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A SYSTEMATIC APPROACH TO BIOLOGICALLY-INSPIRED ENGINEERING DESIGN

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ABSTRACT

To facilitate systematic biologically-inspired design, a design methodology that integrates with function-based design methodologies has been formalized. The goals of this methodology are to go beyond the element of chance, reduce the amount of time and effort required for developing biologically-inspired engineering solutions, and bridge the seemingly immense disconnect between the engineering and biological domains. Using functional representation and abstraction to describe biological systems presents the natural designs in an engineering context and allows designers to make connections between biological and engineered systems. Thus, the biological information is accessible to engineering designers with varying biological knowledge, but a common understanding of engineering design methodologies. Two approaches to validation are presented. One examines current biologically-inspired products either in production or in literature to see if the systematic approach to biologically-inspired design can reproduce the existing designs. The second investigates needs-based design problems that lead to plausible biologically-inspired solutions. This work has demonstrated the feasibility of using systematic design for the discovery of innovative engineering designs without requiring expert-level knowledge, but rather broad knowledge of many fields.

1. INTRODUCTION

Engineering design is considered both an art and a science, which encourages the use of engineering principles, imagination, prior knowledge, stored knowledge and a designer's intuition to create engineering solutions. The resulting solution may or may not be innovative, novel or what some would call creative; however, the design should fulfill a purpose or answer a need [1-6]. To arrive at a solution, it is not uncommon for engineers to make analogies amongst different engineering disciplines (i.e., an electrical resistor and mechanical damper are mathematically analogous) during ideation to find solutions or use metaphors to frame or assist with defining the design problem [7]. The leap made between engineering disciplines using analogies is to be expected as one gains more experience; however, making a leap between domains is less likely to occur without an impetus. Take for instance Velcro©, if it weren't for the curiosity of George de Mestral that caused him to investigate how the tiny burrs he and his dog accumulated from walking through wooded areas, modern day hook and loop may never have been invented or it may not be as effective. George de Mestral's chance observation of a biological system resulted in a very simple, reusable material [8] that has been used for securing everyday items such as shoes to mission critical items needed for exploring space.

It is evident that nature can inspire innovative engineering designs. However, for engineering designers to adopt such a practice, design tools, techniques and methods are needed. Utilizing biological information during the engineering design process has taken many forms. Inspiration for solving or finding direct solutions to engineering problems has been obtained through functional keyword searches, reverse engineering, use of function-structure-behavior models, use of databases, analogical and case-based reasoning, and bioTRIZ among others. These inspiration facilitators are meant to reduce the time and effort required to learn from and mimic nature. Although each facilitator has a different procedure and focuses on a specific step in the overall design process, they all share one thing in common; the promising biological system must be abstracted to capture some fundamental principle. What is lacking is one comprehensive set of tools and methods, a framework, that approaches biologically-inspired design from a single design perspective that can guide a designer from initial problem definition to complete concept.

Due to the seemingly immense disconnect between the engineering and biological domains, biologically-inspired designs often seem exotic or unachievable unless a significant amount of time and effort is devoted to the task. This reveals the knowledge requirement problem of working across domains. A fundamental problem to effectively execute biomimetic designs is that the effort and time required to become a competent engineering designer creates significant obstacles to becoming sufficiently knowledgeable about biological systems (the converse can also be said). Knowledge requirements, however, can be alleviated with (1) the development of design tools that use a perspective common to engineers to interface with the biological information and (2) integration of those design tools with existing engineering design methods.

An internationally accepted and well-known design methodology is the systematic approach to engineering design developed by the German professors Pahl and Beitz. Their pioneering work was published in German in 1977 and translated into English in 1984 [9], and is now in its third edition [10]. The overall design of a product is broken down into distinct design activities, each consisting of multiple steps. The hallmark of this method is the use of separate functional modules that when aggregated create a functional model. The major advantage of this approach is the simplification of the subsequent design process for the individual module. Overall, this and other function-based design methods offer several advantages for biologically-inspired design:

- archival and transmittal of design information;
- reduces fixation on aesthetic features;
- reduces fixation on some particular physical solution;
- allows one to define the scope or boundary of the design problem as broad or narrow as necessary; and
- encourages one to draw upon experience, knowledge stored in a database or through creative methods during concept generation.

Functional abstraction and representation, as used in systematic design, is recognized as a way to connect nature and engineering through a commonality. This research answers the knowledge requirement problem of working across the biological and engineering domains and, through functional modeling, offers the advantages listed above. Multiple supplementary design tools for existing function-based engineering design methods are developed to enable systematic biologically-inspired design. Together they comprise a framework, which offers guidance for engineering designers in the pursuit of biological inspiration. Such design techniques and tools include a search tool for finding biological inspiration, a thesaurus of biological terms that correspond to engineering terms, a method for developing biological functional models, and two approaches to interacting with biological information for the purpose of concept generation.

The systematic approach to biologically-inspired design will provide the necessary support for designers to more quickly access and understand biological information for use with Function-based design methodologies. By creating a bridge between the two domains through the perspective of function, engineers can leverage the elegant designs found in the world around them.

2. RELATED WORK

With biologically-inspired design emerging as its own field, engineering design research has begun to investigate methods and techniques to systematically transfer biological knowledge to the engineering domain. The main goal of these research efforts is to create methods, knowledge, and tools to facilitate design activities. Much of the research has resulted in the creation of inspiration facilitators, design tools that assist with concept generation and comprehensive design approaches.

Inspiration facilitators for biologically-inspired design include keyword searching, populated databases and the development of analogies between biological and engineering principles, components and systems. Focused searching for biological inspiration has been achieved through keyword searches of a biological corpus. Hacco and Shu [11] devised a search process that uses natural language processing to identify relevant non-technical keywords for searching a biological corpus, which was later refined for identifying relevant biological analogies by searching a biological corpus using functional keywords [12, 13]. Chakrabarti et al. [14, 15] developed a software package entitled Idea-Inspire that allows one to search a database comprised of natural and artificial mechanical systems using a function-behavior-structure set. Each entry's motion or process is described functionally by behavioral language with the aim of inspiring ideas rather than solve the problem directly. Although keywords and populated databases can lead to analogies drawn between biology and engineering there are several efforts devoted to formulating those types of analogies. Nachtigall has spent many years identifying analogous systems in nature and produced several books that catalog his findings [16-18]. The books are intended to provide a designer or manufacturer with a large pool of creative implementations to spur more applications.

Mak & Shu [19] examined the processes involved with the selection and use of relevant biological phenomena. It was found that analogies based on strategies, rather than those based on descriptions of phenomena that focus on forms and behaviors are more likely to lead to a suitable design. Research by Linsey et al. explores a method of breaking down products into a vocabulary that can then be easily transferred to an analogous system [20]. Their findings show that representing systems of interest in a semantic form increases the probability of innovation of novel, analogous systems. Hey et al. provides a thorough overview of the relationship between metaphor and analogy use in the design process and offers biomimetic examples [7]. In a similar vein, Vattam et al. [21] provides a thorough analysis of creative analogies in biologically inspired design and their theoretical foundations. Tsujimoto et al. [22] have researched deriving inspiration from the behavioral aspects of natural phenomena rather than simply mimicking it, with applications to robots and computer graphics. Also recognizing that biological principles offer inspiration for innovation were Lindemann & Gramann whom developed a procedural model for knowledge transfer [23]. The procedural model prescribes one to make analogies, abstractions and correlate biological principles to technical systems, but loosely defines the steps and tasks needed. Wen et al. [24] have developed the Product Design from Nature method that assists designers with inspiration based on biological geometric features.

Very few comprehensive design approaches, which offer both design tools and a process to execute biologically-inspired design exist to date. The two most notable are the design spiral of The Biomimicry Institute and the problem-driven and solution-based methods of the Design Intelligence Laboratory. Steps within the design spiral address, "physical design, ... manufacturing process, the packaging, and all the way through to shipping, distribution, and take-back decisions" [25]. There are six phases within this process: identify, interpret, discover, abstract, emulate and evaluate. Each phase is comprised of multiple steps, similar to the systematic process of Pahl and Beitz [10]. The design tool that accompanies the design spiral is the open-source database called AskNature [26] which is a user populated database with biological systems and indexed by design and engineering functionality. The two processes for biologically-inspired design developed by Helms et al. [27] involve defining the biological solution, extraction of the biological principle and application of the biological principle. Specifically, the problem-driven approach follows a set of steps that define the problem, reframe the problem, search for biological solutions, define biological solutions, extract the biological principle and apply the biological principle. It was found through a study that designers tend to fixate on a biological system that they think will solve the problem without thorough investigation. The observed actions were analyzed and named the solution-based approach. The solution-based approach follows the order of identify a biological solution, define biological solution, extract the biological principle, reframe solution and search for a problem that the solution might solve. Both diagrammatic and textual descriptions are used in the design processes. The design tool that accompanies the Design Intelligence Laboratory approach is the Design by Analogy to Nature Engine (DANE) [28], which assists with analogical design activities. While these comprehensive design approaches offer a database driven tool to assist with their respective design process little direction is given for the application of the design tool, thus, it is at the discretion of the designer.

3. FRAMEWORK TO SUPPORT METHODOLOGY

To enable systematic biologically-inspired design to seamlessly integrate with Function-based design methodologies four existing design tools are leveraged and four supplementary design tools that assist with interfacing biological information were developed. Together they comprise a framework, which offers guidance for engineering designers in the pursuit of biological inspiration. The existing design tools are briefly reviewed followed by an overview of each developed tool.

3.1 Existing Design Tools

This research is grounded in Function-based design theory and, therefore, relies on functional abstraction and representation to develop biologically-inspired engineering solutions. The well-defined modeling language comprised of function and flow sets created Stone et al. [29] and later reconciled into its most current set of terms by Hirtz et al. [30], entitled the Functional Basis, is used to achieve functional abstractions and representations. Another tool leveraged is the Design Repository[1] housed at Oregon State University, which contains descriptive product information such as functionality, component physical parameters, manufacturing processes, failure, and component compatibility of over 140 consumer products. Each artifact is decomposed and functionally modeled using the Functional Basis lexicon. All entries can be accessed through browsing or automated design tools, such as the automated morph matrix and MEMIC. Computational concept generation is an efficient way to generate several conceptual design variants with the added benefit of providing lists of engineering components that may be used to solve particular functions. The Morphological Evaluation Machine and Interactive Conceptualizer (MEMIC) was created for use during the early stages of design to produce design solutions for an engineering design from a given functional model using knowledge of existing engineered products [31, 32]. Similarly, the automated morph matrix tool [31] parses the engineering knowledge base to provide solutions to function/flow pairs, which designers utilize for concept generation.

3.2 Developed Design Tools

3.2.1 Engineering-to-Biology Thesaurus. The engineering-to-biology thesaurus [33] was developed to enhance the Functional Basis to encourage collaboration, creation and discovery. The structure of the thesaurus (shown in Table 1) 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 [34] 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 and it increases the probability of a creative or innovative 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.

3.2.2 Organized Search Tool. The organized search tool [35] 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 (e.g., functional model) of the unsolved problem using the Functional Basis lexicon. The verbs (functions) of the abstraction are input as keywords in the organized search tool to generate a list of matches, and subsequently a list of words that occur 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), synonymous with the correspondent words already provided in the Functional Basis flow set. The noun listing is then used in combination with the search verb results for a second, more detailed search to locate specific text excerpts that describe how the non-engineering domain systems perform the abstracted functionality with certain flows. The verb searches are constrained to the chosen corpus and the verb-noun searches are constrained to the extracted sentences that include the search verb.

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[1] www.designengineeringlab.org

3.2.3 Biological Functional Modeling Method.

Abstractions allow one to capture the essence of a product, process, or component within a succinct phrase, diagram, image or domain-independent terms. The method for functionally representing biological systems [36] assists with defining functional abstractions of biological systems for use as a reliable source of inspiration in engineering design. Mimicry categories and scales, in addition to answering a design question, aid the designer with defining boundaries or scope when developing a biological functional model. Biological category assists with framing the information in the right perspective, whereas biological scale deals with how much detail is required for an adequate representation of the biological system to utilize the information with a chosen engineering design method. Choosing a category serves to refine the boundary, but, like scale, its consideration might prompt the designer to consider the same biological system in a new and unique way leading to new ideas. Biological functional models translate key biological information from a biological context into a generalized, engineering context. Thus, the information is accessible to engineering designers with varying biological knowledge, but a common understanding of engineering design methods and lexicons.

3.2.4 Biological Concept Generation Approaches.

Two concept generation approaches were formulated to enable conceptual design of biologically-inspired engineering solutions using existing function-based design tools and methods [36]. Both approaches rely on a knowledge base that includes engineering and biological entries indexed by function. Rather than task the designer with deciding when to consider biological information during concept generation, the two approaches provide guidance through the process and reduce the time and effort required. Following a traditional Function-based design search for solutions, a black box model and functional model are developed, which are used to query a knowledge base for solutions to each function. Then, when the designer queries the knowledge base solutions are returned for functionality in the functional model. The designer then has the choice to analyze and choose biological solutions as inspiration.

4. SYSTEMATIC BIOMIMICRY METHODOLOGY

In this section the overall design methodology is given. In support of the systematic biologically-inspired design methodology, the individual design tools described in the preceding section coalesce to guide the designer from initial problem to complete concept. Figure 1 demonstrates how the developed design tools integrate and support systematic biologically-inspired design. What makes this framework particularly useful for design is the flexibility a designer is afforded when working toward a biologically-inspired solution. Each tool can be used individually and in multiple combinations. For example, the engineering-to-biology thesaurus integrates with and improves the organized search tool, but also aides with creating biological functional models. Specific interaction benefits are pointed out in the framework venn diagram of Figure 1. Using all four parts results in systematic biologically-inspired design.

The comprehensive approaches reviewed in Section 2 do not offer a framework of design tools and techniques to support the designer other than the high level steps. Additionally, they do not follow a specific design perspective. Everything is at the discretion of the designer. While the comprehensive design method presented in this paper is modeled after systematic design, there are still multiple avenues a designer can take to arrive at a biologically-inspired design. The systematic biologically-inspired design method provides enough structure without hindering the creativity and inventiveness of the designer. Rather, this method fosters and guides the abilities of the designer and encourages objective evaluation of results. The systematic approaches of this method help to render designing based on biological inspiration comprehensible and steer the efforts of designers down purposeful paths. Each step of the methodology is discussed in greater detail below. The majority of, if not all, design processes are iterative and this methodology follows the same convention. Cues for when to iterate are provided. Table 1 demonstrates in which step the existing and developed design tools are leveraged.

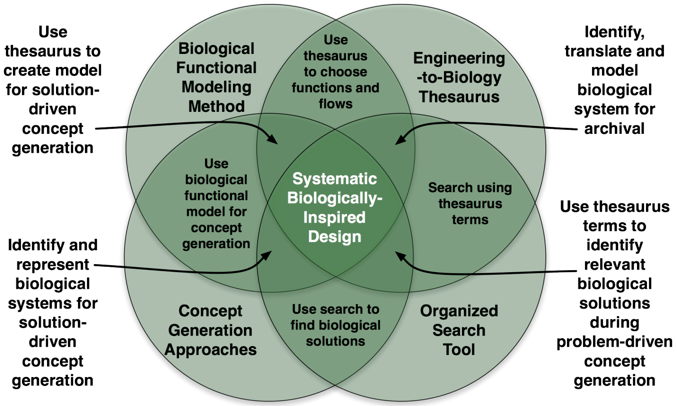

Figure 1. FRAMEWORK OF SUPPORTING DESIGN TOOLS.

4.1 Step 1: Define Problem

The first step determines which direction the design will take. A designer can choose to start from a traditional set of customer needs or explore a curiosity. These two routes are identified as problem-driven and solution-driven, respectively. The problem-driven approach is validated by the case study in Section 5.2 and therefore will be emphasized in this paper. Taking the problem-driven route means the designer must gather a set of needs, requirements and constrains. Many sources exist to aid the designer with proper needs gathering [1-6]. Identifying customer needs is the most critical part of the design process as they form the basis for device functionality and specifications.

4.2 Step 2: Decompose

The second step involves decomposing the needs or interesting biological system into, first, a black box model and, second, a functional model. All models created with this method use the Functional Basis modeling lexicon. With regard to problem-driven design, the black box aims to abstract the overall function of the device that is to be designed. Next, the input and output flows to the black box are determined. These flows are prompted by the customer needs from the first step. The next task is to create the functional model through decomposition of the black box description into sub-functions connected by flows of energy, material or signal [2, 10, 29, 37].

Functional model creation is often an iterative task. Before moving on to the next step, check to see that all customer needs have been met by identifying the flows and sub-function chains that address them [2, 10, 29, 37].

Table 1. DEVELOPED AND EXISTING DESIGN TOOLS USED IN EACH STEP OF THE METHODOLOGY.

		Methodology Steps				
	Tools	Define Problem	Decompose	Query	Make Connections	Create Concepts
Developed	E2B Thesaurus	X	X	X	X	
	Search Tool	X		X		
	Biological Func. Model		X	X	X	X
	Biological Con. Gen.			X		X
Existing	Design Repository			X	X	X
	Functional Basis	X	X	X		
	MEMIC			X		
	Auto Morph Matrix			X		

4.3 Step 3: Query

Step three involves querying a knowledge base to identify solutions to each function/flow pair of the functional model. Two knowledge bases are required: one containing successful engineered systems and the other containing biological systems. To integrate with this method, both are required to be indexed by engineering function and flow. The Design Repository containing descriptive product information serves as the engineered systems body of knowledge. Instead of creating a large knowledge base containing functionally decomposed biological systems, similar to the Design Repository, an introductory biology textbook serves as the biological systems body of knowledge. Although it is not indexed by engineering function, the engineering-to-biology thesaurus provides a starting point to find inspiration with engineering function and flow terms.

The tasks that comprise step three begin with using the MEMIC software or automated morph matrix tool to query the Design Repository and the organized search tool to query the biological corpus. Based on the number of results for engineered and biological solutions, the search may need to be repeated. Search heuristics [38] can also be applied to quickly and reliably search the biological corpus for inspiration. For engineered solutions, it can be helpful to roll-up terms to the next level in the hierarchy. For example, if transport, a tertiary level term, does not return any repository entries then the secondary level term transfer should be used. The same applies to flows. Another trick is to first reduce the detail of the flow. For example, try energy if one of the secondary level terms does not return a match. Reducing the flow detail can often lead to repository entry results.

4.4 Step 4: Make Connections

Step four involves making connections. Connections through analogies, metaphors and first principles assist with bridging the biology and engineering domains. Connections are the leaps that enable the ingenuity of nature to be discovered and adapted for use in engineered systems. Analogies [19, 20, 22, 39-48] are the most widely used and have multiple forms. Direct, indirect, and compound analogies have all been used to connect a biological system to an engineering solution. A direct analogy mimics the biological system one-to-one. An indirect analogy uses the biological system to spur analogies for inspiration but does not mimic every aspect of the biological system. A compound analogy is the combination of multiple biological system attributes that lead to analogous engineered systems. The level of difficulty in accessing and transferring an analogy is largely dependent on how remote or close the distance between the domains is [49]. Because most things in nature exhibit functionality and behavior, analogies with engineering are possible. To exemplify the connection making process for analogies, consider a few textual examples.

A micro flow detection sensor directly mimics the physiology and morphology of hair cells that make up the lateral line system in a fish. The connection is through the principle of a bending moment that is created from perpendicular flow against vertical hair cells. Mimicry is achieved through fabrication of “hair-like” vertical structures on the end of a horizontal cantilever beam [50, 51]. An indirect analogy was created between the common strain gage and the physiology of the campaniform sensillum or flexible exocuticle that many insects possess. An elliptical opening in the insect’s cuticle, which is covered by a thin membrane layer, senses deformation because of the stress concentration [52, 53]. The connection for this system is that the opening causes mechanical coupling and global amplification to occur. Mimicry is achieved by optically measuring the stress concentration at a circular or elliptical hole in a rigid material when pressure is applied; resulting in a novel sensor that can sense strain in all directions (360°) [54]. In the case of designing an electronic display that can be viewed in bright sunlight a compound analogy was used to solve the problem. Hummingbird feather and morpho-butterfly wing attributes were combined to develop a solution [55]. Hummingbird feathers contain a series of alternating layers of thin-films with different thicknesses instead of the intricate christmas tree-like structures within an air gap that butterfly wings possess. The connections here are the air gap and “thin-film like” structures, which are readily used in electronics processing today. Adding an air gap between thin-films of varying thicknesses provided the right inspiration to develop the BrightView project [55].

A designer must also be aware of analogies that hurt the design or ones that are overly complicated. Consider the biological phenomenon of abscission. When a leaf of a plant is damaged it stops the flow of auxin and allows abscisic acid to dominate, thus forming a seal around the base of the leaf stem and over a period of time the leaf falls off [56]. This biological system was used to inspire a solution to the problem of tiny parts sticking to a robot gripper in a microassembly process [57]. Considering indirect analogy for this case allowed the researchers to develop a sacrificial tool assembly. To highlight the analogy, consider the gripper as analogous to the plant, the sacrificial part of the tool analogous to the abscission zone, and the tiny screw as analogous to the leaf that is released. Separation is achieved through the breakdown of the sacrificial part of the tool (abscission zone). Notice that liquids that are analogous to auxin and abscisic acid are not present in the final design. Developing a direct analogy of abscission would require a flowing chemical that secures and releases the tiny screw. Release of the tiny screw would occur some time after the chemical flow stops and a chemical reaction takes place to loosen the part from the gripper. This analogy is time consuming, costly and not very efficient. The indirect analogy that disregards liquids is the stronger design. Therefore, another analogy form should be considered if the results lead to a bad design.

Two other approaches to formulating connections are through first principles [2, 23, 58, 59] and metaphors [7, 60-62]. Analysis of physiology, structure or behavior can lead to a connection made through first principles. Physical laws and concepts, such as the conservation of energy, that govern science as we know it also apply to natural systems. Identifying a first principle shared by both domains leads to a connection and possibly an innovation. Consider how ducks and other birds regulate their temperature during the winter to stay alive. The principle of heat exchange between the body and the legs is carried out to reduce the amount of heat lost though blood that is circulated through the legs [23]. To date, metaphors for biologically-inspired design have only been documented for architectural structures [63]. The multiple approaches to formulating connections allow a designer to discover and become inspired in a manner that best suits him or her.

4.5 Step 5: Concept Generation

The fifth step involves performing concept generation and creating biologically-inspired conceptual solutions. Concept synthesis involves analysis and reflection. Analysis of the returned engineered and biological solutions from Step 3. Reflection on the connections to the engineering domain formulated in Step 4. Synthesis of existing engineering solutions and inventive solutions inspired by biology to derive a new idea. This can be done by making charts, lists, rough sketches, background research, consulting experts, etc. Once synthesis takes place the result will be at least one concept. Depending on the number of solutions returned during Step 3 and the connections made during Step 4, multiple concepts may result. Evaluation of concepts follows systematic design; pugh charts are used to rank concepts and narrow the selection to the top one or three concepts [1-6]. Once a final concept has been reached the next phase of systematic design, embodiment, can initiate.

4.6 Multiple Design Avenues

Offering five high level steps that are customizable to the problem at hand, this methodology should not be viewed as a strict sequence of iterative tool application. Rather, the design methodology here should be viewed as a starting point or a set of guidelines that aim to arrive at a biologically-inspired design. Allowing a process to emerge that follows either problem-driven or solution-driven paths. Starting from customer needs, a curiosity, known biological system or known biological process are all possible with this methodology. The focus of this paper is to demonstrate starting from needs.

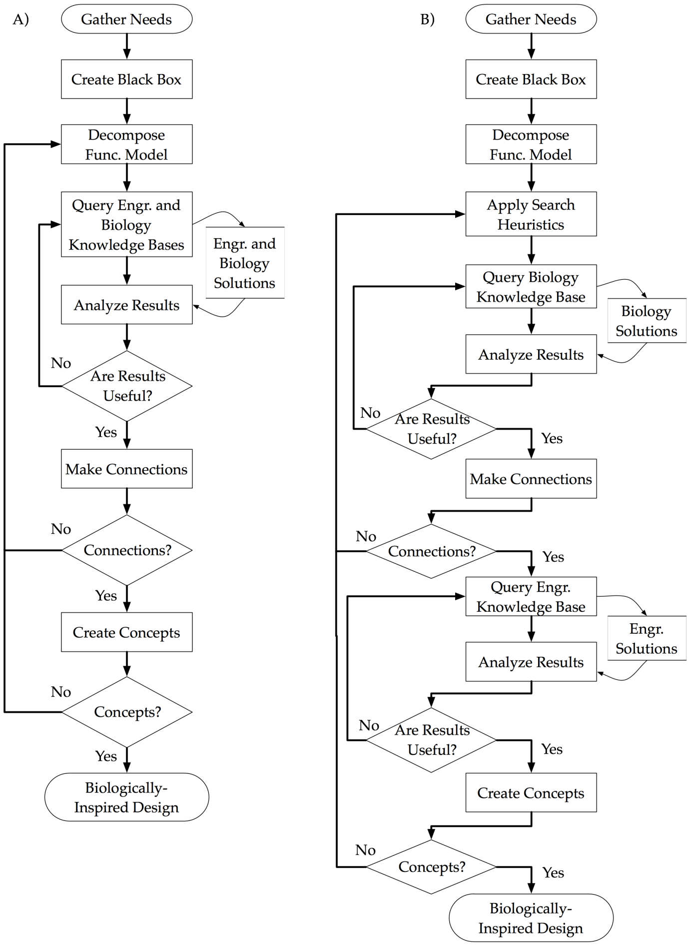

Figure 2. FLOW CHARTS OF THE SYSTEMATIC BIOLOGICALLY-INSPIRED DESIGN PROCESS; A) FOLLOWING TRADITIONAL DESIGN; B) APPLYING SEARCH HEURISTICS.

Figure 2 summarizes the avenues of the problem-driven approach that closely follow traditional systematic design.

Following flow A of Figure 2 the designer is instructed to decompose a functional model from a black box model, resulting in a conceptual functional model. The conceptual functional model, which describes the desired functionalities of a solution rather than an existing solution, is used to query the engineering and biology knowledge bases. In the event that no connections can be formalized then the designer should return to the query step and try different levels of functions and flows. The same holds true for when no concepts are synthesized.

Following flow B of Figure 2 the designer is instructed to use the organized search tool heuristics for the initial query. Once biological solutions are gathered, then the Design Repository is queried to supplement the biological solutions with engineering solutions. One difference here is that the results of the search tool should be screened first before moving on. In the event that no connections can be formalized then the designer should return to the query step and try a different heuristic. The same holds true for when no concepts are synthesized.

5. VALIDATION

Initial validation of the systematic biologically-inspired design methodology is achieved through application of the methodology to (1) check if it reproduces existing biomimetic products and (2) identify a closely related development version of a concept through literature review. Analysis and reproduction of existing biomimetic products through primary function allows the verification of the methodology as the result is known. Validating the methodology for non-existing biomimetic products requires a review of literature to quantify if the concept variants are realistic or science-fiction. Finding a closely related development version of the biologically-inspired conceptual design indicates that the concept is feasible. Similarity is based on functionality and components chosen to achieve functionality.

5.1 Proof Through Existing Biomimetic Products

Validation of a scientific method is crucial to its adoption. Reproducing familiar results through application of the method is often a first step towards validation. Validation of this method will follow a similar course. The first exercise is to analyze existing biomimetic products, apply the systematic design methodology and verify that the biological system used to inspire the original design is utilized in the results in such a way that would lead to a reproduction. The approach taken is through primary function analysis.

Table 2 lists six existing biomimetic products that one can find searching the internet. These technologies represent electrical, civil and mechanical engineering and material science. Not having physical access to analyze the technologies results in relying on textual descriptions to perform validation. From the descriptions, primary function/flow pairs were identified and represented with Functional Basis terminology. The primary function/flow pairs are then used to query the biological knowledge base. Both, representation and querying utilizes the engineering-to-biology thesaurus. If the mimicked biological system is within the query results and described in a way that would make a connection and result in a similar concept to the existing biomimetic technology, then is determined that the method can reproduce the design. A limitation of the biological corpus that comprises the biological knowledge base was determined–not all of the mimicked biological systems exhibited in current biomimetic products are included. For example, the lotus which inspired self-cleaning surfaces is not described in the introductory biology corpus. Also, the morpho-butterfly is mentioned in the corpus, but only to demonstrate the classification of its species. Therefore, a different biological knowledge base is employed. The open source project, AskNature[2], is an on-line database that biologists, engineers, designers, chemists, etc. can contribute to so bio-inspired breakthroughs can be born. AskNature is an attractive alternative knowledge base because the biological knowledge contained within the database is organized by function.

Following the five steps of the methodology, all six existing biomimetic products were reproduced. The three found with the organized search tool required the substitution of biological function and flow terms of the thesaurus, while the three found within the AskNature database needed substitution of only the flow term. Additionally, other biological systems were identified that also solve the function/flow pair, which, if a redesign were undertaken, could result in a different biomimetic design.

5.2 Proof Through Matching Concepts to Existing Products

The second approach to validation involves following the methodology, searching the literature for a comparable design and comparing the resulting biomimetic concept to an existing design. This example follows flow chart B of Figure 2. Following Step 1, the problem is defined as follows. 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 the human eye, durable, composed of common materials and a quick response. Also, the system needs to be autonomous. Meaning a signal generated can alert personnel and does not require a person to monitor the surveillance system. It is known that tagged systems require the user to carry a badge or other device to be tracked or monitored and simply removing the trackable item can defeat the system. Radar or similar systems require calibration and an area map to be created. Each time the area layout is changed, the map needs to be updated. Video surveillance and heat signature systems can be very expensive and often require a person to watch the real-time video feed who can be unreliable. The design should offer advantages over the others listed.

Table 2. ANALYSIS OF EXISTING BIOMIMETIC PRODUCTS TO VALIDATE METHODOLOGY.

Existing Biomimetic Products	Mimicked Biological System	Primary Function/Flow Pair(s)	Source	Reproduced?
Walking stick for visually impaired that uses sonar	Echolocation of bats	Detect Solid	Biological Corpus	Yes
Passive heating and cooling buildings	Termite mounds	Regulate Thermal Energy, Distribute Thermal Energy, Distribute Gas, Remove Gas	Asknature.org	Yes
Self-cleaning surfaces	Lotus	Inhibit Solid, Inhibit Liquid, Decrease Solid	Asknature.org	Yes
Motion detector	Compound vision	Detect Solid, Sense Solid	Biological Corpus	Yes
Color changing material without harmful chemicals	Morpho-Butterfly	Change Visual Signal	Asknature.org	Yes
Microassembly with sacrificial gripper	Abscission of plants	Separate Solid	Biological Corpus	Yes

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[2] asknature.org

With this knowledge the needs are mapped to flows (Table 3) for the creation of a black box model. This follows the decomposition as outlined in Step 2. Figure 3 shows the block box model. Focusing on the detection aspect, the the black box model is further decomposed into the functional model of Figure 4.

Table 3. NEEDS OF SMART FLOORING EXAMPLE MAPPED TO FLOWS.

Needs/Constraints	Functional Basis Flow
Object/Human to detect	Solid Material
Quick detection response	Status Signal
System power	Electrical Energy

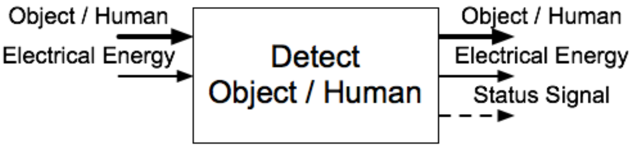

Figure 3. SMART FLOORING BLACK BOX MODEL.

For Step 3, the search heuristics were applied and the biological corpus was queried. Using the general inspiration heuristic, several interesting biological systems were found to perform the black box function of *detect*:

- Hair cell
- Electroreceptors found in electric fish
- Epithelial cells
- Genes that mark recombinant DNA
- DNA
- Birds flocking in large groups
- Echolocation
- Carotid and aortic stretch receptors
- Membrane receptor proteins
- Graded action potentials

Next, following Step 4 of the methodology, the biological systems returned for the function of *detect* are analyzed and reflected upon to formalize connections. Of the query results, many offer connections. Hair cells are analogous to cantilevers and would detect a presence when disturbed, such as being stepped upon. In a similar manner, the carotid and aortic stretch receptors link to flexible materials such as polymers. A polymer would detect a disturbance when pressure is applied, such as being stepped on. Echolocation is analogous to radar. Radar is already used to detect objects, however, it is not a distributed system, as would be needed for a smart flooring concept. The final connection made from the above list is with the electroreceptor of fish. Electroreceptors generate an electric field for navigation of the environment, to locate objects, which is also analogous to radar. Echolocation uses sound waves where electrolocation uses electric waves.

Now that connections have been established, the next step is to query the engineering knowledge base and supplement the biologically-inspired solutions with engineering solutions to complete the design. Table 4 lists engineering solutions for seven of the nine function blocks. Import and export of the solid object will occur spontaneously, which will create the altered flooring signal. With the components of Table 4 and the established analogies the final step of concept generation can begin. Recall that the critical need is unseen by the human eye. The biological system of the hair cell prompts two concept variants. Considering the hair cell as a cantilever and flooring shaped as individual tiles, each tile could act as one cantilever to detect a load. The array of cantilever load sensors would then sense a pressure differential as a person walks across the smart flooring. A concept sketch is shown in Figure 5.

The second concept variant stems from considering the hair cells and carotid and aortic stretch receptors simultaneously. Hair cells are vertical structures, while stretch receptors are found in multiple orientations. Taking inspiration from the hair cell and stretch receptor morphology leads to a detector design that is comprised of a vertical structure that can be stretched in multiple orientations. Offering flexibility and ruggedness for being stepped on. This detector design would not be a good choice for hard tiles, but could work for woven flooring such as carpet. Since pressure is not used in this concept variant, an electrical signal would need to be generated. Flexion should result in a change of resistivity, similar to a strain gage or generate a voltage by the principle of piezoelectricity. Polyamide is a high performance synthetic polymer and is commonly used in textiles. Fabricating polyamide tubes with a conductive gel or paste, that can be woven into carpet to form an array would achieve the biologically-inspired design. Materials research would need to be completed to determine if the polyamide and conductive gel

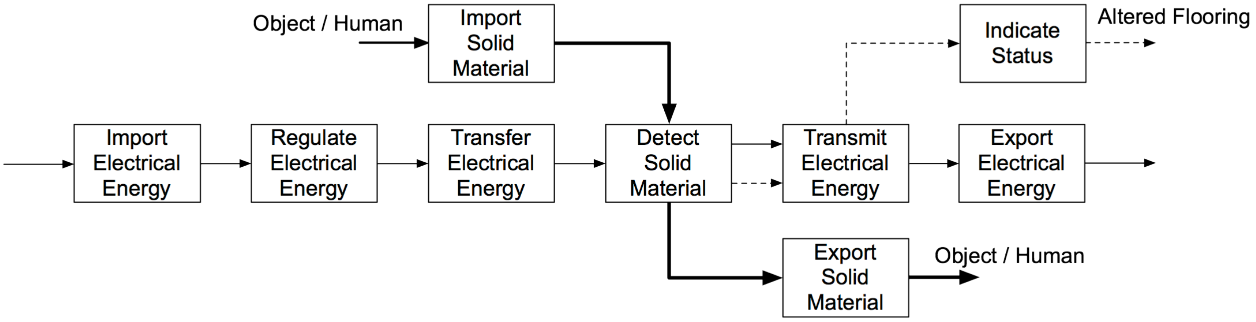

Figure 4. SMART FLOORING CONCEPTUAL FUNCTIONAL MODEL.

or paste would last in a high traffic environment. A concept sketch is shown in Figure 6. Considering the hair cell as a thread, which also possesses high flexibility similar to the carotid and aortic stretch receptors. Conductive thread exists and is used in garments and accessories that merge technology into clothing. Therefore the concept in Figure 6 progresses into conductive thread woven into carpet fibers to replace the polyamide coated conductive gel or paste. For both concept variants, a flexible circuitry layer and buffer layer would need to be underneath the flooring to connect the array to a computer or processor and to protect the underlying circuitry, respectively.

Table 4. ENGINEERING SOLUTIONS FOR SMART FLOORING FUNCTION/FLOW PAIRS.

Function/ Flow	Engineering Solution
Import/ electrical energy	Battery, circuit board, electric motor, electric wire, electric switch
Regulate/ electrical energy	Actuation lever, capacitor, circuit board, automobile distributor, electric switch, heating element, transistor, transformer, thermostat, regulator, volume knob
Transfer/ electrical energy	Battery, circuit board, electric wire, electric motor, electric socket, electric plate, electric switch, heating element, usb cable, light fixture, speaker
Transmit/ electrical energy	Electrical wire, battery contacts, motor controller
Detect/ solid material	Read head, line guide
Indicate/ status signal	Light, tube, displacement gauge, LCD screen
Export/ electrical energy	Circuit board, electric wire, electric switch

Looking to literature for a similar surveillance device uncovered a handful of attempts to create a "smart" floor or flooring. The first concept described above, individual tiles that detect a load placed in an array, has been done. Richardson et al. have developed hexagonal, puzzle-like pieces called nodes that are placed in an array to detect pressure [64]. Their tiles contain force sensitive resistors and interlock to form a self-organizing network that passes data to the tile with an external data connection. An earlier approach to the smart floor involved only one measuring tile made of load cells, a steel plate, and data acquisition hardware, and was not intended to be hidden [65]. Rather, it was created as an alternative to biometric identification by recognizing a person's unique footstep profile. Two other approaches that utilize load cells and layered flooring to conceal the sensors are nearly identical to the first concept variant. Liau et al. place a sensor in the center of every 60cm x 60 cm wood covered tile [66], where Addlesee et al. place a sensor at each intersection of four carpet covered tiles [67]. Load cells are similar in principle to cantilever beams in that deflection is transduced into an electrical signal that can be interpreted. Literature review revealed that the first biologically-inspired concept is feasible and has been attempted.

Investigating the second concept variant for smart flooring revealed only one existing design that is similar. Researchers at Infineon Technologies have woven conductive fibers into carpet and attached them to tiny sensor modules inlaid into the fabric to build a mesh network [68]. The flooring can report where a person is located, which way they are moving and if a sensor module has failed. Each conductor in the design is a copper wire coated with silver to prevent corrosion and then covered with polyester [68]. A German textile company, Vorwerk, has teamed up with Infineon to develop the smart carpet [69, 70]. The Vorwerk/Infineon product is similar in structure to the second concept variant in that a conductor is concealed and woven into a textile product. Again, a literature review revealed that the biologically-inspired concept is feasible.

This case study demonstrated that it is possible to systematically design using the search heuristics and take inspiration from biology in the process. By analyzing the biological system and making connections a designer can become inspired. It is through these correlations that the designer can recognize existing designs that are similar or develop an innovative design.

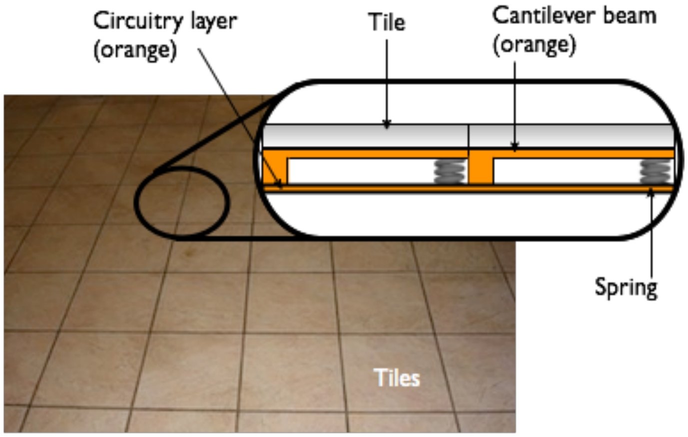

Figure 5. CONCEPT VARIANT ONE FOR SMART FLOORING.

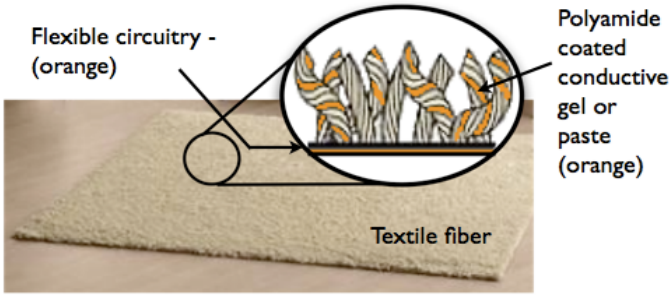

Figure 6. CONCEPT VARIANT TWO FOR SMART FLOORING.

6. CONCLUSION

The design methodology presented here represents a comprehensive design approach devoted to developing biologically-inspired solutions. It challenges and guides a designer to make connections between the engineering and biology domains to facilitate innovative design. Although systematic, the design methodology is also versatile by providing a designer multiple avenues that lead to an inspired design. The methodology is envisioned as an inventive and iterative process, in terms of developing connections between systems at multiple levels of fidelity. As one level, or scale, of the biological system becomes understood it leads to a deeper understanding and a greater curiosity to explore further. Thus, leading to multiple innovative designs. It was shown how the connections made between biological systems and engineered were key to arriving at the biologically-inspired inspired designs. The developed and existing design tools that comprise the support framework coalesce in the systematic biologically-inspired design methodology as demonstrated by the smart flooring cases study. Initial validation of the design methodology was provided through reproducing existing biomimetic products and matching generated concepts in the case study with existing products.

7. FUTURE WORK

Future work includes performing design studies, validation of the solution-driven approach, developing a set of connection examples to provide novices with a starting point as well as increasing the rigor of the methodology. Design studies with students in engineering design courses and/or engineering professionals will provide further validation of the design methodology and supporting design tools. Also, the studies will help to identify weaknesses of the method that need improvement. The solution-driven approach of this methodology, focusing on following a curiosity, also requires validation. Initial validation will be performed similarly to the problem-driven approach.

The methodology relies heavily on the designers' insight and background knowledge of many fields to make the necessary connections between biology and engineering for developing concepts. Individual tasks for each step of the method could be defined to prevent common mistakes from occurring and also assist novice designers. Making connections between the engineering and biological domains for the development of concepts is not always easy, therefore a collection of connection examples would assist novices with getting started with this methodology. Once concepts are available, it is upon the designer to determine if they are feasible. It was shown that identification of an existing product similar to the conceptual product demonstrates feasibility, however, this does not address innovative concepts that currently do not exist. Therefore future work for this method also includes linking the qualitative functional models to quantitative equations and models through the components chosen during conceptual design. This will allow objective verification of the integration and flow transformations within the proposed solution. Thus, the addition of quantitative equations and models will provide a more rigorous approach to verifying the technical feasibility of a biologically-inspired conceptual design.

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REFERENCES

[1] Hyman, B., 1998, Engineering Design, Prentice-Hall, New Jersey.
[2] Otto, K.N., and Wood, K.L., 2001, Product Design: Techniques in Reverse Engineering and New Product Development, Prentice-Hall, Upper Saddle River, New Jersey.
[3] Dym, C.L., and Little, P., 2004, Engineering Design : A Project-Based Introduction, John Wiley, New York.
[4] Ulrich, K.T., and Eppinger, S.D., 2004, Product Design and Development, McGraw-Hill/Irwin, Boston.
[5] Voland, G., 2004, Engineering by Design, Pearson Prentice Hall, Upper Saddle River, NJ.
[6] Ullman, D.G., 2009, The Mechanical Design Process 4th Edition, McGraw-Hill, Inc., New York.
[7] Hey, J., Linsey, J., Agogino, A.M., and Wood, K.L., 2008, "Analogies and Metaphors in Creative Design," International Journal of Engineering Education, 24(2), pp. 283-294.
[8] De Mestral, G., 1955, "Velvet Type Fabric and Method of Producing Same," Prangins, Vaud, USA.
[9] Malmqvist, J., Axelsson, R., and Johansson, M., 1996 of Conference, " A Comparative Analysis of the Theory of Inventive Problem-Solving and the Systematic Approach of Pahl and Beitz," 1996 ASME IDETC/CIE,
[10] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K.H., 2007, Engineering Design: A Systematic Approach, Springer Verlag.
[11] Hacco, E., and Shu, L.H., 2002, "Biomimetic Concept Generation Applied to Design for Remanufacture," Proc. 2002 ASME IDETC/CIE, Montreal, Canada.
[12] Chiu, I., and Shu, L.H., 2007, "Biomimetic Design through Natural Language Analysis to Facilitate Cross-Domain Information Retrieval," AIEDAM, 21(1), pp. 45-59.
[13] Chiu, I., and Shu, L.H., 2007, "Using Language as Related Stimuli for Concept Generation," AIEDAM, 21(2), pp. 103-121.
[14] Srinivasan, V., and Chakrabarti, A., 2009, "Sapphire – an Approach to Analysis and Synthesis," Proc. International Conference on Engineering Design, Stanford, USA.
[15] Chakrabarti, A., Sarkar, P., Leelavathamma, B., and Nataraju, B.S., 2005, "A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas," Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 19(pp. 113-132.
[16] Nachtigall, W., 2005, Biological Design: Systematic Catalog of Bionic Figures, Springer.
[17] Nachtigall, W., 2003, Construction Bionics: Nature - Analogies - Technology, Springer.
[18] Nachtigall, W., 2002, Bionics: Principles and Examples for Engineers and Scientists, 2nd (ed.), Springer.
[19] Mak, T.W., and Shu, L.H., 2004, "Abstraction of Biological Analogies for Design," CIRP Annals, 531(1), pp. 117-120.

[20] Linsey, J., Wood, K., and Markman, A., 2008, "Modality and Representation in Analogy," AIEDAM, 22(2), pp. 85-100.

[21] Vattam, S., Helms, M., and Goel, A., 2010, "A Content Account of Creative Analogies in Biologically Inspired Design," AI for Engineering Design, Analysis and Manufacturing (AIEDAM), Special Issue on Biologically Inspired Design, 24(pp. 467-481.

[22] Tsujimoto, K., Miura, S., Tsumaya, A., Nagai, Y., Chakrabarti, A., and Taura, T., 2008, "A Method for Creative Behavioral Design Based on Analogy and Blending from Natural Things," Proc. 2008 ASME IDETC/CIE, New York, USA.

[23] Lindemann, U., and Gramann, J., 2004, "Engineering Design Using Biological Principles," Proc. International Design Conference - DESIGN 2004, Dubrovnik.

[24] Wen, H.-I., Zhang, S.-J., Hapeshi, K., and Wang, X.-F., 2008, "An Innovative Methodology of Product Design from Nature," Journal of Bionic Engineering, 5(1), pp. 75-84.

[25] Biomimicry Institute, 2010, Biomimicry: A Tool for Innovation, [*Accessed on: Available from:* http://www.biomimicryinstitute.org/about-us/biomimicry-a-tool-for-innovation.html

[26] The Biomimicry Institute, 2011, Ask Nature- the Biomimicry Design Portal, [*Accessed on:* Jan. 10, 2011], *Available from:* http://www.asknature.org

[27] Helms, M., Vattam, S.S., and Goel, A.K., 2009, "Biologically Inspired Design: Process and Products," Design Studies, 30(5), pp. 606-622.

[28] Vattam, S., Wiltgen, B., Helms, M., Goel, A., and Yen, J., 2010, "Dane: Fostering Creativity in and through Biologically Inspired Design," Proc. First International Conference on Design Creativity, Kobe, Japan, pp. 127-132.

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

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

[31] Bryant, C., Bohm, M., Mcadams, D., and Stone, R., 2007 of Conference, "An Interactive Morphological Matrix Computational Design Tool: A Hybrid of Two Methods," ASME 2007 IDETC/CIE, Las Vegas, NV.

[32] Bryant, C., Mcadams, D., Stone, R., Kurtoglu, T., and Campbell, M., 2005 of Conference, "A Computational Technique for Concept Generation," 2005 ASME IDETC/CIE, Long Beach, CA.

[33] Nagel, J.K.S., Stone, R.B., and Mcadams, D.A., 2010, "An Engineering-to-Biology Thesaurus for Engineering Design," Proc. 2010 ASME IDETC/CIE, Montreal, Quebec, Canada.

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

[35] Stroble, J.K., Stone, R.B., Mcadams, D.A., and Watkins, S.E., 2009, "An Engineering-to-Biology Thesaurus to Promote Better Collaboration, Creativity and Discovery," Proc. CIRP Design Conference 2009, Cranfield, Bedfordshire, UK, pp. 353-368.

[36] Nagel, J.K.S., Nagel, R.L., Stone, R.B., and Mcadams, D.A., 2010, "Function-Based, Biologically Inspired Concept Generation," AIEDAM, 24(4), pp. 521-535.

[37] Stone, R.B., 1997, "Towards a Theory of Modular Design," Ph.D. University of Texas at Austin, Austin, TX.

[38] Stroble, J.K., Stone, R.B., Mcadams, D.A., Goeke, M.S., and Watkins, S.E., 2009, "Automated Retrieval of Non-Engineering Domain Solutions to Engineering Problems," Proc. CIRP Design Conference 2009, Cranfield, Bedfordshire, UK, pp. 78-85.

[39] Gick, M., and Holyoak, K., 1980, "Analogical Problem-Solving," Cognitive Psychology, 12(pp. 306-355.

[40] Gentner, D., 1988, "Analogical Inference and Access," in Analogica, Prieditis, ed. Morgan Kaufmann Publishers, Los Altos, CA, Chap. 63-88.

[41] Gentner, D., 1983, "Structure-Mapping: A Theoretical Framework for Analogy," Cognitive Science, 7(pp. 155-170.

[42] Hofstadter, D.R., 1995, Fluid Concepts & Creative Analogies : Computer Models of the Fundamental Mechanisms of Thought, Basic Books, New York.

[43] Bhatta, S.R., and Goel, A.K., 1997, "An Analogical Theory of Creativity in Design," in Case Based Reasoning Research and Development, Berlin/Heidelberg.

[44] Goel, A., 1997, "Design, Analogy and Creativity," IEEE Expert Intelligent Systems and Their Applications, 12(3), pp. 62-70.

[45] Smith, G.F., 1998, "Idea Generation Techniques: A Formulary of Active Ingredients," Journal of Creative Behavior, 32(2), pp. 107–133.

[46] Balazs, M.E., and Brown, D.C., 2001, "Design Simplification by Analogical Reasoning," in Knowledge Intensive Computer Aided Design, Rizzi, Cugini and Wozny, eds., Kluwer Academic Publishers.

[47] Casakin, H., 2006, "Visual Analogy as a Cognitive Strategy in the Design Process: Expert Versus Novice Performance," Journal of Design Research, 4(2), pp. DOI: 10.1504/JDR.2004.009846.

[48] Nagai, Y., and Taura, T., 2006, "Formal Description of Concept-Synthesizing Process for Creative Design," Proc. Design Computing and Cognition'06, J.S. Gero, ed. Dordrecht, pp. 443-460.

[49] Johnson-Laird, P., 1989, "Analogy and the Exercise of Creativity," in Similarity and Analogical Reasoning, S. Vosniadou and A. Ortony, eds., Cambridge University Press, Cambridge.

[50] Fan, Z., Chen, J., Zou, J., Bullen, D., Liu, C., and Delcomyn, F., 2002, "Design and Fabrication of Artificial Lateral Line Flow Sensors," Journal of Micromechanics and Microengineering., 12(pp. 655-661.

[51] Motamed, M., and Yan, J., 2005 of Conference, "A Review of Biological, Biomimetic and Miniature Force Sensing for Microflight," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),

[52] Gnatzy, W., Grunert, U., and Bender, M., 1987, "Campaniform Sensilla of Calliphora *Vicina* (Insecta, Diptera) I. Topography," Zoomorphology, 160(pp. 312-319.

[53] Grunert, U., and Gnatzy, W., 1987, "Campaniform Sensilla of Calliphora *Vicina* (Insecta, Diptera) Ii. Typology," Zoomorphology, 106(320-328).

[54] Wicaksono, D.H.B., Pandraud, G., Craciun, G., Vincent, J.F.V., and French, P.J., 2004, "Fabrication and Initial

Cahracterisation Results of a Micromachined Biomimetic Strain Sensor Inspired from the Campaniform Sensillum of Insects," Proc. IEEE Sensors 2004, 2, pp. 542-545.

[55] Vattam, S., Helms, M., and Goel, A., 2008, "Compound Analogical Design: Interaction between Problem Decomposition and Analogical Transfer in Biologically Inspired Design," Proc. Third International Conference on Design Computing and Cognition, Atlanta, pp. 377-396.

[56] Campbell, N.A., and Reece, J.B., 2003, Biology, Pearson Benjamin Cummings, San Francisco.

[57] Shu, L.H., Hansen, H.N., Gegeckaite, A., Moon, J., and Chan, C., 2006 of Conference, "Case Study in Biomimetic Design: Handling and Assembly of Microparts," ASME 2006 IDETC/CIE, Philadelphia, PA.

[58] Hubka, V., and Ernst Eder, W., 1984, Theory of Technical Systems, Springer-Verlag, Berlin.

[59] Vincent, J.F.V., and Mann, D.L., 2002, "Systematic Technology Transfer from Biology to Engineering," Philosophical Transactions of the The Royal Society London A, 360(pp. 159-173.

[60] Forty, A., 1989, "Of Cars, Clothes and Carpets: Design Metaphors in Architectural Thought," Journal of Design History, 2(1), pp. 1-14.

[61] Casakin, H., 2007, "Metaphors in Design Problem Solving: Implications for Creativity," International Journal of Design, 1(2), pp. 21-33.

[62] Casakin, H., 2006, "Assessing the Use of Metaphors in the Design Process," Environment and Planning B: Planning and Design, 33(2), pp. 253-268.

[63] Dollens, D., 2009, Biodigital Architecture Uses Metaphor to Design Living Systems, [*Accessed on: Available from:* http://sensingarchitecture.com/3832/biodigital-architecture-uses-metaphor-to-design-living-systems-dennis-dollens-video/

[64] Richardson, B., Leydon, K., Fernström, M., and Paradiso, J.A., 2004 of Conference, "Z-Tiles: Building Blocks for Modular, Pressure-Sensing Floorspaces," Conference on Human Factors In Computing Systems (CHI), Vienna, Austria.

[65] Orr, R.J., and Abowd, G.D., 2000 of Conference, "The Smart Floor: A Mechanism for Natural User Identification and Tracking," Conference on Human Factors In Computing Systems (CHI), Hague, Netherlands.

[66] Liau, W.-H., Wu, C.-L., and Fu, L.-C., 2008, "Inhabitants Tracking System in a Cluttered Home Environment Via Floor Load Sensors," IEEE Transactions on Automation Science and Engineering, 5(1), pp. 10-20.

[67] Addlesee, M.D., Jones, A., Livesey, F., and Samaria, F., 1997, "The Orl Active Floor," IEEE Personal Communication, 4(5), pp. 35–41.

[68] Iee-Institution of Electrical Engineers, 2003, "Research News - Walk This Way for the Smart Floor."

[69] Vorwerk & Co., T.G.C.K., 2004, Infineon Thinking Carpet, [*Accessed on: Available from:* http://www.vorwerk-carpet.com/sc/vorwerk/bildmeldung_thinkCarpet_en.html

[70] Crane, D., 2005, New High-Tech Sensor-Laiden Smart Carpet May Revolutionize Building Security, [*Accessed on: Available from:* http://www.defensereview.com/new-high-tech-sensor-laiden-smart-carpet-may-revolutionize-building-security/