ASME 2011 International Mechanical Engineering Congress and Exposition
IMECE 2011
November 11-17, 2011, Denver, Colorado USA

IMECE2011-63247

METHODS FOR SUPPORTING BIOINSPIRED DESIGN

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

1. ABSTRACT

Bioinspired design, the use of nature to inspire solutions to engineering problems, is a powerful approach for innovation but is generally practiced on an *ad hoc* basis. Only recently, however, have researchers sought to develop formal tools and principles to effectively tap the wealth of design solutions found within nature. Research efforts in applying design tools such as the Theory of Inventive Problem Solving (TRIZ), functional modeling, and keyword searches to bioinspired design are summarized in this paper. The efforts to develop effective tools to search biological information for design inspiration are also discussed. This paper presents a case study where BioTRIZ, functional modeling, and bio-keyword searches were taught in a weekend-long workshop to working professionals in the process of obtaining their graduate degrees. The students were then given a project to re-engineer a product using the bioinspired methods. An analysis of their reports is given that discusses student success in implementing bioinspired design methods and student feedback on the methods.

2. INTRODUCTION

Bioinspired design uses nature as an inspiration to design solutions to engineering problems. There are an abundance of time-tested design solutions that exist in the natural world that can be applied to engineering design. There are many examples of bioinspired design, including such product as Velcro, which was invented by Georges de Mestral after examining burrs caught in his dog's fur, and self-cleaning paints that mimic the surface microstructure of the lotus leaf to achieve its self-cleaning property. However, bioinspired design has often been used informally, on a case-by-case basis, due to the difficulty in identifying pertinent analogies between the engineering and biological domains. A designer needs to understand both the engineering problem and biological systems in order to draw an analogy between the two. Fortunately, formal tools and methods have been developed that aid in bioinspired design [1].

This paper will introduce BioTRIZ, functional modeling for bioinspired design, and bio-keyword search as tools to aid engineers in obtaining useful information from biological systems for bioinspired design. A case study will follow that discusses a weekend-long class that taught bioinspired design methods to working professionals who were students in an interdisciplinary engineering program at Texas Tech and in the process of obtaining a graduate degree. The class concluded with a design project in which the students used the bioinspired methods to re-engineer a product. The results of the project are discussed along with an analysis of their solutions and use of the methods.

3. BIOINSPIRED DESIGN METHODS

One of the great challenges for designers attempting to use biological systems to inspire engineering design solutions is the difficulty in drawing useful analogies between the two fields. Because biological systems and engineering systems often use such different mechanisms to accomplish similar functions, designers can become too focused on the biological mechanisms and be unable to conceptualize a functionally-similar engineering system whose form differs from the inspiring biological system. BioTRIZ and functional modeling are two tools that designers can use to help extract design inspiration from biological systems. While these two methods can aid designers in generating ideas from biological systems, designers can also find difficulty in finding biological systems with characteristics relevant to their design problem. To aid in these searches, several tools have been developed to allow designers to search for biological information using more familiar engineering terms. The following sections describe the development and methodology of BioTRIZ, functional modeling for bioinspired design, and biology search tools.

3.1 BioTRIZ

BioTRIZ is primarily based on the Russian Theory of Inventive Problem Solving (TRIZ) developed by Altschuller [2]. TRIZ is a design tool that allows designers to frame a problem in terms of a pair of conflicting parameters and find techniques that have been used to solve similar conflict in past designs. TRIZ identifies 39 system parameters that designers may wish to optimize as well as forty inventive principles (IPs) that can be used to resolve design challenges. The set of conflicts and solutions is presented as a 39 by 39 "contradiction matrix" in which each row and column corresponds to a system parameter and each cell lists the IPs that other designs have used to solve the conflicting parameters of the cell's row and column. TRIZ's system parameters, IPs, and contradiction matrix were developed by surveying nearly three million successful patents and vast amount of physical, chemical, and mathematical knowledge [3]. While TRIZ allows designers to tap vast stores of design information from engineered systems, it contains very little information from natural systems. BioTRIZ uses the methodology of TRIZ to abstract design information from natural systems and give designers a tool that allows that knowledge to be applied to engineering design without requiring that designers possess extensive knowledge of biological systems.

The development of BioTRIZ was led by Dr. Vincent of the University at Bath [4]. Like TRIZ, BioTRIZ condenses design information into a contradiction matrix that lists IPs used to solve conflicts between system parameters. However, while TRIZ shows designers how design problems have been solved in technical and engineering designs, BioTRIZ shows how those problems are solved by natural systems. BioTRIZ is based on the analysis of approximately 500 biological phenomena with over 270 functions and 2500 contradictions [4]. One other important difference between TRIZ and BioTRIZ is that BioTRIZ groups the 39 system parameters of TRIZ into six fields of operation: substance, structure, space, time, energy, and information. Consequently, the conflict matrix for BioTRIZ is only a 6 by 6 matrix. However, BioTRIZ does retain the 40 IPs used in TRIZ. The procedures used to apply BioTRIZ to a design problem are identical to those used for TRIZ.

To compare now natural and engineered systems differ in their application of the IPs, Vincent formed a condensed TRIZ contradiction matrix which matched the form of the BioTRIZ matrix. Comparing the IPs used to resolve identical contradictions, Vincent found that the two matrices have a similarity of only 0.12 where identity is denoted by 1. Vincent did not explain how this similarity metric was calculated [4].

To make the best use of BioTRIZ, Vincent proposed the following five-step methodology [4].

1. *Define the problem in the most general, yet precise way. It is essential to avoid specific directions of thought or premature solution of the problem. Then list the desirable and undesirable properties and functions.*
2. *Analyze and understand the problem and so uncover the main conflicts or contradictions. The technical conflicts are then identified in the TRIZ matrix and listed. Find the functional analogy in biology or go to the biological conflict matrix.*
3. *Compare the solutions recommended by biology and TRIZ. Find the common solutions for biological and engineering fields. List the technical and biological principles thus recommended.*
4. *Based on these common solutions, build a bridge from natural to technical design. To make the technical and biological systems compatible, make a list of their general recommended compositions.*
5. *To create a completely new technology, add to the basic TRIZ principles some pure technical or pure biological ones*

As an example of how BioTRIZ can be used to conceptualize a new product, Vincent et al. consider the problem of the snow tire [4]. Driving safely on icy road requires spikes or chains to be attached to a car's tires. However, these must be removed before the car drives on cleared roads to prevent the attached pieces from damaging an ice-free road. A solution neutral problem statement is "we need adequate friction between a wheel and a road under variable road surface conditions." A constraint for our design is that the vehicle weight cannot change.

We find three pairs of conflicting TRIZ parameters for this problem. We must increase the force between the tire and the road without increasing the vehicle's mass, increase the stress between the tire and ground without increasing vehicle mass, and reducing ground contact area without losing structural stability. Using the BioTRIZ conflict matrix, we find that the inventive principles that are common to all these three conflicts are *segmentation*, *dynamics*, and *another dimension* [4]. After considering these principles, Vincent conceived the cat's paw wheel, which is depicted in Figure 1.

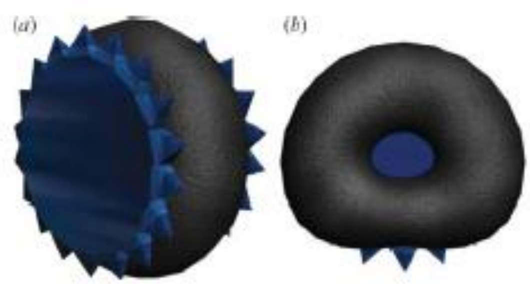

Figure 1. A cat's paw wheel for variable road conditions in the retracted configuration (a) and the extended (b) [8].

Functionally similar to the paw of a cat where claws can be extended or retracted to give the cat traction as needed, the cat's paw wheel can inflate to act as a regular tire or deflate to expose metal spikes that sill grip on an icy road. The inventive principle of segmentation suggested that the high friction component be broken into multiple segments, spikes. The principle of *dynamics* suggested that the spikes could be extended and retracted as needed for the road condition. Finally the principle of *another dimension* suggested that the spikes and tire should occupy different planes so that they could each operate without interference from the other [4].

3.2 Functional Modeling for Bioinspiration

Another method for bioinspired design is functional modeling. Functional modeling allows designers to examine a system at a purely functional level, not concentrating on the physical mechanisms that accomplish those functions. While this method is generally useful in engineering design, it is particularly useful for bioinspired design as it helps designers develop engineering systems that mimic the functional behavior of biological systems without fixating on specific mechanisms used by the inspiring biological system. Many of the research efforts in applying functional modeling techniques to bioinspired design have used the Functional Basis, as described by Hirtz et al. [5]. Although the Functional Basis was developed in the context of electro-mechanical systems, Tinsley et al. determined that the language is an effective medium for transferring biological design solutions to the engineering domain [6].

As biological systems tend to be very complex, they can often be modeled at multiple levels (e.g. cellular vs. organ level). If a designer models a biological system at the wrong level, the model may not provide insight into the functional behavior of interest. Nagel et al. demonstrated that defining the category and scale of the model in advance allows designers to consistently isolate and model the facets of the biological system most applicable to their design [7]. The authors propose that biological phenomena can be modeled in four categories: physiology, morphology, behavior, and strategy. Physiology pertains to the vital functions of organisms, morphology to their physical form, behavior to their response to external stimuli, and strategy to their generic behavior in achieving goals. Further, while biological scale can range from the atomic level to populations, the authors noted that cellular, organ, organism, and behavior scales tend to be the most useful for functional modeling and that these scales are well documented in biology literature.

Based largely on Nagel's experiences using functional modeling to develop bioinspired sensor technologies [8,9], Nagel et al. developed the following seven-step methodology for functionally modeling biological systems [7],

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 the functional model against the design question and black box model.*

Functional modeling's systematic, detailed approach can help designers find properties of biological phenomena that may not be apparent with other design techniques. This technique allows designers to examine biological systems in a familiar, engineering oriented language; designers that have used functional modeling for traditional engineering design can simply extend its use to bioinspired design rather than having to learn a completely new technique. Even with these advantages however, designers still face certain challenges.

The first step in Nagel's method is to identify the system of interest and then find a reference for the biological system of interest.. Simply finding a biological system that is relevant to a design problem poses significant difficulty to designers without sufficient *a priori* knowledge of biology. There is no way to know in advance if a given biological system will lead a designer to a useful design analogy, and choosing a different inspiring system will generally cause the designer to find a different analogy. Presuming that the designer identifies a system relevant to the design problem at hand, finding an appropriate reference for that system is non-trivial given the vast amounts of biological literature available – much of which may be opaque to a designer with an engineering background.

To accurately model a biological system, the designer must have a firm understanding of the system in question to create an accurate model. Indeed, the designer must have some understanding of the system merely to define an appropriate category and scale for the model before creating a functional model. Even with an accurate and useful functional model of the system of interest, the designer's creativity is still necessary to conceptualize a functionally similar engineering system.

As an example of how functional modeling can be used to draw inspiration from biological systems to innovate engineering systems, we will consider the problem a fuel cell bipolar plate. By functionally analyzing the plate, we find that the most important functions for its operation are: distribute fluid, guide fluid, and disperse fluid. If we look to the natural world, we might realize that plant leaves regularly perform these very same functions; veins distribute and guide fluid while lamina disperse fluid. Figure 2 shows a fuel cell bipolar plate that is based on this analogy, alongside a leaf to show the common features [9].

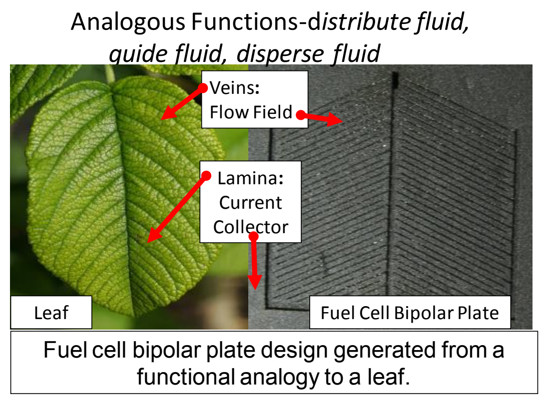

Figure 2. Bipolar fuel cell plate design based on the functional analysis of a leaf [10].

3.3 Biology Search Tools

To aid in drawing analogies from nature, information gathering tools in the form of bio-keyword searches are used. Biological systems that are relevant can be identified using engineering oriented terms and the Functional Basis. A natural language search tool has been developed at the Biomimetics for Innovation and Design (BID) Laboratory at the University of Toronto. The initial effort was created by Vakili and Shu in 2001 by using a search of the index and glossary of an introductory biology textbook with the textbook's glossary acting as a bridge to cross from the engineering to biological keywords. The BID Lab search tool has been improved and now searches an entire biology text and has incorporated WordNet, which is "an electronic lexical database designed and organized according to current psycholinguistic and computational theories of how humans remember language" [11].

Another information gathering tool makes use of the Functional Basis and biologically meaningful keywords with an "engineering-to-biology thesaurus" [12]. After creating a functional model, the terms from the Functional Basis can be used with the thesaurus to find biological correspondents. The biological terms are then searched in order to learn more about biological systems to serve as sources of inspiration for design problems and drawing analogies. These terms can be search for in a conventional search engine, such as Google, or a more targeted database of biological information such as AskNature.org, a repository of biological information specifically designed as a reference for bioinspiration. Both bio-keyword searching tools make use of known biological information and provide a way for engineers to find relevant material to promote the creation of bioinspired solutions.

These search tools, particularly the engineering-to-biology thesaurus and the BID Lab search tool can be particularly useful when used in conjunction with a functional model of the engineering system. Functional models can be used to abstract a biological system to inspire an engineering solution, or inversely to inspire novel solutions to a design problem by identifying important functions in the engineering system and exploring biological systems that perform a similar function. By linking general functional terms to more specific biological terms, bio-keyword search tools help designers find relevant sources of biological inspiration for their design problem.

4. CASE STUDY

Recently, the aforementioned bioinspired design techniques were taught to a class of fifteen interdisciplinary engineering graduate students at Texas Tech University. According to the students' responses to a questionnaire given at the end of the class, the average age of the students was 45 years and they had an average of 20 years of experience in industry. The majority of the students were majoring in Transdisciplinary Engineering, but other majors included Systems Engineering, Mechanical Engineering, and Information Security. These students are working professionals in engineering fields enrolled in a program that allows them to take classes 8 hours a day, Friday through Sunday.

Dr. Daniel McAdams of Texas A&M University was invited to teach bioinspired design to the students during one of these weekend sessions. To practice the methods that were taught, the students completed a three part activity throughout the weekend. Prior to learning the bioinspired methods, the students were given a design problem and an hour to generate ideas. After a day of class, the same problem was revisited and the students applied the methods to create new concepts. At the end of the weekend class, a new design problem was issued and the students were once again given an hour to produce solutions. They were also given a long-term design project to be completed several weeks after the course. Ten of the students in the class submitted a design project. These projects give us valuable insight into how students use these bioinspired design techniques and particularly the challenges they face. We will first explain the design project as it was given to the students and then discuss how the students implemented BioTRIZ, functional modeling, and bio-keyword searches within their projects.

The project asked each student to select an engineering system, product, or technology and attempt to redesign the system using the bioinspired design techniques taught during the course. Any system was acceptable for the project, but a system with innovative characteristics and a clear bioinspired component were preferable. After selecting the system, the students posed the design problem in a solution-neutral manner with clear needs, constraints and performance expectations. Students used a functional model as one of the solution-neutral descriptions of the design problem. Students then attempted to find solutions to the design problem using BioTRIZ and a combination of functional modeling and bio-keyword searches. The students were asked to carefully document their work as they generated concepts with these methods. Finally, the students compared the ideas generated by each method and gave a critique of the methods.

4.1 BioTRIZ

The students were generally successful in using BioTRIZ to generate ideas. Following the method's clear procedure, all of the students were able to find inventive principles applicable to their problem. They only seemed to encounter difficulties after finding the IPs. Three of the students misunderstood the project statement and stopped after finding the IPs rather than proceeding to generate designs from them.

Of the remaining students, two seemed to be somewhat fixated on the original system they had selected, or related existing solutions, generating variations on the initial system rather than original ideas. This fixation may be partly due to the fact that the project is a redesign problem rather than a blank-slate design. For example, one student chose to redesign a mushroom-based packaging filler. One of the IPs selected was "segmentation" to improve the structure due to problems caused by energy absorption. The solution derived by the student was to use small components that could "fill the space like beans or peanuts".

For five of the reports, the solutions generated through the conflict resolutions in BioTRIZ led to concepts that were a part of the final design, rather than creating a complete design. One student chose to look at generating energy from tidal forces. By trying to resolve the issue of capturing more energy in a small physical space, the student used the IP of "transition to another dimension" and created a design that combined the horizontal movement of a shark tail and the vertical movement of a dolphin tail, seen in Figure 3. This could be combined with another one of his other designs, which was to position the capture device below water and the generator above water in order to minimize the amount of the device in corrosive saltwater.

According to a student critique of the bioinspired design method in the reports, the students found BioTRIZ to be a new way of evaluating the problem. One stated that it helped to gain a different perspective on his design because it required the student to partition the problem in new ways. Three of the students commented that the method promoted creative and inventive ideas when trying to resolve the design conflicts. While BioTRIZ can be applied to challenging problems to find novel solutions, students also said that the method was easy to implement and straightforward. The students were guided through the process of finding conflicts and resolving them using the IPs. Three students remarked that the method was fast and time-efficient, however they also acknowledged that the quantity and originality in the designs generated using BioTRIZ was tied to the amount of time and effort applied by the student.

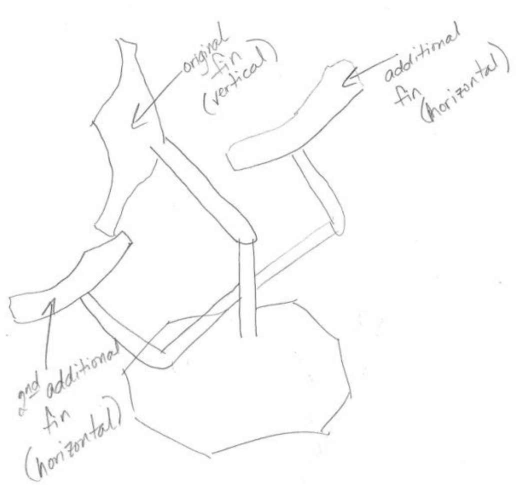

Figure 3. Bioinspired concept to capture more energy from a tidal wave, generated with BioTRIZ.

Using BioTRIZ was also effective when the design process could be viewed as a composition of several trade-off analyses, as noted by two students. One said this helped because trade-offs are classically used in computing, which proved that BioTRIZ fit well into the computing space and could be applied to different disciplines. Another student agreed and continued on to state that BioTRIZ also helped to derive solutions that encompass multiple disciplines.

Two of the students suggested that the method would work well when creating an initial design. The conflicting issues could be found at the beginning and resolved. One student made the observation that BioTRIZ is a "top-down" approach to design, starting at the most general principles and letting the designer work their way down to some specific implementation.

4.2 Functional Modeling and Bio-Keyword Search

Functional modeling was combined with bio-keyword searches since they both make use of the Functional Basis, which can be applied to the engineering-to-biology thesaurus. Unlike BioTRIZ, modeling functional model was only completed by seven students and was correctly used by even fewer students. The greatest challenge the students faced was that very few of them were able to create a useful functional model of their system. Apparently, the majority of the students were not familiar with functional modeling for engineering design. While engineering students with some background using functional modeling might find its use in bioinspired design to be a simple extension of their knowledge, these students had to learn an entirely new technique and did not have enough practice to create effective functional models of their systems. The students that did not fully understand functional modeling tended to have difficulty generating bio-keyword search terms that yielded useful sources of biological inspiration; some models were constructed such that they clearly led to the original engineering solution rather than being solution-neutral. For example, one student chose to re-engineer a flapping-wing design for Micro Air Vehicles. This student did not grasp the value and proper use of a functional model; his novice functional model can be seen in Figure 4.

The search terms derived from this model included each of the inputs or design functions in his functional model, including items such as "flapping-wing" or "wing span". The design concepts developed resembled needs and performance expectations rather than full concepts, for instance "the flapping-wing MAV must have collective pitching and collective flapping".

Another issue found during bio-keyword searches was a fixation on the original design. Once again, this is most likely due to the redesign nature of this project. However, this was more noticeable than for BioTRIZ because of the record of their choice in search terms. The student that chose to redesign the tumbleweed concept for a Mars Rover searched for terms like "wind driven locomotion biology".

Several students did not draw analogies from the biological sources of inspiration they found, but instead directly copied the biological systems. For instance, one student proposed creating electro-mechanical copies of fish as high-acceleration underwater vehicles. This student concentrated on two types of underwater animals: an eel and a pike. The eel-based design, shown in Figure 5, demonstrates the student's replication of an eel found in nature rather than using the animal as a basis for an analogy. Helms, Vattam, and Goel observed similar behavior in a study of design teams in an introductory bioinspired design course at Georgia Tech [12].

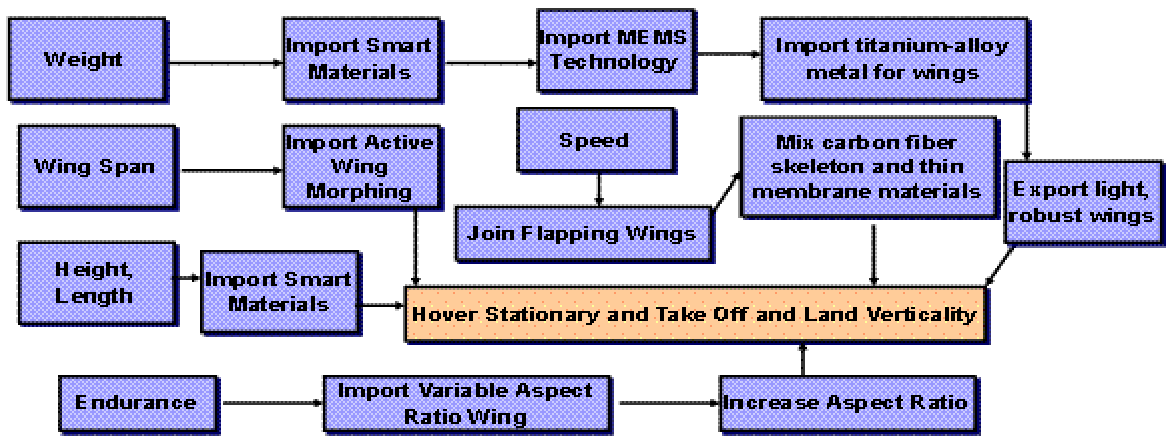

Figure 4. This model is not solution neutral, and many of its entries are not functions (e.g. weight, speed). Using this model led to poor bio-keyword search results.

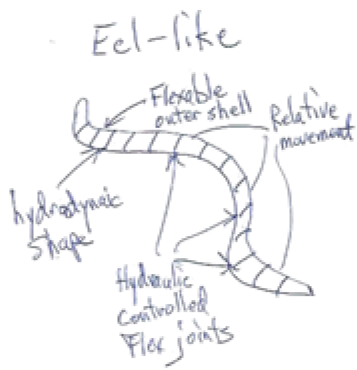

Figure 5. Concept based directly on a biological system, rather than a drawn analogy.

Despite the many problems faced by the students in using functional modeling for bioinspired design, a few students did form useful functional models of their system and drew effective design analogies from the biological sources of design inspirations their searches uncovered. These students commented that the designs generated using functional modeling were different from those using BioTRIZ. Returning to the example of student who chose to design devices to generate power from tidal energy, a very detailed functional model was created and four functional requirements were chosen for the bio-keyword search. From the search, a new concept was created after the search returned that combining the action of the dorsal fins and caudal fins on a fish can produce more thrust, seen in Figure 6. The new design has the same purpose as the one shown in Figure 3 from BioTRIZ, but accomplishes it in a new manner. This demonstrates that functional modeling and BioTRIZ can be used to complement one another rather than choosing one method over the other.

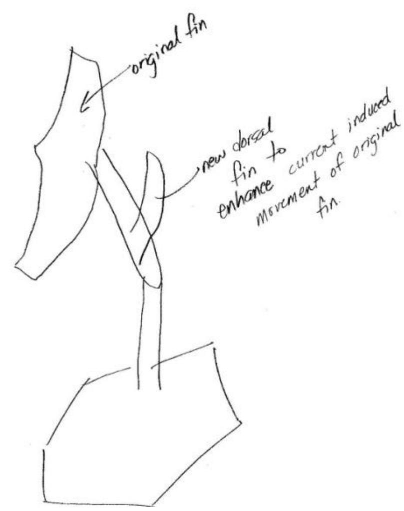

Figure 6. Bioinspired concept to capture more energy from a tidal wave by employing both the large fin of the original design and a secondary dorsal fin. Generated with functional modeling and bio-keyword search.

Not surprisingly, the students who had difficulty using functional modeling found the technique to be much less useful than BioTRIZ. Three of these students also claimed that using the bio-keyword search was hard to do without being biased and two of the students did not follow the method of using the Functional Basis and engineering-to-biology thesaurus to select search terms. The students felt that they needed to visualize a concept while searching and often ended with the same concept as the original product. However, one student did comment that by using the engineering-to-biology thesaurus as a search term guide, he was able to retrieve many more references.

Many observed that the example biological solutions from their keyword searches gave them valuable inspiration for generating new solutions. Using functional modeling required the students to perform problem segmentation and partition the capabilities of the constituents. The students pointed out that an in-depth understanding of the problem was needed in order to create the functional model.

Two of the students remarked that the functional modeling process took longer to complete than BioTRIZ since searching for terms and understanding the findings can be an arduous task. Similar to BioTRIZ, if a designer invested more time and effort in the method, it would lead to more design concepts. However, two other students observed that there were a greater potential number of design concepts that could be found by using functional modeling. There is a large reservoir of raw information and a number of biological examples and case studies that could be used as an inspiration for new ideas.

The student who observed that BioTRIZ as a "top-down" design method went on to describe functional modeling as a "bottom-up" method. This observation raised an important point about functional modeling. BioTRIZ gives students broadly applicable inventive principles from which to generate possible solutions. In contrast, functional modeling and bio keyword searching gives examples of biological systems that perform functions that are needed in the design. The students must then abstract design information from the biological system to find a broadly applicable principle from which they can conceptualize an engineering solution. This added level of abstraction may be a major obstacle for students attempting to use functional modeling for bioinspired design.

5. CONCLUSIONS

Functional modeling, BioTRIZ, and bio-keyword searches all aid designers in finding design inspiration for engineering systems within natural systems. These tools can help designers access the vast amounts of design information contained in nature by giving a systematic approach to finding relevant biological systems and abstracting their designs to forms more accessible to engineers.

Working professionals in a weekend-long workshop learned a series of design methods to aid in bioinspired design. These methods included functional modeling for bioinspired design, BioTRIZ, and bio-keyword searches. Results from the case study indicate the professionals were generally able to quickly learn methods and then to develop solutions using the methods. After analyzing the design projects from these professionals in the case study, we have uncovered many difficulties designers can face when employing these bioinspired design methods.

Using BioTRIZ to find system parameters and the IPs necessary to resolve conflicts was simple and all the students in the case study were able to complete this portion of the method. However, creating solutions from the IPs was more of a challenge. It is necessary to find a way to bridge the gap between knowing the often used principles and creating new, creative solutions.

It is evident that more emphasis needs to be placed on teaching proper functional modeling; if individuals are already accustomed to functional modeling, then learning functional modeling for bioinspiration is probably quite easy. A useful functional model of a system would not only aid engineers in general engineering design, but it would also make the transition to using the technique for bioinspired design much more simple. It aids students in deconstructing a design problem into its functional components so that an analogous function in nature could be more easily found. The use of the functional models and the Functional Basis in conjunction with the engineering-biology thesaurus proved helpful and example systems found using the bio-keyword searches were useful sources of inspiration. The students who understood functional modeling and created a good model were able to retrieve better results from their search when using the terms from the engineering-to-biology thesaurus. While creating a functional model and performing the bio-keyword search takes more time than BioTRIZ, there is a greater potential number of design concepts due to the considerable amount of information on biological systems and case studies. One item to note is that the importance of drawing analogies from nature needs to be emphasized rather than trying to replicate nature directly. Without making use of analogies, a designer loses the opportunity to find innovative solutions that are inspired by nature at the functional level. The bioinspired methods help to reinforce the utilization of analogies, but upon analysis of the case study, it is apparent that the problem occasionally persists. Vattam, Helms and Goel noted similar misuses of analogies in their study with design students at Georgia Tech [12].

Learning more about the strengths and weaknesses of the methods would be helpful in learning when the methods work best and if the methods are not applicable in certain situations. The results from the case study were a start, but the effectiveness of each technique needs to be measured in a controlled experiment. The feedback from the subjects would be valuable in improving upon the methods. Advancements of these methods would encourage the usage of bioinspired design to generate creative and novel design solutions.

6. ACKNOWLEDGEMENTS

Support for this project was provided by the National Science Foundation NSF DUE-0942400. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] Glier, M., McAdams, D., Linsey, J., Accepted, "Concepts in Biomimetic Design: Methods and Tools to incorporate into a Biomimetic Design Course", Denver, CO, DETC2011-48571

[2] Altshuller, G., and Rodman, S., 1999, The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity, Technical Innovation Center, Inc., Worcester, MA.

[3] Vincent, J. F. A., and Mann, D., 2002, "Systematic Technology Transfer from Biology to Engineering," Philosophical Trans. of The Royal Society: Physical Sciences, 360, pp. 159-173

[4] Vincent, J. F. V., Bogatyreva, O. A., Pahl, A. K., Bogatyrev, N. R., and Bowyer, A., 2006, "Biomimetics - Its Practice and Theory," Philosophical Transactions of the Royal Society J, 3, pp. 471-482.

[5] 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.

[6] Tinsley, A., Midha, P. A., Nagel, R. L., McAdams, D. A., and Stone, R. B., 2007, "Exploring the Use of Functional Models as a Foundation for Biomimetic Conceptual Design," eds., Las Vegas, NV, DETC2007-35604

[7] Nagel, J. K., Nagel, R. L., Stone, R. B., and McAdams, D. A., 2010, "Function-Based, Biologically Inspired Concept Generation," Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 24(1), pp. 521-535.
[8] Stroble, J., Stone, R. B., McAdams, D. A., 2009, 'Conceptualzation of Biomimetic Sensors Through Functional Representation of Natural Sensing Solutions', International Conference of Engineering Design, Stanford, California
[9] Stroble, J. K., Watkins, S. E., Stone, R. B., McAdams, D. A., and Shu, L. H., 2008, "Modeling the Cellular Level of Natural Sensing with the Functional Basis for the Design of Biomimetic Sensor Technology," Kansas City, Missouri
[10] Linsey, J, Murphy, J.T., Wood, K.L., Markman, A.B., and Kurtoglu, T., 2006, "Representing Analogies: Increasing the Probability of Success, ASME Design Theory and Methodology Conference, Philadelphia, PA
[11] Chiu, I., and Shu, L. H., 2004, "Natural Language Analysis for Biomimetic Design," Salt Lake City, Utah
[12] Nagel, J. K., Stone, R. B., McAdams, D. A., 2010, "An Engineering-to-Biology Thesaurus for Engineering Design," Montreal, Quebec, Canada, number DETC2010-28233.
[13] Vattam, S., Helms, M., and Goal, A. K., 2007, Biologically-Inspired Innovation in Engineering Design: A Cognitive Study