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**CONCEPTS IN BIOMIMETIC DESIGN: METHODS AND TOOLS TO INCORPORATE INTO A
BIOMIMETIC DESIGN COURSE**

Michael W. Glier, Daniel A. McAdams, Julie S. Linsey
Department of Mechanical Engineering
Texas A&M University
College Station, Texas 77843, USA
Email: dmcadams@tamu.edu

ABSTRACT

Biomimetic design, the use of nature to inspire solutions to engineering problems, has been practiced on an *ad hoc* basis throughout human history. Only recently, however, have researchers sought to develop formal tools and principles to effectively tap the wealth of design solutions found within nature. Texas A&M University is developing an undergraduate course to introduce interdisciplinary engineering students to the current concepts, principles, and methods of biomimetic design, as found in published literature. This paper seeks to concisely present the results and conclusions of the many research efforts that will be incorporated into the developing course. The research reviewed in this paper is discussed with some emphasis on its pedagogical implications.

Research efforts in applying design tools such as functional modeling, analogical reasoning, and the Theory of Inventive Problem Solving (TRIZ) to biomimicry are summarized. This paper also discusses the efforts to develop effective tools to search biological information for design inspiration. As similar courses in biomimetic design have been conducted at the Georgia Institute of Technology and the University of Maryland, the published findings from those courses are also presented.

INTRODUCTION

Biomimetic design uses biological phenomena to inspire solutions to engineering problems. Humans have been mimicking biology throughout history from the mythological example of Icarus to the animal and insect-like robots of today. The natural world offers a wealth of potential design solutions that can be applied to engineering problems. Until recent times however, biomimetic designs have typically been generated on a case-by-case basis without a structured design methodology. One of the great challenges in biomimetic design, for which effective

biomimetic design methodologies must account, is that a designer must possess knowledge of both engineering system and biological systems to draw effective design analogies between the two domains. Fortunately for future designers, biomimetic design tools have been developed to aid in the creation of analogies and to find relevant biological design stimuli.

If, however, a designer is unaware of the available design tools, he or she will lack the advantages those tools grant. Indeed, all of nature's design inspiration may be disregarded by the designer for lack of an organized method with which to tap that knowledge. Given the great value that is often placed on novel, creative solutions to engineering design problems, a designer can scarcely afford to neglect the design inspiration biological systems offer. Texas A&M University is in the process of creating an elective course in its mechanical engineering department that will teach undergraduate engineers the tools and methods for biomimetic design, as found in current published literature.

This paper provides a concise overview of the results and conclusions of the many research efforts that will be incorporated into the aforementioned elective; the efforts will be discussed with some emphasis on their pedagogical implications. The tools and methods for biomimetic design have been organized into four sections: functional modeling, BioTRIZ, analogical reasoning, and information gathering tools. An additional section briefly discusses the existing biomimetic courses at the University of Maryland and at the Georgia Institute of Technology (Georgia Tech).

FUNCTIONAL MODELING

One method that has been successfully used to abstract engineering design information from natural systems is functional modeling. Analyzing a biological system at a purely functional level helps designers to find functionally

similar technological solutions, which may or may not use the same mechanisms as their biological inspiration. Furthermore, functional modeling provides designers with a systematic, complete approach to modeling biological phenomena [1]. Although nearly any functional language can model biological systems, many of the efforts to apply functional modeling to biomimetic design have employed the Functional Basis, as described by Hirtz et al. [2]. Tinsley et al. determined that the Functional Basis is an effective language for transferring biological design solutions into the engineering domain [3].

One of the challenges in functionally modeling biological phenomena lies in properly defining the scope of the system to be modeled. Nagel, et al. demonstrated that carefully defining the *category* and *scale* of a biological system's functional model allows designers to better isolate and model those aspects of the biological system most applicable to their design problem [4].

The authors proposed four biological categories: physiology, dealing with the vital functions of organisms; morphology, pertaining to an organism's physical form; behavior, characterized as an organism's response to stimuli; and strategy, defined as generic behavior to achieve different goals. Biological scale can range from the atomic level to populations, but the authors noted that cellular, organ, organism, and behavior scales tend to be useful and are well documented in biological literature. While biological functional models are generally restricted to a single scale, designers may employ multi-scale models to show specific biological phenomena.

Keeping in mind the importance of category and scale, Nagel et al. developed a seven-step, general methodology for functionally modeling biological systems [4]. This methodology evolved from Nagel's experience using functional modeling to conceptualize biomimetic sensor technologies [5, 6]. The suggested methodology is:

1. *Identify a suitable reference (e.g. a biology textbook) for the biological system of interest.*
2. *Read the overview of the biological system to understand the core functionality of the system.*
3. *Define the design question the functional model aims to answer.*
4. *Define the category of the functional model.*
5. *Define the scale of the functional model.*
6. *Develop a functional model of the biological system using the functional basis modeling language within the bounds set by the design question, biological category, and biological scale.*
7. *Double-check and/or validate (e.g. have a biologist review model at desired biological category and scale) the functional model against the design question and black box model.*

Functional modeling can be a powerful tool for biomimetic design. This method's systematic, thorough approach can reveal aspects of biological phenomena that are not apparent with other approaches. Furthermore, expressing biological systems in terms of the functional basis allows the designers to explore the system in a familiar, engineering-oriented language. For engineering

students who have learned functional modeling in a conventional design curriculum, functional modeling for biomimetic design is an extension of their preexisting knowledge rather than a completely foreign technique.

Nevertheless, creating a functional model for a natural system can challenge a designer whose background lies in the engineering domain. Creating an accurate and useful model requires the designer to have a sound understanding of the system of interest – and perhaps the insight of a biologist – to define the appropriate category and scale. Finally, even after constructing an accurate and useful biological model, the designer must still find ways to mimic the system's functions in an engineering system.

BIOTRIZ

BioTRIZ is another tool designed to enable designers to abstract useful design information from biological systems. BioTRIZ is based on the Russian Theory of Inventive Problem Solving (TRIZ) developed by Genrich Altshuller [7]. TRIZ was developed on the premise that the vast majority of new engineering designs are simply combinations of a single set of general design principles [8]. Working on this assumption, TRIZ incorporates information from nearly three million successful patents and vast stores of physical, chemical, and mathematical knowledge [9]. That information is condensed in TRIZ into 39 system parameters – things that a designer would want to maximize and minimize, and 40 inventive principles – ideas that can help solve a design problem. A designer using TRIZ would pose a design problem as a contradiction such that one of the 39 system parameters is optimized at the cost of another. The designer then consults a 39 by 39 “contradiction matrix” that lists the inventive principles that have been used to resolve that contradiction in other designs. While TRIZ can be a powerful design tool for an engineer, it was developed from a technical and engineering knowledge base; design information from the natural world is absent. BioTRIZ uses the approach of TRIZ to abstract biological design information into more general tool applicable to any form of engineering design.

The development of BioTRIZ was led by Dr. Julian Vincent at the University at Bath [8]. BioTRIZ is based on the analysis of approximately 500 biological phenomena with over 270 functions that form over 2500 contradictions [10]. Unlike Altshuller's work, BioTRIZ groups the many system parameters into only six fields of operation: *substance, structure, space, time, energy, and information*. Rather than a 39 by 39 contradiction matrix as in TRIZ, BioTRIZ employs a more condensed 6 by 6 matrix. BioTRIZ retains Altshuller's inventive principles, but Vincent did expand on them, giving examples of how each principle is employed in biological systems [10]. The procedure for applying BioTRIZ to a design problem is identical to that for TRIZ, except that the designer must use one of the six fields of operation instead of the 39 system parameters.

For comparison, Vincent also constructed a condensed TRIZ contradiction matrix using the six fields of operation. Comparing the inventive principles used in technology (TRIZ) and biology (BioTRIZ) for identical contradictions, Vincent found that the two matrices have a similarity of

only 0.12, where identity is denoted by 1 [10]; Vincent did not explain how this similarity metric was computed. Further, he found that the at scale up to 1 meter, technological design solutions rely most heavily on the manipulation and conversion of energy while biological solutions tend to revolve around information and space [8].

BioTRIZ can be a valuable tool for biomimetic design. Like TRIZ, it provides engineers a straightforward, methodical approach to solving design problems, but BioTRIZ relies on design information not common within the technical world. The ever-increasing need to develop sustainable technology forces engineers to adopt new approaches to design; the reduced emphasis on energy inherent in BioTRIZ is a strong recommendation for this approach. From a pedagogical viewpoint, BioTRIZ is a straightforward design method, with a rigid procedure and a small set of necessary materials. With a brief introduction to the methodology and a few tables, engineering students can leverage a wealth of biological design information without needing to themselves translate biology literature into engineering term and abstract the useful information into something applicable to their design problem.

ANALOGICAL REASONING IN BIOMIMETIC DESIGN

One of the key elements and great stumbling blocks in biomimetic design is drawing analogies between the biological and engineering domains. The disparity between those two domains can help designers find novel solutions to engineering problems, but designers (especially such novices as engineering students) can have difficulty in finding useful analogies between the domains. Although there are numerous studies on forming analogies in engineering design, the majority of those lie outside the scope of this paper. Three studies in particular examine the creation and use of analogies in biomimetic design.

The earliest of these studies was performed by Vakili et al. [11]. This study on a group of seven mechanical and industrial engineering students (senior undergraduates and graduate students) posed a micro-assembly design problem and provided the students with biological models of leaf abscission, the process by which leaves separate from a branch, for biological inspiration. Functional models of the abscission process were given as part of the stimulus. Based on observations of and interviews with the participants, the authors made several recommendations on how to employ functional models of biological phenomena. The participants found that the functional models were cumbersome tools, though the models did help the students extract analogies from the stimulus. Vakili et al. recommended that functional models be used to extract useful design analogies, and that a third party (i.e. not the designers) perform the extraction with a systematic method [11].

A later study by Mak and Shu examined 32 undergraduate mechanical engineering students who were asked to conceptualize a biomimetic system for cleaning clothes, given one of two biological design stimuli; the design stimuli were given as a textual description of some (carefully selected) biological systems [12]. Mak and Shu found that the students tended to fixate on employing their

design stimulus to specific, and often inappropriate, aspects of their design problem. The authors also found that many students could not effectively transfer knowledge between the biological and engineering domain. Mak and Shu suggested that ambiguous or “general” biological design stimuli may be more conducive to ideation than more detailed stimuli.

The most recently published study on analogical reasoning in biomimetic design was performed by Vattam et al. [13]. Unlike the two previous studies that were conducted in a controlled laboratory environment, Vattam et al. performed an *in vivo* study of a design team in Georgia Tech’s introductory course on biomimetic design. The researchers found that the analogies employed in the project could be classified into five types: direct transfer, schema induction, problem transformation, deferred goal, and compositional analogy. Secondly, they determined that analogies were used in nearly every major phase of the design process: problem definition, solution search, initial design, design evaluation, and design analysis – only the redesign phase lacked analogies. Finally, Vattam et al. determined that direct transfer analogies were employed most commonly, especially in the first two major design phases[13].

The study by Vattam et al. seems primarily informative in nature; it gives an analysis of the observed characteristics of one biomimetic design project, but offers little insight on how designers can more effectively practice biomimetic design. In contrast, the studies by Vakili et al. and Mak and Shu point out several pitfalls for designers new to biomimetics. In the context of a course on biomimetic design, the weaknesses identified by those two studies point to areas that need particular emphasis: understanding the biological system of interest, moving past design fixation, finding analogies using function structures, and avoiding detailed design stimuli in the early conceptualization phase.

INFORMATION GATHERING TOOLS

Any attempt to draw analogies between the natural and engineering domains must involve some biological system as a reference. Merely identifying an appropriate biological phenomenon for inspiration may prove infeasible for a designer with no background in biology. To facilitate this task, a great deal of effort and research has been committed to developing tools that enable designers to search for relevant biological information using engineering oriented search terms. Perhaps the largest effort in this field is the development of a natural language search tool at the Biomimetics for Innovation and Design (BID) Laboratory at the University of Toronto.

Vakili and Shu published a report on their efforts to develop a natural language, biology-engineering search tool in 2001. In this initial effort, they searched for biological information relevant to a design problem by searching the index and glossary of an introductory biology textbook. They quickly discovered that using synonyms for engineering oriented keyword increases the chances of finding useful matches. They also found that a “bridge” was necessary to span the gap between engineering keywords and biological keywords. In this instance, the textbook’s glossary served as a bridge. A later paper by Hacco and Shu

extended the first method by searching the entire biology text, rather than just the index. While this approach yielded more matches, the majority of those matches were irrelevant [14]. The overwhelming amount of irrelevant matches revealed the need to identify more relevant and specific search terms.

The BID Lab search tool was greatly improved by the incorporation of WordNet, “an electronic lexical database, designed and organized according to current psycholinguistic and computational theories of how humans remember language” [15]. WordNet has many features that can enhance a search tool’s functionality, but two particularly important features are its ability to distinguish between different meanings or “senses” of a word (e.g. to strike against an employer vs. to strike in baseball) and to handle troponym trees. Troponyms are a subset of verbs that are a particular way of doing another verb (e.g. to scour could be a troponym of to clean). With WordNet’s capabilities, Chiu and Shu greatly reduced the number of irrelevant search results, and designed an algorithm to identify significant verb pairs based on how often the two verbs appear together. Chiu and Shu continued to refine their BID Lab search algorithm, eventually identifying non-obvious keywords and even algorithmically producing a keyword that had been recommended by a human expert [16, 17].

The BID Lab search tool is a great asset when attempting to find potential sources of biological inspiration for a design problem, but it is not available for use outside the BID Lab. While this search tool cannot be used as a teaching tool or as a resource for students working on biomimetic design projects, there are useful and readily accessible materials that have been produced using the BID Lab search tool.

Cheong et al. used the BID Lab search tool to identify biologically relevant keywords for terms in the Functional Basis [18]. Nagel, Stone, and McAdams [4] combined Cheong’s functional basis keywords with similar sets produced at the Indian Institute of Science [19] and Oregon State University [5]. The combination of these word sets constitutes an “engineering-to-biology thesaurus” that provides designers with a more comprehensive set of biologically meaningful keywords for the terms of the Functional Basis. This thesaurus allows designers to more effectively use conventional search tools to find biological systems for design stimulus based on their function. Because the thesaurus is built around the terms of the Functional Basis, it can be used with conventional functional models of engineered systems or conceptual designs to find sources of biological inspiration.

While the BID Lab search tool and the engineering-to-biology thesaurus are designed to leverage existing sources of biological information, two computer-based interactive design tools, called IDEA-INSPIRE [20] and Design by Analogy to Nature Engine (DANE) [21] are built around custom-built databases of biological and engineering systems. Both tools provide designers with qualitative models of biological and engineering systems, present information in multimedia format (e.g. text, photos, graphs, schematics, etc.), and allow users to search the systems by their function [21]. The tools differ primarily in how they

present information to the user and how the biological and engineering systems are functionally modeled.

Chakrabarti et al. performed a preliminary examination of the IDEA-INSPIRE tool by having three designers with undergraduate engineering degrees and formal product design training use IDEA-INSPIRE to solve two design problems from a pool [20]. The software, even with a limited number of entries in its database, accounted for 47% of the ideas generated. DANE was tested by providing it as an optional design tool in Georgia Tech’s course in biomimetic design. Unfortunately, the students had little incentive to use the software and Vattam et al. were unable to draw any firm conclusions about how and why the tool was used [21].

Neither IDEA-INSPIRE nor DANE is available for general use. However, these tools continue to be developed, and their utility increases as their databases of natural systems expand. While these tools have the potential to provide designers with an abundance of well organized, highly accessible biomimetic design information, they are greatly limited by the time and effort that is required to add each new design to their respective databases. Unless this limitation is somehow overcome, tools like IDEA-INSPIRE and DANE will necessarily have small databases compared to the wealth of information accessible through natural language search tools.

COURSES IN BIOMIMETIC DESIGN

Because biomimetic design is such a very new field, there are not yet any established, accepted teaching methodologies for it. Each new course or lecture dealing with biomimetic design is a venture into unknown territory and the instructor has little but his or her own experience as a guide. Both the University of Maryland and Georgia Tech offer classes related to biomimetic design and a few papers have been published that describe the structure of those courses and the reactions of the enrolled students.

Two papers discuss the biomimetic curriculum at the University of Maryland [22, 23]. The earlier paper discusses the addition of a module on biomimetic manufacturing technologies to a junior level class on materials and manufacturing; specifically, the module introduced concurrent fabrication and assembly, self-assembly, and functionally graded materials. A student survey taken after the module indicated “that students have little prior knowledge of bio-inspired products and devices, enthusiasm for the content in the module, and the need for more knowledge on bio-inspired products and devices” [23].

Bruck et al. discuss student responses to a total of seven one-lecture modules on different applications of biomimetic design that are spread out over the core engineering curriculum [22]. Over 90% of students expressed a strong interest in biomimetic design, while at least 50% of every class indicated a desire to learn more about the subject. Due in part to the high interest in biomimetic design, the University of Maryland added a course in biomimetic robotics to its curriculum as a senior elective. This course has been popular among students, with many indicating “that this was one of the best courses they have taken.” The papers offer little insight into effective teaching practices or potential pitfalls for biomimetic

design, but they clearly establish that engineering students are interested in biomimetic course offerings.

At Georgia Tech, Helms, Vattam, and Goel conducted a cognitive study of the biomimetic design process within the context of an interdisciplinary, introductory biomimetic design course offered at that university [24]. This senior-level course contained 45 students who worked on design projects in teams of four to five people. Each team was charged with identifying a design problem and conceptualizing a biomimetic solution over the course of the semester.

Helms, Vattam and Goel observed that once a team selected a biological solution, they usually became fixated on it and the remainder of the design was driven by that solution [24]. Furthermore, six of the class's nine teams focused on design structure rather than function, despite the emphasis the instructors placed considering function. Finally, the researchers found that many designers fell prey to some of eight common errors:

1. *Vaguely defined problems*
2. *Poor problem-solution pairing*
3. *Oversimplification of complex functions*
4. *Using "off-the-shelf" biological solutions*
5. *Simplification of optimization problems*
6. *Solution fixation*
7. *Misapplied analogy*
8. *Improper Analogical Transfer*

Although this study focused on the cognitive aspects of biomimetic design, not the pedagogical, it does provide insight into some of the challenges in effectively teaching this subject.

CONCLUSIONS

Historically, biomimetic engineering has been performed on an *ad hoc* basis with no structure or guidelines to identify useful phenomena of aid the designer in forming appropriate analogies. Recent research in biomimetics has yielded powerful tools that allow designers to access a vast amount of biological design solutions without needing to spend years developing their background knowledge of biology. Table 1 offers an overview of the tools and techniques discussed in this paper.

With natural language search tools and interactive databases, engineers can search through volumes of biological literature using familiar engineering based terms such as the functional basis. Although the BID Lab search tool is not available for general use, engineering students can still leverage its power by employing the engineering-to-biology thesaurus that contains biologically meaningful keywords for terms in the functional basis that were found using the search tool. The interactive design tools DANE and IDEA-INSPIRE have had some promising initial tests, but building their databases requires time and money.

Tools like functional modeling and BioTRIZ provide systematic methods for transferring design information from the biological to the engineering domain. Functional modeling provides designers with an abstract, engineering-oriented view of biological systems. This view can be useful to reveal specific aspects of the system in question, but functional modeling relies heavily upon the proper

definition of category and scale. Properly setting these parameters can be difficult and may require a thorough understanding of the system in question. BioTRIZ allows designers to tap biological design information without requiring a source for biological inspiration, as the phenomenon of interest is, theoretically, already incorporated into BioTRIZ. However, BioTRIZ still requires that its users find creative ways to implement the inventive principles given by the contradiction matrix.

Table 1: Major features of Bioinspired Design Methods and Search Tools

Functional Modeling	Forms a model of a reference biological system
	Models encompass a predefined category and scale
	Extends engineering usage of functional modeling
	Requires understanding of biological system
BioTRIZ	Poses design problem as sets of conflicting parameters
	Condenses 39 TRIZ parameters to 6 categories
	Shows how inventive principles solve problems in nature
	Designers don't need to have knowledge of biological systems
BID Lab Search Tool	Searches natural-language biology databases using engineering keywords
	Can algorithmically identify non-obvious biological keywords
	Not available for general use
Engineering-Biology Thesaurus	Combines several efforts to find biological synonyms for Functional Basis Terms
	Allows conventional search tools to be used for bioinspired design
IDEA-INSPIRE & DANE	Provides organized databases of biological design stimuli
	Database size is limited by the resources needed to add entries
	Not available for general use

The many research efforts summarized in this paper will be integrated into a junior-level elective at Texas A&M University. Many potential pitfalls in teaching biomimetic design are identified by both the studies in analogical reasoning and the study of the biomimetic design course at Georgia Tech. As biomimetic design is a developing field and not a part of standard undergraduate engineering curricula, relatively little is known about how best to teach this subject and how it will affect students' ability to generate creative and novel design solutions. Thus, the elective will serve not only to teach students to find design inspiration in natural systems, but it will also provide valuable insight into how to better teach biomimetic design and into which biomimetic tools and techniques are most accessible to students.

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