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AN ENGINEERING-TO-BIOLOGY THESAURUS FOR ENGINEERING DESIGN

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ABSTRACT

Engineering design is considered a creative field that involves many activities with the end goal of a new product that fulfills a purpose. Utilization of systematic methods or tools that aid in the design process is recognized as standard practice in industry and academia. The tools are used for a number of design activities (i.e., idea generation, concept generation, inspiration searches, functional modeling) and can span across engineering disciplines, the sciences (i.e., biology, chemistry) or a non-engineering domain (i.e., medicine), with an overall focus of encouraging creative engineering designs. Engineers, however, have struggled with utilizing the vast amount of biological information available from the natural world around them. Often it is because there is a knowledge gap or terminology is difficult, and the time needed to learn and understand the biology is not feasible. This paper presents an engineering-to-biology thesaurus that affords engineers, with limited biological background, a tool for leveraging nature's ingenuity. The thesaurus aids in many steps of the design process and increases the probability of a creative, analogical design. Biological terms in the thesaurus are correlated to the engineering domain through pairing with a synonymous function or flow term of the Functional Basis lexicon, which supports functional modeling and abstract representation of any functioning system. The version of the thesaurus presented in this paper represents an integration of three independent research efforts, which include research from Oregon State University, the University of Toronto, and the Indian Institute of Science, and their industrial partners. The overall approach for term integration and the final results are presented. Applications to the areas of design inspiration, comprehension of biological information, functional modeling, creative design and concept generation are discussed.

INTRODUCTION

Utilizing biological information during the engineering design process has taken many forms. Inspiration for solving or finding direct solutions to engineering problems have been obtained through chance observances [1-4], functional keyword searches [5-7], systematic reverse engineering [8, 9], use of function-structure-behavior terms to search a database [10, 11], TRIZ [12], analogical reasoning [13-15], and functional representation through functional models [16-20]. Although each method has a different procedure, they all share one thing in common; the promising biological system or phenomena must be abstracted to capture the functional principle. However, the functional principle is not the only biological aspect that can be mimicked. Morphology (shape), behavior (strategy), material, manufacturing process or any combination of these can be imitated. For instance, principle and morphology of a biological system can be imitated to improve an existing product [21]. A typical strain gauge has interdigitated electrodes, is rectangular and can only sense strain in one direction. The campaniform sensillum or flexible exocuticle that many insects possess inspired a novel redesign of the traditional strain gauge, directly based on morphology, that can sense strain in all directions (360°) [22]. Consider a circular or elliptical hole in a rigid material; it acts as a stress concentrator when pressure is applied. An elliptical opening in the insect's cuticle, which is covered by a thin membrane layer, senses deformation because of the stress concentration [23, 24]. The opening causes mechanical coupling and global amplification to occur, and acts as a biological strain gauge.

The novel strain gauge is just one example of a successful biologically–inspired, engineering design [25-28], however, choosing the biological system or phenomena to imitate is often left up to the designer, of whom typically has limited biological knowledge. Scenarios that involve the designer making educated decisions about how to utilize biological knowledge provided the impetus for developing an engineering design tool that easies the burden on the designer. In 2007, Nagel et al. developed a set of signal flow grammars to provide templates that aid in the manual and automatic assembly of functional models [29]. Nodes are utilized to clearly establish the location of system boundaries and the required input and output flows in a functional model. While a grammar is informative when modeling an unfamiliar system or process, such as a biological system, the very nature of a grammar prevents it from being all-inclusive. A grammar of biological functions did not seem feasible, thus, a flexible engineering design tool that categorizes biological information based on function, material, signal and energy was created. The resultant tool is a thesaurus of biological terms for use with the Functional Basis [30] as a set of correspondent terms, which is named the engineering-to-biology thesaurus. This work is not a biological ontology that allows automated information processing or inference. Rather, it is a means to map terminology between two dissimilar domains for the identification of synonyms. The thesaurus serves as a versatile design tool that affords design engineers, with a limited biological background, a means for utilizing nature's ingenuity.

Lindemann and Gramann acknowledge the difficulties of utilizing biological principles in engineering design in the following statement, "The first difficulty was to find some of the huge number of possibilities within biology you might look at. The main reason is the lack of the specific knowledge especially concerning the terminology. This problem is time consuming and in addition one has to understand the principle of all the different phenomena" [9]. The engineering-to-biology thesaurus aims to circumvent these and other difficulties by providing a list of synonymous biological terms to the basic engineering terms of the Functional Basis modeling language. The simple structure of the thesaurus promotes several key uses for engineering design activities:

- Promotion of knowledge transfer from the biological to engineering domain;
- mapping of biological terminology to engineering function and flow terminology;
- facilitation of biological information in engineering designs without having an extensive background in biological knowledge;
- promotion of creativity in engineering design; and
- assistance during an inspiration search.

In the following sections of this paper several points will be discussed: (1) background research in engineering lexicons and taxonomies related to biologically-inspired design; (2) research efforts related to this work; (3) model for designing the thesaurus structure; (4) approach taken to integrate functional terms from related efforts; and (5) the applications this thesaurus has in engineering design.

BACKGROUND

This research explores the structure and purpose of an engineering design thesaurus and how it enhances an existing design lexicon. Researchers at many Universities are working on the knowledge transfer problem between the engineering and biological domains by developing function or function-behavior-structure based design languages. The design language research efforts of Oregon State University, the Indian Institute of Science and the University of Toronto are the three that comprise the second version of the engineering-to-biology thesaurus. Their research efforts are explained in the following paragraphs.

Oregon State University Research Effort

The formal idea of a standard set of engineering function and flow terms for systematically creating function structures was originally proposed by Pahl and Beitz [31]. A function represents an operation performed on a flow of material, signal or energy. Numerous researchers further evolved this set of generally valid functions and flows. Hundal proposed a further refined set of function and flow classes in [32]; however, flows were excluded. Little *et al.* developed a set of function and flow terms, which classified both functions and flows at class and basic levels [33]. Szykman et al. created a standardized taxonomy of function and flow terms, separated into classes down to the fourth level, for the purpose of computer-based design [34]. Separately, but at the same time, Stone and Wood developed a well-defined standardized modeling lexicon comprised of defined function and flow sets with definitions and examples, entitled the Functional Basis [35]. Hirtz, *et al.* later reconciled the efforts by Stone and Szykman to form the current version of the Functional Basis [30]. Within the Functional Basis there exist eight classes of functions and three classes of flows, both having an increase in specification at the secondary and tertiary levels. There are 21 secondary and 24 tertiary functions, accompanied by correspondent terms to aid the designer in choosing the correct function. Similarly, there are 20 secondary and 22 tertiary flows accompanied by correspondent terms. In 2009, Stroble et al. [36] further expanded the Functional Basis to include a set of biological flow correspondent terms, which comprised the first version of the engineering-to-biology thesaurus. Adding biological function correspondent terms was identified as the next step and is achieved by integration of multiple research efforts.

Indian Institute of Science Research Effort

Chakrabarti *et al.* developed a software package entitled Idea-Inspire that allows one to search a database with a function-behavior-structure set, which is simply a verb-noun-adjective set [10, 37]. Their database is comprised of natural and artificial complex mechanical systems, and currently contains 100 biological system entries. Each entry's motion or process is described functionally by behavioral language in the form of a function-behavior-structure model. When using Idea-Inspire, the user abstracts a desired solution action by choosing terms that describe the function, behavior and structure from a pre-defined list of terms. The Idea-Inspire software yields seven behavioral constructs following the SAPPhIRE model – state change, action, parts, phenomenon, input, organ, and effect – for each search result that adequately fit the chosen function-behavior-structure set [38, 39]. SAPPhIRE explains the causality of natural and engineered systems [38, 39]. The aim of the software is to inspire ideas rather than solve the problem directly, as the name implies.

University of Toronto Research Effort

Researchers at the University of Toronto have worked to provide designers with biologically meaningful words that correspond to engineering functions. Hacco and Shu developed a method for biomimetic conceptual design [40], which was later refined by Chiu and Shu for searching biological literature using functional keywords for design inspiration [5, 6]. The keywords used in the search strategy 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 [41]. Later in 2008, Cheong *et al.* used the search strategy in conjunction with the terms of the Functional Basis to identify biologically meaningful words [42]. The Functional Basis functions in the secondary, tertiary and correspondent levels were analyzed to develop groups of words that were similar according to WordNet. Four cases for identification are discussed and examples presented: synonymous pair, implicitly synonymous pair, biologically specific form and mutually entailed pair [42]. Based on semantic relationships, the engineering function terms of the Functional Basis were used to systematically generate a list of biologically significant and connotative function keywords.

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.* to encourage collaboration, creation and discovery. 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 this section, the thesaurus model, population methods of the biological flows and functions, and particular details about the thesaurus are explained. The second version of the engineering-to-biology thesaurus is provided in the Appendix. Biological correspondent terms to the Functional Basis functions and flows are shown in place of the original engineering correspondent terms.

Thesaurus model

The purpose of a thesaurus is to represent information in a classified form to group synonyms and related concepts. A thesaurus of the English language has classes and categories with an index of terms directing the user to the correct instance (i.e., noun, verb, adjective) of the term under examination. The engineering-to-biology thesaurus proposed here has a unique structure and classification; it is merged with the reconciled Functional Basis as a set of correspondent terms. It does not include an index nor does it include adjectives. Only verbs and nouns that are synonymous to terms of the Functional Basis are considered. The Functional Basis class level terms, however, do emulate the classes of a traditional thesaurus. Furthermore, the secondary and tertiary level Functional Basis terms emulate the categories of a traditional thesaurus. Biological terms that fit in the function and flow sets, and correspond to multiple functions or flows, are repeated and italicized to designate the special case. 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 engineering-to-biology thesaurus increases the interaction between the users and the knowledge resource [43] by presenting the information as a look-up table. This simple format fosters one to make associations between the engineering and biological lexicons, thus, strengthening the designer's ability to utilize biological information.

Biological Functions

The majority of biological information is written in such a way that correlating biological verb terms to Functional Basis functions is straightforward. However, there are always exceptions. Well-known functional terms that appear in a biological text may not have the meaning an engineer would typically know. For instance, the term *bleaching* has multiple meanings and in some cases it does not mean to clean, sterilize or whiten, as most would assume. Rather, the second meaning could be the case, which refers to the process of separation between the retina and opsin in vertebrate eyes and causes the retinal molecule to lose its photosensitivity [44]. It is these types of exceptions that OSU researchers were cognizant of when compiling the set of biological correspondent function terms for the engineering-to-biology thesaurus. Keyword searches using the automated information retrieval tool [45] were performed to gather a list of collocated verbs that occur within the same sentence as the search word. It should be noted that some of the biological function correspondent terms are nouns that name a process that corresponds to the Functional Basis function. All potential biological functions were researched in the Oxford American dictionary [46] and Henderson's dictionary of biological terms [47] before being placed. Placement of terms in the thesaurus was at the discretion of the authors. All other function terms were obtained from research performed at the Indian Institute of Science and University of Toronto. The terms identified from these institutions are made explicit in the next section.

Functional terms from the Indian Institute of Science were collected from the Idea-Inspire software. Every natural system entered into the software's database was indexed using the pre-determined list of verbs, nouns and adjectives. Analyzing the list of verbs by cluster [38] revealed scientific terms applicable to biological systems grouped with engineering terms exactly matching those of the Functional Basis. Utilizing multiple dictionaries as in the OSU analysis, the verbs of Idea-Inspire were paired with Functional Basis functions.

Functional terms from the University of Toronto were collected from the work by Cheong *et al.* whom identified biologically meaningful words to those of the Functional Basis [42]. Because background work was already performed on the semantic relationships of the biologically meaningful words, further investigation was not performed. Rather, the terms were directly added to the thesaurus.

Biological Flows

In the authors' experience, understanding biological terms that were considered flows (material, signal and energy) when utilizing biological systems or phenomena for idea generation or design inspiration posed the most difficulty. 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 decreased efficiency.

Identification of engineering-to-biology thesaurus flow terms was achieved through functional word searches of a biological textbook [36]. Just as for the first version of the thesaurus flow terms, chosen words were determined by their macrorelevancy, which is identified by frequency of use [43]. Functional Basis functions (verbs) were utilized for searching the biological textbook to extract biological words (nouns) that an engineering designer interested in function based design might encounter. 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 [46] and Henderson's dictionary of biological terms [47] before being placed. Placement of terms in the engineering-to-biology thesaurus was at the discretion of the authors.

Thesaurus Particulars

Key challenges to the approach for populating the thesaurus described in this research were the time required to search each term to generate a listing of collocated terms and understand the definition provided in the dictionary of biological terms. Several biological dictionary entries referenced other biological terms that were unclear or unknown to the authors, which required referencing more than one definition to determine the material, energy or signal type of the term in question. The first version of the thesaurus, including only biological flow terms, was checked for correctness by a biologist. Due to the limited number of new biological flow terms and the straightforwardness of placing most biological functions, the second revision of the thesaurus was not checked for correctness by a biologist.

Anyone familiar with the Functional Basis is aware that each class, secondary and tertiary term has a definition and example associated with it. However, definitions of the correspondent terms have not been compiled. Rather, the correspondent terms are synonyms to the Functional Basis terms to aid the designer when choosing the best-suited term. This is also true for the biological correspondent terms. Biological terms that fit in the function and flow sets, and correspond to multiple functions or flows, are repeated in the set of correspondent terms and are italicized to designate the special case of those terms. This treatment is similar to the repeated words of the engineering correspondent terms.

INTEGRATION OF DESIGN LANGUAGES

Compiling multiple research efforts focused on language driven inspiration of innovative engineering designs strengthens the advantages of each effort. The terms utilized for Idea-Inspire must be broad enough to capture the principles of both biological and engineered systems, whereas, the carefully chosen terms of the Functional Basis were initially meant for engineered systems only. The biologically meaningful words discovered by semantic relationships utilized for creative design exercises, demonstrate functional terms that yield good results when searching a biological text for inspiration. Integration of these two research efforts with the OSU effort ensures the success of future design activities. Broad scoping, yet easily overlooked, terms of Table 1, and the previously tested and successful terms of Table 2 are included in the engineering-to-biology thesaurus of Appendix A.

Table 1. Indian Institute of Science Functional Terms [38]

Class	*Secondary*	*Tertiary*	*Bio Correspondents*
Branch	Separate		Free, detach, release
		Remove	Evacuate
	Distribute		Disperse, scatter, spread, spray
Channel	Import		Absorb, attract, consume, inhale, intake
	Export		Repel
	Transfer	Transport	Shift, displace, fly, swim, jump, bounce
	Guide	Translate	Slide
		Rotate	Oscillate, spin, turn, swivel, roll
Connect	Couple		Latch, lock
		Join	Adhere, bond, fuse
		Link	Clamp
Control Magnitude	Actuate		Activate, trigger
	Regulate		Preserve, sustain, preserve, remain, stabilize, maintain
		Increase	Grow, expand, multiply
		Decrease	Compress, coil, divide, fold, shorten, wrap
	Change		Alternate, fluctuate
	Stop		Halt, extinguish, clog, seal, suspend
		Prevent	Constrain, obstruct
Provision	Store		Conserve, hold
		Collect	Absorb, catch
	Supply		Feed
Signal	Sense	Measure	Observe, monitor, gauge, watch
Support			Cling, hold

Table 2. University of Toronto Functional Terms [42]

Class	*Secondary*	*Tertiary*	*Bio Correspondents*
Channel	Export		Bind, block, breakdown, excrete, inactivate
	Transfer	Transport	Circulate, conduct, diffuse, pump
		Transmit	Communicate, transduce
	Guide	Translate	Synthesize, transcribe
Connect	Couple		Extend, link, overlap, stretch
		Link	Activate, bind, project
	Mix		Contract, exchange, fragment
Control Magnitude	Stop	Inhibit	Cover, destroy, inhibit, surround
Convert	Convert		Decompose, degrade, develop, grow, mutate, photosynthesize
Provision	Store		Convert, deposit, photosynthesize
		Collect	Breakdown, concentrate, digest, reduce
Support			Develop, wrap
	Stabilize		Bind, connect

It is interesting to note that Table 1 does not include any terms for the function of convert because transform (the correspondent for convert) and change are considered as the same cluster for the Idea-Inspire software. Additionally, some of the biological correspondents in Table 1 are identical to the original Functional Basis set of correspondent terms. These terms were repeated in case the designer did not have simultaneous access to the both sets of correspondent terms. Table 2 is shorter, but offers on average more correspondent terms per Functional Basis term due to the rigorous method of determining biologically meaningful terms. Moreover, Table 2 offers a fascinating observation about the sustainability of natural systems–multiple terms have multiple functions. Consider *connect*, it could mean bringing two objects together or it could refer to stabilizing support. Also consider *bind*, this term could refer to stability, liking or exporting. Both research efforts provide substantial contributions to the engineering-to-biology thesaurus.

Table 3 lists the OSU contribution of biological function correspondent terms for the second version of the engineering-to-biology thesaurus. All but 4 of the Functional Basis function terms have identified biological correspondents.

Table 3. Oregon State University Functional Terms

Class	*Secondary*	*Tertiary*	*Bio Correspondents*
Branch	Separate		Bleaching, meiosis, flower, replicate, mitosis, segment, electrophoresis, react, dialysis, denature
		Divide	Division, prophase, metaphase, anaphase, cleave, cytokinesis
		Remove	Deoxygenated, filtrate, deamination, liberate, expulsion
	Distribute		Exchange, circulate, diffusion
Channel	Transfer		Migrate
	Guide		Orient, position,tunnel
		Allow DOF	Articulate
Connect	Couple		Recombination, mate, build, phosphorylate, bond, synthesis
		Join	Bind
	Mix		Blend
Control Magnitude	Actuate		Induce, trigger
	Regulate		Gate, electrophoresis, respire, organogenesis
		Increase	Hyperpolarize, pinocytosis
	Change		Pinocytosis, catalyze, degrade, alter, bind,slip, contract, hydrolysis, inflammation of, twist, spread, mutate, adiate, charged, acclimatize
		Increment	Attach
		Decrement	Decarboxylation, constrict
		Shape	Elongation, stretch, attach, spread
		Condition	Osmosis, constrict
	Stop		Interphase
		Inhibit	Repress
Convert	Convert		Polymerize, burn, synthesize, hydrolysis, gluconeogenesis, metabolize, glycolysis, translation,respiration, photosynthesis, fermentation, ionize
Provision	Store	Contain	Absorb
	Supply		Lactate
Signal	Sense	Detect	Locate, see, smell
	Indicate		Fluoresce, mark, communicate, react
	Process		Learn
Support	Stabilize		Homeostasis
	Position		Envelope

APPLICATIONS

The engineering-to-biology thesaurus was developed with the intention of promoting collaboration between the biology and engineering domains, resulting in discovery of creative, novel ideas. The following subsections describe plausible applications of the presented thesaurus, which are summarized in Figure 1. However, with few boundaries in the field of design, this thesaurus could be employed in ways the authors' have not considered.

Comprehension

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" [43]. The engineering-to-biology thesaurus has the potential to aid engineering designers with the comprehension of biological contexts and facilitate information transfer in two ways; (1) direct translation of biological text into engineering "speak" and (2) abstraction of a biological system or phenomena in engineering terms.

Direct translation can be achieved by substituting biological words that appear in the thesaurus with their corresponding Functional Basis terms. Essentially, this will rewrite the biological information in engineering "speak" and increase the likelihood of a designer making connections between the two sets of information and gaining inspiration as a result. Many design methods rely on abstractions and describing an abstracted biological principle in engineering terms is advantageous. Not only does it increase the likelihood of a designer, with limited biological knowledge, understanding the biological principle, but also it lends itself to analogical reasoning and easy comparison to other abstractions. Efficient information retrieval through the engineering-to-biology thesaurus allows an engineering designer to cross into the biological domain and gain functional knowledge without becoming overwhelmed by unfamiliar biological systems and phenomena.

Searching for biological inspiration

Searching a natural-language corpus, such as a textbook, for biological inspiration based on engineering functionality or using engineering terms typically produces results that are mixed. Results containing the search word(s) often use the search word(s) out of context, not at all or in a different sense then the designer intended. By utilizing the biological correspondent terms of the thesaurus when searching for a specific function or flow that solves the engineering problem, search results improve and become more focused on the desired biological systems or phenomena.

Functional modeling of biological systems

The engineering-to-biology thesaurus provides direction when choosing the best-suited function or flow term to objectively model a biological system. A wide range of biological terms have been collected and placed into the thesaurus, which can accommodate a designer when developing functional models of well known to just introduced biological systems. 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 an additional benefit to biological functional models.

Concept Generation

Describing biological systems and phenomena through functionality allow knowledge that otherwise would not be considered, to be used in function-based engineering design methods. A biomimetic design repository enables the storage of such knowledge, which can be used in a multitude of ways. Storing the biological information based on the function the biological system or phenomena solves allows quick access to principle solutions. There are a total of 19 biological entries in the design repository, 13 are phenomena and 6 are systems (organisms) for this purpose. The design repository facilitates automatic concept generation and comparison of biological and engineered components.

Computational concept generation is a quick way to generate several conceptual designs, which gives engineers a glimpse of the possible components that they may use. Researchers in the OSU Design Engineering Lab utilize a design repository in conjunction with computational concept generation software, which includes descriptive product information such as functionality, component physical parameters, manufacturing processes, failure, and component compatibility. The concept generator used in this research is based on an algorithm that ranks viable conceptual design variants [48]. This tool is intended for use during the early stages of design to produce numerous feasible concepts utilizing engineering and biological component relationships as found in the design repository. A matrix version of the desired conceptual functional model is used to parse the component interactions, compatibility and functionality of the design repository entries. The algorithm processes the matrix input and returns a mixed set of engineering components and/or biological solutions for each function-flow pair of the functional model. The designer chooses from the resulting concept generator suggestions, engineered and biological, to develop a complete conceptual design. All tools mentioned in this section are located at: www.designengineeringlab.org.

Collaboration, creation, discovery

Terms contained within the engineering-to-biology thesaurus can be utilized for increasing creativity in engineering designs and 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 prompts collaboration between biology and engineering researchers.

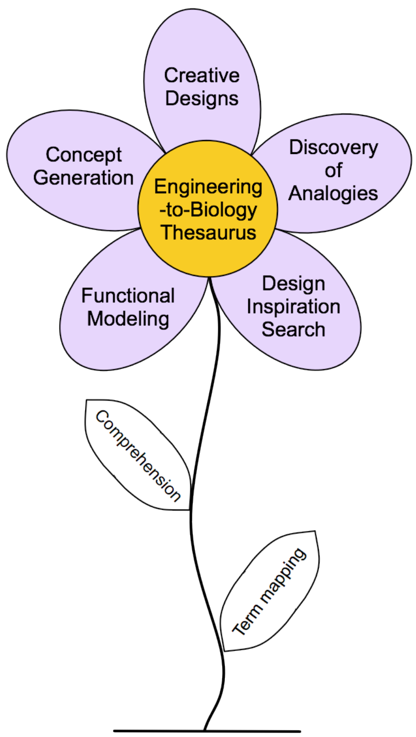

Figure 1. Engineering-to-Biology Thesaurus Applications

CONCLUSIONS

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 from the decomposition of design solutions, engineered and biological, organized at different levels of abstraction allow analogs to be discovered with cues taken from each level. This paper presented an engineering-to-biology thesaurus that (1) allows designers to focus on becoming competent at engineering design; (2) lessens the burden when utilizing knowledge from the biological domain by providing a link between engineering and biological terms; and (3) lists biological correspondent terms that an engineering designer interested in function-based design might encounter.

The version of the thesaurus presented in this paper represents an integration of three independent research efforts, which include research from Oregon State University, the University of Toronto, and the Indian Institute of Science, and their industrial partners. The overall approach for term integration and the final results are presented. Through this research, biological function and flow correspondent terms were mapped to engineering terms and placed into pre-determined classifications set by the Functional Basis structure. It was observed that the majority of biological flow correspondent terms are grouped at the tertiary level, whereas biological function terms are primarily grouped at the secondary level.

Implications of the proposed thesaurus on the engineering and biology communities were explored. Breaking down a biological solution into smaller parts, based on functionality, allows one to liken a biological system or phenomenon to an engineered system for ease of understanding and transfer of design knowledge. 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.

FUTURE WORK

Future work for improvement of the engineering-to-biology thesaurus includes examining terms through clustering and discovering more terms from different texts. While collocated terms provide an indication for macrorelevant terms, clustering analysis could be utilized to find less obvious, but equally important, biological terms for thesaurus population. Additionally, biological texts that focus on a topic of interest (i.e., insects, fungi) should be analyzed for relevant biological terms that an introductory text may not include.

Future work for the adoption of biologically inspired engineering design involves integration of the thesaurus terms into computational concept generation software. This will enable a greater number of biological organisms, strategies and phenomena that achieve desired functionality to be found during concept generation. Thereby increasing the likelihood of biomimetic concept generation.

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ANNEX A

ENGINEERING-TO-BIOLOGY THESAURUS

Class	*Secondary*	*Tertiary*	*Biological Function Correspondents*
Branch	Separate		Bleaching, meiosis, *react*, flower, replicate, mitosis, segment, *electrophoresis*, dialysis, denature, free, detach, release
		Divide	Division, prophase, metaphase, anaphase, cleave, cytokinesis
		Remove	Deoxygenate, filtrate, deamination, liberate, expulsion, evacuate
	Distribute		Circulate, diffusion, exchange, disperse, scatter, spread, spray
Channel	Import		*Absorb*, attract, consume, inhale, intake,
	Export		*Bind*, block, breakdown, excrete, inactivate, repel
	Transfer		Migrate
		Transport	Circulate, conduct, diffuse, pump, shift, displace, fly, swim, jump, bounce
		Transmit	Communicate, *transduce*
	Guide		Orient, position, slide, tunnel
		Translate	*Synthesize*, transcribe
		Rotate	Oscillate, spin, turn, swivel, roll
		Allow DOF	Articulate
Connect	Couple		Recombination, mate, build, phosphorylate, bond, synthesis, latch, lock, extend, link, overlap, *stretch*
		Join	*Bind*, adhere, bond, fuse
		Link	Clamp, *activate*, *bind*, project
	Mix		Blend, *contract*, exchange, fragment
Control Magnitude	Actuate		*Activate*, induce, trigger
	Regulate		*Electrophoresis*, gate, organogenesis, respire, preserve, sustain, preserve, remain, stabilize, maintain
		Increase	Hyperpolarize, *pinocytosis*, *grow*, expand, multiply
		Decrease	Compress, coil, divide, fold, shorten, *wrap*
	Change		*Pinocytosis*, *degrade*, alter, *bind*, catalyze, *contract*, hydrolysis, inflammation of, twist, *mutate*, radiate, charged, slip, acclimatize, alternate, fluctuate
		Decrement	Decarboxylation, *constrict*
		Shape	Elongate, *stretch*, attach, *spread*
		Condition	Osmosis, *constrict*
	Stop		Clog, extinguish, halt, interphase, seal, suspend
		Prevent	Constrain, obstruct
		Inhibit	Cover, destroy, inhibit, repress, surround
Convert	Convert		Polymerize, *synthesize*, burn, gluconeogenesis, metabolize, *grow*, *transduction*, fermentation, glycolysis, hydrolyze, hydrolysis, respiration, ionize, decompose, *degrade*, *develop*, *mutate*, *photosynthesize*
Provision	Store		Conserve, *hold*, *convert*, deposit, *photosynthesize*
		Contain	*Absorb*
		Collect	*Absorb*, catch, breakdown, concentrate, digest, reduce
	Supply		Feed, lactate
Signal	Sense	Detect	Locate, see, smell
		Measure	Observe, monitor, gauge, watch
	Indicate		Fluoresce, communicate, *react*, mark
	Process		Learn
Support			*Develop*, *wrap*
	Stabilize		Homeostasis, cling, *hold*, *bind*, *connect*
	Position		Envelope
Overall increasing degree of specification →			

Class	Secondary	Tertiary	Biological Flow 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, sperm, hippocampus, somite, parathormone
		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
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
	Chemical		Calorie, metabolism, glucose, glycogen, ligand, nutrient, starch, fuel, sugar, mitochondria, synthesis, o, lipids, glucose, gibberellins
	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
	Thermal		Temperature, heat, infrared
Overall increasing degree of specification ➔			