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Automated Retrieval of Non-Engineering Domain Solutions to Engineering Problems

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Abstract

Biological inspiration for engineering design has occurred through a variety of techniques such as creation and use of databases, keyword searches of biological information in natural-language format, prior knowledge of biology, and chance observations of nature. This research focuses on utilizing the reconciled Functional Basis function and flow terms to identify suitable biological inspiration for function based design. The organized search provides two levels of results: (1) associated with verb function only and (2) narrowed results associated with verb-noun (function-flow). A set of heuristics has been complied to promote efficient searching using this technique. An example for creating smart flooring is also presented and discussed.

Keywords:

Engineering design, Function, Biomimicry, Information retrieval

1 INTRODUCTION

The idea generation and inspiration for engineering designs can be arrived at in a multitude of ways. Formal methods include, but are not limited to, brainstorming, analogy, 635 method, gallery, delphi, synectics, analysis of current products, and analysis of natural systems [1]; brain-ball, C-sketch, and morphological analysis [2], functional reasoning [3]; systematic classification [4]; or creative conceptual design [5] [6]. Whichever method is preferred and utilized, design is about meeting a need of society through fulfilling it's required functions [7].

Function based design, encompassing the above idea generation and inspiration methods, aims to represent a system or product in it's most abstract form using functionally descriptive words. Using the same functionally descriptive keywords to search for analogies or solution strategies to the desired function is an obvious corollary. Therefore, the search algorithm presented in this paper is formulated in the manner stated by Abbass: "we need somehow to choose the problem solving approach before representing the problem" [8].

"Science is the study of the natural world; it is concerned with understanding what is. Engineering design is concerned with creating new things; it makes extensive use of science, but is a quite different activity. … it is only the support of science that has made possible the quickened pace and great achievements of engineering today, and in most fields nowadays the designer must have a solid background of scientific knowledge." – [9]

Science, as inspiration for analogous solution priniciples, has greatly influenced engineering as a whole. For instance, the recently formalized and growing field of Biomimetics or Biomimicry is a design discipline devoted to studying biological systems and imitating related principles to solve engineering problems [10]. 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, self-cooling buildings etc.).

Searching for and retrieving analogous solution information as part of function based design, has several methods. Searching the Internet, a database and a subject domain specific corpus are common approaches. However, each method contains unique properties that provide successful results. The same is true for this research and in Section 5 a set of heuristics (not related to modern heuristics such as genetic algorithms, tabu search, ant colony optimization, simulated annealing or immune systems) are introduced that allow engineering designers to mine data for inspiration or direct solutions.

2 RELATED WORK

2.1 Information Retrieval in Design

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 [11]. 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. 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 [12]. 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 [13].

2.2 Biology in Design

Previous problem solving by inspiration based on biological principles may have happened by chance, but several engineering design researchers have created methods for transferring biological phenomena for use in the engineering domain. A short list of prominent research in biologically inspired products, theories, and design processes include: [14-16] [17,18]. With the right tools, knowledge transfer between the biological and engineering domains can be facilitated and biomimetic designs can be systematically realized.

Chakrabarti *et al.* developed a software package entitled Idea-Inspire that allows one to search a database by choosing a verb-noun-adjective set [19]. Their database is comprised of biological and engineered mechanical systems. Each entry's action is described functionally by behavioral language in the form of a function-behavior-structure model. Chakrabarti's Idea-Inspire software yields seven behavioral constructs for each biological phenomenon within the search results, the aim is to inspire ideas rather than solve the problem directly. Wilson and Rosen approach biological systems through reverse engineering to determine behavioral characteristics [20]. This method begins assuming a biological system has been identified using other methods and involves functionally abstracting or decomposing the biological system into physical and functional parts. A behavioral model and truth table depicting system functionality allows the designer to describe the biological system with domain-independent terms, which allows for the transfer of general design principles.

A searchable database that focuses on technology transfer between biology and engineering is the TRIZ-based (Teoriya Resheniya Izobretatelskikh Zadatch) method by [21]. TRIZ provides the user with the results of analyzing 3,000,000 patents and over 6000 physical, chemical, mathematical and engineering solutions all classified in terms of function. By reformatting the problem into abstract representation, a list of possible solutions is generated, which leads the designer to a specific solution. Shu *et al.* have developed a method for identifying relevant biological analogies by searching through biological knowledge in natural-language format using functional keywords [22,23]. The engineering domain keywords are expanded using WordNet to create a set of natural-language keywords to yield better search results, which could be based on multiple keywords. This method has successfully generated biologically inspired solutions to engineering problems [24].

Researchers at the University of Toronto have also worked to provide designers with biologically meaningful words that correspond to the Functional Basis functions. They analyzed the functions in the secondary and tertiary levels as well as correspondent terms to develop groups of words that were similar according to WordNet [12]. Biologically meaningful words were identified through a methodology developed by Chiu *et al.* [25] using bridge verbs, verbs that were modified by a frequently occurring noun. Four cases for identification are discussed and examples presented [12]. Based on semantic relationships, the engineering function terms of the Functional Basis were used to systematically generate a list of biologically connotative keywords. Synonyms, troponyms and hypernyms of functions were identified, effectively creating a thesaurus of biological terms that map to Functional Basis functions.

3 RESEARCH APPROACH

Due to the vast array of information available via the Internet, books, libraries and other sources, knowing where to start searching for design inspiration can be difficult. There are no wrong ways to search for analogies in design; rather there may be more effective and efficient ways. The approach presented in this paper is to conduct an organized verb-noun search of a non-engineering corpus, such as a textbook or Internet resource. This search utilizes the lexicon of engineering terms known as the reconciled Functional Basis and the automated retrieval tool created at Missouri University of Science and Technology. The majority of non-engineering corpi are written in natural-language format, which prompted the use of a Functional Basis function (a verb) and a flow (a noun). In general, by selecting an introductory text that covers a broad spectrum of topics in the non-engineering domain, a wide range of analogies presented at a level that is understandable for engineering design can be found. The goals of this research are to:

- Create a method for concept generation to identify suitable non-engineering domain inspiration for function based design from a searchable corpus.
- Create a general approach for design by analogy that supports the search of non-engineering domain inspired solution strategies for engineering design problems.
- Extract analogy-inspired solution strategies for specific engineering problems from non-engineeirng texts through organized verb-noun searches with the automated retrieval tool.

Two specific design strategies are used for generating solutions to engineering problems through automated retrieval of information: (1) the Functional Basis, and (2) the organized verb-noun search algorithm. Both tools are summarized in the next sections to give the reader a background for understanding the organized verb-noun search algorithm. Following that, an overview of the organized verb-noun search algorithm advocated in this research is presented.

3.1 Functional Basis

The set of generally valid functions and flows proposed by Pahl and Beitz [1] was further evolved by Stone and Wood into a well-defined modeling language comprised of function and flow sets with definitions and examples, entitled the Functional Basis [26]. Hirtz, *et al.* later reconciled the Functional Basis into its most current set of terms [13]. Here, a function represents an operation performed on a flow of material, signal or energy. 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 24 tertiary functions, each with a set of correspondent terms to aid the designer in choosing the correct function. Similarly, there are 22 tertiary flows, with certain ones having correspondent terms. Tables 1 and 2 provide the function set and the flow set at the class and secondary levels, respectively.

Note: The function set in Table 1 comprises the verbs for the automated verb-noun search in Section 4. However, the nouns referenced in Sections 4-6 are not those listed in Table 2.

3.2 Organized Verb-Noun Search Strategy

In this section, we present a specific strategy developed 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

Class	Branch	Channel	Connect	Control	Convert	Provision	Signal	Support
Secondary	Separate	Import	Couple	Actuate	Convert	Store	Sense	Stabilize
	Distribute	Export	Mix	Regulate		Supply	Indicate	Secure
		Transfer		Change			Process	Position
		Guide		Stop				

Table 1: Partial Functional Basis function set. [25]

Class	Material	Signal	Energy	
Secondary	Gas	Control	Acoustic	Hydraulic
	Human	Status	Biological	Magnetic
	Liquid		Chemical	Mechanical
	Solid		Electrical	Pneumatic
	Plasma		Electromagnetic	Radioactive/Nuclear
	Mixture		Human	Thermal

Table 2: Partial Functional Basis flow set. [25]

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 function (verb) and flow (noun) entry fields with search and directory options. Search options prompt the designer to choose from exact word, derivatives of the word, and partial word. If the designer does not want to search by verb-noun, a function only option is also available.

For this paper, the non-engineering domain chosen for examples is biology. To enhance this search strategy, the biologically meaningful function terms identified by Cheong *et al.* [12] can be included with the original search verb when performing the second search. Additionally, the biological meaningful flow terms identified by Stroble *et al.* in their engineering to biology thesaurus can be used to relate engineering flows to their biological synonym [27]. The search typically yields more than one biological phenomenon. Thus, the designer will examine the text excerpts and decide which biological phenomena are best suited for solving the problem.

The designer utilizing this organized search technique does not need an extensive background in the non-engineering domain but, rather, the designer must have sufficient engineering background to abstract the unsolved problem to its most basic level utilizing the Functional Basis taxonomy.

4 ORGANIZED VERB-NOUN SEARCH ALGORITHM

The sub-sections below describe how the organized verb-noun search algorithm is executed. The designer initiates the search using a function word, chooses how the search word is treated and all other steps are automated. Search results are then presented to the designer whom must decide which biological phenomena are best suited for solving the problem. Search heuristics provided in Section 5 present scenarios an engineering designer might encounter when searching for design inspiration or solutions.

4.1 Step 1: Initial Verb Search

Functional Basis functions are the foundation for the organized verb-noun search. In context, the “verb” is any secondary or tertiary level function from the Functional Basis. To produce additional search results, the class level Functional Basis words can also be used. However, those words are generally discouraged as the resulting text excerpts or matches are often repeated and offer limited insight. Thus, the designer should choose the correct verb from the Functional Basis, based on the definitions and examples provided in appendix of [13] for the problem that needs to be solved. For example, to find out how biological systems measure various parameters, the word *measure* (tertiary level under Signal in the Functional Basis) should be the chosen search verb. The results of the verb search are used to generate the list of frequently occurring subject domain specific nouns in Step 2.

4.2 Step 2: Generate a list of frequently occurring collocating nouns

The “nouns” generated in this step can be likened to Functional Basis flows, as they are often representations of material, energy and signals within the chosen subject domain. Using a function as the search keyword yields many results, however, a poor choice of keyword can yield vague or unhelpful results. By generating the set of subject domain specific nouns, a complementary set of search keywords to the original verb keyword is provided to focus and minimize time spent searching.

Utilizing the collocation strategy by [28], the results of Step 1 are passed through a script that generates the set of subject domain specific nouns. The result entails a list of words that occur in the Step 1 results and the number of occurrences for each word. With the most frequent word starting the list, the words are sorted in descending order down to single occurrences. Additionally, only content-bearing words are counted and English language articles, spelled-out forms of numbers, single letters, common adjectives, verb phrase headers and other frequently used verbs are ignored. Each of the subject domain specific nouns is used in the second search (Step 3). Occasional adjectives or verbs appearing in the noun list should be dismissed as most, if not all, are abstract in nature. Now the designer has the two pieces that are needed for the complete organized search.

4.3 Step 3: Perform Verb-Noun search

This salient step is the key to eliminating the majority of non-relevant search results, leading to a quick judgment of the search keyword and its success, thus saving time and effort. With the original search verb and a list of subject domain specific nouns, the designer can search non-engineering knowledge in natural-language format to identify focused matches, in this particular case, for relevant biological phenomena. The nouns used for this portion of the algorithim are not input into the automated retrieval tool in the same fashion as the verb keyword.

The nouns generated in Step 2 are automatically paired with the verb keyword and searched. Control of the noun list is only through the chosen non-engineering corpus. An additional search option, to increase the search robustness, is to cross-reference the search verb with the biologically meaningful functions identified by Cheong *et al.* [12]. One who is familiar with the Functional Basis can think of it as a function-flow search. To perform the verb-noun search, each period delimited sentence of the chosen documents is scanned for concurrent instances of the verb and noun pair, not necessarily in consecutive order. This verb-noun search recursively executes for each subject domain specific noun generated in Step 2, starting with the most frequent, while keeping the verb the same. If the designer chooses to include thesaurus terms the search algorithm would then repeat the verb-noun search, switching only the verb word. For example, the search pairs might be (biologically meaningful words corresponding to stabilize are italized [12]):

- Stabilize-cell, membrane, temperature, structure, …
- *Connect*-cell, membrane, temperature, structure, …
- *Bind*-cell, membrane, temperature, structure, …

4.4 Step 4: Display search results

The resulting matches from each verb-noun search are complied to form the set of phenomena that correspond with the function represented by the verb and displayed to the designer on screen. Results are displayed according to the type of search, and are separated by searched document and presented in a sequential format on screen. If verb only searches were conducted, only the sentences containing the verb are displayed. For verb-noun searches, the list of subject domain specific nouns is listed first with frequency number and references to their occurrence in the searched document. As mentioned before, searching multiple documents displays each set of results individually to deter confusion.

4.5 Step 5: Interpreting results

The organized verb-noun search algorithm results can suggest direct solutions by examining the resulting compiled excerpts that describe biological phenomena, and mapping them to possible engineering design solutions using analogical reasoning. Determining whether or not to use a particular biological phenomenon is largely up to the designer's discretion.

5 HEURISTICS FOR INFORMATION RETRIEVAL

Strategies for retrieving focused results from a subject domain specific corpus are presented here. Depending on the stage of the design process, search criterion may vary widely, thus a set of heuristics has been complied to promote efficient searching using this technique. Our definition of heuristics for information retieval is: A method of extracting useful information from a user defined corpus, empirical in nature, to aid in engineering design. Functional models are used in function based design and are considered input for these scenarios. Stone *et al.* [29] identified three modular heuristics for functional models, two of those heuristics have been adapted to this research and modified with the concept of primary/carrier flow by Nagel *et al.* [30]. The Delta cordless circular saw functional model in Figure 1 is provided to demonstrate several of the heuristics. The function based design heuristics that grew out of using the automated retrieval tool presented in this paper are listed below:

- General inspiration search

To provide the broadest set of analogies, perform a verb only search with the Functional Basis function that is closest to the desired functionality of a conceptual design. Creating a black box model is a reliable method for narrowing down possible functions when performing the verb only search. Furthermore, opting for the partial word search will return the most matches by generating the most nouns related to the subject of the searched corpus.

- Dominant flow
    - a. Concept has dominant material flow
    - b. Concept has dominant energy flow
    - c. Concept has dominant signal flow

A dominant flow can be of material, energy or signal type.

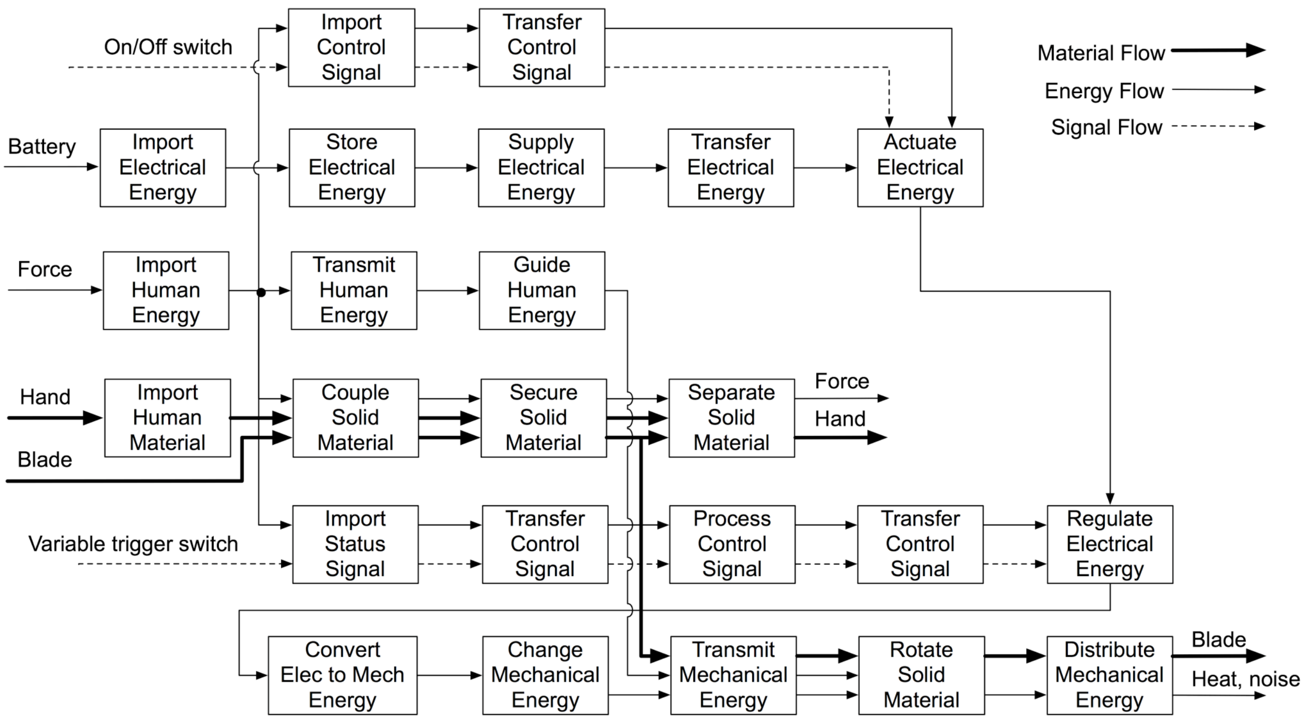

Figure 1: Delta cordless circular saw functional model.

It must enter or be initiated within the system, pass through until it exits or is converted into another flow and be of importantce to the system as a whole. The dominant flows, or primary flows, in Figure 1 are: (1) on/off switch control signal, (2) variable trigger switch control signal, (3) electrical energy of the battery, (4) mechanical energy of the rotating blade, and (5) human hand guiding the blade. With a dominant flow, nouns are of great importance and choosing the exact search word option during a verb-noun search yields only the text excerpts for prime nouns; reducing the clutter in the results.

- Branching flow

A branching flow is a material, energy or signal flow that creates parallel function chains. Human energy as force and the blade in Figure 1 are examples of branching flows. From a functional standpoint they are carrier flows as they are necessary to the system but not of primary importance to the user. Thus, a verb-noun search with the derivations of the search word option chosen yields nouns that support the function word leading to encompassing, yet focused results.

- Redesign phase
    a. Rework components, more elegant solution
    b. Concept needs innovation
    c. Looking for analogy

Perhaps the most interesting heuristic is that of redesign. The full potential of the automated retrieval tool is realized when innovation or analogies are the result. Calling upon any synonymous functions during a verb-noun search will greatly increase the designer's chances of discovering a direct solution. Increasing the elegance of an older design can be achieved by updating system components. This goes back to primary flows achieving the function, thus an exact search word option verb-noun search is the best choice for this scenario.

- User defined verb – Non Functional Basis verb

The fifth heuristic is included for the anomalous case when the Functional Basis functions do not produce usable search results for the chosen non-engineering domain corpus. In this instance other verb-noun pairs must be generated by the designer.

6 EXAMPLE

To demonstrate the organized verb-noun search, a smart flooring example is presented. The automated retrieval tool is utilized to search for biology inspired analogies that can be implemented in a product.

When using the Functional Basis for product design there are a few basic steps needed before the search for inspiration or solutions can be performed. First, one must define the customer needs and convert them into engineering terms [31]. Second, one must develop the conceptual functional model of the desired new product using the Functional Basis function and flow terms. Examples can be found in [32] and [30]. The designer now has several Functional Basis functions that could be used with the automated retrieval tool to gain inspiration. However, to minimize the search time, the designer should start with a black box representation of the desired solution, which designates the main function and flow term [1]. The main function is most likely the keyword (verb) chosen for generating useful biological phenomena via the automated retrieval tool.

6.1 Smart Flooring

The 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 block box model (Figure 2) and the functional model (Figure 3) are created. The main function of *detect* is input into the automated retrieval tool for a verb-noun search and the exact word option is selected, as Figure 3 contains many dominant flows. The search resulted in 29 text excerpts shown in Figure 4 in the form of individual sentences. Both relevant and non-relevant text excerpts are displayed in Figure 4 to demonstrate the format of the search results.

The corpus chosen for this automated retieval of biological solutions to engineering problems was *Life, The Science of Biology* by Purves *et al*. [33]. Our corpus is comprised of 58 separate files, one for each chapter of the textbook. The results are separated by each file in the corpus and each instance of a match references the paragraph and sentence within the searched file. Additionally, if the designer wishes to observe the generated nouns from a verb-noun search, they are displayed in alphabetical oerder, with paragraph and sentence citations above the collection of results.

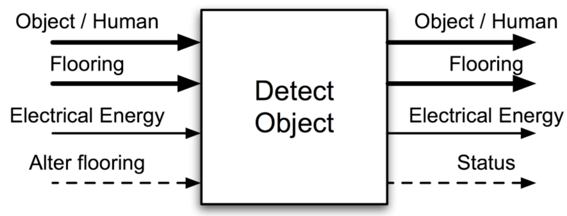

Figure 2: Smart flooring black box model.

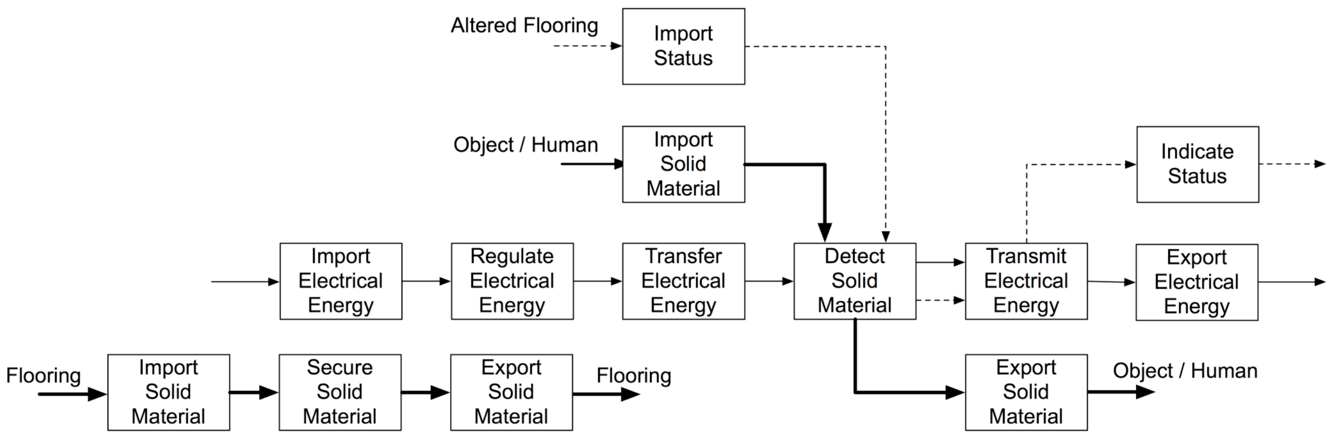

Figure 3: Smart flooring functional model.

Results for chapter 11

(1) Paragraph 107 Sentence 0: 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 rThe repair mechanism can detect the "wrong" base because a newly synthesized DNA strand is chemically modified some time after replication.
(2) Paragraph 120 Sentence 2: This technique measures the length of the DNA fragments, and can detect differences in fragment length as short as one base.

Results for chapter 12

(3) Paragraph 8 Sentence 2: This fact is important because it means that even recessive mutant alleles are easy to detect in experiments.

Results for chapter 13

(4) Paragraph 155 Sentence 0: Sequencing has also provided the necessary information for the design of primers and hybridization probes used to detect these and other pathogens.

Results for chapter 17

(5) Paragraph 73 Sentence 0: In addition to genes for antibiotic resistance, several other marker genes are used to detect recombinant DNA in host cells.
(6) Paragraph 93 Sentence 4: The second is the use of "DNA chips" to detect the presence of many different sequences simultaneously.
(7) Paragraph 102 Sentence 5: This method may provide a rapid way to detect mutations in people.
(8) Paragraph 130 Sentence 2: Some diabetics' immune systems detect these differences and react against the foreign protein.
(9) Paragraph 176 Sentence 5: If an organism is present in small amounts, PCR testing will detect it.

Results for chapter 18

(10) Paragraph 106 Sentence 1: We will describe their use to detect the mutation in the ?-globin gene that results in sickle-cell anemia.
(11) Paragraph 145 Sentence 2: It is also possible to detect early in life whether an individual has inherited a mutated tumor suppressor gene.
(12) Paragraph 169 Sentence 1: Scientists attending this conference quickly realized that the ability to detect such damage would also be useful in evaluating environmental mutagens.
(13) Paragraph 169 Sentence 2: But in order to detect changes in the human genome, scientists first needed to know its normal sequence.

Results for chapter 19

(14) Paragraph 108 Sentence 1: For example, they have been invaluable in the development of immunoassays, which use the great specificity of the antibodies to detect tiny amounts of molecules in tissues and fluids.

Results for chapter 23

(15) Paragraph 78 Sentence 2: However, as soon as they detect homoplasies, systematists change their classifications to eliminate polyphyletic taxa.

Results for chapter 24

(16) Paragraph 6 Sentence 1: Because modern molecular techniques enable us to detect substitutions at the level of nucleotides, molecular evolutionists can measure even these nonfunctional changes.
(17) Paragraph 23 Sentence 2: One way to detect homologous genes in distantly related organisms is to find identical or nearly identical families of genes that produce similar effectsin a wide varity of organisms.
(18) Paragraph 40 Sentence 2: The more types of molecules we use, the better we can detect homoplasies.

Results for chapter 40

(19) Paragraph 10 Sentence 6: Smell and taste receptors, for example, are epithelial cells that detect specific chemicals.

Results for chapter 45

(20) Paragraph 1 Sentence 6: Dogs can be trained to detect the signature odors of such items, so they are used by police, customs agents, and other investigators to identify those odors wherever suspicious activities are occurring.
(21) Paragraph 32 Sentence 16: 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.
(22) Paragraph 51 Sentence 5: Thus while the hawk is flying, it sees both its projected flight path and the ground below, where it might detect a mouse scurrying in the grass.
(23) Paragraph 67 Sentence 3: These sensory cells enable the fish to detect weak electric fields, which can help them locate prey.
(24) Paragraph 67 Sentence 6: 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.
(25) Paragraph 71 Sentence 5: Eyes vary from the simple eye cups of flatworms, which enable the animal to sense the direction of a light source, to the compound eyes of arthropods, which enable the animal to detect shapes and patterns, to the lensed eyes of cephalopods and vertebrates.

Results for chapter 49

(26) Paragraph 44 Sentence 4: Electrodes placed on the surface of the body at different locations, usually on the wrists and ankles, detect those electric currents at different times and therefore register a voltage difference.

Results for chapter 50

(27) Paragraph 35 Sentence 4: 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 (see Chapter 45).
(28) Paragraph 110 Sentence 1: That is why urine tests are used to detect illegal drug use by athletes and other individuals.

Results for chapter 53

(29) Paragraph 72 Sentence 4: The larger a flock of pigeons, the greater the distance at which they detect an approaching hawk, and the less likely the hawk is to succeed in capturing a pigeion.

Figure 4: Search results for the smart flooring example.

6.2 Discussion of Results

For the purposes of this example, each result or match was given a number to make referencing individual results easier. The verb-noun search, utilizing the verb *detect*, yielded a list of 29 results. Of those results, 8 of them are relevant, which are bolded and italicized in Figure 4: Match #5, 19, 21, 23, 24, 25, 27 and 29. All other matches were deemed irrelevant because the corresponding descriptions referred to performing the function *detect* using non-biological means or equipment operated by humans. The following phenomena summarize the relevant matches, (1) the hair cell, a mechanoreceptor, found in the ear of most animals or on the body of most insects; (2) electric fields, produced by electroreceptors found in electric fish; (3) smell and taste receptors or epithelial cells; and (4) genes that mark recombinant DNA; and (5) birds flock to deter predators, are natural ways of detecting and can provide analogy for an engineered sensing solution. We were unable to derive an analogous solution that fulfills the customer need of *unseen to the human eye* using "genes that mark recombinant DNA" as stimulus. Remaining as sources for potential inspiration and analogy are the phenomena of hair cells, electroreceptors and epithelial cells. Flocking birds is difficult to directly adapt to smart flooring, but the idea of several sensors grouped together would increase the detection rate. Detecting a certain material could adapt the idea of epithelial cells, by "tasting" materials. Electroreception could be used like radar and even detect the presence of an object when it is just above the flooring. Perhaps the natural phenomenon that most readily allows an analogy and inspiration is (1) – Hair cells are like cantilevers and would detect a presence when disturbed, such as being stepped upon. It can be concluded that the automated retrieval tool was successful at extracting specific biological phenomena that perform the function *detect*.

To demonstrate how biological inspiration from hair cells could be utilized in a smart flooring product, an image that embodies one possible conceptualization is provided in Figure 5. This conceptualization exploits the tactile response provided when a hair cell is forcefully deformed. Shaded strands in the close-up view of the carpet fibers represent durable feedback elements woven into the carpet, providing hidden sensing capabilities.

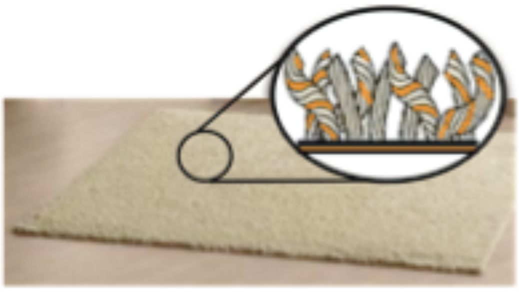

Figure 5: Image of conceptualized smart flooring product.

7 SUMMARY AND CONCLUSIONS

In efforts to bridge biology and engineering through functionality an automated retrieval tool was presented, which provides engineering designers with analogies from non-engineering domains to the engineering systems they wish to create. The automated retrieval tool developed at the Missouri University of Science and Technology significantly reduces the time spent searching biological information for solutions or inspiration by utilizing the function term of interest and subject domain specific nouns. Furthermore, the search extracts solutions to engineering problems from non-engineering domain texts and narrows resulting matches based on functionality. Non-engineering flow terms (nouns) combined with engineering function terms create a powerful tool for designers seeking biological phenomena to solve human problems or improve existing products. Engineering tools necessary for the automated retrieval were presented along with the organized verb-noun search algorithm. A set of heuristics for generating specific types of results were developed and the method behind the four significant ones were discussed. The heuristics are in place to make searching a non-engineering text user-friendly and provide precise results.

An example demonstrating how the automated retrieval search tool was used to generate biological phenomena that could be utilized or improve detection for security or surveillance was presented. Biological phenomena relevant to the function *detect* were discussed and analyzed. It was shown that starting with a black box representation of the desired solution minimized the time spent searching, as suitable biological solutions were captured in the first search. Analogical reasoning points to hair cells as the best solution for the smart flooring example out of five resulting biological phenomena that perform the function of *detect*. The organized verb-noun search algorithm of the automated retrieval tool provides targeted results, which quickly prompt creative solutions and stimulates designers to make connections between the biological and engineering domains.

8 FUTURE WORK

Future work includes developing a web-based version of the automated retrieval tool to increase accessibility and ease of use. Also, a feature that allows results to be downloaded is a proposed. With the designer in mind, the automated retrieval results could be incorporated into the other web-based engineering design tools employed by Missouri University of Science & Technology, thus catering to many schools of thought. Furthermore, including the retrieval tool results into the Concept Generator, MEMIC, [34] will provide designers with biological descriptions and analogies based on product requirements leading to the mixing of engineering and biological principles.

The organized verb-noun search algorithm was presented here utilizing information from biology; however, this retrieval tool can be used for mapping any non-engineering subject to engineering through functionality. It would be interesting to look at how law, history or even psychology maps to engineering, as the generated nouns are subject domain specific.

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