An Overview of Biomimetic Sensor Technology

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ABSTRACT
Purpose – To provide an overview of the wide range of biomimetic sensor technology and highlight their innovations.
Design/Methodology/Application – The reader is introduced to biomimetic sensors, their types, their advantages and how they are different from traditional sensors. Background information is also provided regarding sensor design, inspiration and innovation.
Findings – There are two approaches to sensor design, which lead to diverse advantages and innovations. Classification of biomimetic sensors indicated which natural sense sensor designers and researchers underutilize.
Originality/Value – Provides information of value for those seeking innovative sensor designs and research information for those who want to research in this area.

Keywords: Biomimetic, biomimicry, biology-inspired, sensor, innovation

Paper Type: General Review

Introduction

This paper aims to provide an overview of the wide range of biomimetic sensor technology, including details about inspiration and innovation. Hereinto, the term *biomimetic* is used in the classical sense as developed by Schmitt - *the study and imitation of nature's methods, mechanisms, and processes (Schmitt, 1969)*. This review does not include *biosensors*, devices that use specific biochemical reactions mediated by isolated enzymes, immunosystems, tissues, organelles or whole cells to detect chemical compounds usually by electrical, thermal or optical signals (Nic*, et al.*, 2006). Biomimetic is synonymous with biology- or biologically-inspired, therefore the scope of the sensor technology covered in this review is broadened to include mimicry of biological function, morphology, behavior, and manufacturing.

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. Development of sensor technology becomes stagnant when the current options for improvement or innovation are no longer competitive. Utilizing concepts from a non-engineering domain such as biology has shown to spark inspiration and innovation for a variety of future technologies [cite Bar-Cohen]. In particular, biomimetic sensor technology is an emerging branch of sensor research, which offers several advantages over traditional sensor technology. Nature has developed and optimized an incredible variety of sensors for navigation, spatial orientation, prey and object detection, etc., which provide engineers new ideas for improvements to current technology, new sensor technology and potential sensor miniaturization (Bleckmann*, et al.*, 2004).

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 (Martin-Pereda and Gonzalez-Marcos, 2002). However, not all biomimetic sensors function according to the biological principle being mimicked. Once the biological system is fully 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 lead to sensor technology innovations.

The following section reviews biomimetic design as a branch of engineering design and presents systematic methods for achieving biological inspiration. Advantages of biomimetic sensor designs as apposed to traditional sensor designs are also provided. Then, the classification scheme utilized for this overview is presented along with a numerical breakdown of the researched sensor types. The next section, Sensor Types, provides the research information and innovative sensor designs to the reader, explaining the type of mimcry and what was imitated. Finally, an outlook, in the opinion of the authors, on the future of biomimetic sensors is given.

Design, Inspiration and Innovation

Accessing archived sensor design information during the creation of a new product that senses a common parameter is standard practice. Sensing unusual parameters can require out-of-the-box thinking or borrowing ideas from another discipline. This sort of motivation has allowed nature to impact the field of sensor design. Bacteria, plants, insects, mammals, retiles and the like have diverse form and function, and may be considered as adaptive systems with elegant methods of sensing and communication (Rolfe, 1997). The biological domain provides inspiration at many levels, such as cellular, organism and species. For instance, if a system level sensor design is desired with consideration of details for interfacing, communication or packaging, one can study the interaction of one species with another or look to any ecosystem for ideas. Not only is nature rich with sensing methods, but also it provides strategies associated with the use of those sensing methods. Although more abstract, generalizing the biological principle and developing an analogy can lead to innovative engineering solutions.

Mimicking a biological system for the creation of biomimetic sensors happens in multiple ways: functional design, morphological design, principle, strategy or behavior, manufacture, or any combination of these. Thus, what is considered biomimetic is broad scoping. Inspiration for such devices is achieved through systematic procedures, observation of nature and utilization of databases. According to Bar-Cohen, sorting biological capabilities along technological categories allows identification of characteristics that can be mimicked by the engineering domain (Bar-Cohen, 2006). Searching a natural-language text with functional keywords yields text excerpts that contain relevant biological solutions or analogies (Chiu and Shu, 2007, Stroble, *et al.*, 2008). Chakrabarti *et al.* developed a software package entitled Idea-Inspire that allows one to search a database by choosing a verb-noun-adjective set, which results in a mixture of biological and engineering solutions for inspiration (Chakrabarti, *et al.*, 2005). An engineering-to-biology thesaurus was developed by Stroble *et al.* to serve as an intermediary between the biology and engineering domains to aid engineers with comprehension of biology, promote creativity and among other uses, search for biological inspiration (Stroble, *et al.*, 2008).

Adapting many of the features and characteristics of biological systems can significantly improve sensor technology. Directly copying the functionality, principal, morphology or strategy of the biological system is the easiest form of biomimicry. This is much like reverse engineering a biological system (Wilson and Rosen, 2007). However, abstracting the biological system using analogical reasoning, approaches biology with the engineering design problem in mind looking for a solution through mimicry (Mak and Shu, 2004). These two design approaches are illustrated in Fig. 1. This review is not intended to provide advice on how to mimic natural sensing, but to provide an overview of the documented methodologies.

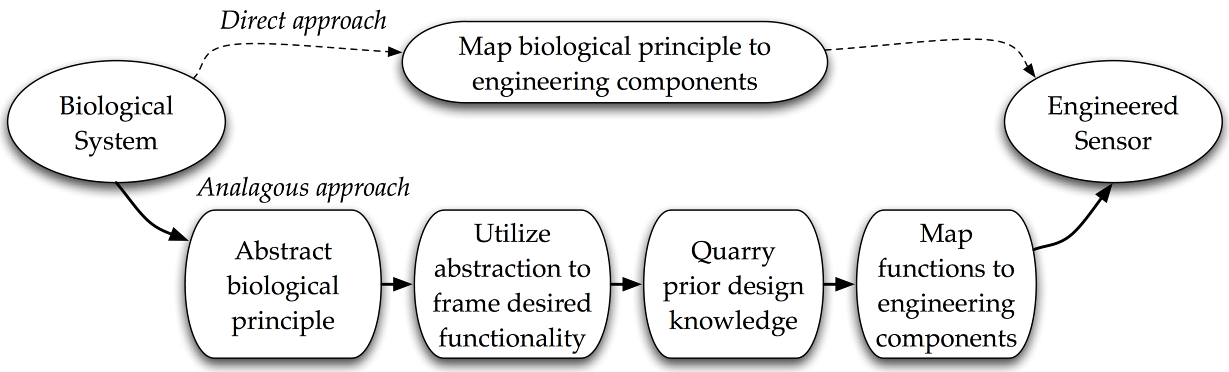

Figure 1: Direct and Analogical Biomimcry Approaches

Studying nature to gain design inspiration or to understand how sensory information is handled by biological systems has resulted in remarkable innovations. Nature has been developing biological sensors for billons of years; therefore the lasting solutions have evolved to fulfill unique ecological niches, which make them ideal for study and imitation. Biological sensors typically exhibit low energy requirements, high sensitivity and redundancy. Although small, having tens or even hundreds of receptor organs in parallel, each containing dozens of receptor cells, promotes parallel sampling and processing of sensory information, which improves the signal-to-noise ratio through averaging (Bleckmann*, et al.*, 2004). 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.

Sensor Classification

There are a number of specific sensor types, however, to present the various biomimetic sensors in this review, a classification scheme by White (White, 1987) and later updated by Fraden (Fraden, 2004), is utilized. Through this scheme, sensors can be grouped into ten categories:

- Acoustic;
- Biological;
- Chemical;
- Electric;
- Optical;
- Magnetic;
- Mechanical;
- Radiation;
- Thermal;
- Other;

with over 40 types of measureands in nine categories. The sensor type categories of biological and other do not apply to the current variety of biomimetic sensors and will be left out of this review. Extensive research of published biomimetic sensors has resulted in 29 different sensors, which are categorized and shown in Table 1. Majority of the sensors have inherent mechanical qualities measuring strain, force, deformation, position etc., typically with voltage. To understand where engineers are focusing their research, six types of extroreceptors were used to further refine the sensor classification. Extroreceptors are biological cells that take in stimuli external to the biological system and transduce the signal, which generates a response from the system (Sperelakis, 1998). Two of the sensors, however, describe novel ways of sensing internal stimuli such as posture and muscle location by mimicking human proprioceptors. The six types of extroreceptors are (Sperelakis, 1998):

- Chemoreceptors
- Electroreceptors
- Magnetoreceptors
- Mechanorecpetors
- Photoreceptors
- Thermoreceptors

Table 2 shows that the majority of biomimetic sensors mimic the mechanorecptor with chemoreceptors and photoreceptors as the second highest of interest. It was previously mentioned that biological systems have diverse function and form; this can be further identified by the groupings of sensor types under receptor types. The majority of the electric type sensors of Table 1 fall under the photoreceptor type of Table 2 and not the electroreceptor type because the sensors mimic vision or the way light is interpreted in nature. Electric and optical type sensors are extremely versatile with the ability to measure a variety of parameters, which allows them to span many receptor types.

Table 1: Sensor Breakdown by Type Classification

Type	Acoustic	Chemical	Electric	Optical	Magnetic	Mechanical	Radiation	Thermal
Number	3	5	7	2	0	10	0	2

Table 2: Sensor Breakdown by Mimicked Sensory Physiology

Receptor Type	Mechano	Photo	Chemo	Thermo	Electro	Magneto	Proprio
Sensor Type	Acoustic, Mechanical, Electric	Optical, Electric	Chemical, Electric	Thermal, Radiation	Electric, Optical	Magnetic, Optical	Mechanical, Electric
Number of Sensors	11	6	6	2	1	1	2

Sensor Types

The following sub-sections provide insight into the technique chosen for mimicry, what portion of the biological system was imitated, the innovation afforded and what receptor type the biomimetic sensor technology falls under. A short description for each sensor type is also provided. All of the sensors reviewed within this section are listed in Fig. 2.

Acoustic Sensors

Acoustic type sensors are excited by longitudinal mechanical (sound) waves with certain frequencies created by alternate physical compression and expansion (oscillation or vibration) of a medium such as gas, liquid or solid, which are a function of temperature. To date, principles from the human inner ear cochlea and dolphin ecolocation have been utilized for inspiration. A cochlear amplifier design has been shown to outperform typical surface acoustic wave resonators by narrow-band frequency analysis over a broad range through active dampening (Bell, 2006). The structural parallels suggest direct mimicry of morphology and fits under the mechanoreceptor type. An analog auditory sensing system suppresses background noise during speech recognition in much the same way humans can by directly mimicking the functional principle behind front-end signal processing of the cochlea (Hasler, *et al.*, 2002), which is a mechanoreceptor type. A new concept for a sonar receiver has been developed based on the morphology and functional principle of the dolphin lower jaw; direct mimicry lead to the innovation of using endfire arrays in monopulse mode for angular localization, which provide high-resolution output in shallow water (Dobbins, 2007). This is of the mechanoreceptor type.

Chemical Sensors

Chemical type sensors identify and quantify specific substances or chemical reactions in a medium such as gas, liquid or mixture and exhibit selectivity to the desired target substance with little or no interference from surrounding substances. Sensitivity, the minimal concentration or change needed for successful sensing, is synonymous with resolution for chemical sensors. The human senses of taste and smell are currently the focus of research, which aims to replace human taste and smell testers; these sensors can also double as a method for drug "sniffing" and other pharmaceutical applications. All chemical sensors described in this sub-section are of the chemoreceptor type. A microchip with electrode recognition sites or "taste buds" has been developed to measure taste and map the selected compound to the five primary tastes of salty, sweet, sour, bitter and umami, which directly mimics the functionality of the human tongue (Toko, 2000, Toko, 2004). Directly mimicking the human taste bud is a piezoelectric quartz crystal with a molecularly imprinted polymer coating, one that has an enhanced "memory effect," which is inherently stable, long-lasting, can be washed and has high reproducibility (Tan, *et al.*, 2001). The bulk acoustic wave sensor demonstrates a shift in the frequency response to indicate the sensed analyte molecules (Tan, *et al.*, 2001).

Three approaches to replicating the human nose have been successful at detecting and identifying an odorant. A metal oxide or conductive polymer that changes resistance in the presence of an odorant, atop electrodes, is the most common method which directly mimics the functionality and morphology of the olfactory epithelium thin mucus layer (Nagle, *et al.*, 1998, Toko, 2000). A less direct method, yet analogous to the olfactory epithelium functionality, is a sensor utilizing a quartz crystal microbalance comprised of a polymer-coated resonating disk that changes mass in the presence of an odorant, thereby changing the resonant frequency of the sensor (Nagle, *et al.*, 1998). Also analogous to the olfactory epithelium functionality is a fiber optic sensor coated with a chemically active fluorescent dye, which changes polarity in the presence of an odorant (Bar-Cohen, 2006, Nagle, *et al.*, 1998). A shift in the fluorescent spectrum indicates an odorant is present through a wavelength change, making this sensor ideal for applications in electrically noisy environments.

Electric Sensors

Electric type sensors detect analog or discrete electric parameters (electric field, voltage, current, capacitance, etc.) and transform the input into another electric parameter that is output or are processed by circuitry. Electric fish, common fly, primate eye, human eye and human muscle system all provided biological inspiration for the sensors in this category. Directly mimicking the function and morphology of active electrolocation in *Mormyriformes*, a sensor with dual-purpose electrodes detects, localizes, measures the distance of and analyzes objects (Bleckmann, *et al.*, 2004, Schwarz and von der Emde, 2001, von der Emde, 2004). Electrolocation functions in unfavorable conditions were other sensors fail and falls under the electroreceptor type. A small, low-power analog VLSI implementation of a fly neuronal model provides a remarkably accurate response for small-target tracking (Higgins and Pant, 2004). This photoreceptor type sensor directly mimics the behavior or strategy of the fly. Analog circuitry inspired by the fly has been developed to imitate the parallel "miniretinal" processing that occurs in hexagonally oriented photoreceptors, directly mimicking the fly's morphology (Wright, *et al.*, 2004). Extremely fast throughput, sub-pixel resolution (hyperacuity), and six-fold photon capture (Wright, *et al.*, 2004) make this photoreceptor type an improvement over traditional photometric sensors. Also inspired by the fly is a visual sensor that combines motion detection with variable speed scanning, which mitigates the concern of distance and light levels (Viollet and Franceschini, 1999). The non-camera approach to motion detection and tracking using local motion detection photodiodes (Viollet and Franceschini, 1999) is analogous to the functionality of the fly visual system and puts this under the photoreceptor type.

Directly mimicking the morphology of the primate eye foveal region of the retina and neurological behavior of primate visual processing, a neuromorphic vision sensor that reduces the amount of data without losing information for fast processing has been developed (Van der Spiegel, *et al.*, 2002, Van der Spiegel and Nishimura, 2003). This sophisticated vision system is of the photoreceptor type. A theoretical approach to improving machine vision was proposed by directly modeling the functional architecture of the human vision system (Harvey and Heinemann, 1992). Neural networks and vision sensors mimic the location and classification channels to increase object recognition in busy environments (Harvey and Heinemann, 1992) and make this of the photoreceptor type. An electronic, implantable sensor, directly imitating the internal proprioceptor functionality of humans, has been created to monitor muscle movements for feedback control of medical prostheses (Loeb and Tan, 2005). This is of the mechanoreceptor type.

Optical Sensors

Optical type sensors are stimulated by light, natural and artificial in the ultraviolet to mid-infrared spectral range, and require a light source, light guidance devices and a photodetector. Changes in the desired parameter, light, can be measured directly, or changes in a light guidance device serving as an intermediary between the desired parameter and detector allows for non-contact measurement of diverse parameter types. Principles from the insect compound eye and magnetically sensitive chemical processes within migrating birds have been utilized for mimicry. The self-aligned microlenses for omni-directional detection or wide field-of-view directly imitate the functionality, morphology and manufacture of a compound eye ommatidia array and are the first efforts towards true 3D artificial compound eyes (Jeong, *et al.*, 2005). This is of the photoreceptor type. A theoretical concept for a vision-based magnetic compass that relies on radical-pair processes directly mimics the modulation of sensitivity of the light receptors in the eye (Ritz, *et al.*, 2000). This concept is of the magnetoreceptor type.

Magnetic Sensors

Magnetic type sensors directly measure geo-magnetic or artificial magnetic fields if they are the desired parameter, or detect changes in an artificial magnetic field created as an intermediary between the desired parameter and detector, which allows for non-contact measurement of diverse parameter types. Of the published biomimetic sensor research, none fit into this classification.

Mechanical Sensors

Mechanical type sensors detect parameters associated with mechanical energy (movement, force, strain, flow, etc.) or material properties and transform the parameters into suitable outputs, or processed by circuitry. Biological systems that provided inspiration for mechanical type sensors were: winged insects, mammalian muscles, human skin, arthropods with flexible shells, crustaceans and fish of the *chordata* phylum. All mechanical sensors described in this sub-section are of the mechanoreceptor type. Directly imitating the functionality and morphology of winged insects, an artificial haltare that measures the Coriolis force has been created for use in mechanical flying insects, which provide a significant improvement over MEMS gyroscopes (Wu, *et al.*, 2002). A detailed length and velocity sensor design directly mimics the functionality, behavior and morphology of the human muscle spindle, which is useful for motion control systems, as well as, medical prosthetics (Jaxx and Hannaford, 2004, Jaxx, *et al.*, 2000). An artificial muscle constructed of electroactive polymers, analogous to human muscle functionality and behavior, can withstand high torque and requires little voltage to activate (Bar-Cohen, 2006).

The skin and sensitivity of human fingers has been mimicked as a tactile sensor for biorobotic applications. Measuring fractional conditions and the stretch of the skin via a silicone finger with molded bellows and coils provides feedback for adapting grip force and directly mimics the meissner corpuscles functionality (Sano, *et al.*, 2006). Also mimicking the meissner corpuscles functionality is a tactile sensor with embedded carbon microcoils floating in polysilicone, which compress and extend freely, yielding a quick and accurate response (Yang., *et al.*, 2005). A strain sensor based on the campaniform sensillum of arthropods directly imitates the behavior of global strain amplification through composite materials, mitigating the need for multiple strain gauges [cite #19 Skordos]. Similarly, a micro strain sensor was fabricated via MEMS techniques to create a SiO_2/SiN thin film over a membrane-in-recess (Wicaksono, *et al.*, 2004). Both of these designs improve upon current strain gauge sensor technology.

A micro flow detection sensor, which directly mimics the functionality and morphology of the *chordata* hair cells that make up the lateral line system, transfers the bending moment to a horizontal cantilever beam and provides high integration density (Fan, *et al.*, 2002, Motamed and Yan, 2005). The piezoresistive sensor is coated with parylene to add strength making it robust, lightweight and suitable for distributed arrays. A complex MEMS fabricated cantilever beam structure with integrated electrical switches are analogous to the antennae functionality of crustaceans, which are evolved hair cells (Ayers*, et al.*, 1998, McGruer*, et al.*, 2002, Motamed and Yan, 2005). These sensors provide a quick response to minute force. The mechanical sensor created to measure transient linear acceleration, direction and magnitude of gravity and angular velocity of a system in 3D space is direct mimicry of the human vestibular system functionality (Dario*, et al.*, 2005). This sensor is the only proprioceptor type of this category.

Radiation Sensors

Radiation type sensors are excited by the emission of charged (α and β particles and protons) or uncharged (neutrons) particles from atomic nuclei, or nuclear electromagnetic γ and x rays. These types of sensors either detect the presence of radioactivity or measure the radiative energy. Of the published biomimetic sensor research, none fit into this classification.

Thermal Sensors

Thermal type sensors absorb radiation from the mid- and far infrared spectral range, monitor temperature over a specified range or measure the specific heat of a material. Thermal sensing occurs through contact and non-contact methods. The IR sensing beetles of the genus *Melanophila* and cutaneous receptors found in human skin has been utilized for inspiration. A novel photo-mechanical IR detector directly mimics the functionality and morphology of the *Melanophila* pit organs and provides a highly sensitive, cost effective IR sensor, which is an improvement over the popular bolometer design (Bleckmann*, et al.*, 2004). This technology fits under the thermoreceptor type. A robotic navigation device monitors the heat transfer coefficient change from a heated surface to its surrounding environment via fluctuation in the surrounding fluid velocity (Marques and Almeida, 2006). ThermalSkin (Marques and Almeida, 2006) directly imitates the thermal anemometer principle of human skin and is of the thermoreceptor type.

Acoustic
- Cochlear amplifier
- Cochlear speech recognition system
- Dolphin based sonar receiver

Chemical
- Artificial human tongue
- Artificial chemical recognition sites
- Piezoelectric artificial human nose
- Conducting polymer artificial human nose
- Chemo-fluorescent artificial human nose

Electric
- Artificial electrolocation device
- Fly based vision system
- Fly based, hexagonal oriented vision system
- Fly based, non-camera motion detection system
- Artificial bilayer lipid membrane
- Primate eye based vision system
- Human eye based vision system
- Artificial muscle monitoring

Optical
- Artificial ommatidia array
- Vision-based magnetic compass

Mechanical
- Artificial halters
- Artificial muscle spindle
- Artificial meissner corpuscles
- Artificial lateral line system
- Campaniform sensillum strain sensor
- Carbon microcoil tactile sensors
- Electroactive polymer muscle
- Micromachined campaniform sensillum strain sensor
- Artificial posture monitoring
- Artificial crustacean antenna

Thermal
- Photo-mechanical IR Sensor
- ThermalSkin

Figure 2: Summary of Biomimetic Sensors

Outlook

Nature offers a model and serves as a guide for engineering designers, whom are looking outside of the engineering domain for inspiration, to address engineering problems with natural solutions. 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 functionality of biological sensors; what could be easily observed or understood was chosen for further examination. While fascinating and significant, the authors 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. Several methods for finding inspiration or exploring the biological domain are available, now it is up to engineering designers to embrace the movement towards biology inspired designs.

This review uncovered that little attention was placed on thermal, optical and acoustic type sensors and none at all for radiation and magnetic types. These gaps indicate that nature does not provide novel approaches to those sensing areas or those areas are simply untapped, just waiting to be discovered. Only time will tell. From the biological standpoint, the thermo, electro and magnetoreceptor, and proprioceptor type sensors are largely un-researched by the engineering community. This finding also provides a direction for further biomimetic sensor research.

The authors strongly agree with Bar-Cohen's assessment of biomimetic technology – "The inspiration from nature is expected to continue leading to technological improvements and the impact is expected to be felt in every aspect of our lives (Bar-Cohen, 2006)". As cooperation and collaboration between biologists and engineers continues to increase, the phenomenological view of the natural world will increasingly influence the engineering perspective. Leading to further advancements in biomimetic technologies and potentially result in solutions to unsolved engineering problems.

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