Biology Inspired Sensor Design

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Abstract

Sensors are an integral part of many engineered products, systems, and manufacturing processes as they provide feedback, monitoring, safety, and a number of other benefits. Utilizing concepts from a non-engineering domain such as biology has been shown to spark inspiration and innovation for a variety of technologies. Bacteria, plants, insects, mammals, reptiles and the like have diverse forms solving a variety of engineering functions, and may be considered adaptive systems with elegant methods of sensing and communication. Of particular interest are the sensing capabilities of biological systems, thus a biology inspired branch of sensor research has emerged. Nature has developed and optimized an incredible variety of sensors which provide engineers new ideas for improvements to current technology, new sensor technology and potential sensor miniaturization.

This article aims to introduce the reader to biology inspired design, commonly referred to as biomimetic design or biomimicry; the study and imitation of nature's methods, mechanisms, and processes to solve human problems. Furthermore, biology inspired design includes mimicry at many levels. This article does not discuss biosensors, devices that use specific biochemical reactions mediated by isolated substances to detect chemical compounds. Rather, the focus is on imitating nature by electrical and mechanical means without the incorporation of biological elements.

Biology Inspired Design

All forms of nature have influenced the many disciplines of engineering in some way. In recent years, plants and insects have significantly impacted electrical engineering designs. These biological systems offer exemplary methods of flight, imaging, sensing, adaptation to environment, and locomotion to name a few, of which, engineers have learned from and created novel technologies. Biomimetic robots that mimic the look and functionality of an insect, on a larger scale, are achieving feats that typical robots could not and are changing expectations. The same can be said for unmanned air vehicles that copy the articulated wing of an insect or bird, and the motion detection systems modeled after insect compound vision. Moreover, the biological domain provides inspiration at many levels, such as cellular, organism and species. For instance, if a system level sensor design is desired that considers the details for interfacing, communication or packaging, one can study the interaction of one species with another or look to any ecosystem for ideas. However, biological inspiration is not as easy as looking up a product in a catalog, the designer must depict the biological system as a system engineered by nature. An abstraction will do just that. Just as circuit designers use schematics to abstract the function of a circuit, generalizing a biological system using an abstraction can lead to innovative engineering solutions. Abstractions are critical because they allow an engineering designer to draw parallels between engineering and biology domains, which lead to adaptation of non-engineering solutions to solve engineering problems. Koryo Miura observed that plant leaves unfold in two directions at once, utilizing the abstract principle of two dimensional folding and the art of origami, he developed a folding technique (Miura-ori) for erecting solar panel arrays in space that requires little storage room and provides maximized surface area. Miura-ori has also been applied to maps and Japanese drink cans, which makes the map easy to collapse and the can strong using 30% less material.

Mimicking a biological system for the creation of biology inspired technology happens in multiple ways, which can be categorized by: principle, morphology, strategy (behavior), manufacture, or any combination of these. A biological system is any biological organism, organism sub-system or portion of an organism that is observed to exist (i.e. Bacteria, grasshopper, insect compound vision, DNA, human heart). The definitions of the mimicry categories with regards to biological systems are:

- Principle - the fundamental basis, quality or attribute of a biological system.
- Morphology - the form of a living organism; the associations amongst an organism's structures.
- Strategy - the reaction of a biological system in response to a particular situation or stimulus; behavior.
- Manufacture - the production of something by a biological system.

One can gather from these categories that biology inspired design is an interdisciplinary area of research. Inspiration for such devices is achieved through systematic procedures, observation of nature and utilization of information databases. Functional decomposition of biological systems that show potential for mimicry allows for identification of characteristics that can be mimicked by the engineering domain. Yet, determining which biological process to do in reverse to achieve a desired outcome can be as equally important.

Biological organisms operate in much the same way that engineered systems operate, each part or piece in the overall system has a function, which provides a common ground between the engineering and biology domains. For the sake of philosophical argument, it is assumed that all biological parts and sub-systems have intended functionality. Adapting features and characteristics of biological systems can significantly advance engineered systems. How does one develop a biology inspired technology? Asking a friendly biologist to explain the functionality of the biological system in question is one way. Or, one could view the biological system from an engineering perspective and break it down into manageable parts, figure out what function each part performs and look for parallels in the engineering domain. This technique is called functional decomposition and results in block diagrams describing part functionality and interactions, much like the diagrams utilized by control system engineers. Functional decomposition works well for analyzing biological systems because it is impractical to match a comparable engineering component to each part of the biological system. In some cases, one engineering component could replicate the function of more than one biological part and the converse is also true. What the reader should be aware of is that matching biological functionality to an engineering component is a manageable and worthwhile task.

Directly copying the principle, morphology, strategy or manufacturing technique of a biological system is the easiest form of biomimicry. This direct approach is much like reverse engineering, where components or strategies from the engineering domain are paired to near-equivalents in the biological domain. This one-to-one matching, however, is rarely feasible and often results in poorly designed products. Engineering components, rather, are chosen based on a pairing of functionally between the engineered domain and the biological domain. To make this point clearer, consider the human nose. Sniffing moves air mixed with odorant molecules along turbinates creating an airflow pattern to move the odorant molecules along the thin mucus coating of the nose's olfactory epithelium. Underneath the mucus lies hundreds of sensory receptor cells that are covered with hair-like structures called cilia; as the odorant molecules make their way through the cilia, they bind with the receptor cells resulting in receptor cell depolarization (i.e. a sense of smell). Replication of the entire process though which a human nose recognizes the smell of an odorant molecule would be a painstaking and impractical task. However, replicating the mucus coating which catches odorant molecules and reduces polarization is more feasible. One option for biomimetic imitation of the human nose is accomplished by utilizing an electrode to detect the change in resistivity of either a metal oxide or a conductive polymer, when in the presence of an odorant. This electric nose design mimics the olfactory epithelium thin mucus layer and sensory cell depolarization functionality.

In the second approach to biology inspired design, abstraction of the biological system using analogical reasoning allows an engineering designer to look for a specific solution through mimicry. The analogous approach relies on the idea of "big picture" thinking; figuring out the essence of the overall biological system and of each part or sub-system that achieves the overall goal. An example demonstrating usage of an analogy is a micro manufacturing technique inspired by the sacrificial process of abscission. When plants become damaged or winter is near, plants sacrifice (shed) leaves or fruit to stay alive, thus the essence of abscission is to separate parts of the plant. Utilizing the idea of separation by sacrifice, a robot tool for micro assembly was devised that included sacrificial parts, therefore effectively solving the engineering problem of micro parts sticking to the robot, due to van der Waals force, causing assembly down time. These two design approaches are illustrated in Fig. 1.

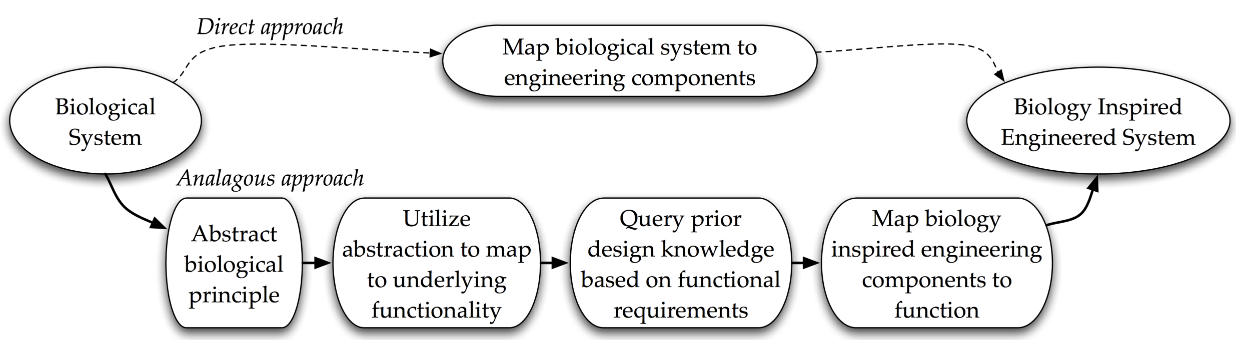

Figure 1: Approaches to biology inspired design

Sensors

Sensing in Nature happens in several ways and across all species. Nature has been developing biological sensors for billions of years; therefore the lasting solutions have evolved to fulfill unique ecological niches, which make them ideal for study and imitation. Not only is nature rich with sensing methods, but also it provides strategies associated with the use of those sensing methods. Biological sensors typically exhibit low energy requirements, high sensitivity and redundancy. Furthermore, they exhibit parallel sampling and processing of sensory information by having tens or even hundreds of receptor organs in parallel, each containing dozens of receptor cells, which improves the signal-to-noise ratio through averaging. This also reduces the likelihood of error due to loss of or failure of a receptor organ. A great lesson from nature is redundancy; in most biological systems there are many instances of redundancy.

To get a better idea about natural sensing, lets quickly introduce the main types of sensing organs and their purposes. The broad categories of sensing organs are extroreceptors, proprioceptors and interoceptors. Extroreceptors monitor stimuli external to the biological system (i.e. sounds, electric field). Proprioceptors monitor stimuli internal to the biological system (i.e. muscle tension, pressure within the body). Interoceptors monitor internal stimuli, although, without conscience perception (i.e. within the respiratory system walls). Engineers have studied the extroreceptor organs the most as these contain receptor cells that are essential to an organism understanding its environment and surroundings; the underlying purpose of technical sensors. The biological details are not needed to understand how sensing occurs in Nature. In fact, many engineers already know the basics of biological sensors. Anyone familiar with transducers understands that a voltage or current signal from the equipment is really a coded version of the measurand (i.e. position, weight, flow rate) which can be decoded in a computer or PLC. Biological sensors work the same way! The receptor organs are excited by a stimulus, which causes a series of chemical reactions effectively changing the stimulus into a cellular signal, which the biological system can then recognize and respond to. Transforming the stimulus into a cellular signal is termed transduction. All biological transducers that sense stimuli external to the biological system can be labeled as chemo, electro, magneto, mechano, photo and thermoreceptor types based on sensory physiology. What is really fascinating, is that organisms of the Animalia Biological Kingdom utilize electricity in their signaling; all stimuli are converted into electrical signals the cells, central nervous system and brain recognize. Consult the books as the end of this article to learn more.

As mentioned before, there are four categories to classify what biological functionality is mimicked and generally the two that explore deeper than the system level, are utilized for developing biology inspired sensors. Manufacture in nature typically occurs by self-assembly (at the micro and nano scale) and strategy refers to a response after a stimulus has been detected, therefore, biology inspired sensors predominately mimic the morphology or principle of the biological sensor. An example of morphology can be taken from a log-polar CCD motion tracking system modeled after the primate’s retina. The CCD imager has a circular shape instead of the traditional rectangular shape with a concentrated central region having high-resolution, just like the fovea of the retina. The peripheral region, where receptors decrease with eccentricity while their size increases, allows for high temporal response and provides a fast saccadic motion to foveate the object for closer examination. Log-polar transformations provide an elegant way to deal with the trade-off between resolution and amounts of data. As one can gather, interesting and novel discoveries can be made when researching how a biological system functions. Often the biological solution is elegant and utilizes materials or structures in ways that are counterintuitive to a trained engineer. An example of unique structure use is the sonar receiver system modeled after dolphin echolocation. This design was inspired by learning how the teeth of the lower jawbone form arrays of resonant receivers which allow for beam forming with the required delays derived acoustically by the jawbone fatty channels. Instead of using pulses of sound and waiting for the reflected echo like in standard sonar receivers, the dolphin uses endfire arrays in monopulse mode for angular localization much like those used in radio or radar technologies. Mimicking the dolphin provides a high-resolution output in shallow, near shore and littoral waters of the ocean that can localize a target the size of a sardine, which current sonar receivers cannot achieve. Nature's sensors are truly unique, simple and worth learning from.

The basic concepts behind sensory physiology, the fundamental ideas of how biological systems relate to their environment, can be adopted as a working model to construct different types of sensor technology. Keep in mind, biology inspired sensors can be considered biology inspired technology without functioning identically to the biological principle or constructed to match the biological morphology. Once the biological system is understood, the engineer can decide if direct or analogous mimicry is the best course of action. Both types of design have been successful and have led to sensor technology innovations. Let us examine a successful biology inspired sensor that emulates the morphology and principle of the insect protective, flexible covering or exocuticle.

Biological Strain Gauge

A strain gage is a simple device used to measure deformation and engineering approaches can be comprised of resistive foil, piezoelectrics, semiconductors, etc. The common strain gauge is a resistive device consisting of a patterned foil on an elastic carrier (backing) and then applied to the strained surface. Ignoring materials, shape and bonding of the sensor and focusing on functionality, the strain gauge and its instrumentation converts mechanical energy into an electrical signal. Arthropods inherently perform this same function through their campaniform sensillum or flexible exocuticle. Additionally, the campaniform sensillum model offers design advantages over the simple resistive strain gauge:

- global amplification;
- wire grid is no longer needed;
- and two dimensional displacement.

A micro biomimetic strain gauge was inspired by the arthropod and directly imitates the principle and morphology of the campaniform sensillum. The campaniform sensillum is basically an opening in the exocuticle, as seen in Figure 2, which is covered by the cap and surrounded by many other layers. The biology inspired micro strain gauge was fabricated on a silicon wafer via lithography techniques to create a 500 μm wide, 13 μm deep membrane-in-recess structure (Figure 3), of which, the membrane emulates the cap and is made of layered silicon oxide (SiO) and silicon nitride (SiN). The circular structure exhibits global strain amplification mitigating the need for multiple strain gauges. How are the biological and resistive strain gauges similar? How do the gauges compare to the biological system? To answer these questions, functional decomposition of both gauges and the arthropod campaniform sensillum were performed. Figure 4 shows the functionality and interactions of the respective systems during deformation and measurement. The components that accomplish the system functionalities are listed on the right hand side of each block. One thing to note about the information presented in Figure 4 is that electrical energy needed to power the strain sensor and system is assumed to exist and is not represented. Similarly, biological energy powering the arthropod biological system is not represented in Figure 4.

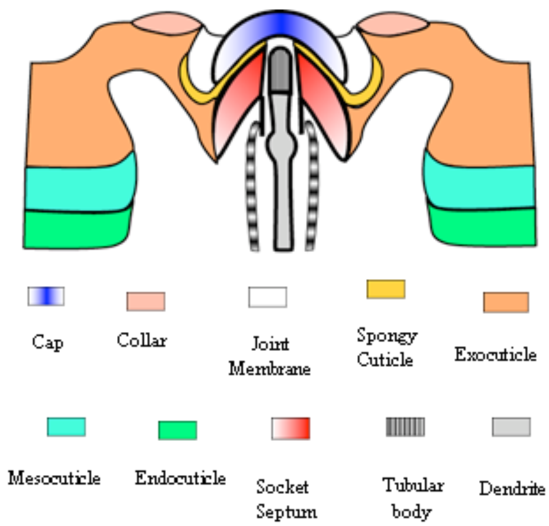

Figure 2: Campaniform sensillum morphology [published with permission from D H B Wicaksono].

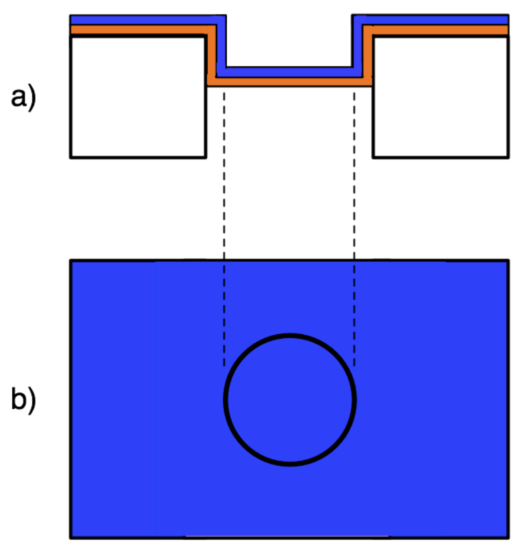

Figure 3: Biomimetic strain gauge as a micro membrane-in-recess structure; a) side view of structure showing layers atop a silicon substrate, SiO - orange layer, SiN - blue layer; and b) top view of structure.

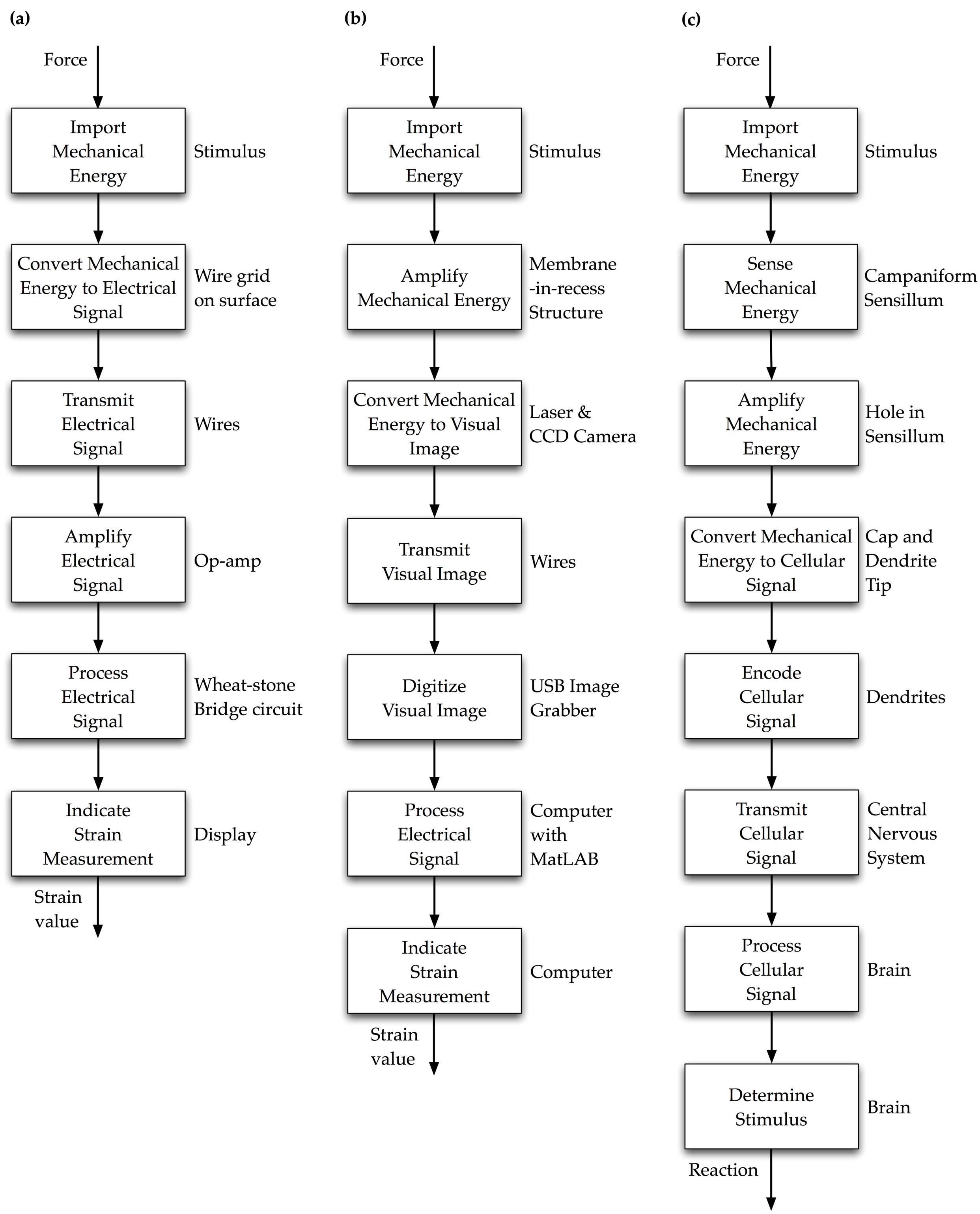

Figure 4: Functional decomposition of a) resistive strain gauge, b) biology inspired strain gauge and c) arthropod campaniform sensillum.

The block diagram representing the resistive strain gauge functionality (Figure 4a) depicts that bending or compressing the strain gauge converts mechanical force into an electrical parameter, resistance in our case, which is converted to a voltage, amplified and processed by instrumentation to achieve a strain measurement. As one can see, Figure 4a is simple and intuitive compared to the campaniform sensillum of Figure 4c. However, the result is the same. Resistive strain gauges are patterned to they measure deformation in only one direction, where as, the circular form of the biology inspired strain gauge and campaniform sensillum allow for multi-dimensional sensing.

The sophisticated campaniform sensillum of Figure 2 consists of an opening in the exocuticle that contains connected membranes covering the dendrite opening and a mechanical linkage which amplifies and converts the mechanical energy into an stimulus signal of two directional deformations. One direction is the monoaxial transverse compression of the dendritic tip of a sensory neuron cell, which acts as a transducer, and the second direction is the vertical displacement of the cap. By having two directional displacement the natural sensor exhibits non-linearity and high sensitivity. This unique biological system amplifies the stimulus before transducing it to make sure it is an adequate stimulus worth acknowledging (Figure 4c). Reverting back to abstractions, the essence of the campaniform sensillum is strain amplification, which converts a mechanical stimulus into a cellular (electrical) signal, just like the resistive strain gauge.

Figure 4b represents the functionality behind the biology inspired strain gauge in FIgure 3. The membrane-in-recess concentrates and amplifies the non-linear deflection incurred by mechanical force, which is imaged using a laser, beam splitter, filters and a CCD analog video camera. The strain measurement is extracted from camera images that demonstrate changes in the diffraction pattern inside the hole, the intensity pattern, using MatLAB software on a computer. It is clearly shown in Figure 4 how the biology inspired strain gauge directly mimics the campaniform sensillum functionality, and to a certain degree, the morphology. Both systems amplify before converting the mechanical energy to an electrical signal, utilize a circular structure with membrane and require encoding of the signal to be processed. Although the biomimetic strain gauge does not contain structures that mimic the dendrite tip, joint membrane, spongy cuticle and socket septum, the membrane-in-recess accomplishes those roles, with the role of the campaniform sensillum opening fulfilled by the silicon substrate. As a result, the biology inspired strain gauge sacrifices traditional fabrication methods and materials for sensitive, non-linear measurements of strain in multiple dimensions.

Looking Forward

Exploring the use of functional decomposition with biological systems and phenomena has lead to an interesting way of incorporating the elegance of nature into engineering design concepts. Using engineering terms to functionally describe a biological system allows an engineer to liken the functionality of a biological system to common mechanical and electrical components that perform parallel functions. Sensing unusual parameters can require out-of-the-box thinking or borrowing ideas from another discipline and studying nature to gain design inspiration or to understand how sensory information is handled by biological systems has resulted in remarkable innovations in many disciplines of engineering. However, there must be a unique feature or method of processing the stimulus, which mimics a biological sensing solution to classify the sensor as biomimetic. Thus, for biology inspired sensor conceptualization, it is imperative to understand the biology behind natural sensing to leverage the elegance in engineering design.

Nature offers a model and serves as a guide for engineering designers. We, and other researchers, have found numerous examples of biological inspiration for photonic and optic designs. Utilization of systematic methods to find biological inspiration has enabled researchers to examine the intricate and ingenious solutions that nature has devised. Designs that emphasize redundancy, low power, high sensitivity and multi-purposes are lessons to be learned from nature. Majority of biomimetic sensor research has directly emulated the morphology and functional principle of biological sensors; what could be easily observed or understood. While fascinating and significant, we believe that to maintain the innovation momentum engineers need to consider analogical reasoning in their designs. Functional abstraction promotes creativity and removes the component boundaries that engineers all too often impose upon themselves. Methods for finding inspiration or exploring the biological domain are available, but it is up to engineering designers to embrace those methods and develop biology inspired designs. Inspiration from biology is not a necessity for novel engineering design, however, it is a nice addition to the engineer's toolbox.

Read More About It

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Dr. Robert Stone is a Professor of Interdisciplinary Engineering at Missouri University of Science and Technology (formerly University of Missouri-Rolla). He held the Distinguished Visiting Professor position in the Department of Engineering Mechanics at the US Air Force Academy for 2006-07. Also, he has received numerous awards for his research in product design. His. Ph.D. is from the University of Texas at Austin.