A Computational Concept Generation Technique for Biologically-Inspired, Engineering Design

The natural world provides numerous cases for analogy and inspiration in engineering design. Nature has the highest potential to influence engineering design during the early stages of design, particularly during concept generation. However, identifying and presenting the valuable knowledge from the biological domain to an engineering designer during concept generation is currently a somewhat disorganized process or requires extensive knowledge of a particular method. The proposed research aims to define and formalize the information identification and knowledge transfer processes, which will result in a systematic method for developing biologically-inspired, or biomimetic, engineering designs. The computational framework for discovering biological inspiration during function-based design activities is presented and discussed through an illustrative example.

Introduction

Engineering design is considered both an art and a science, which encourages the use of engineering principles, imagination and a designer's intuition to create novel engineering solutions. Nature is a powerful resource for engineering designers. The natural world provides numerous cases for analogy and inspiration in engineering design [1-4]. Biological organisms, phenomena and strategies, which can be grouped and referred to as biological systems, are, in essence, living engineered systems. These living systems provide insight into sustainable and adaptable design and offer engineers billions of years of valuable experience, which can be used to inspire engineering innovation. Many engineering breakthroughs have occurred based on biological phenomena and it is evident that mimicking biological systems or using them for inspiration has led to successful innovation (e.g., velcro, flapping wing micro air vehicles, synthetic muscles, self-cleaning glass, etc.).

Nature has the highest potential to influence engineering design during the early stages of design, particularly during concept generation when inspiration or analogies from engineering and other sources (e.g., biological domain) are utilized for developing novel or creative designs. Concept

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generation methods and tools help stimulate designer creativity and encourage exploration of the solution space beyond an individual designer's knowledge and experience [5-12]. There are multiple approaches to concept generation for engineering design; however, most are not computational. Although in recent years, computation-based or automatic concept generation has gained importance in the engineering design research community and has taken many forms [13-19]. Identifying and presenting the valuable knowledge from the biological domain to an engineering designer during concept generation is currently a manual, in most cases, and somewhat disorganized, process. The proposed research aims to define and formalize the information identification and knowledge transfer processes, which will result in a systematic method for developing biologically-inspired, or biomimetic, engineering designs.

This paper describes version three of the established automatic concept generation software developed by researchers of the Design Engineering Lab at Oregon State University. In order to facilitate concept generation for biologically-inspired, engineering design, two bodies of knowledge are required - successful engineered systems and biological systems - both indexed by engineering function. A Design Repository [20] containing descriptive product information serves as the engineered systems body of knowledge. Instead of creating a database containing functionally decomposed biological systems, similar to the design repository, an introductory biology textbook serves as the biological systems body of knowledge. To circumvent the terminology difference issue – indexed by natural language rather than engineering function – an engineering-to-biology thesaurus is utilized [21, 22]. Structurally, the thesaurus acts as a set of correspondent terms to the functions and flows of the Functional Basis, which provides term mapping between the biological and engineering domains for the support of concept generation. Integrating biological system information with an established, computational method for concept generation enables designers to consider taking inspiration from biology without having to expend extra effort to learn a new method.

This paper begins by introducing the reader to related biologically-inspired design research and information retrieval in engineering design. The following section introduces and provides background knowledge on the supporting design tools of the Functional basis, MEMIC, organized search tool and the engineering-to-biology thesaurus. Next, the proposed computational framework and algorithm for discovering biological inspiration during function-based design activities is presented and discussed. The paper ends with an illustrative example, conclusions and future work that has been identified.

Related Work

Work in the area of computational biology inspired design related to this research involves the design of databases, software and search methods. Chakrabarti et al. developed a software package entitled Idea-Inspire that allows one to search a database by choosing a verb-noun-adjective set [23, 24]. Their database is comprised of natural and complex artificial mechanical systems. Each entry's motion is described functionally by behavioral language in the form of a function-behavior-structure model. As an automated approach, the Idea-Inspire software aims to inspire ideas rather than solve the problem directly. Another database driven method is ontology driven bio-inspired design repository developed by Wilson et al. [25]. This ontology is encoded using description logics, which is a subset of first-order logic that has been used for information modeling in several areas. Subsumption, an inference mechanism afforded in description logics, is used to retrieve relevant biological strategies from the repository. This method allows precise retrieval of relevant biological strategies from the repository. Chiu and Shu have developed a method for abstracting engineering design analogies by searching biological literature using functional keywords [26, 27]. The engineering domain keywords are cross-referenced with Wordnet to define a set of natural-language keywords for yielding better results during the search. Typically, searches are based on multiple keywords. This method has successfully generated engineering solutions analogous to biological phenomena [28].

Work in the area of information retrieval in design related to this research involves the design of a hierarchal thesaurus, software and search methods. A general approach to design information retrieval was undertaken by Wood et al., which created a hierarchical thesaurus of component and system functional decompositions to capture design context [29]. Through a framework for systematic formalization of informal information in the early design process they propose that informal knowledge in design can be reused. Strategies for retrieval, similar to search heuristics, of issue based and component/function information were presented. Bouchard et al. developed a content-based information retrieval system named TRENDS [30]. This software aims at improving designers' access to web-based resources by helping them to find appropriate materials, to structure these materials in way that supports their design activities and identify design trends. The TRENDS system integrates flexible content-based image retrieval based on ontological referencing and clustering components through Conjoint Trends Analysis (CTA). Cheong et al. developed a set of search cases, specific to the incorporation of biology in engineering design, for determining biologically meaningful keywords to sets of engineering keywords [31]. Although the results are subjective, the process for retrieving the words is systematic. They were successful in determining biologically meaningful words to several functions found in the reconciled Functional Basis.

Background

This section provides background information on the two computational tools and respective supporting design tools that are required to achieve the proposed computational framework for discovering biological inspiration. Researchers of the Design Engineering Lab developed each design tool described below–accessible at www.designengineeringlab.org.

Functional Basis Design Language

Functional representation through functional modeling has a long history of use in systematic design methods [7]. The Stone, et al. [32] created a well-defined modeling language comprised of function and flow sets with definitions and examples, entitled the Functional Basis. Hirtz, et al. [33] later reconciled the Functional Basis into its most current set of terms, with research efforts from the National Institute of Standards and Technology (NIST), two universities, and their industrial partners. In the Functional Basis lexicon, a function represents an action or transformation (verb) being carried out, and a flow represents the type (noun), material, signal or energy, passing through the functions of the system. There exist eight classes of functions and three classes of flows, both having an increase in specification at the secondary and tertiary levels. Both functions and flows have a set of correspondent terms that aid the designer in choosing correct Functional Basis terms during model creation. The complete function and flow lexicon can be found in [33]. Functional models for any product can be generated using this design language. Functional models reveal functional and flow dependencies and are used to capture design knowledge from existing products or define the dependencies for future products. Advantages to using a design language for modeling include repeatability, archival and transmittal of design information, comparison of functionality and product architecture development [6, 7, 32].

Design Repository

Over the course of several years, a web-based repository to store design knowledge has been developed and refined [34, 35]. The Design Repository housed at Oregon State University contains descriptive product information such as functionality, component physical parameters, manufacturing processes, failure, and component compatibility of over 113 consumer products. Each consumer product was functionally modeled using the Functional Basis lexicon [33]. Each repository entry is designated as an artifact or assembly of artifacts, whether it performs a supporting function (secondary to the product's operation) and the class of the artifact when entered into the repository database. Additionally, several artifact attributes are captured. These attributes are stored in a relational database where each record contains an artifact name, part number, and part family that can be used to catalog similar artifacts. Information about the actual function of an artifact is captured as a subfunction value. Design tools like function-component matrices (FCMs) and design structure matrices (DSMs) can be readily generated from single or multiple products and used in a variety of ways to enhance the design process.

Concept Generation Software-MEMIC

Computational concept generation is a quick way to generate several conceptual designs, which gives engineers a glimpse of the possible engineering components that they may use. The Morphological Evaluation Machine and Interactive Conceptualizer (MEMIC) was created to produce design solutions for a product design from a given functional model using knowledge extracted from a web-based design repository [14, 15]. The concept generator software MEMIC accepts a user-input and uses functionality and compatibility information to generate, filter, and rank full concept variants. 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. The algorithm utilizes the relationships contained in a function-component matrix (FCM) and the compatibility information contained in a design structure matrix (DSM) generated by the repository of existing consumer products [36, 37]. The algorithm processes the matrix version of an input functional model and returns a listing of engineering component solutions for each function-flow pair of the functional model. This allows a designer to easily choose between multiple solutions for a given function and interactively build a complete conceptual design.

Organized Search Tool

The organized search tool is designed to work with non-engineering subject domain specific information. The majority of non-engineering domain texts are written in natural-language format, which prompted the investigation of using both a Functional Basis function and flow term when searching for solutions. Realizing how the topic of the text is treated increases the extensibility of the organized verb-noun search algorithm. This organized verb-noun combination search strategy provides two levels of results: (1) associated with verb only, of which the user can choose to utilize or ignore, and (2) the narrowed results associated with verb-noun. This search strategy requires the designer to first form an abstraction of the unsolved problem using the Functional Basis terms. The verbs (functions) provided in the Functional Basis are used as keywords in the organized search to generate a list of matches, and subsequently a list of words that occur most frequently in proximity to the searched verb in those matches. The generated list contains mostly nouns, which can be thought of as flows (materials, energies and signals), analogous to the correspondent words already provided in the Functional Basis flow set. The noun listing is then used in combination with the verb for a second search to locate specific excerpts that describe how the non-engineering domain systems perform the verb (function) used in the organized searches.

This search strategy is embodied in an automated retrieval tool that allows an engineering designer to selectively choose which documents to search and to upload additional searchable information as it is made available. The user interface initially presents the designer with a function (verb) entry field and search options. Search options prompt the designer to choose from exact word, derivatives of the word, and partial word. Once the documents are searched for the function term the designer is presented with a flow (noun) listing for each searched document followed by a group of sentences that include the function and listed flows, as shown in Figure 1. If the designer does not want to search by verb-noun then the designer simply scrolls down to the group of sentences, which include the desired function. For this application, the non-engineering domain chosen for examples is biology.

The designer utilizing this organized search technique does not need an extensive background in the non-engineering domain but, rather, sufficient engineering background to abstract the unsolved problem to its most basic level utilizing the Functional Basis taxonomy. The search tool typically yields more than one biological organism, strategy or phenomenon. Thus, the designer must examine the text excerpts and decide which biological system is best suited for solving the engineering problem.

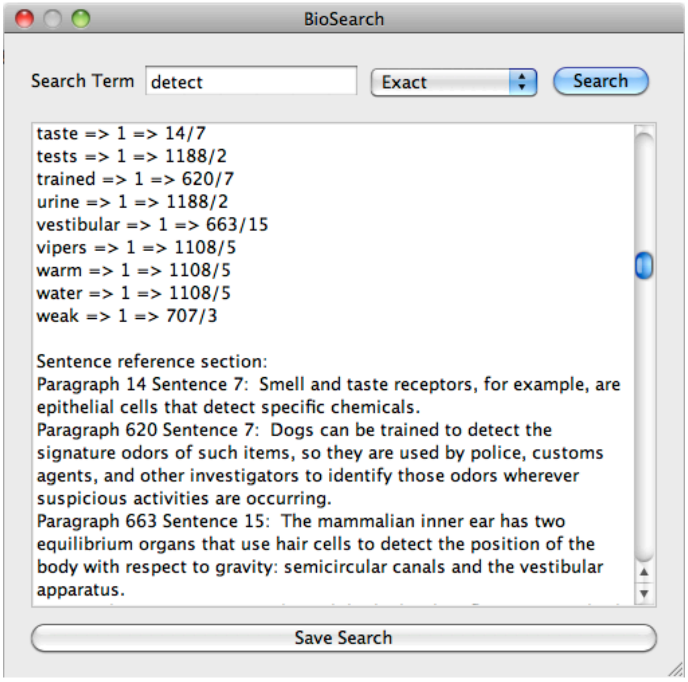

Fig 1. Example Output of the Organized Search Tool

Engineering-to-Biology Thesaurus

The engineering-to-biology thesaurus [21, 22] was developed to enhance the Functional Basis developed by Hirtz et al. [33] 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. 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. A tool such as the engineering-to-biology thesaurus increases the interaction between the users and the knowledge resource [38] 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. The thesaurus aids in many steps of the design process it increases the probability of a creative, analogical design. Plausible applications of the thesaurus include design inspiration, comprehension of biological information, functional modeling, creative design and concept generation. Overall, the thesaurus provides a designer several opportunities for interfacing with biological information.

Table 1 Example Function and Flow Terminology Relationships

Functional Basis Terms			Biological Correspondents
Class	**Secondary**	**Tertiary**	
Material	Liquid		Acid, auxin, cytokinin, glycerol, pyruvate
	Solid	Object	Cilia, kidney, melatonin, nephron, xylem
		Composite	Enzyme, nucleotide, prokaryote, symplast
	Mixture	Solid-liquid	Cell, lipid, phytochrome, pigment, plastid
Energy	Chemical		Glucose, glycogen, mitochondria, sugar
Branch	Separate		Aneuploidy, bleaching, dialysis, meiosis
		Divide	Anaphase, cleavage, cytokinesis, metaphase
Connect	Couple		Bond, build, mate, phosphorylate
Control Magnitude	Regulate		Gate, electrophoresis, respire

Concept Generation Technique

Automated concept generation methods promise engineers a faster realization of potential design solutions based upon previously known products and implementations. The technique described here requires the designer to input desired functionality and based on an algorithm several concept variants are presented to the designer. Functionality is a useful metric for defining a conceptual idea, as functional representation has been shown to reduce fixation of how a product or device would look and operate [6, 7].

The proposed computational concept generation technique requires a functional model that abstractly represents a conceptual engineered solution that solves the problem in question. The functional model is then digitized and represented as a matrix of forward flows. Each function/flow pair of the functional model is then searched in the OSU Design Repository and the chosen biological corpus to identify solutions. The search algorithm parses the repository entries for the exact engineering function/flow pair, where as, the biological corpus is parsed repeatedly with the biological terms corresponding to the engineering terms per the engineering-to-biology thesaurus. Multiple solutions from both domains, to each function/flow pair, are returned and often do not fit together as they would in a traditional engineered system. To make a concept work, a leap is required from the designer to understand that component mapping is an analogy that relates a biological system to an engineered system. The computational technique proposed here assists with making the leap from biology to engineering, but to arrive at the final concept, the designer is required to make the leap within the engineering domain.

Engineers 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. Therefore, a computational technique that can identify and present valuable biological knowledge, indexed by engineering terms, to an engineering designer during concept generation would significantly increase the likelihood of bio-inspired designs. The computational concept generation technique proposed here will promote biologically-inspired, engineering designs that partially (i.e., one or two components) to completely (i.e., entire design) mimic a biological system. This technique therefore lends itself more toward innovative design problems where novel solutions tend to dominate.

Computational concept generation provides the added advantage of limitless resources for inspiration. The technique described in this section can be extended by adding entries into the Design Repository and texts into the biological corpus database. With this technique the well-known customer needs driven engineering design approach is utilized, which is an additional advantage.

Algorithm

Our proposed technique utilizes the Functional Basis, Design Repository, MEMIC, organized search tool and engineering-to-biology thesaurus to create, filter and inspire concept variants. The algorithm is a combination of the previous research efforts that developed MEMIC and the organized search tool. Simultaneously, the algorithm interacts with the Design Repository to find engineering solutions and a chosen biological corpus to find biological inspiration. The following sections provide detail regarding the algorithm parts.

Part 1: Parse Design Repository for Engineering Solutions

The proposed concept generation technique utilizes function-component relationships established through an FCM to compute a set of engineering components that solve the function/flow pairs of the input functional model. Next, the resultant set is filtered using component-component knowledge through a DSM. Each match is stored for display to the user. The resultant engineering components found in the repository that are compatible are displayed to the user as a list of potential solutions that have previously solved that function/flow pair.

Part 2: Parse Biological Text for Biological Solutions using Thesaurus Terms

First, the algorithm swaps the engineering function and flow terms for corresponding biological function and flow terms. The biological corpus is then searched for the biological function and all sentences containing the function are extracted for further processing. The algorithm then searches those sentences for any of the corresponding biological flow terms. Each match is stored for display to the user. When multiple biological function terms are present, the search is executed recursively until all corresponding biological functions have been searched. The resultant biological information is displayed to the designer as individual sentences containing the desired function/flow pairs, which are indicators of potential solutions from the biological domain.

Concept Generation Example

To illustrate the proposed computational concept generation technique, a smart flooring example is presented. The computational tool is utilized to search engineered and biological systems for solutions that can be implemented in the example product. When using the Functional Basis for product design there are a few basic steps needed before function-based concept generation can begin. First, one must define the customer needs and convert them into engineering terms [6, 7, 39]. Second, one must develop either a conceptual functional model of the desired new product or a functional model of an existing product to be redesigned using the Functional Basis function and flow terms. Examples can be found in [32, 37, 40]. With the functional model, the designer now has several function-flow pairs that represent the desired new product. These pairs are utilized by the computational concept generation technique to gain inspiration.

Smart Flooring

Consider the following scenario. A customer wants to create a security/surveillance product that looks like ordinary carpet, mats, rugs, etc. to detect intruders, a presence or movement. Requirements for the smart flooring include being unseen by human eye, durability, and composed of common materials. Given these customer needs, the conceptual functional model in Figure 2 is created. The model of Figure 2 was created with a boundary of the flooring in place, energy is being supplied to the detection mechanism and when an object or human interacts with the flooring a signal is generated. Importation of human/object symbolizes interaction and exportation symbolizes the human/object exiting the boundary. In order to use the computational concept generation technique, an adjacency matrix (Table 2) representing the forward flows of the model in Figure 2 is created. The concept generation technique resulted in 31 engineering solutions and 60 biological text excerpts in the form of individual sentences as shown in Table 3.

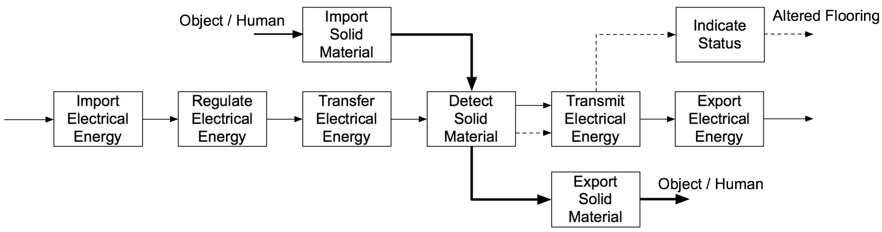

Fig 2. Smart Flooring Conceptual Functional Model

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

Table 2 Smart Flooring Adjacency Matrix

Table 3 Smart Flooring Concept Generation Results

Function/ Flow	Engineering Solution	Biological Solution
Import/ solid material	N/A	N/A
Import/ electrical energy	Battery, circuit board, electric motor, electric wire, electric switch	1. The light energy absorbed by the antenna system is transferred from one pigment molecule to another as an electron. 2. To keep noncyclic electron flow going, both photosystems I and II must constantly be absorbing light, thereby boosting electrons to higher orbitals from which they may be captured by specific oxidizing agents. 3. Photosystem II absorbs photons, sending electrons from P680 to pheophytin-I-the first carrier in the redox chain-and causing P680 to become oxidized to P680+. 4. Electrons from the oxidation of water are passed to P680+, reducing it once again to P680, which can absorb more photons. 5. In sum, noncyclic electron flow uses a molecule of water, four photons (two each absorbed by photosystems I and II), one molecule each of NADP+ and ADP, and one Pi. 6. The attractive force that an atom exerts on electrons is its electronegativity. 7. Na+ ions would diffuse into the cell because of their higher concentration on the outside, and they would also be attracted into the cell by the negative membrane potential. 8. These positive charges electrostatically attract the negative phosphate groups on DNA. 9. Because opposite charges attract, the DNA moves toward the positive end of the field. 10. Leptin appears to be one important feedback signal in the regulation of food intake.
Regulate/ electrical energy	Actuation lever, capacitor, circuit board, automobile distributor, electric switch, heating element, transistor, transformer, thermostat, regulator, volume knob	1. Changes in the gated channels may perturb the resting potential. 2. An opposite change in the resting potential would occur if gated Cl- channels opened. 3. The inactivation gate remains closed for 1-2 milliseconds before it spontaneously opens again, thus explaining why the membrane has a refractory period (a period during which it cannot act) before it can fire another action potential. 4. When the inactivation gate finally opens, the activation gate is closed, and the membrane is poised to respond once again to a depolarizing stimulus by firing another action potential. 5. The binding of neurotransmitter to receptors at the motor end plate and the resultant opening of chemically gated ion channels perturb the resting potential of the postsynaptic membrane. 6. The structure of many plants is maintained by the pressure potential of their cells; if the pressure potential is lost, a plant wilts. 7. Negatively charged chloride ions and organic ions also move out of the guard cells with the potassium ions, maintaining electrical balance and contributing to the change in the solute potential of the guard cells. 8. This unloading serves two purposes: It helps maintain the gradient of solute potential and hence of pressure potential in the sieve tubes, and it promotes the buildup of sugars and starch to high concentrations in storage regions, such as developing fruits and seeds.

Transfer/ electrical energy	Battery, circuit board, electric wire, electric motor, electric socket, electric plate, electric switch, heating element, usb cable, light fixture, speaker	1. We have just noted proteins that function in blood clotting; others of interest include albumin, which is partly responsible for the osmotic potential in capillaries that prevents a massive loss of water from plasma to intercellular spaces; antibodies (the immunoglobulins); hormones; and various carrier molecules, such as transferrin, which carries iron from the gut to where it is stored or used. 2. Since the electronegativities of these elements are so different, any electrons involved in bonding will tend to be much nearer to the chlorine nucleus-so near, in fact, that there is a complete transfer of the electron from one element to the other. 3. Redox reactions transfer electrons and energy. 4. Another way of transferring energy is to transfer electrons. 5. A reaction in which one substance transfers one or more electrons to another substance is called an oxidation-reduction reaction, or redox reaction. 6. Thus, when a molecule loses hydrogen atoms, it becomes oxidized: Oxidation and reduction always occur together: As one material is oxidized, the electrons it loses are transferred to another material, reducing that material. 7. As we shall see, another carrier, FAD (flavin adenine dinucleotide), is also involved in transferring electrons during the metabolism of glucose. 8. The citric acid cycle is a cyclic series of reactions in which the acetate becomes completely oxidized, forming CO2 and transferring electrons (along with their hydrogen nuclei) to carrier molecules. 9. The transfer of electrons along the respiratory chain drives the active transport of hydrogen ions (protons) from the mitochondrial matrix into the space between the inner and outer mitochondrial membrane. 10. The light energy absorbed by the antenna system is transferred from one pigment molecule to another as an electron. 11. The high energy stored in the electrons of excited chlorophyll can be transferred to suitably oxidized nonpigment acceptor molecules.
Transmit/ electrical energy	Electrical wire, battery contacts, motor controller	1. These electrical changes generate action potentials, the language by which the nervous system processes and communicates information. 2. Ganglion cells communicate information about contrasts between light and dark that fall on different regions of their receptive fields. 3. Whether or not the sensory cell itself fires action potentials, ultimately the stimulus is transduced into action potentials and the intensity of the stimulus is encoded by the frequency of action potentials. 4. In the rest of this chapter we will learn how sensory systems gather and filter stimuli, transduce specific stimuli into action potentials, and transmit action potentials to the CNS. 5. Auditory systems use mechanoreceptors to transduce pressure waves into action potentials. 6. Earlier in this chapter, we saw how crayfish stretch receptors transduce physical force into action potentials. 7. Sitting on the basilar membrane is the organ of Corti, the apparatus that transduces pressure waves into action potentials in the auditory nerve, which in turn conveys information from the ear to the brain.

Detect/ solid material	Read head, line guide	1. Since both AT and GC pairs obey the base-pairing rules, how does the repair mechanism "know" whether the AC pair should be repaired by removing the C and replace it with T, for instance, or by removing the A and replacing it with G? The repair mechanism can detect the "wrong" base because a newly synthesized DNA strand is chemically modified some time after replication. 2. The cnidarian's nerve net merely detects food or danger and causes its tentacles and body to extend or retract. 3. Most sensory cells possess a membrane receptor protein that detects the stimulus and responds by altering the flow of ions across the plasma membrane. 4. The mammalian inner ear has two equilibrium organs that use hair cells to detect the position of the body with respect to gravity: semicircular canals and the vestibular apparatus. 5. These sensory cells enable the fish to detect weak electric fields, which can help them locate prey. 6. This change is detected by the carotid and aortic stretch receptors, which stimulate corrective responses within two heartbeats. 7. Any objects in the environment, such as rocks, plants, or other fish, disrupt the electric fish's electric field, and the electroreceptors of the lateral line detect those disruptions. 8. Bats use echolocation, pit vipers sense infrared radiation from the warm bodies of their prey, and certain fishes detect electric fields created in the water by their prey. 9. In addition to genes for antibiotic resistance, several other marker genes are used to detect recombinant DNA in host cells. 10. Length of the night is one of several environmental cues detected by plants, or by individual parts such as leaves. 11. Animals whose eyes are on the sides of their heads have nonoverlapping fields of vision and, as a result, poor depth vision, but they can see predators creeping up from behind. 12. How does the sensory cell signal the intensity of a smell? It responds in a graded fashion to the concentration of odorant molecules: The more odorant molecules that bind to receptors, the more action potentials are generated and the greater the intensity of the perceived smell.
Indicate/ status signal	Light, tube, displacement gauge, lcd screen	1. The durability of pheromonal signals enables them to be used to mark trails, as ants do, or to indicate directionality, as in the case of the moth sex attractant. 2. To cause behavioral or physiological responses, a nervous system communicates these signals to effectors, such as muscles and glands. 3. The information from the signal that was originally at the plasma membrane is communicated to the nucleus. 4. A change in body color is a response that some animals use to camouflage themselves in a particular environment or to communicate with other animals. 5. The binding of a hormone to its cellular receptor protein, which causes the protein to change shape and provides the signal to initiate reactions within the cell. 6. The lung tissues reacted to this onslaught by swelling-the hallmark of pneumonia. 7. When the substrate binds, the enzyme changes shape, exposing the parts of itself that react with the substrate. 8. Separation of the chromatids marks the beginning of anaphase, the phase of mitosis during which the two sister chromatids of each chromosome-now called daughter chromosomes, each containing

		one double-stranded DNA molecule-move to opposite ends of the spindle. 9. This pathway consists of a series of redox reactions in which electrons derived from hydrogen atoms are passed from one type of carrier to another and finally are allowed to react with O2 to produce water. 10. This new oxaloacetate can react with a second acetyl CoA, producing a second molecule of citrate and thus enabling the cycle to continue. 11. In other combinations, the red blood cells of one individual form clumps because of the presence in the other individual's serum of specific proteins, called antibodies, that react with foreign, or "nonself," cells.
Export/ electrical energy	Circuit board, electric wire, electric switch	1. Depending on the channel, this stimulus can range from the binding of a chemical signal to an electrical charge caused by an imbalance of ions. 2. This binding causes changes in the membrane potential of the sensory cells, which release neurotransmitters onto the dendrites of the sensory neurons. 3. When an action potential arrives at the neuromuscular junction, neurotransmitter from the motor neuron binds to receptors in the postsynaptic membrane, causing ion channels in the motor end plate to open.
Export/ solid material	N/A	N/A

Discussion

Importation and exportation of solid material did return engineering results; however, in regards to the voluntary human/object that interacts with the flooring the results are out of context. Therefore, the engineering solutions are ignored and not presented here. Considering the flow of *electrical energy*, and the respective functions, the Design Repository returned several engineering component solutions. Solutions of electrical wire, electrical switch, circuit board and battery are commonplace, but offer a wide range of functionality. Although a biological solution may not have practical uses for *importing, regulating, transferring, transmitting* and *exporting electrical energy*, the concept generator results are interesting and informative. Essentially, what an engineer can gain from these biological results is that natural systems do utilize electrical energy for communication, sensing, regulating metabolism, photosynthesis and many other processes.

Results that are more intriguing are the biological phenomena relevant to the function of *detect*. Of the twelve returned solutions, hair cells, electroreceptors, echolocation, carotiod and aortic stretch receptors, membrane receptor proteins, graded action potentials and DNA offer the greatest potential to inspire a detection mechanism. The hair cell operates like a cantilever and would detect a presence when disturbed, such as being stepped upon. Electroreception and echolocation could be used like radar and even detect the presence of an object when it is just above the flooring. Detecting a certain material could adapt the idea of carotiod and aortic stretch receptors, by monitoring deformation in a material. Membrane receptor proteins and graded action potentials alter the flow of ions, thus indicating a difference in the environment. Chemical modifications within the flooring material, as suggested by DNA, could also signal the presence of a solid object. Perhaps the natural phenomena that most readily allow analogy discovery and inspiration are the hair cells and carotiod and aortic stretch receptors. These two solutions offer natural tactile responses that could be exploited to achieve the customer requirements.

Functional results for *indicating* a *status signal* are a mixed set of analog and digital methods. Engineered solutions suggest lights, LCD screen, tube, or an analog gauge, and the biological solutions suggest a change in color or shape, swelling, molecule production and expelling of pheromones. Again, the biological results may be more informative than useful; however, in the event that the resultant engineered solutions are not useful the designer has the opportunity to investigate the biological solutions for inspiration. It can be concluded that the concept generation technique was successful at extracting specific biological phenomena that perform the functions of the conceptual functional model.

Conclusions

Concept generation and synthesis is perhaps the most exciting, important, and challenging step of engineering design. The research proposed in this paper makes fundamental contributions to engineering design through the creation of a computational concept generation technique for biologically-inspired, engineering design. The key contributions of this research extend beyond computational design practices and biological information retrieval. The tool proposed here represents a first step toward enabling widespread biologically-inspired concept generation. Also, this research will enable engineers knowledgeable of customer needs driven design activities, but a limited biological background, to begin biomimetic design activities. Mimicking nature offers more than just the observable aspects that conjure up engineering solutions performing similar functions, but also less obvious strategic and sustainable aspects. It is these less obvious analogies that this research aims to facilitate as they hold the greatest potential impact for engineering as a whole.

The computational concept generation technique assists with developing biologically-inspired, engineering designs that partially (i.e., one or two components) to completely (i.e., entire design) mimic a biological organism, strategy or phenomenon. Integrating biological system information with MEMIC, an established computational concept generation method, affords a computational foundation for accessing engineering information stored in a design repository. Utilizing the organized search tool afforded a strategic method for indexing non-engineering information for use with design activities. Example results from the proposed technique were demonstrated with the smart flooring example.

The designer must remain flexible throughout the concept generation process and be open to consider biological systems from different viewpoints, which might prompt the designer to discover novel and innovative ideas. By placing the focus on function rather than form or component, the utilization of biological systems during concept generation has shown to inspire creative or novel engineering designs. An example demonstrating how the computational concept generation technique was used to generate biological phenomena that could be utilized for designing a security or surveillance device was presented. Biological phenomena relevant to the functions of *detect, regulate, indicate, transmit* and *transfer* were discussed and analyzed. Analogical reasoning points to the biological solutions of hair cells, electroreceptors, membrane receptor proteins, carotiod and aortic stretch receptors, echolocation, DNA, and graded action potentials as inspiration options to the function of *detect* for the smart flooring example. The other functions yielded informative results of how natural systems utilize electrical energy. The proposed concept generation algorithm provides targeted results, which quickly prompt creative solutions and stimulates designers to make connections between the biological and engineering domains.

The biological domain provides many opportunities for identifying analogies between what is found in the natural world and engineered systems. It is important to understand that the computational concept generation technique does not generate concepts; that is the task of the designer. However, the proposed technique does provide a systematic method for discovering biological inspiration based on function, so that it may be easier for the designer to make the necessary connections leading to biologically-inspired designs.

Future work for the proposed computational concept generation technique involves implementation of the algorithm and testing of the code. Further work would include integrating images into the concept generation results. Visuals can stimulate designers in a different manner than text alone. Another avenue for this research is for discovering analogies between the biology and engineering domains. Thus, the concept generator could be utilized for analogy identification for research purposes, but also assisting engineering design students in learning analogical design.

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