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Modeling the Cellular Level of Natural Sensing with the Functional Basis for the Design of Biomimetic Sensor Technology

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Abstract—After surveying biology for natural sensing solutions six main types of extraneous sensing were identified across the biological kingdoms. Natural sensing happens at the cellular level with receptor cells that respond to photo, chemo, eletro, mechano, thermo and magnetoreceptor-type stimuli. At the highest level, all natural sensing systems have the same reaction sequence to stimuli: perception, transduction, and response. This research is exploring methods for knowledge transfer between the biological and engineering domains. With the use of the Functional Basis, a well-defined modeling language, the ingenuity of natural sensing can be captured through functional models and crossed over into the engineering domain, for design or inspiration. Furthermore, a morph-matrix that lists each component in the model can easily compare and contrast the biological and engineering design components, effectively bridging the two design domains. The six main types of receptor families were modeled for the Animalia and Plantae Kingdoms, from the highest to the 4th sub-level, with emphasis on the transduction sequence. To make the biological sensing models accessible to design engineers they were placed in the Missouri University of Science & Technology Design Repository as artifacts. The models can then be utilized for concept generation and biomimetic design through searching the design repository by functional characteristics. An example of a biomimetic navigation product based on the principle of electric fish is provided to illustrate the utilization of the natural sensing models, morph-matrices and design repository.

Index Terms — Biomimicry, Sensing, Design Methodology, Bioelectric Phenomena

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I. INTRODUCTION

Optimized designs found in nature are simple, yet multi-functional. Biomimicry, imitating nature to solve human problems, is receiving wider attention in the engineering community and biological phenomena are motivating new products. Phenomena at the macro and micro levels have inspired new materials, antibiotics, adhesives, sensing, and methods for cleaning to just name a few [1,2]. However, engineering designers typically do not recall and fully understand the principles governing the biological phenomena to readily apply them directly to design. Thus, several methods for bridging the biological and engineering design domains have come into fruition, which is the focus of this research.

Several approaches to the knowledge transfer between biology and engineering design domains are already underway. Searchable databases filled with biological phenomena and engineering solution entries [3,4] allow designers to search by function-behavior-structure or by choosing a verb-noun-adjective set with the goal of inspiring, rather than solving the problem directly. Rigorous methods that result in direct solutions include keyword searching a corpus and functional modeling. Work by Vikalli and Shu [5, 6] and by Chiu and Shu [7] show a successful strategy using word collocation for keyword searching a natural language corpus, in this case a biology textbook. Using Wordnet, engineering terms are transformed into keywords that have a synonymous meaning, which are used for searching the biological corpus. This method resulted in a biomimetic solution now used in manufacturing with micro-parts [8]. Wilson and Rosen [9] utilize reverse engineering and a seven-step method for abstracting a domain unspecific model of a biological system, which is used for idea generation.

Also using reverse engineering and resulting in a direct solution is functional modeling coupled with morph-matrices.

Core functionality of a system is extracted and functions and flows are visually modeled, of which, analogous engineering components for each are compiled in matrix form [10]. Tinesly et al. [11] explored the use of functional models for biomimetic conceptual design and determined that the Functional Basis, a well-defined modeling language [12], successfully transferred biological phenomena into the engineering domain.

The purpose of this paper and research is to continue to explore the transfer of knowledge from biology to engineering through utilization of functional modeling and the Functional Basis, on the micro level, specifically with how sensing occurs within natural systems. The work presented herein is exploratory and will not be measured by quantitative means; rather it will be evaluated on qualitative merit. The following sections introduce uncommon terms used in this paper; discuss functional decomposition, natural sensing and concept generation; and provide an illustration of concept generation and how natural sensing can contribute to engineering design.

II. NOMENCLATURE

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

Biomimcry - a design discipline devoted to studying nature's best ideas and imitating these designs and processes to solve human problems.

Functional Basis - a well-defined modeling language comprised of function and flow sets at the class, secondary and tertiary levels. A function represents an action being carried out, where as a flow represents what type of material, signal or energy is performing the function.

Functional Model - a visual description of a product or process in terms of the elementary functions that is required to achieve its overall function or purpose.

Design Repository - a web-based repository used to store design knowledge, which includes descriptive product information, functionality, components, and functional models for 113 consumer products and 14 biological phenomena.

Function-Component Matrix - a binary matrix with product components designated by columns with functions designated by rows. Cells marked with a "1" indicate that the product performs the function.

Design Structure Matrix - a matrix in which rows and columns represent the set of components within a product. Here the DSM represents all products within the Design Repository. Cells marked with a "0" indicate that the two components do not interact within the system.

Transduce or Transduction - the transformation of sensory stimulus energy into a cellular signal that is recognized by the organism.

III. FUNCTIONAL DECOMPOSITION

Among the methods available for generating engineering designs and concepts, functional decomposition has been chosen for this research. Biological organisms operate in much the same way that engineered systems operate [13], each

part or piece in the overall system has a function, which provides a common ground between the two domains. For the sake of philosophical argument, it is assumed that all the biological phenomena and organisms in this study have intended functionality. Functional decomposition provides several advantages for engineering design [14-17]:

- Systematic approach for establishing functionality
- Comparison of product functionality
- Creativity in concept generation
- Archival and transmittal of design information
- Product architecture development

Functional decomposition is preferred for biological phenomena and organisms because it is impractical to match a comparable engineering component to each piece of the biological system. However, matching functionality to an engineering component is a manageable and worthwhile task, which is reinforced by the example in Section VI.

IV. NATURAL SENSING

After surveying biology for natural sensing solutions six main types of extraneous sensing were identified across the biological kingdoms. Natural sensing happens at the cellular level with receptor cells that respond to photo, chemo, electro, mechano, thermo and magnetoreceptor type stimuli. At the highest level, all natural sensing systems have the same reaction sequence to stimuli: perception, transduction, response [18]. Table 1 compares the biological terms to the equivalent Functional Basis terms. All Functional Basis terms, definitions and examples can be found in [19].

Table 1. Comparison of Biological and Engineering Domain Terms.

Biological Term	Functional Basis Term
Perceive	Sense
Transduce	Convert, Transform
Respond	Regulate

The reaction sequence to stimuli, represented as a functional model using Functional Basis terms, can be seen in Figure 1. Energy represents the stimuli type that enters the modeled system, which can be mechanical, chemical, electrical, thermal, magnetic or electromagnetic (solar). Figure 2 depicts the second level of functionality by expanding the transduction (convert) block and showing its sub-functions, for the Animalia Kingdom only. Table 2 further clarifies what the Functional Basis terms are describing at the second level in the biological system. Third and fourth levels of functionality, Figures 3 and 4 respectively, represent the intricate detailed actions that occur during sensing for creatures of the Animalia Kingdom. The Animalia and Plantae Kingdoms are the chosen biological systems of this study and are very similar when it comes to sensing.

Creatures of the Animalia Kingdom take in stimuli as energy and convert (transduce) it into electrical signals

through amplification, which can be interpreted through their intelligence, where as, foliage of the Plantae Kingdom convert stimuli into chemical signals. All Plantae Kingdom functional models are the same as Animalia Kingdom models, but do not contain the discrimination block(s), as show in Fig. 5-7, as foliage is not intelligent. Furthermore, the fourth level model for the Plantae Kingdom only differs for amplification. The functional models of the Animalia and Plantae Kingdoms were entered into the web-based design repository, designed at the Missouri University of Science & Technology (Missouri S&T) (formerly University of Missouri-Rolla), for use with the Missouri S&T developed concept generation tools.

V. CONCEPT GENERATION

The Missouri S&T design repository, which includes descriptive product information such as functionality, component physical parameters, manufacturing processes, failure, and component connectivity, now contains detailed design knowledge on over 113 consumer products and 14 biological phenomena. Design tools like function-component matrices (FCMs) and design structure matrices (DSMs) can be readily generated from single or multiple products/phenomena and used in a variety of ways to enhance the design process. The concept generator used in this research is based on an algorithm that utilizes the Functional Basis and the design repository to generate and rank viable conceptual design variants [10]. This tool is intended for use during the early stages of design to produce numerous feasible concepts utilizing engineering component relationships as found in the design repository. Starting with a conceptual functional model a functional matrix, binary matrix indicating forward flows, is created and imported into the concept generator. The algorithm processes the input and returns a mixed set of engineering components and/or biological phenomena for each function-flow pair of the functional matrix. The designer chooses from the resulting concept generator suggestions, and inserts them into a morphological matrix for comparison to other designs or chooses as the final design components. All tools mentioned in this section are located at: <http://function.basiceng.umn.edu/delabsite/repository.html>.

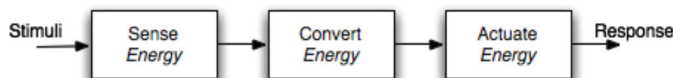


Fig.1 Functional Model of Reaction Sequence to Stimuli.

Table 2. Comparison of Second Level Terms.

Biological Term		Functional Basis Term
Perceive		Sense
Transduce	Detect	Detect
	Amplify	Amplify, Increment
	Discriminate	Process
	Adapt	Condition
Respond		Regulate

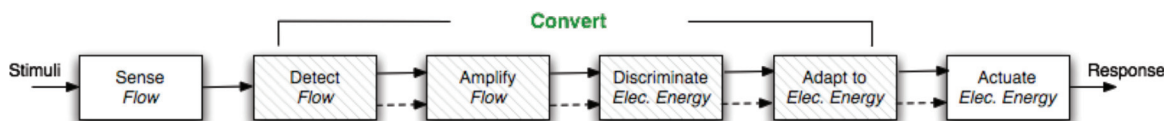


Fig.2 Animalia Kingdom Second Level Functional Model of Sensing

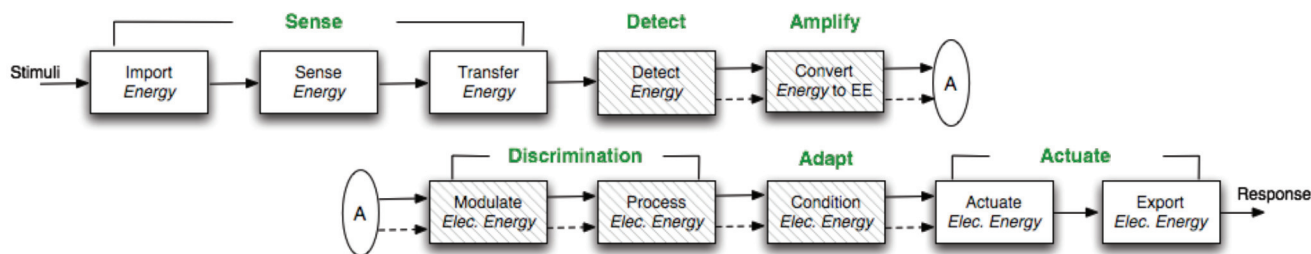


Fig.3 Animalia Kingdom Third Level Functional Model of Sensing

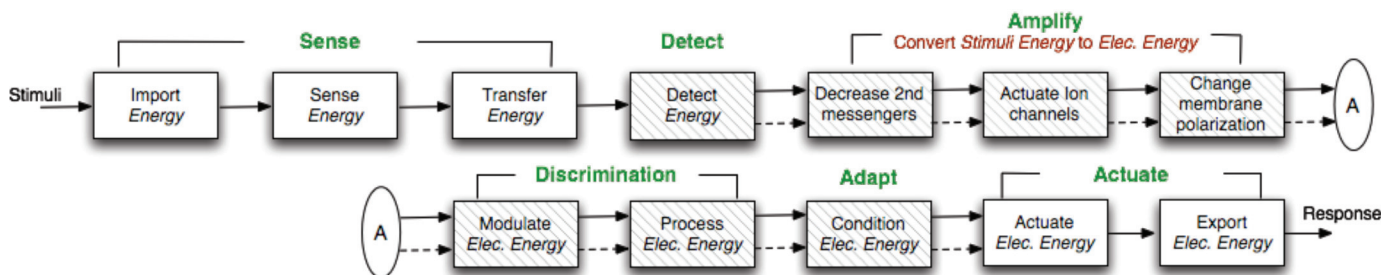


Fig.4 Animalia Kingdom Fourth Level Functional Model of Sensing

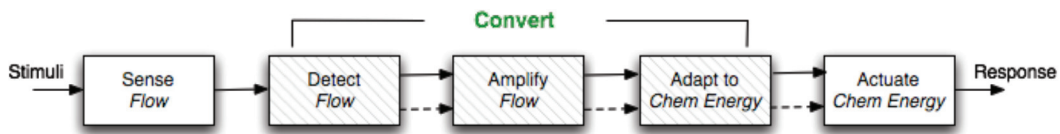


Fig.5 Plantae Kingdom Second Level Functional Model of Sensing

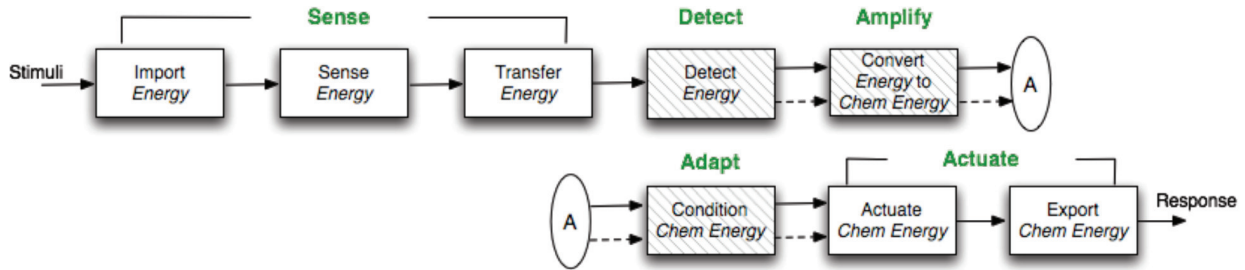


Fig.6 Plantae Kingdom Third Level Functional Model of Sensing

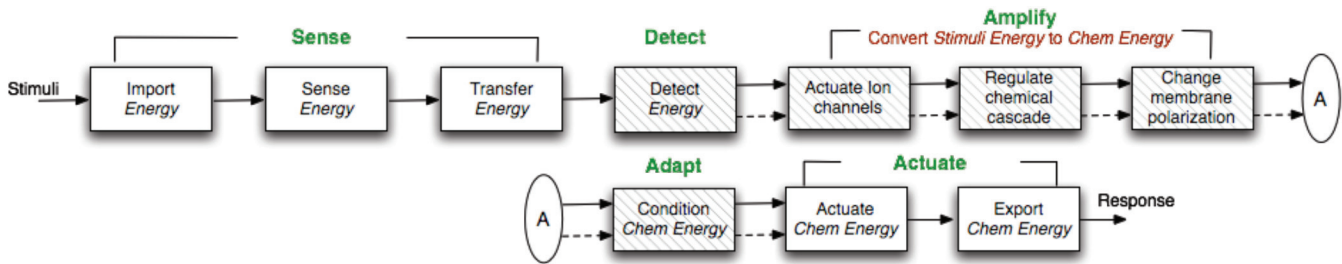


Fig.7 Plantae Kingdom Fourth Level Functional Model of Sensing

VI. EXAMPLE

To illustrate the aforementioned design tools and how biological phenomena can be utilized within engineering design, an example of a navigation product is presented.

Figure 8 shows the conceptual functional model of the navigation product, which explains the ideal core functionality and how it will interact with the surrounding environment. A functional matrix of the conceptual functional model is shown in Figure 9, and an FCM and DSM (not shown) of all repository entries are created via the repository website. These three matrices are chosen within the concept generator, processed and display sets of feasible components for each function within the functional matrix. Part of the concept

generator result window is displayed in Figure 10. This image demonstrates that Animalia electroreceptors and sensors can detect solid objects, according to what is in the repository.

Electric fish use passive electrical pulses to create a mental image of their surrounding environment. This phenomenon of electrolocation, via electroreceptors in an electric organ, is the functionality to be modeled [20,21]. To move the navigation product from conceptual design to biomimetic technology, the morphological matrix in Table 3 was designed. The phenomenon of electroreception was analyzed to compare electric fish to an auto generated concept variant. It can be seen that the components are very different, but mimicking the functionality of biological phenomena is highly probable.

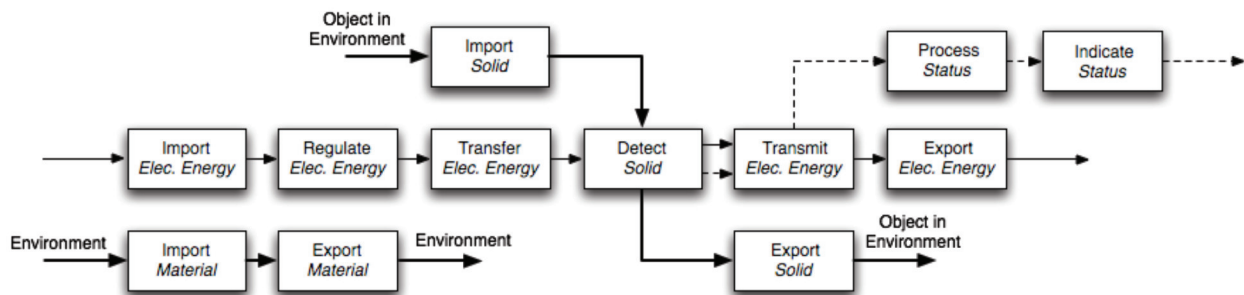


Fig.8 Conceptual Functional Model of Navigation Product

	import electrical energy	import solid material	regulate electrical energy	transfer electrical energy	detect solid material	transmit electrical energy	export electrical energy	import material	export material	process status signal	indicate status signal	export solid material
import electrical energy	0	1	1	0	0	0	0	0	0	0	0	0
import solid material	0	0	0	0	1	0	0	0	0	0	0	0
regulate electrical energy	0	0	0	1	0	0	0	0	0	0	0	0
transfer electrical energy	0	0	0	0	1	0	0	0	0	0	0	0
detect solid material	0	0	0	0	0	1	0	0	0	0	0	1
transmit electrical energy	0	0	0	0	0	0	1	0	0	1	0	0
export electrical energy	0	0	0	0	0	0	0	0	0	1	0	0
import material	0	0	0	0	0	0	0	0	1	0	0	0
export material	0	0	0	0	0	0	0	0	0	0	0	0
process status signal	0	1	0	0	0	0	0	0	0	0	1	0
indicate status signal	0	0	0	0	0	0	0	0	0	0	0	0
export solid material	0	0	0	0	0	0	0	0	0	0	0	0

Fig.8 Functional Matrix of Navigation Product

VII. CONCLUSION

Exploring the use of functional decomposition with biological organisms and phenomena has lead to an interesting way of incorporating the elegance of nature into engineering design concepts. The biological functional models in this research were applied to sensor technology development.

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 the same functions. The Functional Basis can model micro-scale biological functionality and successfully transfer biological designs to the engineering domain without losing abstract functionality. Additionally, the concept generation tools and web-based design repository can successfully incorporate biological organisms and phenomena. An example of a navigation product was presented to illustrate how design tools and biological phenomena can be utilized within engineering design. The method presented within this paper provided a structured engineering design methodology and a direct solution to the problem, which can only improve as more biological phenomena and consumer product entries are put into the design repository.

VIII. FUTURE WORK

Improving the succession rate of biomimetic sensor conceptual designs will largely depend on how many biological entries are available in the Missouri S&T design repository. More biological entries are planned, such as whole organisms, parts of organisms and biological strategies. A quantitative study analyzing the hypothesis of product component reduction in biomimetic sensors as compared to their non-biomimetic counterparts should be investigated. This work could be extended to other areas of design.

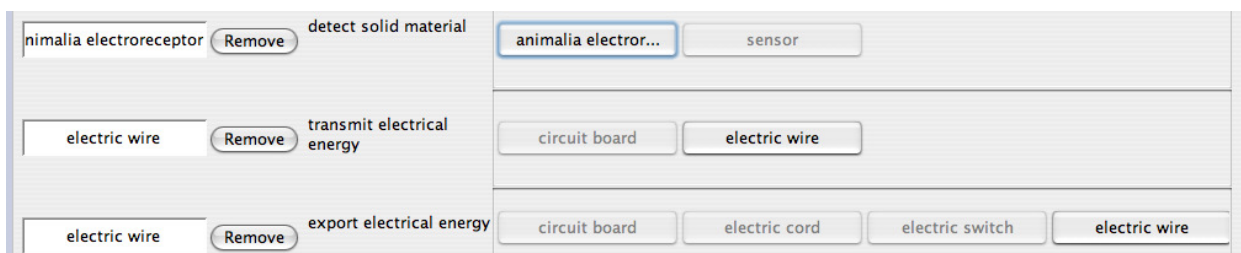


Fig.9 Snippet of Concept Generation Tool Software

Table 3. Morphological Matrix for Navigation Product

Function – Flow Pairs		Primary Function	Components	
Biological Solution	Engineering Solution		Biological Solution	Engineering Solution
Import Elec. Energy	Import Elec. Energy	Import	Electrocytes	Battery
Regulate Elec. Energy	Regulate Elec. Energy	Regulate	Electromotor neurons	Circuit board
Transfer Elec. Energy	Transfer Elec. Energy	Transfer	Electromotor neurons	Electric wire
Actuate Elec. Energy	Actuate Elec. Energy	Actuate	Electric organ	Indicator light/display
Detect Solid Material	Detect Solid Material	Detect	Electroreceptors	Mimicked Animalia electroreceptors
Transmit Elec. Energy	Transmit Elec. Energy	Transmit	Electromotor neurons	Electric wire
Export Elec. Energy	Export Elec. Energy	Export	Electromotor neurons	Electric wire
Process Elec. Energy	Process Status	Process	Brain	Circuit board
Register Status	Indicate Status	Indicate	Brain	Indicator light/display
Register Status	Register Status	Register	Brain	Indicator light/display

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