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# **Training Mechanical Engineering Students to Utilize Biological Inspiration during Product Development**

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## **Abstract**

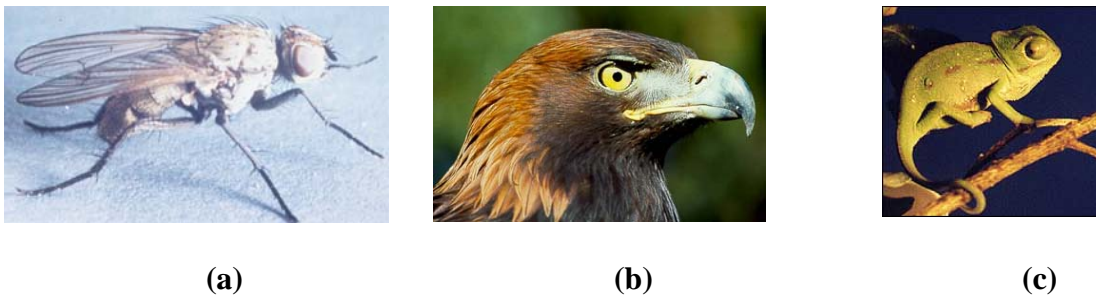
The use of bio-inspiration for the development of new products and devices requires new educational tools for students consisting of appropriate design and manufacturing technologies, as well as curriculum. At the University of Maryland, new educational tools have been developed that introduce bio-inspired product realization to undergraduate Mechanical Engineering students. These tools include the development of a bio-inspired design repository, a concurrent fabrication and assembly manufacturing technology, a series of undergraduate curriculum modules, and a new senior elective in the bio-inspired robotics area. This paper first presents an overview of the two new design and manufacturing technologies that enable students to realize bio-inspired products, and describes how these technologies are integrated into the undergraduate educational experience. Then, the undergraduate curriculum modules are presented, which provide students with the fundamental design and manufacturing principles needed to support bio-inspired product and device development. Finally, an elective bio-inspired robotics project course is present, which provides undergraduates with the opportunity to demonstrate the application of the knowledge acquired through the curriculum modules in their senior year using the new design and manufacturing technologies.

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## 1 Introduction

For millions of years, plants and animals have been evolving in nature to function in a robust and efficient manner that enables them to sustain their existence in variety of ways. One example is the common fly, shown below in *Figure 1*. The fly, like so many other creatures, has been evolving over time to become highly efficient. Its wings are extremely thin, with a distribution of mass that optimizes the muscle efficiency at flapping frequencies of up to 1000 Hz in near-hovering and forward flight conditions for enhanced maneuverability to avoid predators [1]. Another example of a creature that has evolved is the golden eagle, pictured below. The golden eagle is a bird of prey, usually hunting small animals. Because golden eagles live in high places and their prey live on the ground, the structure and size of the eagle's eye has evolved so that it is disproportionately large and has five times the rods and cones of a human eye and two foveae instead of one to provide it with the ability to see food from very far away [2]. While there has been evolutionary adaptation of shape, structure, and mass of creatures to their environment for survival, some have also evolved a physiological adaptation ability. For example, the chameleon shown below can change colors depending on its surroundings, which camouflages it from predators [3].



**Figure 1.** Examples of Designs Found in Nature: (a) house fly; (b) golden eagle; (c) chameleon.

Engineers are frequently asked to design new materials, structures, mechanisms, and processes. To design these new products and artifacts often requires a search for new ideas. One source for new ideas can be found in nature. By learning about the way plants and animals have evolved and function in nature through millions of years of evolution, engineers can gain sources of inspiration for developing new products, which are referred to as “bio-inspired” or “biologically-inspired” products. Many existing design tasks can also be re-examined to find new solutions using nature as a tool for inspiration. Unfortunately, many engineers may not think to use nature as a source of inspiration because most undergraduate engineering curriculums do not adequately emphasize its importance. It is believed that educating engineers in the ways natural structures and systems have evolved and function will enable them to apply these concepts to future designs.

The idea of mimicking nature to achieve similar functionality dates back to the story of the attempt by Icarus to fly by using wings made from feathers and wax [4]. However, in the last few decades researchers have been interested in developing formal scientific and engineering paradigms for obtaining design solutions that do not just mimic nature but can also be inspired by it, which has resulted in very positive outcomes for robotics, aerodynamic systems, biomedical devices, materials, and computational systems. The materials community has gained

much knowledge from nature to develop better microstructures for materials, and several books have been published dealing with the natural materials themselves as well as synthetic replicas, or biomimetic materials [5-7]. The robotics community has also turned to nature for inspiration to develop robots, like snake robots and cockroaches, that use animal-like gaits rather than wheels for better functionality and efficiency to meet special requirements, such as traversing obstacle-ridden terrain by crawling and maneuvering over reduced-friction surfaces using rectilinear motion [8,9]. Structural engineering researchers have also been studying nature for new ideas on how geometry affects load handling ability and how it can be sensed to create stronger and more adaptive structures [10-12]. Success has already been realized using bio-inspired concepts, and undergraduate students are now being educated so they will be able to use ideas taken from nature and apply them to future designs.

Slowly, bio-inspired concepts have been implemented into a variety of products. The reason for this slow growth has been two challenges that need to be overcome for engineers to discover the full potential of nature's designs. *The first challenge is to make students more aware of biological concepts and the application to the design of bio-inspired products.* Currently, many students overlook solutions found in nature simply because they do not know to look there or how they can apply the solutions to the development of engineered products. Students are only trained to look for design ideas using conventional methods from their engineering education and experience. *The second challenge is to allow students to physically realize their bio-inspired products.* Currently, even if an student is aware of the vast potential of bio-inspired design, it is difficult for them to find manufacturing technologies that allow them to build and test their design in a cost-effective manner.

Prior to implementing the curriculum improvement efforts, the following pedagogical issues in the education of Mechanical Engineering students were identified as being related to the aforementioned challenges:

- For the first *design-oriented* challenge, it is clear that only a few traditional design and engineering books presenting examples of bio-inspired designs, despite the flow of ideas from biology to engineering originating in the 1950s and 60s through the formalized concepts of *biomimetics* and *bionics* [13,14]. Lack of concrete examples made it difficult for students to learn how to utilize bio-inspiration during the product development process. *To address this challenge, the development of a repository of several well-known bio-inspired products is described in this paper.* This repository provides reference material and case studies for students interested in exploring the use of bio-inspiration in design. To develop this repository information first had to be archived from biologists and make it accessible to engineers. Therefore, the repository of products and concepts must include detailed information regarding the biological source of inspiration, as well as the applications of such concepts. Secondly, since engineers often generate design concepts to satisfy functional requirements, a repository of bio-inspired concepts had to capture the functionality of the products and concepts being recorded. Furthermore, engineers and biologists may use different terminology to describe the functions of a system, a method was needed to record this functional information that will be easy to use for both biologists and engineers. Such a method must make use of a common language and ensure the expressiveness of the functions being recorded. Also, to ensure the success of this language, it must be extensible. Thirdly,

this information must be made easily accessible; therefore, the repository needs to support a content-based search by which engineers could quickly retrieve products or concepts that satisfy certain functions. Consequently, intuitive and flexible search tools have to be developed to allow users to navigate and retrieve design concepts. Lastly, the success of such a repository of information depends upon the amount of knowledge it contains. Therefore, the repository is extensible so that engineers and biologists can add their new designs and biological discoveries. The repository reported in this paper addresses these challenges, and complements another approach being developed at The Center for Biomimetic and Natural Technologies at the University of Bath that focuses on integrating biology into an indexing method for design retrieval, known as TRIZ, by introducing biomimetic design concepts [15].

- For the second *product-realization* challenge, it was realized that unlike conventional engineered systems, biological systems are more geometrically complex and highly heterogeneous, using multi-scale variation in the geometry (e.g., *fractals*) and material properties (e.g., *graded*) to achieve improved material-function compatibility. Furthermore, to achieve high degree of fault tolerance and adaptive behavior, they make use of sensors and actuators distributed throughout the system. It is reasonable to expect that the designs that are based on bio-inspired concepts will make use of geometrically complex heterogeneous structures and embedded components. Conventional manufacturing processes are therefore not able to easily manufacture bio-inspired designs because of these unique considerations. In order to ensure that the designs based on bio-inspired concepts are physically realizable and affordable, designers and researchers developing such designs need access to fabrication processes that can manufacture geometrically complex heterogeneous structures in a cost-effective manner. Recently, a new class of processes has emerged. These processes perform concurrent fabrication and assembly and, hence, are more suitable for realizing bio-inspired designs. *Since traditional curriculums do not discuss these types of manufacturing processes, a series of teaching modules is described in this paper that introduce students to concurrent fabrication and assembly processes so they can utilize these processes to physically realize their bio-inspired design concepts.*

Although the design repository and concurrent fabrication and assembly manufacturing technology are needed in order for students to learn about designing and realizing bio-inspired products, it will be difficult for them to properly utilize these tools without introducing the appropriate design, manufacturing, and materials subjects into the curriculum. These teaching materials must provide students with an understanding of the motivation behind bio-inspired products, an understanding of what has already been achieved, and knowledge of the core mathematical and scientific principles behind the realization of bio-inspired products that have been achieved through design and manufacturing.

This paper will describe educational activities being pursued in the Department of Mechanical Engineering at the University of Maryland to meet these challenges through new educational tools and curriculum. The next sections will introduce the approach and techniques that were used to create a new repository of bio-inspired products and concepts, a new multi-stage molding technology for manufacturing of bio-inspired products with no assembly, new undergraduate

curriculum modules for bio-inspired product realization, and a senior elective titled bio-inspired robotics.

## 2. Development of New Bio-inspired Products and Concepts Repository

In developing a repository of bio-inspired products and concepts, it is important to include information about the biological systems, as seen in the biological effects database, while also presenting information on product development that will aid engineers. When creating a functional language to access this information, a functional basis has proven to aid in archiving and retrieving the information. However, it is also important to allow the user freedom to express the functions in terms of language and sentence structure. Whatever terms are used should be common language terms and not arranged in an arbitrary hierarchy. The natural language analysis has also shown that by searching for many alternatives to a single function term, many useful results may be found. Lastly, easy to use and flexible search tools are required to locate meaningful results.

The complete system has three parts: (a) Repository of bio-inspired products and concepts, (b) Functional Description Template, and (c) Search tools. The interaction of these three elements is shown in *Figure 2*. In order to add a product or concept into the repository, the user must fill out the data entry form. The entry may be made by a biologist adding concepts from biological research or by an engineer archiving a bio-inspired product. In either case, the Functional Description Template is used to record the functions of the product or biological system. Following this process, the entry is stored. A user may then use a search form to locate information on bio-inspired work. The products or concepts that are returned can then be applied to the design to create a new bio-inspired design. This design can then be added into the repository as a new bio-inspired product, and also provided to the biologist so they have an opportunity for feedback on the implementation of the natural principles in the bio-inspired design by the engineer through the data entry form.

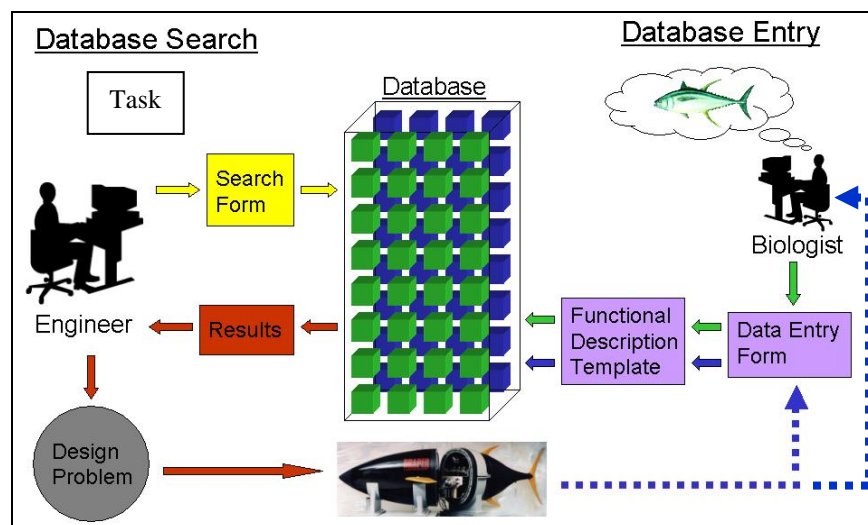


Figure 2. System Overview

## 2.1 Contents of Repository

The repository being developed archives bio-inspired products and concepts. Bio-inspired products refer to products in any stage of development that have taken their inspiration from nature. These products may be anything from a new material substance to a complex mechanical device; they do not necessarily have to be consumer products. A bio-inspired concept refers to an observation of some function being met in nature. This concept need not be implemented into a product yet. Such concepts may be archived into the repository and any potential applications may be recorded. Currently, the repository contains 85 records of bio-inspired products. These products were identified and researched through a search of journal papers, conference papers, magazine articles, and websites that discuss current bio-inspired research. The searches that were conducted explored bio-inspired actuators, sensors, materials, robots, and various other mechanical devices and consumer products that were inspired by nature. All of the products that were located were then recorded into the repository. If a bio-inspired concept is being archived, the product information fields will remain empty, except possibly the applications field. The product function, or in the case of a concept the function of the biological system, requires many fields that are populated by using the Functional Description Template.

## 2.2 Functional Description Template

In order to develop an easy to use and expressive method for recording functions (i.e., the desired behavior of a structure or system), it was necessary to first understand how people naturally express a functional statement. To accomplish this, an informal study was done asking people to write down the functions of common products. From these results, it was clear that there was no uniform way to represent a function. Some functions were very brief statements, while others were lengthy descriptions. However, all the functional statements used the same elements to form a sentence (verbs, nouns, etc., but not adjectives or adverbs). Therefore, if common arrangements of these terms could be identified, then standardized templates could be provided for users and the desired terms could be entered. This concept is the basis for the Functional Description Template, a new method for recording product functions in the design repository that provides a predetermined sentence structure as a template to allow the user to form more complete functional descriptions. The methods of data entry used to fill in the template are a combination of freeform text entry and menu selection, which allow the recorded information to be efficiently archived and retrieved while ensuring that the system is easy to use by both engineers and biologists. In the design repository, the template makes use of the following three primary terms for both biological and engineering functions: (a) *Action (the intended behavior)*, (b) *Entity (which is participating in the action)*, and (c) *Property (characteristics of the behavior of structure and/or system)*. Prepositions and conjunctions are also available. Adjectives and adverbs, however, are currently not used in the Functional Description Template. This omission is due to the fact that such terms were found to be non-essential to describing a function and merely offer additional information. However, the addition of these terms to the template could be completed at a later time.

## 2.3 Performing Search on the Repository

It is essential that the information stored in the repository be easily accessible to users in a straightforward manner and must provide meaningful results. To accomplish this, the following three search tools have been made available: (a) keyword search, (b) category filter, and (c) function search. In the keyword search, a user enters the desired search terms using freeform text entry fields. The search for the bio-inspired design repository is conducted by using a string matching algorithm that is a combination of two other string matching algorithms; namely, equivalence method and similarity method. For the category filter, results are filtered based upon the fields that are recorded using menu selections that were chosen many different possibilities by qualitatively judging their usefulness on a wide variety of examples. These fields include: (a) *Product Type*, (b) *Biological Type*, and (c) *Development Stage*. The final search tool is the function search, which is used to specifically search for products or concepts that meet a particular function or set of functions. While the keyword search may be used to search the functions of the products and concepts in the repository, the function search is specifically designed to search by function. This search tool aids the user in creating the functional statements for which to search and conducts a more flexible search that returns more useful results.

## 2.4 Example

Consider a scenario in which a student is designing an automated vehicle that can be used for underwater surveillance. The student, familiar with the recent advances in bio-inspired engineering, decides to search the repository of bio-inspired products and concepts. The student may search for ideas using a combination of the search tools described above. In this case, a search is conducted for the keywords “underwater reconnaissance”, as well as the function “move device in liquid”. From this search, many results are returned, some of which contain only the keyword “underwater” and some of which contain a variation of the function “move device in liquid”. However, the top result is one that describes an unmanned underwater vehicle that was inspired by the tuna [16]. This entry in the repository contains the keyword “underwater” in the product description and contains the keyword “reconnaissance” in the applications. Furthermore, one of the product’s functions, “propel robot through water”, closely matched the search function. The student may then view the complete record, as shown in *Figure 3*.

### **Product Information**

*Product Name:* VCUUV

*Product Type:* Mechanism: Robot

*Product Description:* An unmanned underwater vehicle with a low drag body and flexible hull.

Uses vorticity control for both propulsion and maneuvering, and caudal and pectoral fins for steering.

*Development Stage:* Product development

*Applications:* Mine reconnaissance, surveying, cable laying

### **Functions**

- Propel robot through water
- Detect position of mines
- Measure volume of mines
- Regulate linear velocity of robot



- Regulate angular velocity of robot

### **Biological Inspiration**

*Biological Name:* Yellow fin Tuna

*Biological Type:* Animal: Fish

*Biological Description:* The tuna has a very streamlined body and is highly maneuverable. It can accelerate and decelerate rapidly and maneuver in tight space

### **Resources**

*Primary Source:* J.M. Anderson and P.A. Kerrebrock, “The Vorticity Control Unmanned Undersea Vehicle (VCUUV): Performance Results,” *11<sup>th</sup> International Symposium on Unmanned Untethered Submersible Technology*, Draper Report No. P-3747, Durham, NH, August 1999.

*Additional References:* <http://www.draper.com>

**Figure 3.** Example of record from search of bio-inspired design repository

## **2.5 Comparison with Biomimicry Database**

There are significant similarities and differences between this repository and the Biomimicry Database from the Biomimicry Institute (available at <http://database.biomimicry.org/start.php>). The main similarities are in terms of archiving supporting information (product description, references, source of biological inspiration). The main differences are in the ways the functions are described. Biomimicry database uses challenges and strategies fields to capture the design requirements and the underlying concepts. Challenges field describes human design problems that need solutions. Strategies field describes potential solutions to those problems. Both challenges and strategies fields are described using natural language. In this repository, formal functional descriptions are used to list the top level functional requirements for the product. In addition, decomposition is used to capture how high level requirements are decomposed into subsystem requirements. Formal taxonomies have been used to enable more targeted searches. Both approaches have merit and they should ultimately be merged into a single database structure.

## **3. Concurrent Fabrication and Assembly using Multi-Piece Multi-Stage Molding**

For students to implement designs such as the one described in the case study, a new *Concurrent Fabrication and Assembly* technology based on *Multi-Piece Multi-Stage Molding* process was developed at the University of Maryland to affordably manufacture large quantities of bio-inspired products based on polymers and embedded components. This technology is focused around the design and manufacturing of molds from inexpensive mold materials, such as polyurethane. Designing the mold for bio-inspired products is a very challenging task, because the complexity of the material distributions and geometries are not conducive to generating the single parting direction required for a standard two-piece mold. In addition, complex molds often require very complex undercuts to realize the entire structure. Multi-piece molds overcome these restrictions by having many parting directions. These molds have more than one primary parting surface, and consist of more than two mold pieces or sub-assemblies. Each of these mold

pieces will have a different parting direction. The freedom to remove the mold pieces from many different directions eliminates the undercuts produced by two-piece molds. A multi-piece mold can be visualized as a 3D jigsaw puzzle, where all the mold pieces fit together to form a cavity and then can be disassembled to eject the molded part. Moreover, since there are no actuated side cores in multi-piece molds, the tooling cost is significantly lower. This makes multi-piece molding technology an ideal candidate for making geometrically complex objects.

Multi-stage molding is usually accomplished through some form of specialized molding technique. This means that the various polymers composing the different material sections are injected in sequence into a mold or set of molds. The liquefied polymers then solidify into their desired shapes by taking on the form of the mold cavities in which they reside. An important advantage of multi-stage molding is its ability to produce fully assembled components 'in-mold'. This means that an entire assembly consisting of multiple pieces can be produced by a single set of molds, thereby eliminating the need for additional assembly operations and the use of bolts, welds, glue, or other fasteners. Thus, the fabrication and assembly of the component occur concurrently.

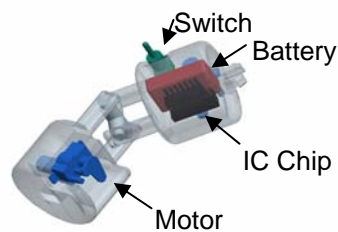
The concurrent fabrication and assembly of components using the multi-piece multi-stage molding process allows one to fabricate heterogeneous structures with material interfaces that are geometrically complex and exhibit superior fracture and fatigue behavior, as well as improved functional performance [17, 18]. Specifically, multi-stage multi-piece molds have the following benefits:

- *They can be used to create multi-material objects.* A partially assembled mold is used to pour one material. After completing one molding stage, the mold assembly is modified by removing and adding mold components and a different material is poured to produce a different portion of the object. By using multiple stages, a geometrically complex multi-material object can be manufactured. The ability to create multi-material objects allows designers to select different materials for different portions of the object, thus helping to improve material-functional compatibility for the overall object.
- *They can be used to create objects in which prefabricated sensors/actuators can be embedded in the object during the molding process.* The ability to embed prefabricated sensors/actuators during the molding process helps to eliminate the need for post-molding assembly and significantly improves reliability.

In summary, multi-piece multi-stage molds can be used to create geometrically complex heterogeneous ceramic and polymer objects that are impossible to create using traditional molding techniques. This approach has the following advantages over conventional:

- Scalable
- Reduces the number of components
- Improves reliability
- Easier to manufacture
- Fast production
- Reduces production cost

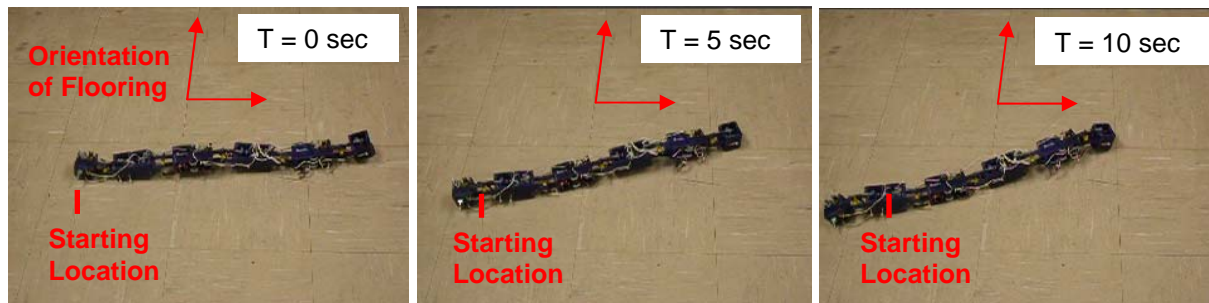
An example of a bio-inspired design that was manufactured using this technology is a snake robot module. A solid model of the module is shown in *Figure 4*, and the actual module is shown in *Figure 5*. The mechanical structure of the module was assembled in-mold, and consists of a universal joint, a motor with linkage across the joint for locomotion, and docking connectors for modularity. The male and female connectors are located at opposite ends of the structure, and are geometrically correct, although a more flexible material must be used in order for them to be functional (something that can easily be done with a different grade of polyurethane). The module was assembled via a two-stage transfer molding process, where a second material was used to make the universal joint. The entire module consisted of only three parts, the two on either side of the joint, and the cross-shaped piece making the joint; consequently, no additional fasteners or shafts are required. The concave interior feature of the female side of the docking mechanism was created using a split-core technique. An assembled snake robot in motion can be seen in *Figure 6*. Based on the multi-piece multi-stage molding process, a new teaching module has been developed that is described in the following section to train students to fabricate bio-inspired products similar to the snake robot in *Figure 6*.



**Figure 4.** Solid Model of Multifunctional Structural Module.



**Figure 5.** Molded Multifunctional Structural Module.



**Figure 6.** Assembled snake robot in motion

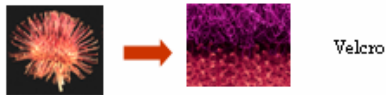
#### 4. Teaching Modules to Support Biologically Inspired Product Realization

To realize bio-inspired products using the new design tool and manufacturing technology, a new undergraduate curriculum for mechanical engineers was developed and implemented at the University of Maryland [19]. This curriculum involves several single-lecture modules that cover a broad range of topics in bio-inspired design, manufacturing, and materials that are

implemented in several core courses, as well as some senior electives. The courses and modules developed for these courses are as follows:

**Module #1: Bio-Inspired Concept Generation and Evaluation**

*Objective:* To expand the concept generation phase of the design process to include concepts originating from nature.



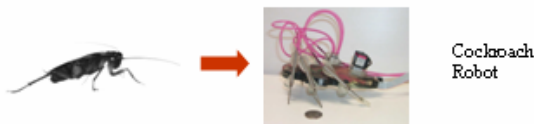
**Module #4: Bio-Inspired Actuators**

*Objective:* To demonstrate how actuation in nature can be used as inspiration to perform similar actuation tasks in engineered devices.



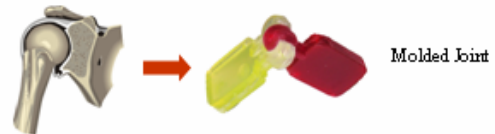
**Module #2: Bio-Inspired Robotics**

*Objective:* To show how robots can be developed using kinematics and control strategies inspired by different animals.



**Module #5: Bio-Inspired Manufacturing**

*Objective:* To describe new methods of concurrent fabrication and assembly that are inspired by nature.



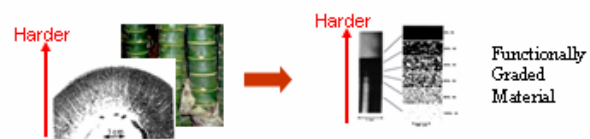
**Module #3: Bio-Inspired Sensors**

*Objective:* To demonstrate how sensing in nature can be used as inspiration to perform similar sensing tasks in engineered devices.



**Module #6: Bio-Inspired Materials**

*Objective:* To demonstrate how nature uses novel microstructures to engineer structures that provide optimal performance characteristics.



**Figure 7.** Some details of modules for new bio-inspired product realization curriculum.

- Bio-Inspired Design: Introduction to Subject** - This presentation offers an introduction to bio-inspired engineering design as it applies to product development. First, a brief overview of product development is given and the challenges in creating next generation products are explained. Next, the engineering design process is examined more closely, specifically concept generation. The issue being discussed is where engineers look for ideas. The questions that are then asked are “What ideas can nature offer engineers?” and “Why look to nature?” The answers to these questions are given through a series of examples. First, nature is shown to have achieved many remarkable feats and developed many unique “inventions”. Nature’s solutions to structures, sensors, materials, propulsion, and more are given as examples. Next, a look is taken at nature’s ability to create optimal designs and also follow design rules. Finally, several current products and also future products in development which make use of bio-inspiration are shown. Lastly, some comparisons are made between conventional engineering design and nature’s design.
- Bio-Inspired Design: Artificial Muscles** - This presentation introduces biological muscle characteristics that are important from the actuation point of view, and compares them with traditional actuators. Then, it discusses attempts to attain some of the characteristics of biological muscle, using technologies known as “artificial muscle”. The structural hierarchy, basis of actuation, and actuation characteristics of biological muscle are illustrated while comparing it to artificial actuators, hydraulic actuators in particular, as a reference point to

engineering applications. Later, the presentation introduces and discusses three artificial muscle technologies: dielectric elastomer actuators (DEA), conjugated polymers, and shape memory alloys (SMA). The basis for actuation, characteristics, and application examples for each of these technologies is explained and contrasted in light of the biological and artificial actuator discussion.

- *Bio-Inspired Design: Mobile Robots* -This presentation discusses how bio-inspiration can be used to develop a new class of mobile robots. Initially, an overview of robots is given and the focus of the presentation is identified as mobile robots and their locomotion capabilities. The motivation for bio-inspiration in mobile robot design is then explained. Some of the questions being explored are “What can nature offer engineers?” and “Can bio-inspired designs outperform traditional technology?” The next matter that is discussed is how engineers can select a source of bio-inspiration to fit a set of design requirements. Specifically, the issues of maneuverability and terrainability are addressed. Finally, several examples of bio-inspired mobile robots are shown in detail, including the motivation and bio-inspiration for their design, as well as technical specifications and comparisons to conventional mobile robots. These examples include robots inspired by the cockroach, snake, tuna, and fly.
- *Bio-Inspired Design: Sensors* - This presentation demonstrates how principles that biological organisms use to sense their environment can be applied to engineered sensor systems. The presentation first defines sensors, and explains what types of sensing occur in nature. Different types of next-generation bio-inspired sensors are then discussed in detail, including the motivation for their design and a comparison to the biological sensor that was the inspiration. An artificial nose and the use of optic flow in insect navigation are fully discussed, and many other examples are briefly presented, including bio-inspired sonar, strain sensors, flow sensors, gyroscopes, and tactile sensors. The improved characteristics of these sensors as compared to traditional sensors are discussed. Furthermore, it is shown how these improved sensors can be incorporated to yield improved engineered products. Finally, some discussion is given to how bio-inspiration will continue to improve sensors and products that incorporate sensors in the future.
- *Bio-Inspired Manufacturing: Concurrent Fabrication and Assembly* - This presentation describes methods of bio inspired manufacturing involving concurrent fabrication and assembly techniques. Initially, a description of the differences between conventional manufacturing ideas and biological ‘manufacturing’ ideas is presented. Then several types of concurrent fabrication and assembly methods are introduced. Following this introduction, examples of concurrent fabrication and assembly are given. Several types of concurrent fabrication and assembly are introduced in detail. Finally, there is a discussion of design and modeling for concurrent fabrication and assembly.
- *Bio-Inspired Manufacturing: Self-Assembly* - This presentation describes how bio inspired manufacturing can be realized through self assembly techniques. Initially, a description of the differences between conventional manufacturing ideas and biological ‘manufacturing’ ideas is presented. Then the key concepts and benefits of self assembly are introduced. Following this introduction, examples of self assembly occurring at different length scales and by different mechanisms are given. There are two in depth case studies showing nanoporous

ceramics created by templated self assembly and electrostatic self assembly. Finally, possible product enhancements due to self assembly are described.

- *Bio-Inspired Materials: Functionally Graded Materials* - This lecture covers the use of Functionally Graded Material (FGM) concepts for the development of bioinspired products. Students are first introduced to natural structures that consist of FGMs and their benefits. Principles for describing, modeling, designing, and fabricating FGMs for bioinspired products are then discussed. Emphasis is placed on the grading of material properties for optimizing performance, using graded metal-ceramic composites as a model synthetic material system. Examples of bioinspired products using FGMs for active structures and MEMS are also provided

Detailed descriptions of these modules can be found at [www.bioinspired.umd.edu](http://www.bioinspired.umd.edu), and are available in PDF format by emailing a request to the authors. Some details of the modules can be seen in *Figure 7*, and abstracts and corresponding content for the modules follow.

The curriculum in each component of the module was assessed after each one was delivered by having students respond to a survey with the following questions and response options:

1. Before attending this presentation, were you aware of any products and/or technologies that were bio-inspired?
  - I knew about several products
  - I knew about one or two products
  - I never heard of them
2. Did this presentation convince you to look for bio-inspired solutions to engineer products/technologies?
  - I will definitely look
  - If I have time, I will look
  - I am not convinced of the usefulness
3. Did this presentation give you a concrete idea on how to use bio-inspiration to develop products/technologies?
  - I now have a very good idea
  - I have some idea, but will need more help
  - I have no idea

Overall, initial findings from the assessment results indicated that 75% of the students had very little prior knowledge of bio-inspired products. Assessment results further indicated more than 90% students expressed strong interest in the subject. In addition, they indicated that they were able to acquire introductory knowledge from the modules. In every class at least 50% students indicated that they would like to learn about this subject.

The assessment results were fairly consistent between modules in that many students had heard a little about bio-inspired products, but in general did not have a great deal of prior exposure. Their experience in the lecture however did spark interest in further knowledge of the subject, however

they seemed to need more knowledge on the concept of bioinspiration than they were provided. As a result, a new senior elective titled Bio-Inspired Robotics was developed (see Section 5).

## 5. Bio-Inspired Robotics Senior Elective Course

Prior curriculum development experiences of the authors indicated that effective teaching of bio-inspired product development required rich design case studies to motivate students. Bio-inspired robots serve as an excellent source of case studies for teaching bio-inspired product development because they seem to fascinate students from a wide variety of backgrounds and appear to be a good candidate to hold their attention.. To this end, a new bio-inspired robotics senior elective course was developed at the University of Maryland that has been offered once a year over the last three years, and will continue to be offered during every Spring semester (results reported in this section are primarily based on the version offer in Spring 2006). This course covers the fundamentals and applications of biologically inspired robots. There are abundant sources of information on how to design these robots, and they can be easily built in semester long projects. These robots are highly multi-disciplinary, consisting of sensors, actuators, mechanical structures, electronics, and software. Components from these diverse disciplines need to be tightly integrated to create successful robots. Thus, the course was designed to convey this multi-disciplinary knowledge in four main parts:

- ***Fundamentals of Traditional Robotic Manipulators:*** In order to conceive, analyze, and create new robot designs, one must be familiar with the fundamentals of traditional robots. This part of the course begins with the history and taxonomy of traditional robots. Different popular robot configurations are introduced. This part also covers forward kinematics, inverse kinematics, and dynamics of serial manipulators to analyze proposed robot designs.
- ***Fundamentals of Biologically Inspired Robotics:*** This part of the course begins with a discussion on the role of biological inspiration in robot design. Several examples of bio-inspired robots are discussed in detail, including the motivation and biological inspiration for their design, as well as technical specifications and comparisons to conventional robots.
- ***Sensors and Actuators for Robotics:*** This part of the course discusses traditional and biologically inspired sensing technologies that are widely used in robotics applications. First, an overview of sensors is presented, followed by a look at biological sensing and what nature's sensors are capable of achieving. Traditional and biologically inspired actuators that can be used in the robotics applications are also covered.
- ***Design and Fabrication of Biologically Inspired Robots:*** This part of the course covers techniques for designing and fabricating biologically inspired robots. This part also covers selecting and programming micro controllers for controlling biologically inspired robots. The basics of numerically controlled machining and injection molding technologies for fabricating structural members of biologically inspired robots are also described.

This course is intended to emphasize hands-on learning. As a part of the course projects, student teams have an opportunity to design and build their own snake-inspired or polypedal robots. These projects are expected to provide a very valuable design and manufacturing experience for mechanical engineering students. In addition to describing the course modules in detail, this

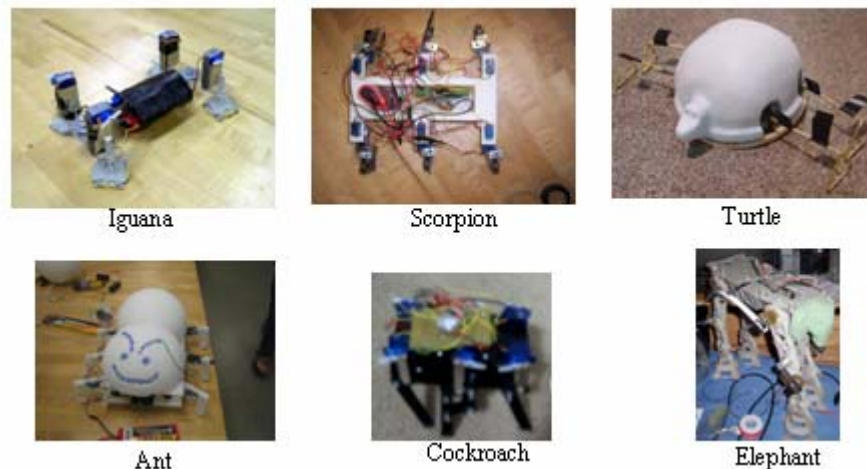
seminar also discusses the experience of the authors in designing and building snake-inspired robots.

As a part of this course, students did a team design project. Students were grouped into teams of three students. Every team was tasked to design and build a biologically-inspired mobile robot. Students were explicitly told that they could not use designs involving wheels and locomotion concept has to be inspired by a biological source. The robot had to have an on-board power supply and electronics (i.e., tethered-designs were discouraged). The design goal was to build a robot that will go along a straight line for two minutes. The robot performance will be measured in terms of the length traveled expressed as body lengths. To ensure robustness of the gait design, the robots were tested on two different surfaces: (1) parking lot and (2) carpet.

Teams were given a servo motor and a compatible micro controller recommendation. This neutralized any advantage a team can have by using stronger servo motors, and made it incumbent upon the student to determine the most efficient natural locomotion if they were to obtain the best performance. As a part of their project, students had to:

1. Design and build the mechanical structure to realize an approximation of a biological creature
2. Design a gait
3. Implement the gait in the software
4. Design the necessary circuit to connect the servo motors to the micro controller
5. Select the appropriate batteries

It was predominantly attended by the mechanical engineering students. There were few aerospace and computer engineering students. Nine student teams were formed. These teams attempted to build the following robots (see *Figure 8*): Ant Robot, Frog Robot, Elephant Robot, Penguin Robot, Cockroach Robot, Scorpion Robot, Turtle Robots (2 Teams), and Iguana Robot.



**Figure 8.** Robots built by students in Bio-inspired Robotics Course.

Six teams produced working robots that successfully moved forward along a straight a line. Robot speeds ranged from 14 body length/minute to 2 body length/minute. Three teams created robots that that were able to actuate all their joints, but were unable to move forward due to flaws in the gait design or mechanical structure.

Despite extensive use of CAD and simulation tools, all teams went through a very large number of design iterations. Common reasons behind these iterations were as following:

- Motor torque was not sufficient to drive the designed structure. There was no convenient way for teams to get the robot pose data from Pro/E to Matlab. Hence, during the gait there existing poses that required large torque.
- There was excessive deflection in the robot limbs (robots limbs were made out of lightweight plastics to reduce weight and attain high speed) and it interfered with the intended gait. There was no convenient way for teams to accurately estimate limb deflections and incorporate them in the kinematic simulations).
- Robots made awkward contacts with the floor due to slight errors in the synchronization of different motors. Hence the gait did not function correctly.
- Friction was not estimated and modeled correctly. Hence some robot designs showed excessive slipping.
- There was no convenient and accurate way to estimate energy consumption. Hence teams had to use extra batteries and as a result increased the mass of the robots.
- They were unable to account for manufacturing tolerances. Hence, considerable time was spent on tailoring joint angles to compensate for manufacturing tolerances.
- Student teams often had trouble in controlling the software versions. Often, they would put the wrong version of some piece of code on the robot. They also did not document their rationale well and sometimes had trouble in tracing the reason for a design change.

These iterations significantly enhanced students understanding of how mechanical structures behave under motion.

Overall student response was quite positive. Many of them indicated that this was one of the best courses they had taken at the University of Maryland. Student response indicated the following:

- No student had designed a multi-disciplinary device prior to taking this course.
- All students stated that it is highly unlikely that they would have learned the material covered in this course if they had not taken this course.
- 91% student stated that this course provided them skill sets and knowledge necessary to design and build bio-inspired robots.

- 87% student stated that this course gave them enough background to utilize bio-inspired concepts in general product design areas.
- 74% student stated that this course provided them skill set and knowledge to utilize sensors and actuators in robotics applications.

A natural question to ask at this point is whether the demand for the class is driven by the “robotics” theme or by the “bio-inspiration” theme in the course. A previous version of the course was titled Bio-Inspired Product Development. That course also had a very strong student response. However, student feedback suggested that the course be made more focused. Hence, it was decided to focus the course on bio-inspired robotics. The “bio-inspiration” theme is an attractive aspect of the course. This is also confirmed by student surveys. Students expressed significant interest in learning additional material in the bio-inspired topic areas when they were introduced the six modules mentioned in Section 4.

Preliminary findings indicate the following:

- There was an overwhelming response to this course and a very large number of students signed up for the course. Only 30 students could be admitted due to limitations of the lab resources. Students worked unusually hard in completing their projects. This confirms that biologically-inspired topic is a good choice for attracting students’ attention and can be used to emphasize engineering informatics challenges.
- New tools will need to be developed to properly introduce multi-disciplinary design principles into the curriculum. These tools will (1) provide tighter integration across domains, (2) allow specifications of gait designs, (3) provide better visualization capabilities of robot movements, and (4) manage engineering models.
- It appears that a good pedagogical approach to teaching bio-inspired product development principles will be just-in-time lecturing. The idea behind this approach will be to assign projects such that students get into a situation where not knowing the biological principles severely limits their chances of completing the project in time. In such situations, students will be motivated to learn and use the bio-inspired design principles. Additionally, a significant portion of the project grade will have to reward the effective use of bio-inspiration. This will require a grading approach that will rewards a good design process in equal measure to the final design outcome.

## 6. Conclusions

The work presented in this paper describes three distinct contributions to motivate engineering students to use bio-inspiration to design and realize products. They are:

(1) Created a *design repository* of bio-inspired products and concepts, which contains detailed information about existing products in various stages of development and biological systems that

may provide new design concepts. Furthermore, the function of these products and concepts were recorded to aid students in solving design problems. This repository was based on a new *Functional Description Template*. This new template allows users to quickly and easily enter functions into the repository while retaining a natural language form, and was designed to be easily used by both engineers and biologists. It also allows greater expressiveness in recording functional statements.

(2) Developed a *concurrent fabrication and assembly technique using multi-stage multi-piece molding* technology for manufacturing products from bio-inspired designs. This technique solves many of the mold design issues for complex material distributions and geometries, and includes cutter selection and path generation, which are programmed to minimize the cost and time to fabricate the molds.

(3) Developed a *curriculum enhancement to support bio-inspired product realization* to educate and train undergraduate mechanical engineering students to include bio-inspired ideas in their products using the new design tool and the new manufacturing technology.

(4) Develop a new senior elective course titled *Bio-Inspired Robotics*. Preliminary findings indicate that this topic area is able to hold students' attention and allows them to successfully exploit biological inspiration.

Another benefit of this work is that bio-inspired knowledge can now be easily indexed and searched by function. In a sense, a functional decomposition of nature can now be performed and engineers can search nature by function. Hopefully, such work will inspire future biological research in attempts to generate new design concepts for engineers. The new manufacturing technology should enable these new design concepts to be affordably manufactured in large quantities, and the educational curriculum should enable the next generation of engineers to utilize these technologies.

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## **8. References**

- [1] Lehmann, F.O. and Dickinson, M.H., "The changes in power requirements and muscle efficiency during elevated force production in the fruit fly *Drosophila melanogaster*", *Journal of Experimental Biology*, Vol. 200, pp. 1133-1143 (1997).
- [2] Land, M.F. and Nilsson, D.-E., *Animal Eyes*, Oxford University Press, UK, 2002.

- [3] Cuadrado, M., Margin, J., and Lopez, P., “Camouflage and escape decisions in the common chameleon *Chamaeleo chamaeleon*”, *Biological Journal of the Linnean Society*, Vol. 72, 547-554 (2001).
- [4] S. Vogel, *Cat’s Paws and Catapults: Mechanical Worlds of Nature and People*, W.W. Norton & Company (1998).
- [5] Mann, S. ed. Biomimetic materials. New York: VCH, 1996.
- [6] Sarikaya M., Aksay, I. A. eds. Biomimetics: design and processing of materials. Woodbury, N.Y.: AIP Press, 1995.
- [7] Richard P. Wool, R.P. and Sun, X.S. Bio-based polymers and composites. Boston: Elsevier Academic Press, 2005.
- [8] Duro, R. J., Santos, J., Graña , M. eds. Biologically inspired robot behavior engineering. New York: Physica-Verlag, 2003.
- [9] Hirose, S. Biologically inspired robots: snake-like locomotors and manipulators. New York: Oxford University Press, 1993.
- [10] Bejan, A. Shape and structure, from engineering to nature. New York: Cambridge University Press, 2000.
- [11] Mattheck, C. Design in nature : learning from trees. New York: Springer-Verlag, 1998.
- [12] A. Skordos, P.H. Chan, J.F.V. Vincent, and G. Jeronimidis. A Novel Strain Sensor Based on the Campaniform Sensillum of Insects. *Philosophical Transactions of the Royal Society London A*, Vol 360, pp 239 – 253, 2002
- [13] V. Hubka and W.E. Eder, *Design Science: Introduction to the Needs, Scope and Organization of Engineering Design Knowledge, 2<sup>nd</sup> Edition*, Springer-Verlag (1995)
- [14] G. Pahl and W. Beitz, *Engineering Design: A Systematic Approach, 2<sup>nd</sup> Edition*, Springer-Verlag (1995).
- [15] J.F.V. Vincent and D.L. Mann. Systematic Technology Transfer from Biology to Engineering. *Philosophical Transactions of the Royal Society: Physical Sciences*, Vol 360, pp 159-173, 2002
- [16] J.M. Anderson and P.A. Kerrebrock The Vorticity Control Unmanned Undersea Vehicle (VCUUV): Performance Results. *11<sup>th</sup> International Symposium on Unmanned Untethered Submersible Technology*, Draper Report No. P-3747, Durham, NH, August, 1999.

- [17] H.A. Bruck, G. Fowler, S.K. Gupta, and T.M. Valentine, "Using Geometric Complexity to Enhance the Interfacial Strength of Heterogeneous Structures Fabricated in a Multi-stage, Multi-piece Molding Process," *Experimental Mechanics*, Vol 44, pp 261-271, 2004.
- [18] R.M. Gouker, S.K. Gupta, H.A. Bruck, and T. Holzchuh, "Manufacturing Of Multi-Material Compliant Mechanisms Using Multi-Material Molding", *International Journal of Advanced Manufacturing Technology*, 30(11-12):1049-1075, 2006.
- [19] H.A. Bruck, A.L. Gershon, and S.K. Gupta, "Enhancement of Mechanical Engineering Curriculum to Introduce Manufacturing Techniques and Principles for Bio-inspired Product Development", *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, pp 1-6, 2004.