggers”—the molecules responsible for initial stimulus detection. They emphasize coupling the triggers into optical and electrical detection systems and bypassing the impossible task of re-creating biological signal transduction. Thus far, in-house researchers have successfully created composite polymer films that electronically report changes in a protein’s structure upon IR stimulation. They have also built an imaging array based on this technology, resulting in the world’s first biomimetic thermal imager. Current efforts aim to reduce the size and weight of the biomimetic array to allow integration with a Micro-Air Vehicle.

The enormously complex, multistep biological processes associated with biomimetics often operate nonlinearly. In addition, the molecules involved in these processes are sometimes fragile, and integration with other systems can become problematic. Despite these drawbacks, the research holds considerable promise. For instance, biomimetics frequently uses composite materials that provide combinations of properties that no single material can achieve.

Optical Structures

As evidenced through studies of biological visible and ultraviolet systems, nature has evolved incredibly intricate coatings and patterns to reflect, absorb, and transmit light. The complexity of these natural coatings has made replicating them in the laboratory a challenge. For example, many of the curved surfaces involved in fabricating biological coatings would require gray-scale lithography, a sophisticated technique that at present is not considered “standard” in micro- and nanofabrication. Two specific examples include the hawk moth’s eye cornea and the beetle’s IR sensilla. The 15-micrometer (μm, 10-6 meters) domed structures of the beetle IR sensilla are gigantic compared to the feature sizes now produced by the microprocessor industry. Commercial companies are currently engaged in applying advanced lithographic procedures to replicate biological surfaces, and many of these techniques are being applied to nonstandard (i.e., nonsilicon) materials like germanium.

Believing that replicating the surface structure of a snake’s IR pit organs would constitute a significant advancement in optical coatings for IR optics, ML scientists involved in biomimetic research have given top priority to this endeavor. The micropits of the IR pit organ, for example, are approximately 300 nanometers (10^{-9} meters) in diameter, and the scale ridges are spaced at 3.5 μm. The latter dimension has implications for the IR spectrum, and the former has visible-light consequences. In recent publications, ML researchers have reported successful holographic duplication of snake-scale structure in a photopolymer matrix.[5] A holographic approach uses light to record the fine details of a biological surface. By combining this “reading” beam and a reference beam, one produces an interference pattern that can record a multitude of biological information. Advances in materials-fabrication techniques and optical coatings currently under way have the potential to improve the performance of virtually every military optical system that exists.

Thermal and Photon (Quantum) Detectors

Before proceeding from coatings to the application of biomimetics to IR sensors, one would do well to review the state of artificial or man-made sensors. Broadly speaking, IR sensors fall into two categories: thermal detectors and photon—or quantum—detectors. On the thermal side are thermocouples, thermopiles, bolometers, and pneumatic (Golay) detectors. For example, the microbolometer format for thermal imagers currently dominates this class of state-of-the-art, noncooled IR detectors for applications in US Army thermal-imaging systems, civilian firefighting applications, and even Cadillac's night-vision systems for automobiles. On the photon-detector side are photoconductive, photovoltaic, and electromagnetic detectors. In general, this class of detectors—commonly used for space applications—is made from semiconductor materials and must be cryogenically cooled. The response time of the detector and the speed of the potential target have always constituted the principal difference between these two categories. Thermal detectors respond relatively slowly (on the order of milliseconds: 10^{-3} seconds) compared to photon detectors (on the order of microseconds: 10^{-6} seconds).

Researchers have concluded that biological IR sensing is a thermal process, but how then does one apply this knowledge to new detector strategies? To compete with an artificial, inorganic detector that directly converts a photon to an electron, one needs to make the biological thermal process more efficient. In a biological system, IR photons are absorbed into the system via molecular resonant frequencies inherent in the chemical structure of the tissue. In essence, this energy transfer from the IR photons causes the molecules within the system to "vibrate" on the molecular level. This molecular motion eventually dissipates as thermal energy on a very minute scale. Researchers at ML believe that the thermal change is sufficient to trigger a signal in the terminal nerve masses of the IR pit organ that eventually leads to a change in the neuron firing rate to the brain, which in turn interprets this change as either "hot" (increased rate) or "cold" (decreased rate). A successful biomimetic approach would simplify this process by engineering the "trigger" in this process—the original IR-absorbing biological macromolecule.

Bacterial thermoproteins provide a model for this engineering process since they have the ability to manipulate bacterial genes easily and produce the desired recombinant proteins via fermentation. To increase the efficiency of this biological system, ML researchers are exploring ways of optically sensing thermally induced changes in protein structure. One common laboratory technique—the use of circularly polarized light in circular dichroic (CD) spectroscopy—optically records changes in protein secondary structure to study the dynamics within the biological system. A recent publication addressed temperature-induced changes in polymer-hydrogel swelling behavior using synthetic coiled-coil domains and CD spectroscopy to examine the dynamic range and elasticity of the structure.[6] ML researchers are examining similar sensing concepts (fig. 1).[7] A critical step in the maturation of biomimetics for electromagnetic sensing will entail meshing traditional synthetic polymer synthesis and processing with biochemistry and molecular biology and then successfully applying "soft-matter" lithography. This approach of combining biological macromolecules with synthetic polymers is key to maintaining the functionality of the biological element, while imparting an appropriate avenue of signal transduction and/or propagation.

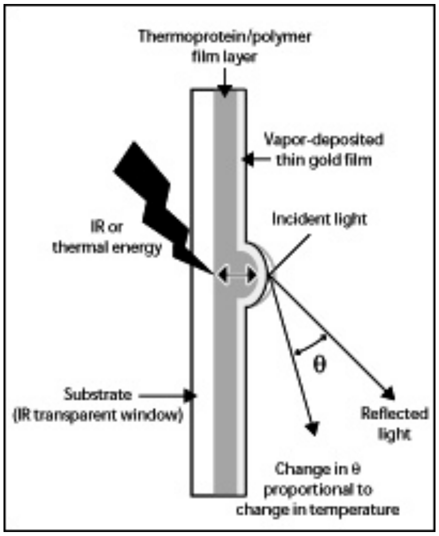

Figure 1. Schematic drawing of a thermal sensor based on a thermoprotein. (Reprinted from Morley O. Stone and Rajesh R. Naik, "Applications: Biomimetic Electromagnetic Devices," in *Encyclopedia of Smart Materials,* ed. J. A. Harvey [New York: John Wiley & Sons, Inc., 2000], 112–21.)

Conclusion

There is a growing awareness of the contribution that biomimetics can make to numerous well-established research areas, of which electromagnetic sensing is a small part. The highly interdisciplinary nature of biomimetic work makes it difficult for a single research group to be successful unless its expertise truly spans multiple scientific disciplines. Additionally, few areas span basic, fundamental science to applied research as completely as biomimetics. Bearing this grand challenge in mind, one remains cognizant of still-undreamt advances that can occur by imitating nature's optimization, which has occurred across millions of years. Continued research in biomimetics by the Air Force could lead to the development of dynamic materials, devices, and processes that directly support the war fighter by heightening the performance of vitally important military technologies and by reducing costs. These advances in the understanding of the natural world benefit science at large and provide opportunities for innovative commercial applications never before possible.

Notes

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