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Enhancement of Mechanical Engineering Curriculum to Introduce Manufacturing Techniques and Principles for Bio-inspired Product Development

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ABSTRACT

Bio-inspired products and devices take their inspiration from nature [Gold00]. Current mechanical engineering curricula do not cover manufacturing techniques and principles needed to develop such products and devices. *We have been enhancing the mechanical engineering undergraduate curriculum by integrating recent advances in the manufacturing of bio-inspired products and devices through the following activities:*

1. Insert a new sequence of instructional materials on bio-inspired concepts into the mechanical engineering curriculum.
2. Disseminate the materials developed for the new modules and course notes through a dedicated web site.

As a result of the curriculum enhancement, a new generation of mechanical engineers will acquire the knowledge necessary to develop products and conduct research for a wide variety of applications utilizing bio-inspired concepts. The project (1) integrates emerging manufacturing technologies based on biological principles into the Mechanical Engineering curriculum, (2) utilizes multi-media technology for disseminating course content, and (3) trains graduate students and faculty participating in its implementation in an emerging technology and thereby contribute to faculty development. Specifically, curriculum is being developed that discusses the following manufacturing technologies and principles:

1. *Concurrent Fabrication and Assembly:* Manufacturing techniques and principles, such as solid freeform fabrication, compliant mechanisms, and multi-stage molding, that can eliminate the manufacturing and assembly of individual components as is the case for almost all natural systems.
2. *Self Assembly:* Principles for manufacturing a variety of products from a few building blocks using bio-

inspired techniques such as templating and supramolecular chemistry.

3. *Functionally Graded Materials:* Bio-inspired development of new products through the gradual variation of material properties at multiple length scales through manufacturing processes such as sputtering and powder processing.

The curriculum development effort makes two significant contributions to mechanical engineering education: (a) integration of a new research on bio-inspired products and devices into the mechanical engineering curriculum through new courses and revision of existing courses, (b) development of new instructional material for mechanical engineering education based on bio-inspired concepts. There are also broader impacts in the following areas: (a) undergraduate students who might not otherwise pursue studies in mechanical engineering will be attracted to the multidisciplinary area of bio-inspired products, (b) dissemination of the curriculum enhancement through conference presentations, a workshop, and dedicated web site, and (c) a biologically-oriented pedagogical approach to mechanical engineering education that ensures broader access to the knowledge needed to enhance the interest and skills of future engineers and researchers educated through this research program.

NOMENCLATURE

Biologically Inspired Manufacturing, Concurrent Fabrication and Assembly, Design for No Assembly, Compliant Mechanisms, Functionally Graded Materials

I. INTRODUCTION

Natural evolution has come up with robust and efficient solutions to engineering problems that can be adopted for our benefit. Employing these adapted natural solutions to engineering problems gives rise to bio-inspired products and

devices. For example, Gecko Tape [Cleev03] is an adhesive that is based upon the method by which geckos are able to walk on nearly any surface at any angle. This “bio-inspired product” requires a new set of manufacturing technologies to enable large scale production. As the design of bio-inspired products becomes more prevalent, the necessity for the capability of manufacturing these products grows in kind. Modern engineers must come up with new manufacturing techniques and processes that can accommodate the large scale production of these bio-inspired products.

In order for students to be competitive in this field, they must have knowledge of the manufacturing technologies, techniques and principles that can be used in the production of bio-inspired products and devices. It is also important for them to understand the distinction between products that are “biomimetic” (duplicating nature) and those that are “bio-inspired” (being conceived by natural concepts). The best way to garner this knowledge is through in class exposure.

A module called “Manufacturing Techniques for Bio-Inspired Products and Devices” has been created to add to a Junior level class entitled, “Engineering Materials and Manufacturing Processes”. This module will introduce a new class of emerging manufacturing processes that are specially suited for realizing bio-inspired products. The technologies that will be discussed are: Concurrent Fabrication and Assembly, Self Assembly, and Functional Graded Materials. This module will now be discussed in detail.

II. MANUFACTURING TECHNIQUES AND PRINCIPLES FOR BIO-INSPIRED PRODUCTS AND DEVICES MODULE

This module is designed to introduce students to techniques and principles for manufacturing bio-inspired products and devices. It consists of three components: (1) Concurrent Fabrication and Assembly, (2) Self Assembly, and (3) Functionally Graded Materials. Each component is designed to be delivered within a single lecture. The concepts that are introduced to the students in each component will now be discussed. In particular, emphasis is placed on how these techniques differ from conventional manufacturing processes to create new product and device concepts that are bio-inspired.

Ila. Concurrent Fabrication and Assembly

Unlike conventional products which require significant assembly, Concurrent Fabrication and Assembly is a process by which a product can be manufactured whereby with little or no assembly in a manner similar to the way complex natural structures are designed to grow from seeds or eggs. Biomimetic products, such as artificial bones, can be made with these processes, or bio-inspired products, such as a graded composite cylinder. Among these are: *Solid Freeform Fabrication*, *Multi Stage Molding*, and *Compliant Mechanisms*. Each of these approaches will now be discussed.

Solid Freeform Fabrication (SFF) refers to the class of processes that build parts using a layered manufacturing paradigm. These include manufacturing technologies like Shape Deposition Manufacturing [Bail99,Merz94,Raja00],

Selective Laser Sintering [Beam00,Jeps99,Park99], and 3D Printing [Jack99,Wu00]. Unlike the traditional machining processes that remove material from raw stock to obtain the final object, solid freeform fabrication is a material additive process. Solid freeform fabrication allows for the rapid production of computer-generated models, including those designs that incorporate cavities and under-cuts (which can not be accomplished via CNC machining). Multiple materials may be used, and the material can be varied in a controlled manner at any point to create composites and graded materials. Material is selectively added to the part, layer by layer, to create a three dimensional geometry. In addition, making many parts in parallel can reduce the manufacturing time significantly. This is similar to the way natural structures such as trees build up mass.

Multi Stage Molding techniques enable fabrication of plastic objects without assembly by injecting or casting different materials into the mold sequentially or in parallel [Kuma02]. Assembly takes place as parts are being formed. This manufacturing process allows for the design of products that make use of differing material properties for enhanced functionality, such as the way skin covers a skeleton in natural organisms. It can also make articulating joints based on bio-inspired Design for No Assembly concepts to replace multi-member linkages in products such as rotorcraft structures (Figure 1).

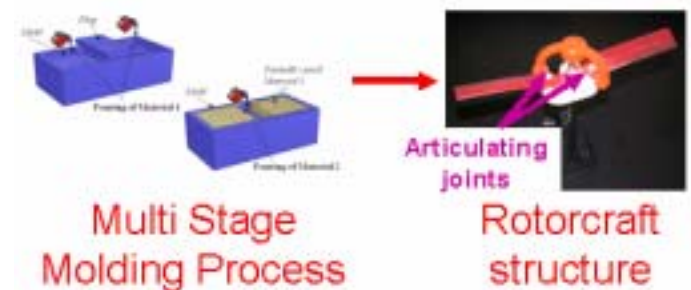


Figure 1. Multi Stage Molding process for manufacturing products, such as a rotorcraft structure, with articulating joints based on bio-inspired Design for No Assembly concepts.

Compliant Mechanisms make use of highly resilient materials that elastically deform, without rigid joints, to produce displacement or force [Lu03, Howe96]. The lack of rigid joints eliminates friction and lubrication issues. In addition, these mechanisms can create motions that are not possible with conventional rigid systems. These mechanisms are very prevalent in natural systems such as insect wings, and are related to the concept of “Design for No Assembly”. Design for No Assembly is an approach to the design process such that the outcome is a product that requires fewer assembly steps in the manufacturing process. Unlike conventional products, like pumps, natural analogs such as a heart can achieve the same function within a single structure by using biological principles such as electromechanical transduction to achieve the pumping action. By utilizing these same principles, it is possible to create bio-inspired products, especially in small scale structures like MEMS devices [Kota01]. This leads to products that may be less costly to manufacture in terms of both time and money.

Generally, compliant mechanisms facilitate the design of components that do not require assembly steps.

IIb. Self Assembly

Self Assembly is a method of fabrication whereby the components of a device or system spontaneously assemble into their desired structure [Huie03]. There are several different methods of inducing this spontaneous assembly to choose from, such as templating and supramolecular chemistry, depending on the structure desired. This component in the module emphasizes the advantages of using Self Assembly over conventional manufacturing processes. In conventional manufacturing processes, parts are assembled sequentially. Specialized tooling is required for the precise orientation of parts in the automated assembly process. In addition, the amount of physical space generally required for the fabrication of a particular product is orders of magnitude larger than the product itself (i.e., large factories producing small items).

Self Assembly attempts to make use of the production principles that have been honed by nature over millions of years. The assembly process in nature is highly concurrent and massively parallelism, but inherently slow as evidenced by the long time it takes to produce a single organism. Nature is able to adapt to the ambient conditions – these conditions need not be precisely controlled as is required in conventional manufacturing. Applying these natural principles to products made of predominantly inorganic materials is the goal of Self Assembly procedures. Bio-inspired procedures (e.g., Electrostatic Self Assembly) will attempt to retain the massively parallel nature of Self Assembly, but at higher throughput, while Biomimetic approaches (e.g., cloning) will retain all characteristics associated with the natural mechanism, including the low throughput.

Generally, when a product is able to self assemble, there is an underlying pattern guiding the process. If there is a deviation from the pattern, the end result will differ. Natural systems are able to adapt to changes in the surrounding environment that would destroy synthetic systems. In the short term, natural systems can heal, and in the long term, natural systems can change or evolve to adapt to changes in the environment.

Self Assembly offers a bio-inspired production method that can substantially increase efficiency and quality, while reducing waste. Self Assembly can also allow for multi scale control over material organization to create products that were previously thought impossible to manufacture. In addition, products can be made in many size scales without a loss in control over the manufacturing process.

The common abalone shell is made from essentially the same materials as a regular stick of chalk (Figure 2) [Meld03]. Taking the main ingredient in both chalk and abalone shell (calcium carbonate), and preparing it in two different ways will elucidate the differences. Chalk can be created by mixing the calcium carbonate and a binder, and pouring the mixture into a mold. Assembling the calcium carbonate and binder into nano-scale structures with specific orientation and proportions creates abalone shell. There are striking differences of orders of magnitude between the abalone shell and the chalk in terms

of material strength and toughness. The chalk is very brittle, while the abalone shell is incredibly tough and has very high strength. Applying this method to other materials can lead to new material systems with incredible properties.

Self Assembly occurs over many length scales – from the atomistic scale through the macro scale. There are also several driving mechanisms by which Self Assembly takes place: energy, force, chemistry, and geometry. Examples of these mechanisms are as follows:

- Energy-Driven
 - Thermal (*Crystallization*)
- Force-Driven
 - Field Assisted (*Electrostatic*)
- Chemically-Driven
 - Hydrophobic Attraction (*Micelles*)
- Geometrically-Driven
 - Templating (*Single Crystal Growth*)

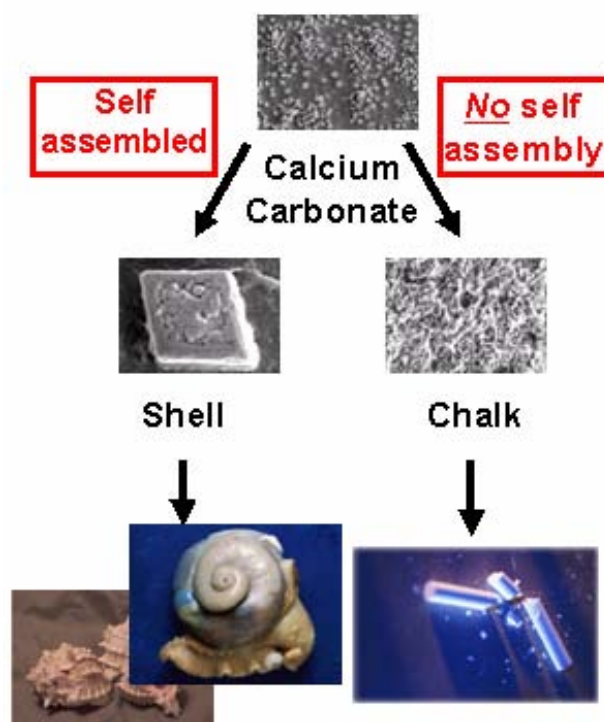


Figure 2. Comparison of calcium carbonate products (a) naturally self assembled (shell) and (b) conventionally processed (chalk)

Self Assembly follows a set of rules. These rules can be modeled mathematically using concepts such as cellular automata and fractal geometry. Students are introduced to these rules in order to understand the mathematical principles that are being used to describe Self Assembly processes, such as Electrostatic Self Assembly [Zeng00].

IIc. Functionally Graded Materials

Functionally Graded Materials (FGMs) are used to produce components featuring engineered gradual transitions in microstructure and/or composition, the presence of which is

motivated by functional performance requirements that vary with location within a part [Sure98]. Abrupt transitions in material properties within a structure often result in undesirable stress concentrations that degrade structural performance by promoting crack growth along an interface. In nature, stresses are controlled by gradually varying the material behavior. Biological structures such as bone and bamboo provide evidence that FGMs have been selected through natural evolution to optimize resistance to failure through the unique coupling of strength and stress distribution, as shown in *Figure 3* [Amad97]. These concepts are now being used to engineer a variety of new structures, such as thermomechanically processed Nickel-Alumina joints with minimized interfacial stress concentrations [Will93, Will96, Wang96, Rabi98, Bruc01, Bruc02a, Bruc02b]. In the case of bamboo, new bio-inspired graded composite cylinders are being designed that can produce similar strength and stress distributions as bamboo, but not necessarily using the same microstructural fiber-reinforcement mechanism as would be associated with a biomimetic concept.

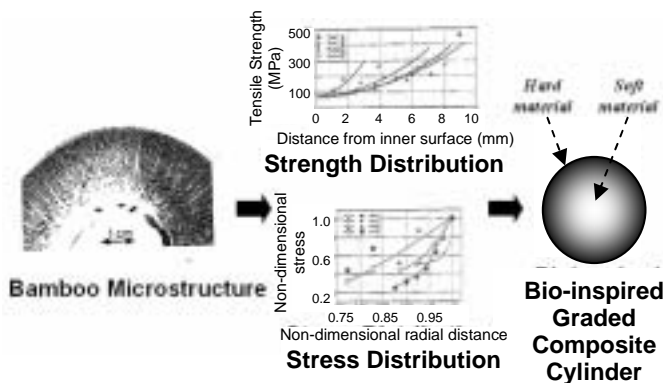


Figure 3. Example of functionally graded biological structure (*Bamboo*) and corresponding bio-inspired product (*graded composite cylinder*)

In this component of the module, conventional products manufactured using discrete components with different properties, such as a honeycomb airframe structure, are compared with bio-inspired products manufactured using FGMs. The advantages of FGMs in the removal of discrete components and subsequent elimination of weak interfaces is stressed. Since FGMs are manufactured from composite materials, students are also introduced to the principles used to model composites, such as rule-of-mixtures formulations, and manufacture them. More advanced approaches, such as finite element analyses, are also introduced to the students for modeling the bio-inspired product manufactured using FGMs. Thus, this component can serve as a replacement for a conventional composites lecture. After being presented this material, students should have the ability to understand how to design, model, and fabricate a bio-inspired product using FGMs.

III. ASSESSMENT OF MODULE

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:

- 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
- 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
- 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

Assessment results from the Self Assembly and FGM components, which were delivered in a small class (6 students) and large class format (45 students) respectively, can be found in Table I. While only the latter class was statistically significant, results from both of the classes were fairly consistent 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, additional material was added to this lecture to educate students on the concept of bioinspiration as it applied to materials in order to help them better understand the concept and generate more interest in the subject.

Table I. Assessment Results for Components of Manufacturing of Bio-inspired Products and Devices Module

Component	Question 1 (Prior Knowledge)	Question 2 (Interested in Topic)	Question 3 (Knowledge Acquired)
Self Assembly	Yes: 0 A little: 3 None: 3	Yes: 4 A little: 2 None: 0	Yes: 2 A little: 4 None: 0
FGM	Yes: 8 A little: 27 None: 10	Yes: 22 A little: 23 None: 0	Yes: 10 A little: 35 None: 0

IV. CONCLUSIONS

A new curriculum has been developed for Mechanical Engineering students at the University of Maryland that introduces bio-inspired product and device development. As part of this curriculum, a module has been developed that describes techniques for manufacturing bio-inspired products and devices using: (1) Concurrent Fabrication and Assembly, (2) Self Assembly, and (3) Functionally Graded Materials. Assessment results for two of these components indicate that

students have little prior knowledge of bio-inspired products and devices, enthusiasm for the content in the module, and the need for more knowledge on bio-inspired products and devices. Modifications have been made to better clarify the concept of bioinspiration in order to address the latter concern.

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