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CONCEPTUALIZATION OF BIOMIMETIC SENSORS THROUGH FUNCTIONAL REPRESENTATION OF NATURAL SENSING SOLUTIONS

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ABSTRACT
Classification of natural systems by engineering terms found in the Functional Basis, a well-defined modeling lexicon, links the ingenuity of the natural world to the engineering domain. Functional representation through language and models describes the function or purpose of a biological organism's capabilities, which is then utilized for conceptual design and inspiration of new products and processes. The research presented in this paper explores two biological kingdoms for natural sensing solutions and the fundamental processes that occur during sensing, allowing the relationships between biology and engineering to be established. The resultant information serves as a guide to engineers with limited biological knowledge for leveraging the unique biological designs. Surveying biology specifically for natural sensing solutions finds six main types of extraneous sensing in existence. Engineering terms analogous to biological descriptions demonstrate that biological organisms can be likened to engineered systems at varying levels of fidelity. Functional representation was found to be a reliable method for transferring knowledge between the biology and engineering domains.

Keywords: Biomimicry, Sensing, Function, Functional modeling, Concept generation

1 INTRODUCTION
Animals, plants, bacteria and other forms of life that have been in existence for millions of years have continuously competed to best utilize the resources within their environment. Natural designs are simple, functional, and remarkably elegant. Thus, nature provides exemplary blueprints for innovative designs. Engineering design is an activity that involves meeting needs, creating function and providing the prerequisites for the physical realization of solution ideas [1-3]. Engineering, as a whole, is about solving technical problems by applying scientific and engineering knowledge [1, 4]. Traditionally, the scientific knowledge of engineering is thought of as chemistry or physics, however, biology is a great source for innovative design inspiration. By examining the structure, function, growth, origin, evolution, and distribution of living things [5], biology contributes a whole different set of tools and ideas that a design engineer wouldn't otherwise have.

"Science is the study of the natural world; it is concerned with understanding what is. Engineering design is concerned with creating new things; it makes extensive use of science, but is a quite different activity. … It is only the support of science that has made possible the quickened pace and great achievements of engineering today, and in most fields nowadays the designer must have a solid background of scientific knowledge." –[6]

Biology has greatly influenced engineering as a whole. Nature has inspired engineering design for centuries. More recently, the formalized field of Biomimetics or Biomimicry has developed. Biomimetics is devoted to studying nature's best ideas and imitating these designs and processes to solve human problems [7]. One cannot simply dismiss engineering breakthroughs utilizing biological phenomena as chance occurrences; it is evident that mimicking biological designs or using them for inspiration leads to leaps in innovation (e.g., Velcro, flapping wing micro air vehicles, synthetic muscles, self-cooling buildings, self-cleaning glass, antibiotics that repel bacteria without creating resistance).

This research focuses on making biological designs accessible to design engineers. Functionally representing biological systems through systematic design techniques leads to the conceptualization of biology inspired engineering designs. Utilizing functional representation and abstraction to describe biological systems presents the natural designs in an engineering context. Thus, the biological system information is accessible to engineering designers with varying biological knowledge, but a common understanding of engineering design methods. Looking to the biological domain for design inspiration leads to creative or novel engineering designs through analogical reasoning or directly copying what is found in the natural world.

Although most biologically inspired designs are mechanical, structural or material, this research focuses on how biological organisms sense external stimuli for the use of novel sensor conceptualization. In the following sections, related work on knowledge transfer between the biological and engineering domains, natural sensing from the biological perspective, and modeling of natural sensing using engineering terms are covered. Sequences of chemical reactions and cellular signals during natural sensing are investigated and ported over to the engineering domain using the Functional Basis lexicon and functional models. For the sake of philosophical argument, it is assumed that all the biological organisms and systems in this study have intended functionality, as demonstrated through functional models.

2 NOMENCLATURE

Terms used throughout this paper that are specific to this research are described in this section.

- *Biomimicry* - a design discipline devoted to the study and imitation of nature's methods, mechanisms, and processes to solve human problems.
- *Biological organism* – a biological life form that is observed to exist.
- *Biological system* – any biological situation, organism, organism sub-system or portion of an organism that is observed to exist or happen (i.e. Bacteria, sensing, grasshopper, insect compound vision, DNA, human heart).
- *Functional Basis* - a well-defined modeling language comprised of function and flow sets at the class, secondary, tertiary levels and correspondent terms.
- *Functional model* - a visual description of a product or process in terms of the elementary functions and flows that are required to achieve its overall function or purpose.
- *Flow* – refers to the material, signal or energy that travels through the sub-functions of a system.
- *Function* – refers to an action being carried out on a flow to transform it from an input state to a desired output state.

3 RELATED WORK

Initial problem solving by inspiration from nature may have happened by chance or dedicated study of a specific natural entity such as a gecko. More recently several engineering design researchers have created methods for transferring biological phenomenon to the engineering domain. The goal is to create generalized biomimetic methods, knowledge, and tools such that biomimetics can be broadly practiced in engineering design. A short list of prominent research in biologically inspired products, theories, and design processes is: [8-12]. With the right tools, knowledge transfer between the biological and engineering domains can be advanced and biomimetic designs can be realized.

Chakrabarti, et al. developed a software package entitled Idea-Inspire that allows one to search a database by choosing a verb-noun-adjective set [13]. Their database is comprised of natural and complex artificial mechanical systems. Each entry's motion is described functionally by behavioral language in the form of a function-behavior-structure model. As an automated approach, the Idea-Inspire software aims to inspire ideas rather than solve the problem directly. Currently, there are only 100 natural system entries, which limits the inspiration for biomimicry.

A searchable database that focuses on technology transfer between biology and engineering is the TRIZ (Teoriya Resheniya Izobretatelskikh Zadatch) method by [14]. This inventive problem-solving tool developed in Russia provides the user with 3,000,000 patents and over 6000 physical, chemical, mathematical and engineering solutions all classified in terms of function [14]. To generate ideas or solutions the user must rephrase the design problem into an abstract representation before searching. As seen with [13], this search tool is also limited by the minimal biological knowledge that is currently in its database. Wilson and Rosen developed a method for systematic transfer from biology to engineering through reverse engineering biological systems [15]. This method does not include a searchable database and allows the designer to search for a suitable biological phenomenon without boundaries. Once a biological system has been identified there are seven steps that result in idea generation. A behavioral model and truth table depicting system functionality allows the designer to describe the biological system with domain-independent terms and transfers general design principles.

Hacco and Shu, and Chiu and Shu have developed a method for abstracting engineering design analogies by searching biological literature using functional keywords [16-18]. The engineering domain keywords are cross-referenced with Wordnet to define a set of natural-language keywords for yielding better results during the search. Typically, searches are based on multiple keywords. This method has successfully generated engineering solutions analogous to biological phenomena [19-21]. For example, analogical reasoning deduces the phenomenon of plant abscission to the black box functionality of separate solid. Plant abscission inspired the use of a sacrificial part during microassembly to overcome the issue of "surface forces that dominate gravitational forces, resulting in sticking between microgripper and micropart" [22].

The common thread linking the aforementioned related works is the principle of functionally abstracting the biological phenomenon or organism being studied, or decomposing it into physical and functional parts. Functional modeling with the Functional Basis also employs this principle, which is the method of knowledge transfer utilized in this research.

4 RESEARCH APPROACH

Representing the world in terms of its function – what it does – as opposed to its form – what it is – is commonly used in engineering design. Functional representation enables a thorough understanding of the requirements and use of some products while decreasing the tendency of designers to fixate on some particular physical solution for the problem. Functional representation is recognized as a way to connect nature and engineering through analogy. When viewed functionally, biological organisms and systems operate in much the same way that engineered systems operate [6]: each part or piece in the overall system has an intended function. Function provides a common ground linking the two domains. Functional decomposition provides several advantages for engineering design [1-3, 23]:

- Systematic approach for establishing functionality
- Functionality captured at multiple levels of fidelity
- Comparison of product functionality
- Creativity in concept generation
- Archival and transmittal of design information

Functional modeling has a long history of use in systematic design methods [1]. Stone, et al. created a well-defined modeling language comprised of function and flow sets with definitions and examples, entitled the Functional Basis [23]. Hirtz, et al. later reconciled the Functional Basis into its most current set of terms, with research efforts from the National Institute of Standards and Technology (NIST), two U.S. universities, and their industrial partners [24]. In the Functional Basis lexicon, a function represents an action (verb) being carried out, where as a flow represents the type of material, signal or energy (noun) passing through the sub-functions of the system. There exist eight classes of functions and three classes of flows, both having an increase in specification at the secondary and tertiary levels. Both the functions and flows have a set of correspondent terms that aid the designer in choosing the correct Functional Basis term. The function and flow sets can be found in [24].

To create functional representations of biological sensing, disregarding the individual organism or system and focusing at the Kingdom level, external stimuli are modeled as energies or signals. Material is not considered here because it is assumed that a material causes stimulation due to external or built-up energy moving it. Example forms of energy stimuli are vibrations and heat, where as, signal stimuli would be seeing an enemy or receiving a command from the leader of the pack. The Functional Basis flow set lists fifteen different forms of energy, of which biological energy is included, however, because the biological organism or system is the focus in this research the equivalent engineering energies are used instead to accurately describe what is happening. Labeling all forms of energy that flow through a biological organism or system *biological* would not be descriptive enough for engineering designers to relate to and utilize. Therefore, investigating the exact energy form is required for developing a suitable functional representation.

5 BIOLOGY UNDERLYING NATURAL SENSING

To claim that a biomimetic sensor is one that simply transduces a stimulus, as explained in this section, would designate all sensors on today's market biomimetic. Instead, 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 biomimetic sensor conceptualization, it is imperative to understand the biology behind natural sensing to leverage the elegance in engineering design. This section covers fundamental knowledge of the biological processes involved during natural sensing and specifically how natural sensing occurs in the Animalia and Plantea Kingdoms.

Natural sensing occurs by stimuli interacting with a biological organism or system, which elicits a positive or negative response. All organisms possess sensory receptor cells that respond to different types of stimuli. The receptors that are essential to an organism understanding its environment and surroundings, and of most interest to the engineering community for mimicry are grouped into the class known as extroreceptors. The three classes of receptors are [25, 26]:

- Extroreceptors – External – chemoreceptors, electroreceptors, mechanorecptors, magnetoreceptors, photoreceptors, and thermorecpetors
- Proprioceptors – Internal – vestibular, muscular, etc.
- Interoceptors – Internal without conscious perception – blood pressure, oxygen tension, etc.

Proprioceptors and interoceptors are excellent biological sensing areas to study for developing medical assistive technologies, however, they are not researched in this study. The receptors of interest are the six families under the class of extroreceptors, which sense stimuli external to the organism [25]. Once a stimulus excites the biological organism, a series of chemical reactions occur converting the stimulus into a cellular signal the organism recognizes. Converting or transforming a stimulus into a cellular signal is termed transduction. Although all biological organisms share the same sensing sequence of perceive, transduce, and respond, they do not transduce in the same manner. Biological organisms that are capable of cognition have the highest transduction complexity and all stimuli result in electrical cellular signals [25]. Other organisms have varying levels of simpler transduction, but result in chemical cellular signals [27].

5.1 Animalia Kingdom

The Animalia Kingdom simply refers to multi-cellular, eukaryotic organisms capable of cognitive tasks [5]. Within this set of organisms, transduction occurs in one of two ways [25, 26]:

- Direct coupling of external stimuli energy to ion channels, allowing direct gating
- Activation of 2nd messengers - external stimuli energy or signal triggers a cascade of messengers which control ion channels

Transduction in this Kingdom is a quick process that happens within 10μm - 200ms per stimulus [26]. During transduction, a sequence of four events occur, which are uniform across the six receptor families [25]:

1. Detection (protein binding, signal propagation about receptor cell)
2. Amplification (cascade of intracellular chemical signals)
3. Discrimination (modulation of chemical reactions into an electrical code sent to the nervous system)
4. Adaptation (over time, a prolonged stimulus has less of an effect)

Recognition of a stimulus happens within the nervous system, as denoted by discrimination in the transduction sequence. Mechano, chemo, thermo and photoreceptors are the dominant receptors in organisms of the Animalia Kingdom, however fish and birds utilize electro and magnetoreceptors, respectively, for important tasks as shown in Table 1.

Table 1. Example Animalia Kingdom sensations resulting from stimuli

Receptor Family	Sensations that are detected
Chemo	Taste, Smell
Electro	Electro-location, Impedance changes, Conductivity changes
Magneto	Flight navigation
Mechano	Vibration, Pressure, Stretch/strain, Force, Muscle/joint position, Hearing (sound pressure), Water flow (fish), Orientation (lateral line in fish), Angular velocity (halteres), Echo-location (dolphins ,bats)
Photo	Light (vision), Polarized light detection, IR
Thermo	Heat/IR, Cold

5.2 Plantae Kingdom

The Plantae Kingdom simply refers to multi-cellular, eukaryotic organisms that obtain nutrition by photosynthesis [5]. Transduction converts external stimuli into internal chemical responses and occurs by either [25, 28]:

- Direct coupling of external stimuli energy to ion channels, allowing direct gating
- Activation of 2nd messengers - external stimuli energy triggers a cascade of messengers which control ion channel gates (most common)

Transduction within plants is a slow process, often taking hours to complete. Cross talk between signaling pathways permits more finely tuned regulation of cell activity than would the action of individual independent pathways [29]. However, inappropriate cross talk can cause second messengers to be misinterpreted [29], much like high frequency circuits that couple to other electronic devices causing an undesired effect. During transduction a sequence of three events occur, which are uniform across the six receptor families [25]:

1. Detect (protein binding and signal propagation about receptor cell)
2. Amplify (cascade of intracellular chemical signals)
3. Adaptation (change in turgor pressure or chloroplast orientation)

Photo, mechano, chemo, magneto and thermoreceptors, in that order, are the dominant receptors in organisms of the Plantae Kingdom as shown in Table 2. Particular stimuli result in particular reactions, which are known as tropisms in this Kingdom. Electroreceptors are the least understood in Plantae Kingdom organisms and experiments do not provide consistent results, however, it has been suggested that electrical signals can traumatize organisms of this Kingdom [27].

Table 2. Example Plantae Kingdom sensations resulting from stimuli

Receptor Family	Sensation that is detected
Chemo	Starvation, Growth
Electro	Possible trauma
Magneto	Gravity
Mechano	Pressure/force, Stretch/strain, Wounding, Wrapping around an object
Photo	Light (solar energy), Growth, Chloroplast movement, Turgor changes (water)
Thermo	Heat, Cold

6 MODELING BIOLOGY

Representing sensing functionally using the lexicon of the Functional Basis allows biological sensing solutions to be stored in an engineering design repository and utilized for concept generation. These biological solutions can then be recalled and adapted to engineered systems. The Functional Basis terms best suited to represent biological sensing at the highest level are provided in Table 3. Accompanying the Functional Basis lexicon is a set of definitions, describing each term and which type of flow can be operated upon by each function. Sense was chosen to represent perceive over detect or measure as the definition of sense explains, “to perceive, or become aware, of a flow” [24], which is exactly what occurs during natural sensing. The same can be said about the transduce-convert relationship. The definition of convert and its correspondent term transform aligns with the definition of transduce, thus making a good match. Respond is not as straightforward as responses can vary widely, however, from the stand point of a response is initiated due to the stimulus, the Functional Basis term actuate is a good match. Actuate is defined as, “to commence the flow of energy, signal or material …” [24] and the correspondent terms of enable, initiate, and start adequately describe what is occurring in the biological system. A functional model of the high level natural sensing sequence is given in Figure 1 with the *flow* intentionally generalized, and should be replaced by the correct energy or signal per application.

Table 3. Comparison of high level natural sensing terms

Biological Term	Functional Basis Term
Perceive	Sense
Transduce	Convert
Respond	Actuate

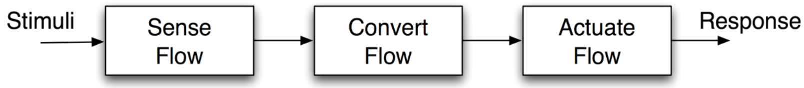

Figure 1. High level natural sensing sequence functional model

As previously mentioned in Section 5, transduction is not similar between the Animalia and Plantae Kingdoms. The differences between the two Kingdoms at the secondary level are compared in Table 4. Organisms of the Plantae Kingdom do not exhibit cognitive processes, thus they do not discriminate between stimuli and react to all stimuli in a predetermined manner. Convert does not appear in the Functional Basis term portion of Table 4 because it is the combination of steps within the transduction sequence that perform the conversion. Modeling a biological organism or system is not as straightforward as modeling a kitchen appliance that has only two levels of fidelity, black box (system) and sub-function (sub-system). The designer must consider how much detail is required for adequate representation of the biological system to utilize the information with a chosen engineering design method. Comparison of biological terms to Functional Basis terms at the tertiary and deeper levels is difficult as each family of receptors detects, amplifies, discriminates, or adapts in a unique way. Researchers developing computational models of biological systems follow the biological scales (atomic, molecular, molecular complexes, sub-cellular, cellular, multi-cell systems, tissue, organ, multi-organ systems, organism, population and behavior) when developing multiscale models [30]. This same scale can be utilized for functional representation of biological systems, allowing engineers with enough effort and resources to specify the biological model's level.

Take for example the function convert; engineers can convert electrical energy to mechanical (rotational) energy using a motor, or convert AC power to DC power with a rectifier circuit. Biological systems take many steps to convert and as Table 4 shows sensing takes four. These four steps, however, are at the organ level, which is two levels above the cellular level [30]. Similarly, the engineering process of conversion could be viewed at a level deeper than system or sub-system and models could be made that describe the physics behind a motor or rectifier circuit. Models at a very low (or the lowest) level are not always helpful because there can be too many details to work with, but the functional model level of fidelity is at the discretion of the designer. It is important when developing functional representations of biological systems to not mix information at one level with information at another level to accurately describe the desired system (the same could be said for an engineering system); however, this is difficult especially for those with limited biological knowledge and may require assistance from a biologist.

Table 4. Comparison of second level sensing terms for both Kingdoms

<table>
<tr><th colspan="2" rowspan="2">Biological Term</th><th colspan="2">Functional Basis Term</th></tr>
<tr><th>Animalia Kingdom</th><th>Plantae Kingdom</th></tr>
<tr><td colspan="2">Perceive</td><td colspan="2">Sense</td></tr>
<tr><td rowspan="4">Transduce</td><td>Detect</td><td>Detect</td><td>Detect</td></tr>
<tr><td>Amplify</td><td>Change</td><td>Change</td></tr>
<tr><td>Discriminate</td><td>Process</td><td></td></tr>
<tr><td>Adapt</td><td>Condition</td><td>Condition</td></tr>
<tr><td colspan="2">Respond</td><td colspan="2">Actuate</td></tr>
</table>

To illustrate a deeper level of natural sensing the processes of Animalia chemoreception and Plantae photoreception were chosen. The detailed biological events occurring during chemoreception, recognition of a taste or smell, by an organism of the Animalia Kingdom are provided in Table 5. The detailed biological events occurring during photoreception, the recognition of light, by an organism of the Plantae Kingdom are provided in Table 6. Tables 5 and 6 demonstrate in list format the chosen Functional Basis terms that should be used for creating very detailed functional models of natural sensing; also allowing one to comprehend the similarities between the two domains. Tables 5 and 6 also list the Functional Basis Correspondent terms that aided in the selection of function terms. The biological action of Respond, the final action of the sensing sequence, is handled slightly different when investigating at a deeper level as demonstrated in the Tables. Actuate is preferred to describe response at a general level, however, at a deeper level the exact response can be chosen. Figures 2 and 3 are general models of Animalia chemoreception and Plantae photoreception. Possible function term choices are: regulate, change, guide, indicate, stop, position or inhibit. Animalia and Plantae Kingdom functional models at multiple levels of fidelity can be found in [31].

Table 5. Comparison of Terms for Animalia Chemoreception

Biological Term		Engineering Term	
Action	*Description of events the action is comprised of*	Functional Basis Correspondent Term	Functional Basis Term
Perceive	Chemical stimulus occurs	Input	Import
	First signal propagation about receptor cell	Feel, determine	Sense
	Second signal propagation about receptor cell	Carry, deliver	Transfer
Detect	Receptor cell transforms external stimulus into a biological stimulus of the same type	Perceive	Detect
Amplify	Fluctuation of second messengers for a chemical cascade	Modulate, adjust, dampen, vary	Increment, Decrement
	Ion channels open or close for Na+ or K+	Initialize, start	Actuate
	Cell membrane depolarizes	Invert, modify, demodulate	Change
Discriminate	Change electrical signal into a frequency	Modulate	Change
	Send frequency to brain	Conduct, convey	Transmit
	Recognize chemical stimulus	Compare, check	Process
Adapt	Adapt to prolonged chemical stimulus	Adapt	Condition
Respond	React based on electrical signal, any number of responses could happen, it is based on the stimulus	Enable, initiate, control, maintain, adjust, halt, align, announce, orient, direct, shift, steer, resist, protect	Actuate, regulate, change, guide, indicate, stop, position or inhibit
	Reaction is now external	Emit	Export

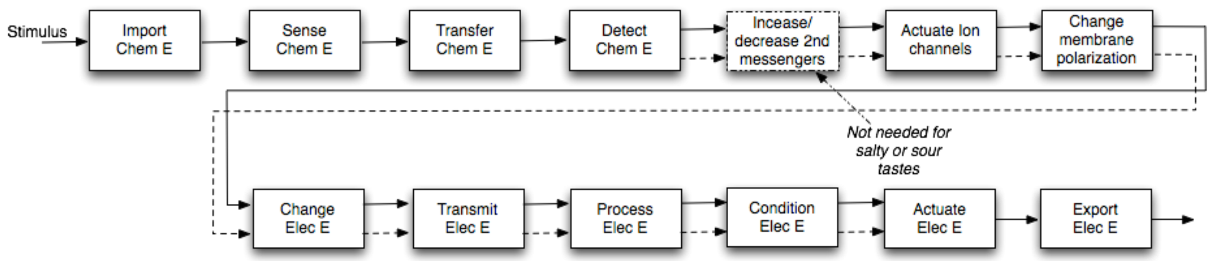

Figure 2: Functional Model of Animalia Chemoreception, Cellular Level

Table 6. Comparison of Terms for Plantae Photoreception

Biological Term		Engineering Term	
Action	*Description of events the action is comprised of*	Functional Basis Correspondent Term	Functional Basis Term
Perceive	Stimulus occurs	Input	Import
	First signal propagation about receptor cell	Feel, determine	Sense
	Second signal propagation about receptor cell	Carry, deliver	Transfer
Detect	Receptor cell transforms external stimulus into a biological stimulus of the same type	Perceive	Detect
Amplify	Ion channels open or close for Na+ or K+	Initialize, start	Actuate
	Chemical cascade of second messengers for a	Control, maintain, equalize	Regulate
	Cell membrane depolarizes	Invert, modify, demodulate	Change
Adapt	Adapt to prolonged electromagnetic stimulus	Adapt	Condition
Respond	React based on chemical signal, any number of responses could happen, it is based on the stimulus	Enable, initiate, control, maintain, adjust, halt, align, announce, orient, direct, shift, steer, resist, protect	Actuate, regulate, change, guide, indicate, stop, position or inhibit
	Reaction is now external	Emit	Export

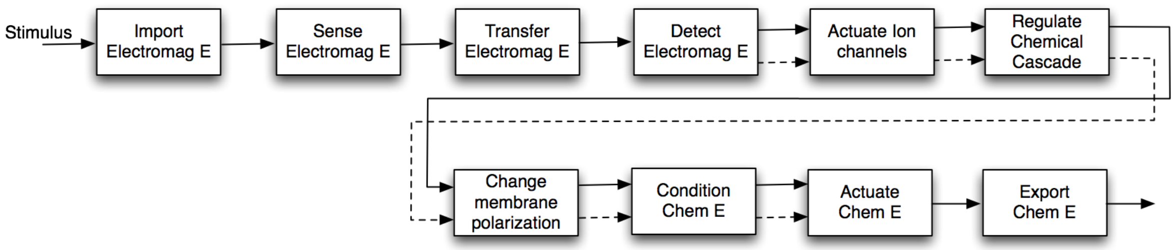

Figure 3: Functional Model of Plantae Photoreception, Cellular Level

When using the Functional Basis for the conceptualization of biomimetic sensor designs, the designer begins by defining the purpose of the sensor using methods outlined in [1, 3, 31, 32]. Examples of defining functionality for biomimetic and non-biomimetic conceptual designs can be found in [33]. Once the desired functionality is known, a conceptual functional model is created, which describes the basic functionality of the unrealized product. To correlate functions with components, automatic concept generator software [34] searches the design repository for biologogical strategies and organisms that solve the desired functions. Concept generation results in several viable conceptual design variants as a mixed set of engineering components and/or biological phenomena for each function-flow pair of the conceptual functional model. The designer must then decide if the biological system(s) that solve the desired functions are beneficial to use for design inspiration. Directly copying the natural system may be sufficient, however when it is not, analogical reasoning may be employed to make a decision. The complete method of conceptual biomimetic sensor design, including an example, can be found in [31].

7 CONCLUSION

Classification of natural solutions by basic engineering functions enables knowledge transfer from biology to the engineering domain. Utilizing functional representation to describe biological systems presents the biological information in an engineering context. Thus, biological systems are made accessible to engineering designers with varying backgrounds of biological knowledge, but a common understanding of engineering design methods. The Functional Basis modeling language has shown to facilitate the transfer of knowledge between biology and engineering, by translating the biological information into familiar engineering terms. Also, the Functional Basis correspondent terms played a critical role in the process of choosing engineering functions that best represent biological systems. Functional representation of biological systems has many inherent properties, such as, archival of analogous systems, sub-systems and components between the two domains, which supports knowledge based design. It allows engineers to capture biological functionality at multiple levels (scales) and use those varying level models to best serve engineering design.

Through the process of this research it was realized that functions are not difficult to correlate between the biology and engineering domains. Although the concept of flow was generalized in this paper, it was observed that biological flows are commonly difficult to cipher, thus, a working set of biological correspondent terms were developed to aid in the process of functional representation [35].

The processes of Animalia chemoreception and Plantae photoreception were presented from the biology and engineering viewpoints, allowing one to comprehend the similarities between the two domains. Furthermore, the knowledge gained through exploring the process of sensing in the Animalia and Plantae Kingdoms afforded functional models of natural sensing [31], independent of environment or time. The generalized natural sensing functional models served as design inspiration for conceptual sensor designs by guiding the designer to a pertinent biological topic, which provides a starting point for mimicry in engineering designs.

Utilization of engineering design tools such as functional models with biological systems allows designers to incorporate unique biological features into designs through automated concept generation and analogous component matching. In this case, promoting the development of innovative biomimetic sensor technology. The resultant information from this study serves as a guide to engineers with limited biological knowledge for leveraging unique biological designs through systematic design techniques. Biology contributes a whole different set of tools and ideas that a design engineer wouldn't otherwise have. Therefore, we believe future designs inspired by biology will be simple, use less materials, and have a life-cycle comparable to natural systems.

8 FUTURE WORK

Biological Kingdoms that are not as well known to engineers could be explored for unique functionality. The Eubacteria Kingdom consists of bacteria, which are unicellular microorganisms. Bacteria are interesting because they have several different morphologies that fulfill the same purpose. The Fungi Kingdom contains various types of fungus that are invisible to the human eye and those that are closely related to plants and animals such as mold, yeast and mushrooms. An interesting and less known Kingdom is the Protista Kingdom. It is comprised of a diverse group of microorganisms whose cells are organized into complex structures enclosed by a membrane, without specialized tissues, which are unclassifiable under any other Kingdom. The Protista Kingdom has animal, plant and fungus like organisms, of which, exhibit characteristics familiar to organisms in other Kingdoms.

Functional modeling has shown successful for transferring biological knowledge to the engineering domain by focusing on functionality. Biological processes, natural sensing as a whole and various biological phenomena and organisms have been modeled. The investigative work in this study could be extended to other specific areas of biology, such as motors or energy harvesting. Developing biological correspondent terms for the Functional Basis function set to compliment the biological flow correspondent terms would further reduce confusion when modeling biological systems.

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