Generating an Engineering to Biology Thesaurus To Promote Better Collaboration, Creativity and Discovery

J.K. Stroble[1], R.B. Stone[2], D.A. McAdams[3], S.E. Watkins[1]

[1]Electrical and Computer Engineering, Missouri University of Science and Technology, 1870 Miner Circle, Rolla, MO 65409, USA

j.k.stroble@ieee.org

[2]Interdisciplinary Engineering, Missouri University of Science and Technology, 1870 Miner Circle, Rolla, MO 65409, USA

[3]Mechanical Engineering, Texas A&M University, MS 1250, College Station, TX 77843, USA

Abstract

Biological inspiration for engineering design has occurred through a variety of techniques such as database searches, keyword and antonym searches, knowledge of biology, observations of nature and other “aha” moments. This research aims to alleviate the knowledge gap problem by providing a link between engineering and biology with a thesaurus. The biologically connotative terms that comprise the thesaurus were collected utilizing an organized verb-noun search; collocated words were extracted from texts based on a functional search word. This thesaurus should enable the engineering and biology communities to better collaborate, create and discover.

Keywords:

Engineering design, Function, Analogical reasoning

1 INTRODUCTION

The natural world provides numerous cases for analogy and inspiration in engineering design. From simple cases such as hook and latch attachments to articulated-wing flying vehicles, nature provides many sources for ideas. Though biological systems provide a wealth of elegant and ingenious approaches to problem solving, there are challenges that prevent designers from leveraging the full insight of the biological domain. A fundamental problem to effectively execute biomimetic designs is that the effort and time required to become a competent engineering designer creates significant obstacles to becoming sufficiently knowledgeable about biological organisms and phenomena (the converse can also be said). In an effort to bridge the gap between the engineering and biological domains, the creation of a partial thesaurus that will contain biologically connotative words related to engineering function and flow terms, is envisioned. This approach should enable the search for biomimetic solutions to engineering functions and aid with comprehension of biological material.

The purpose of a thesaurus is to represent information in a classified form to group related concepts. The engineering to biology thesaurus proposed here has a unique structure and classification; it is merged with the reconciled Functional Basis [1] as a set of correspondent terms. Thus, the classification is predetermined according to that of the authors’ model; however, it remains the intermediary between the biology and engineering domains. A tool such as the biology to the engineering thesaurus increases the interaction between the users and the knowledge resource [2].

In the following sections several points will be discussed: (1) the nomenclature of function based design; (2) the related work and research efforts (3); the model for designing the thesaurus structure; (4) the method used to populate the thesaurus; (5) the implications such a thesaurus has on the engineering and biology communities; and (6) two example applications of the engineering to biology thesaurus.

2 NOMENCLATURE

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

Biologically connotative term – a word that will appear in a biological text and not an engineering text.

Biological phenomena – a biological fact or situation that is observed to exisit or happen.

Corpus – a collection of written material in machine-readable form, assembled for the purpose of studying linguistic structures.

Flow – refers to the type of material, signal or energy that travels through the sub-functions of a device.

Function – refers to an action being carried out on a flow to transform it from an input state to a desired output state.

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.

3 BACKGROUND AND RELATED WORK

3.1 Function based design

Design specifications and requirements set by a customer, internal or external, influence the product design process by providing material, economic and aesthetic constraints on the final design. In efforts to achieve the customer’s needs without compromising function or form, function based design methodologies have been researched, developed and evolved over the years. Most notable is the systematic approach of Pahl and Beitz [3]. Since the introduction of function structures, numerous functional modeling techniques, product decomposition techniques and function taxonomies have been proposed [4-7].

The original list of five general functions and three types of flows developed by Pahl and Beitz [3] were further evolved by Stone, *et al.* into a well-defined modeling language comprised of function and flow sets with definitions and examples, entitled the Functional Basis [8]. Hirtz, *et al.* later reconciled the Functional Basis and NIST developed taxonomy into its most current set of terms [1]. The reconciled Functional Basis is utilized for developing hierarchical functional models, which describe the core functionality of products and processes in domain independent function and flow terms. Branching from the Functional Basis efforts is the lexical-analysis-based approach to function based design by Fantoni *et al.* [9]. By utilizing synonyms and antonyms of desired functions and exploring changes in flow, this method claims to convert each problem into an opportunity.

A functional reasoning method developed by Zhang et al. is the Behavior-driven Function-Environment-Structure (B-FES) modeling framework, which assigns function to behavior before function to physical structures [10]. This framework provides an opportunity to explore a wide variety of solutions based on behavior, without constraint set by function. Function/means tree is a hierarchal function based design method, which demonstrates the causal relationship between function and means at different levels [11]. Xu *et al.* utilize hierarchical function structures to create a non-numeric key element vector, of which, functional design knowledge is extracted for use with automated design synthesis [12]. Multi-objective optimization functions apply design constraints to extracted knowledge to produce design solutions.

3.2 Creativity in design

Creativity in engineering design is considered to have two distinct forms, novelty and usefulness. Thompson and Lordan explain this dichotomy as '[n]ovelty may take the form of something completely new or it may be a combination of existing ideas or products. For something to be creative it must satisfy a need, it must serve a purpose and it must make a positive contribution' [13]. According to Cross, the generation of creative thoughts, either satisfactory or not, can be described with four generalized models: analogy, combination, first principles, and emergence [14]. In regards to utilizing biological designs, research has shown that the use of analogy has been the most successful method in engineering design. Mak *et al.* [15] and Chakrabarti *et al.* [16] both demonstrate that creative, engineered solutions were inspired by their biological analogs, at varying levels of abstraction.

Several design-by-analogy methods have been developed and go beyond the formal design methods that just include analogies and metaphors within the design process. McAdams *et al.* takes a unique approach to design-by-analogy by utilizing a design repository of prior engineering solutions that includes information about product functionality [17]. A quantitative measure based on functional similarity is presented and validated through case studies. Also following a model based approach is the analogical design research by Bhatta *et al.* They explore analogies using two types of models: case specific, Structure-Behavior-Function models of physical devices and case independent, Behavior Function models of physical principles [18]. Hey *et al.* found that while 'metaphors and analogies in design … can enhance creativity and innovation' tools and methods that assist in the search process for suitable analogies are lacking [19]. To increase the likelihood of generating a design solution Hey *et al.* suggest reframing or creating multiple representations of the design problem. Through re-representation, multiple linguistic representations are created for key word searches in various databases, which result in a larger set of analogous solutions [19].

Goel reiterates the important application of analogies in his statement '[a]nalogical reasoning appears to play a key role in creative design' [20]. Although Goel was researching AI and concept generation software, he and all the aforementioned researchers have shown that the desirable consequence from analogical reasoning is creativity in design.

3.3 University of Toronto research effort

Researchers at the University of Toronto have recently worked to provide designers with biologically meaningful words that correspond to the Functional Basis functions. They analyzed the functions in the secondary, tertiary and correspondent levels to develop groups of words that were similar according to WordNet [21]. Biologically meaningful words were identified through a methodology developed by Chiu *et al.* [22] using bridge verbs - verbs that were modified by a frequently occurring noun - categorizing bridge verbs and screening match results. Four cases for identification are discussed and examples presented: synonymous pair, implicitly synonymous pair, biologically specific form and mutually entailed pair [21]. Based on semantic relationships, the engineering function terms of the Functional Basis were used to systematically generate a list of biologically significant and connotative keywords. A short list is shown in Table 1.

4 ENGINEERING TO BIOLOGY THESAURUS

The engineering to biology thesaurus presented in this paper was developed to enhance the reconciled Functional Basis by Hirtz *et al.* [1]. The structure of the thesaurus was molded to fit the knowledge and purpose of the authors; synonyms and related concepts to the Functional Basis are grouped at class, secondary and tertiary levels. In the paragraphs below, the thesaurus model and population method are explained followed by implications of a engineering to biology thesaurus.

4.1 Thesaurus model

Studies have shown that user feedback in the form of questions is the most important source for analyzing information needs [23]. In the authors' experience, correlating biological terms to the Functional Basis functions was not an issue. The authors' had the most difficulty understanding biological terms that were considered flow type (material, signal and energy) when utilizing biological organisms or phenomena for idea generation or design inspiration. Guessing if a biological material is liquid, solid or a mixture by its name generally resulted in a wrong choice, which made the biological concept perplexing. Similarly, needing a reference to look up biological terms each time a potential organism or phenomenon was found made the research tedious, and disrupted thought patterns leading to decreasedefficiency. Thus, flow correspondent terms were chosen for the first draft of the engineering to biology thesaurus, which can be seen in Table 2.

Functional Basis term	Convert	Mix	Transport	Store	Stabilize	Collect
Biologically meaningful term	Decompose	Exchange	Circulate	Deposit	Bind	Concentrate

Table 1: Short list of biologically connotative function words.

4.2 Population Method

Population of the engineering to biology thesaurus was achieved through functional word searches of a biological textbook that covers a broad range of topics, described as an organized verb-noun search. Chosen words were determined by their macrorelevancy, which is identified by frequency of use [2]. Functional Basis functions (verbs) were utilized for searching the biological textbook to extract biologically connotative words (nouns) that an engineering designer interested in function based design might encounter. Variations of the stem function word were not considered during the searches. For example, detect is the stem function word and the variations of this verb: detection, detects, detected, and detecting were not included in search results. The nouns that were collocated, within the sentence, to the search word were counted and sorted by frequency and all nouns that appeared more than two times were considered macrorelevent. Each macrorelevent term was researched to determine if it was of signal, material or energy type in the new Oxford American dictionary [24] and Henderson's dictionary of biological terms [25] before being placed. Placement of terms in the thesaurus was at the discretion of the authors and trite, domain independent terms were dismissed from the engineering to biology thesaurus.

4.3 Implications on Biological and Engineering Communities

The engineering to biology thesaurus was generated with the intention of promoting collaboration between the biology and engineering domains, resulting in discovery of creative, novel ideas. The following paragraphs describe plausible applications of the presented thesaurus. However, with few boundaries in the field of design, this thesaurus could be employed in ways the authors' have not considered.

Comprehension

The engineering to biology thesaurus has the potential to aid engineering designers with the comprehension of biological contexts by substituting Functional Basis terms for commonly used biological words. Lopez-Huertas wrote that a thesaurus "…is thought of as a way of easing communication between texts and users in order to increase the interaction in information retrieval, and thus facilitate information transfer" [2]. Achieving efficient information retrieval through a thesaurus allows an engineering designer to cross into the biological domain to gain functional knowledge, without becoming overwhelmed by biological organisms and phenomena.

Searching for biological inspiration

Searching a natural-language corpus for biological inspiration based on engineering functionality or using engineering terms typically produces results that are mixed. Hits that contain the search words often use them out of context or in a different sense then the designer intended. By utilizing the biologically connotative flow terms with desired functionality, search results improve and become more focused on biological systems.

Functional modeling of biological systems

The engineering to biology thesaurus provides direction when choosing the best suited flow term to objectively model a biological system. Functional modeling of biological systems allows representation of solutions to specific engineering functions and direct knowledge discovery of the similarities and differences between biological and engineered systems as viewed from a functional perspective. The creation of engineered systems that implement strategies or principles of their biological counterparts without reproducing physical biological entities is another benefit to biological functional models.

Collaboration, creation, discovery

Terms contained within the engineering to biology thesaurus can be utilized to discover biological analogs to existing engineered systems and visa versa. Analogical reasoning often requires an interdisciplinary team to ensure the analogy is properly represented, whatever the mix of domains. Exploration of biomimetic designs prompt collaboration between biology and engineering researchers.

5 EXAMPLE APPLICATION

In this section, two examples utilizing the engineering to biology thesaurus are presented. A simple translation of the phenomenon abscission is presented first to demonstrate how this thesaurus can aid with comphrehension. Second, a comprehensive example is given regarding the method of sensing within bacteria; signal transduction occurs to alert the bacteria of stimuli via a two-component regulatory system [26].

5.1 Simple Translation

A text excerpt describing abscission is presented in its original form and in a "translated" form using the term relationships established through the engineering to biology thesaurus. The phenomenon of abscission exerpt is taken from the biology textbook *Life, The science of biology* [27].

'In many species, leaves senesce (deteriorate because of aging) and fall at the end of the growing season, shortly before the onset of the severe conditions of winter. Leaf fall (abscission) is regulated by an interplay of the hormones ethylene and auxin. Finally, the entire plant senesces and dies.

The effect of auxin on the detachment of old leaves from stems is quite different from root initiation. This process, called abscission, is the cause of autumn leaf fall. Leaves consist of a blade and a petiole that attaches the blade to the stem. Abscission results from the breakdown of a specific part of the petiole, the abscission zone. If the blade of a leaf is cut off, the petiole falls from the plant more rapidly than if the leaf had remained intact. If the cut surface is treated with an auxin solution, however, the petiole remains attached to the plant, often longer than an intact leaf would have. The time of abscission of leaves in nature appears to be determined in part by a decrease in the movement of auxin, produced in the blade, through the petiole.'

The translated version of the text exerpt:

In the fall season, leaves of plants indicate a status signal to humans shortly before the onset of severe winter conditions. Leaf fall referred to as abscission is regulated by the interplay of liquid material and liquid-liquid mixture materials internal to the plant. The effect of the liquid material auxin on the detachment of old leaves from stems is quite different from root initiation. Leaves which are material-solid-objects utilize a material-solid-object called a petiole, which attaches the blade to the stem (also a material-solid-object). The abscission zone is where the material-solid-object petiole detaches from the material-solid-object stem. Separation is the main function of this phenomenon. Separation can be deterred with the material-liquid auxin, which is created in the blade of the leaf. The time of the status signal offered by plants, death or all leaves abscise, appears to be determined in part by a decrease in a particular material-liquid flowing through plant leaves.

Class (Primary)	***Secondary***	***Tertiary***	***Biological Correspondents***
Material	Human		Being, body
	Gas		Oxygen, nitrogen, chlorine
	Liquid		Acid, chemical, water, concentration, solute, cytokinin, pyruvate, fluid, nicotine, auxin, opium, glycerol, carotenoid, plasma, repressor
	Solid	Object	body, substrate, microfilament, microtubules, structure, DNA, motor, fiber, chain, matter, nucleus, organ, tissue, muscle, ligand, cilia, gtp, flagella, RNA, tRNA, mRNA, tube, vein, heart, plant, ribosome, seed, apoplast, endotherm, ectotherm, stem, kidney, egg, ovaries, leaves, embryo, bacteria, gene, oncogene, cryptochromes, urea, chloroplasts, carbon, glucagons, adipose, angiosperm, meristems, mineral, stoma, shoot, capillary, receptors, hair, bone, tendon, neuron, photoreceptors, mechanoreceptors, host, chromosome, algae, petiole, promoter, phyla, lysosome, introns, exon, archaea, allele, cone, strand, centriole, spore, euryarchaeota, sporangia, zygote, sulfur, ctenophore, lipoproteins, stp, nephron, hyphae, plasmodesma, angiosperms, conifer, plasmid, xylem, pigment, hippocampus, somite, parathormone, sperm
		Particulate	
		Composite	Molecule, enzyme, virus, phloem, ribozyme, prokaryote, macromolecule, polymerase, nucleotide, polypeptide, organelle, symplast, mesophyll, brood, codon, messenger
	Mixture	Gas-gas	Air, dioxide
		Liquid-liquid	Solution, poison, slime, blood, urine, cytoplasm, peptide, hormone, melatonin, thyroxine, calcitonin, thyrotropin, estrogen, somatostatin, cortisol, glucagons, adrenocrticotropin, testosterone
		Solid-solid	Adenosine, glial, glomerulus, blastula, monosaccharides, membrane mulch, phosphate, gibberellin, plastids
		Solid-Liquid	Lipids, glutamic acid, synapse, peptidoglycan, cell, centrosomes, phytochrome, retina, insulin, protein, hemoglobin
		Liquid-Gas	
		Solid-Gas	
		Solid-Liquid-Gas	
		Colloidal	
Signal	Status		Change, variation, lateral, allosteric, swelling, catalyzes, translation, exposed, active, separated, cycle, form, reaction, redox, deficiency, saturated, diffusion, broken, vicariant, hybridization, orientation, resting, cues, magnetic, volume, under, organized, fruiting, fatty, anaphase, metaphase, conjugation, osmolarity, senescence
		Auditory	Sound
		Olfactory	Smell
		Tactile	Cold, pain
		Taste	Gustation
		Visual	Length, shortened, long, dark, full, double
	Control		Place, inhibit, release, excretory, development, match, inducer, digest, integrate, translation, transduction, equilibrium, grown, splicing, capture, distributed, prophase, phosphorylation
		Analog	Flowering, center, synthesis, binding, photosynthesis
		Discrete	Flower, translocation
Energy	Human		
	Acoustic		Echolocation, waves
	Biological		Blood, glucose, gibberellins
	Chemical		Calorie, metabolism, glucose, glycogen, ligand, nutrient, starch, fuel, sugar, mitochondria, synthesis, o, lipids
	Electrical		Electron, potential, q, feedback, charge, fields
	Electromagnetic	Optical	Light, infrared
		Solar	Light, sun, ultraviolet
	Hydraulic		Pressure, osmosis, osmoregulation
	Magnetic		Gravity, fields, waves
	Mechanical		Muscle, pressure, tension, removing, stretch, depress
		Rotational	
		Translational	
	Pneumatic		Pressure
	Radioactive/ Nuclear		
	Thermal		Temperature, heat, infrared
Overall increasing degree of specification ➔			

Table 2: Engineering to biology thesaurus.

Analyzing the biological phenomena with engineering terms allows engineers to look at the phenomena of abscission as the separation of solid materials due to liquid materials, disregarding specifics. By not confining the design space, the designer captures the underlying principle of the biological phenomena, which increases the interaction in information retrieval and facilitates information transfer between the domains.

5.2 Functional Modeling and Analogical Reasoning

In effort to demonstrate the versatility of the engineering to biology thesaurus a comprehensive example exploring the use of signal transduction in engineering design is considered next. A majority of biomimetic designs have been modeled after physical biological phenomena that can be observed, meaning direct imitations of biology, and are represented in mechanical, civil and architectural designs [28-30]. Direct mimicry has also lead to two biomimetic designs based on the fly. A elementary motion detector chip based on the physiology of the common house fly was developed, which includes a photoreceptor circuit integrating each ommatidia of the compound eye and signal processing circuit to simulate the wide field motion sensitive neurons found in flies [31]. Second, artificial compound eyes developed by polymeric synthesis self-align to transmit light to a CMOS sensor array [32]. Mimicking unseen phenomena, such as activity on the cellular level, is more difficult as biological terminology becomes narrow and requires more knowledge of the subject. This example is a qualitative measure of the engineering to biology thesaurus.

The topic of signal transduction in prokaryotes explains how bacteria sense their environment for survival. Bacteria respond to nutrients, synthesizing proteins involved in uptake and metabolism, and non-nutrient signals both physical and chemical [26]. Signaling pathways in bacteria consist of modular units called transmitters (sensor proteins) and receivers (response regulator proteins), which comprise the two-component regulatory system (TCRS). Example bacterial processes that are controlled by TCRS are chemotaxis, sporulation and osomoregulation.

Tiaz and Zeiger explain bacteria employ TCRS to sense extracellular signals as the following. ‘Bacteria sense chemicals in the environment by means of a small family of cell surface receptors, each involved in the response to a defined group of chemicals (hereafter referred to as ligands). A protein in the plasma membrane of bacteria binds directly to a ligand, or binds to a soluble protein that has already attached to the ligand, in the periplasmic space between the plasma membrane and the cell wall. Upon binding, the membrane protein undergoes a conformational change that is propagated across the membrane to the cytosolic domain of the receptor protein. This conformational change initiates the signaling pathway that leads to the response.’ - [26]

Figure 1 provides a visual representation of the sensing process; (A) Defining cellular boundaries and substances present in bacteria ; (B) Conformational change sends a signal to cytosolic domain triggering the transmitter to release protein phosphate; (C) phosphate binds to the reciever initiating the output response.

To utilize TCRS with function based design, a functional model of the method shown in Figure 1 is given in Figure 2. Ligans are found in the thesaurus under material-solid-object and energy-chemical. In the case of TCRS, ligands are utilized as chemical signals, thus chemical energy was the chosen flow. Bacterium, the singluar form of bacteria, is listed as a material-solid-object in the thesaurus because a prokaryote cell does not have a well defined nucleus. Binding of ligand to the protein is captured with the *join chemical energy and solid material* function flow pair. After coupling, detection of the stimulus signal occurrs, which is propagated to the cytosolic domain, releasing protein phosphate. A signal pathway is now established, which regulates the chemical energy within the bacterium to produce a response. The two components of TCRS are transmitter and receiver proteins, however, from a functional stand point chemical energy is needed to couple with and change the bacterium material to elicit a response. This abstraction of TCRS can now be utilized for analogical reasoning.

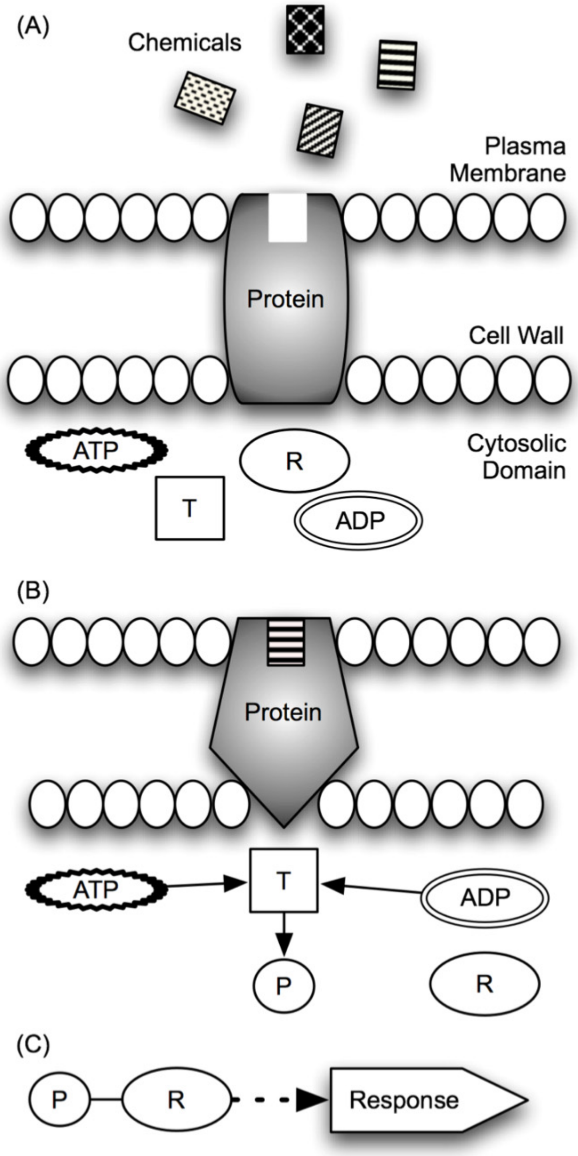

Figure 1: Method of sensing extracellular signals with TCRS in bacteria.

Engineered systems that mimic TCRS are wireless entry devices, such as a garage door opener or an automobile key fob. The handheld switch sends electrical energy in the form of a wireles signal to join with the reciever in the solid material, once detected electrical energy is regulated to open the door with the solid material changing position. It is not required to design strictly using the flows recognized in the biological system with analogical reasoning. Rather, adhering to the biological phenomena abstraction is most important. Although this example utilizes reverse engineering to match a biological system to an existing engineered system, engineering designers can utilize, the functional model of the

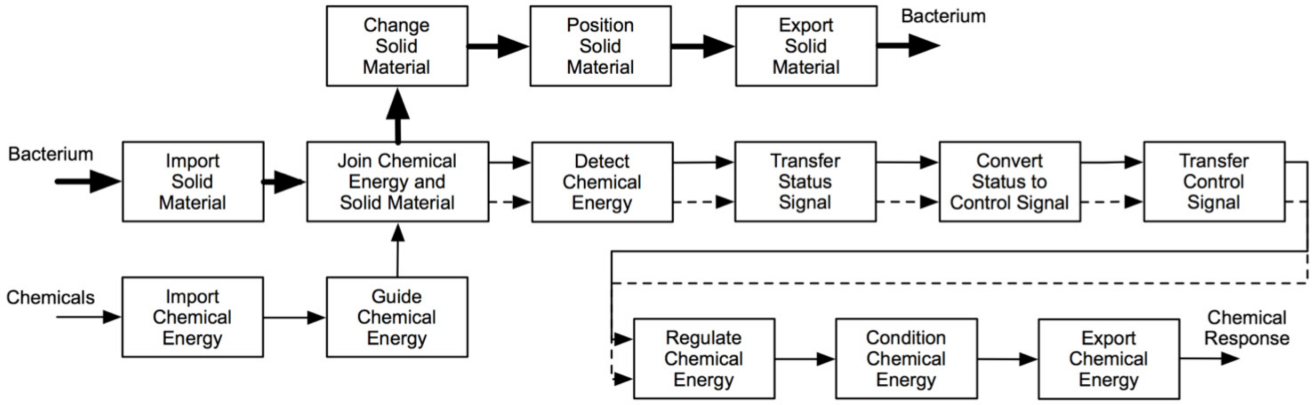

Figure 2: Functional Model of TCRS.

biological phenomena to develop conteptual designs of new products and processes.

6 CONLUSIONS

The natural world provides numerous cases for analogy and inspiration in engineering design. From simple cases such as hook and latch attachments to articulated-wing flying vehicles, nature provides many sources for ideas. Though biological systems provide a wealth of elegant and ingenious approaches to problem solving, there are challenges that prevent designers from leveraging the full insight of the biological domain. Biologically inspired or analogical designs require that designers have knowledge of previous design solutions during engineering design activities. The learned representations are organized at different levels of abstraction that facilitate the decomposition of design solutions, and allow analogs to be discovered with cues taken from each level. We presented a engineering to biology thesaurus that (1) allows designers to focus on becoming a competent engineering designer; (2) lessens the burden when utilizing knowledge from the biological domain by providing a link between engineering and biological terms; and (3) lists biologically connotative words that an engineering designer interested in function based design might encounter.

Through this research, flow type biologically connotative terms were mapped to engineering terms and placed into pre-detertmined classifications set by the Functional Basis structure. It was observed that the majority of biologically connotative terms can be grouped at the tertiary level, indicating the preciseness of terms in the biological domain. Several material type flow terms can be grouped as material-solid-object, material-solid-composite or material-mixture-liquid-liquid. Signal is more of a subjective flow classification as materials and energies can also act as signals, as shown with the TCRS example in section 5.2, within the biological domain. Therfore, most signal flow terms are grouped at the secondary level. The most populated secondary energy flow terms, with no surprise, was chemical energy. Many chemical substances provide energy, such as sugars or starches, which humans can relate to.

Breaking down a biological solution into smaller parts, based on functionality, allows one to liken a biological organism or phenomenon to an engineered system for ease of understanding and transfer of design knowledge. The biological correspondent terms that comprise the engineering to biology thesaurus were collected utilizing an organized verb-noun search that extracts collocated words from a biological text based on the stem search words from a biological text based on the stem search word alone. The first draft of the engineering to biology thesaurus and the method for compiling the terms were presented and discussed. Implications of the proposed thesaurus on the engineering and biology communities were explored. The thesaurus will enable the engineering and biology communities to better collaborate, create and discover through comprehension of concepts, functional decomposition and guidance for inspirational searches. Furthermore, the engineering to biology thesaurus is a subject domain oriented, intermediary structure, which can be updated as needs are identified.

7 FUTURE WORK

An immediate step towards improving the engineering to biology thesaurus would be reconciling the efforts performed by researchers at the University of Toronto and Missouri S&T. Including the biologically meaningful function words with the biologically connotative flow terms presented here would create a complete set of biological correspondent terms for the Functional Basis. To further strengthen the thesaurus, the population search method presented in Section 4.2 should be repeated to include variations of the stem function word. We predict this would lead to more results as biology textbooks are written in natural-language format and a longer list of biologically connotative flow terms.

Other design tools created at Missouri S&T could be updated to utilize the engineering to biology thesaurus presented in this paper. Specifically, an automated retrieval tool recently developed searches a user defined corpus using Functional Basis functions and subject domain oriented or Functional Basis flows. The search could be enhanced by cross referencing the user input search terms with the thesaurus and searching each possible combination of function and flow terms. The web-based repository of design information could possibly utilize the terms contained within the thesaurus to discover biological analogs to existing engineered systems. A similar type of “reverse engineering” prompted the discoveries made by Tinsley *et al.* [33], however, the web-based repository was not utilized in that research.

8 ACKNOWLEDGMENTS

This research is funded by the National Science Foundation grant DMI-0636411. A special thanks to the University of Toronto for allowing Missouri S&T to access to their website.

9 REFERENCES

[1] Hirtz, J., Stone, R., Mcadams, D., Szykman, S. and Wood, K., 2002, A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts, Research in Engineering Design, 13(2): 65-82.

[2] Lopez-Huertas, M.J., 1997, Thesarus Structure Design: A Conceptual Approach for Improved Interaction, Journal of Documentation, 53(2): 139-177.

[3] Pahl, G. and Beitz, W., 1996, Engineering Design: A Systematic Approach, 2 ed, Berlin; Heidelberg; New York, Springer-Verlag.

[4] Otto, K.N. and Wood, K.L., 2001, Product Design: Techniques in Reverse Engineering and New Product Development, Upper Saddle River, New Jersey, Prentice-Hall.

[5] Ulrich, K.T. and Eppinger, S.D., 2004, Product design and development, ed, Boston, McGraw-Hill/Irwin.

[6] Ullman, D.G., 2002, The Mechanical Design Process 3rd Edition, ed, New York, McGraw-Hill, Inc.

[7] Hundal, M., 1990, A Systematic Method for Developing Function Structures, Solutions and Concept Variants, Mechanism and Machine Theory, 25(3): 243-256.

[8] Stone, R. and Wood, K., 2000, Development of a Functional Basis for Design, Journal of Mechanical Design, 122(4): 359-370.

[9] Fantoni, G., Taviani, C. and Santoro, R., 2007, Design by functional synonyms and antonyms: a structured creative technique based on functional analysis, Proceedings of the I Mech E Part B: Journal of Engineering Manufacture, 221(6): 673-683.

[10] Zhang, W.Y., Tor, S.B., Britton, G.A. and Deng, Y.M., 2002, Functional Design of Mechanical Products Based on Behavior-Driven Function-Environment-Structure Modeling Framework, MIT Innovation in Manufacturing Systems and Technology (IMST), http://hdl.handle.net/1721.1/4031.

[11] Robotham, A.J., 2002, The use of function/means trees for modelling technical, semantic and business functions, Journal of Engineering Design, 13(3): 243-251.

[12] Xu, Q.L., Ong, S.K. and Nee, A.Y.C., 2006, Function-based design synthesis approach to design reuse, Research in Engineering Design, 17: 27-44.

[13] Thompson, G. and Lordan, M., 1999, A review of creativity principles applied to engineering design, Proceedings of the I Mech E Part E: Journal of Process Mechanical Engineering, 213(1): 17-31.

[14] Cross, N., Year, Creativity in design: not leaping but bridging, Creativity and Cognition, Loughborough University, Loughborough, 27-35.

[15] Mak, T.W. and Shu, L.H., 2008, Using descriptions of biological phenomena for idea generation, Research in Engineering Design, 19: 21-28.

[16] Chakrabarti, A., Sarkar, P., Leelavathamma, B. and Nataraju, B.S., 2005, A functional representation for aiding biomimetic and artificial inspiration of new ideas, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 19: 113-132.

[17] Mcadams, D. and Wood, K., Year, Quantitative Measures for Design By Analogy, Proceedings of DETC2000, Balitmore, MD.

[18] Bhatta, S., Goel, A. and Prabhakar, S., Year, Innovation in Analogical Design a Model-Based Approach, Third International Conference on Artifical Intelligence in Design (AID-94), Lausanne, Switzerland, 57-74.

[19] Hey, J., Linsey, J., Agogino, A.M. and Wood, K.L., 2008, Analogies and Metaphors in Creative Design, International Journal of Engineering Education, 24(2): 283-294.

[20] Goel, A., 1997, Design, analogy and creativity, IEEE Expert Intelligent Systems and Their Applications, 12(3): 62-70.

[21] Cheong, H., Shu, L.H., Stone, R.B. and Mcadams, D.A., 2008, Translating terms of the functional basis into biologically meaningful words, ASME Design Engineering Technical Conference, Design Theory and Methodology Conference, New York City, NY, Pages.

[22] Chiu, I. and Shu, L.H., 2005, Bridging Cross-Domain Terminology for Biomimetic Design, Proceedings of IDETC/CIE 2005, Long Beach, California, Pages.

[23] Dalrymple, P.W., 1990, Retrieval by reformulation in two library catalogs: toward a cognitive model of searching behavior, Journal of the American Society for Information Science, 41(4): 272-281.

[24] McKean, E., 2005, The new Oxford American dictionary, New York, Oxford University Press.

[25] Lawrence, E. and Holmes, S., 1989, Henderson's dictionary of biological terms, ed, New York, Wiley.

[26] Taiz, L. and Zeiger, E., 2006, Chapter 14: Gene Expression and Signal Transduction, in Plant Physiology, Sinauer Associates, Inc., Sunderland.

[27] Purves, W.K., Sadava, D., Orians, G.H. and Heller, H.C., 2001, Life, The Science of Biology, 6 ed, Sunderland, MA, Sinauer Associates.

[28] Brebbia, C.A., Sucharov, L.J. and Pascolo, P., 2002, Design and nature: Comparing design in nature with science and engineering, ed, Southampton; Boston, WIT.

[29] Brebbia, C.A. and Collins, M.W., 2004, Design and nature II: Comparing design in nature with science and engineering, ed, Southampton, WIT.

[30] Brebbia, C.A. and Technology, W.I.O., 2006, Design and nature III: Comparing design in nature with science and engineering, ed, Southampton, WIT.

[31] Harrison, R.R. and Koch, C., 1999, A Robust Analog VLSI Motion Sensor Based on the Visual System of the Fly, Autonomous Robots, 7(3): 211-224.

[32] Jeong, K.-H., Kim, J. and Lee, L.P., 2005, Polymeric synthesis of biomimetic artifical compound eyes, The 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea, Pages.

[33] Tinsley, A., Midha, P.A., Nagel, R.L., Mcadams, D.A., Stone, R.B. and Shu, L.H., 2007, Exploring the use of Functional Models as a Foundation for Biomimetic Conceptual Design, ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Las Vegas, Nevada.