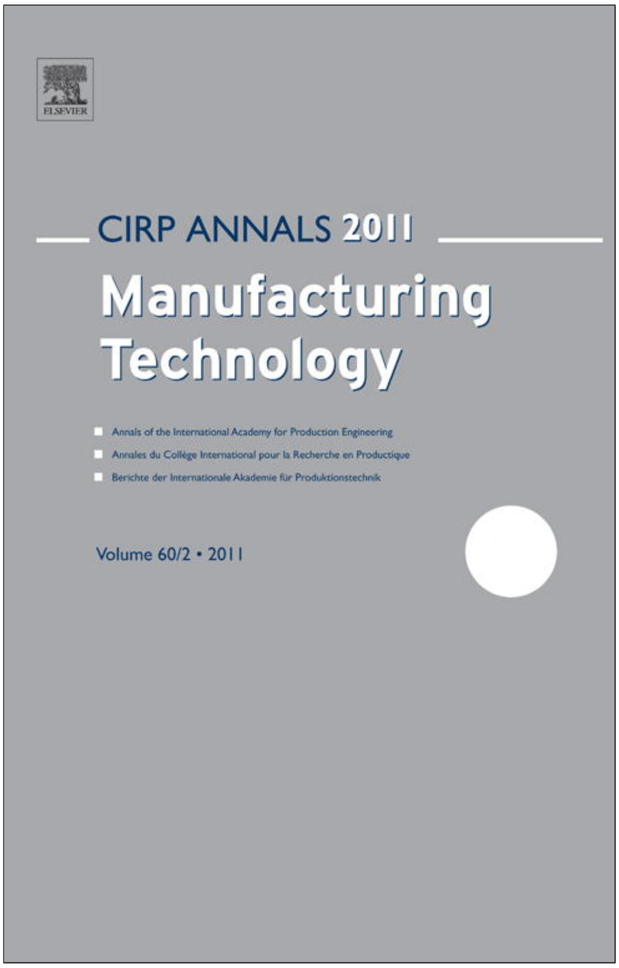
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Biologically inspired design

L.H. Shu (2)[a,*], K. Ueda (1)[b], I. Chiu[a], H. Cheong[a]

[a] University of Toronto, Canada
[b] University of Tokyo, Japan

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ABSTRACT

This paper reviews research on biologically inspired design, and has three main parts. The first part surveys examples relevant to three groupings of manufacturing research. The second part presents general methods that support biomimetic design, including different approaches for the steps involved in identifying and applying relevant biological analogies for any given problem. The third part details examples that illustrate the use of a general biomimetic design method, which identifies analogies from natural-language biological information. Finally, insights and conclusions are drawn and synthesized.

1. Introduction

Many elegant solutions to engineering problems have been inspired by biological phenomena. Examples of biologically inspired design relevant to three groupings of manufacturing research are presented in Section 2. While much work in biologically inspired design involves specific cases of design that copy particular biological models, not always described is how these biological models were identified or selected. It is possible that engineers open to using biological models for design may have difficulty in finding relevant biological analogies for a given problem. Therefore, Sections 3 and 4 present an overview of generalized methodologies that support biologically inspired design. Section 5 details examples that demonstrate the use of a generalized methodology to identify and apply biological analogies to engineering problems. Section 6 concludes with insights following the examples from both Sections 2 and 5.

1.1. Terminology

As many fields of study involve the intersection between biology and engineering, it is useful to define related, commonly used terms. This will clarify the position of biologically inspired design in this intersection. In addition, several terms are used interchangeably for biomimetic or biologically inspired design.

Bioengineering, biological engineering, biotechnical engineering: Application of engineering principles and tools, e.g., physics, mathematics, analysis and synthesis, to solve problems in life sciences, and may involve the integration of biological and engineering systems.

Biomechanics: Application of mechanical principles, e.g., mechanics, to study and model the structure and function of biological systems.

Biomedical engineering: Application of engineering principles and techniques to the medical field, e.g., design and manufacture of medical devices, artificial organs, limbs, etc.

Biophysics: Term used by Otto Schmitt to mean both: applying physical sciences to solve problems in biological sciences, and biologists' approach to problems in physical sciences/engineering [36,81].

Bionics: Application of biological function and mechanics to machine design. Jack E. Steele used the term ~1960 to mean 'like (ic) life (bio)' or systems that copy some function or characteristic from natural systems [110]. However, the 1970s television series, Bionic Woman, about a human with electromechanical implants, also gives 'bionic' the connotation of 'biological + electronics,' or use of electronic devices to replace damaged limbs and organs.

Biomimetics: Used in title of paper by Schmitt, and defined as, the 'study of formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones' [36,81,110].

Biomimesis, Biomimicry, Biognosis, Bioinspiration, Biomimetic design, Bioanalogous design, Biologically inspired design: Synonymous with biomimetics to mean emulating natural models, systems, and processes to solve human problems. The term 'biomimcry' is in the title of a popular book by Janine Benyus, that gives it a connotation of sustainability [3].

With the exception of the bidirectional term biophysics, there are two main directions in the above intersection between biology and engineering. The first aims to apply principles in engineering to solve problems in life sciences, and includes terms such as bioengineering, biomedical engineering and biomechanics. The second aims to apply principles of biological systems to solve problems in engineering. This paper will focus on the latter, using the terms biomimetic design and biologically inspired design interchangeably.

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[*] Corresponding author.

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2. Examples relevant to manufacturing research

Examples of successful biomimetic design are plentiful. In addition to the more often cited biomimetic products, e.g. Velcro, there are many examples of biomimetic manufacturing that are inspired by natural processes. In some cases, biomimetic methods surpass the capabilities of conventional manufacturing, e.g., fabrication in the nano and microregimes. Manufacturing methods based on biological processes are potentially more sustainable than conventional manufacturing processes. For example, while conventional production of silica may require extreme temperature, pressure and pH, silica shell formation by unicellular diatoms in nature occurs under ambient temperature, pressure and near neutral pH in an aqueous solution such that the organism is not harmed. Another motivation common to much of the biomimetic manufacturing research involves the concepts of self-cleaning, self-assembly and self-organization found in biology. These concepts appeal not only to those working in the nano or microscales, but also in macro assembly and at the production system level.

Below, research related to biomimetic manufacturing is organized according to the following three groupings:

1. Cutting, electrophysical and chemical processes, forming, and grinding/abrasive processes.
2. Machines, surfaces, and precision engineering.
3. Life-cycle engineering and assembly, design, production systems and organizations.

2.1. Cutting, electrophysical and chemical processes, forming, grinding/abrasive processes

This section presents biomimetic machining, e.g., cutting and drilling; forming through freeze casting and biotemplating; fiber fabrication; and corresponding application examples.

2.1.1. Cutting

Many biological organisms have sharp edges to facilitate the organism's survival through either protection, e.g., cactus spines, or predation, e.g., mosquito proboscis, and animal and fish teeth. Biomimetic cutting methods have been developed based on the mosquito proboscis, rodent teeth and piranha teeth. Oka et al. developed a hypodermic syringe based on the mosquito proboscis [68]. A mosquito proboscis consists of an outer sheath covering an inner stylet that has a row of serrations on either side. These serrations increase the efficiency of the cutting edge, thus reduce compression and nerve stimulation during a mosquito bite, rendering the initial bite painless [41]. The hypodermic syringe developed by Oka et al., shown in Fig. 1, replicates the dimensions and serrations of a mosquito proboscis to enable the needle to slide through human tissue more easily, causing less pain.

Berling and Rechberger developed a shredder inspired by self-sharpening in the teeth of rodents, e.g., rats and rabbits [29,64]. Rodent incisors self-sharpen while the animal chews its food; softer dentine backing is continually worn away, exposing new sections of harder enamel material that comprise the sharp cutting edge. The biomimetic shredder self-sharpens by wearing away the tungsten carbide-cobalt 'dentine-like' backing against the shredded material to continually sharpen the hard titanium nitride 'enamel-like' cutting edge, as shown in Fig. 2.

Meyers et al. proposed a scissor design based on the ability of piranha teeth to cut through flesh [64]. Serrations on the scissor blades match the angle, spacing and configuration of piranha teeth. Such scissors are intended for cutting through flesh, such as in surgical applications.

Investigations in biomimetic drilling methods are currently applied to planetary exploration and core sampling, but may also be applicable to drilling in machining and manufacturing processes. Challenges for planetary exploration include harsh surface conditions and the required compactness of equipment to minimize payload. Gao et al. sought to overcome the need for high axial force in low gravity environments, e.g., on the moon or an asteroid, when using a conventional rotary drill [30]. Percussive drills may offer low power consumption and overhead mass, but also low drilling rate. Gao et al. proposed a biomimetic drill based on the ovipositor of wood wasps that employ a reciprocating motion, rather than the rotary or percussive motion of other drills. Wood wasps use their ovipositor to drill holes in trees to deposit their eggs. This drill consists of two halves with backward-pointing

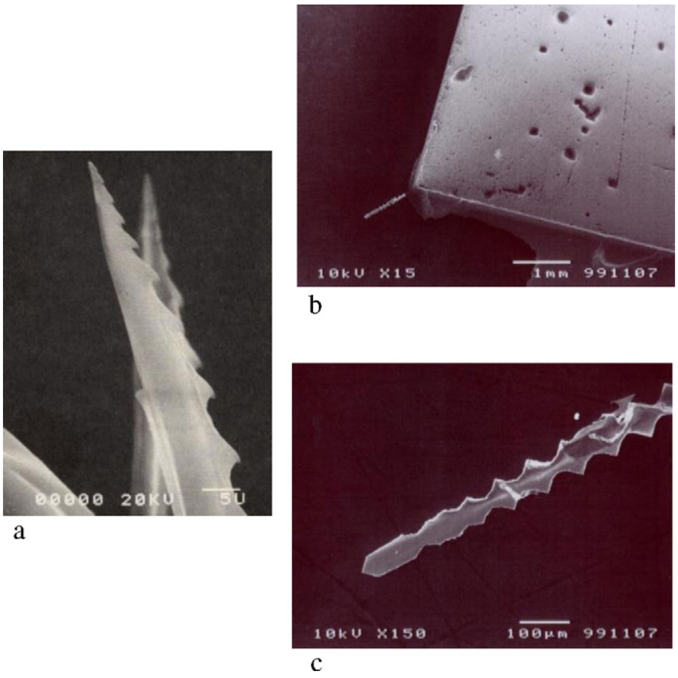
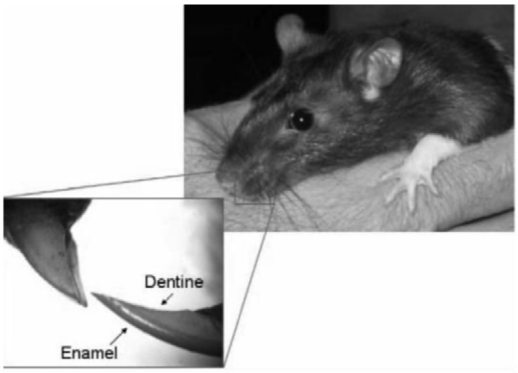
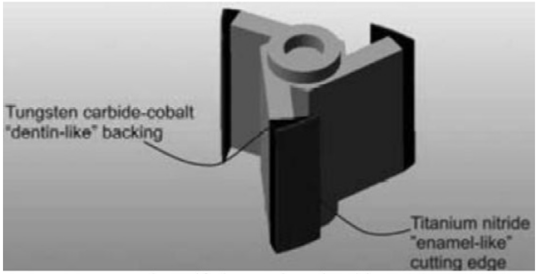


Fig. 1. Mosquito-proboscis based syringe by Oka et al. [68]. Reprinted with permission. Copyright Elsevier 2002. (a) Magnified mosquito's needle; length: ~ 1–2 mm; diameter: ~ 30 μm. (b) Scanning electron micrograph of manufactured trace blood collection system (needle & tank). (c) Magnification of needle.

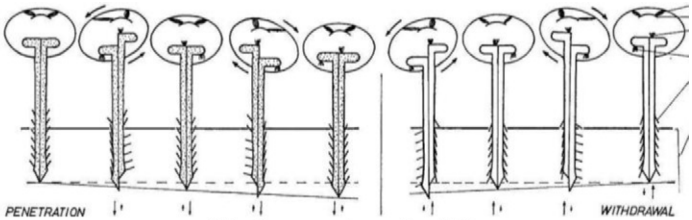


a. Self-sharpening rodent-teeth

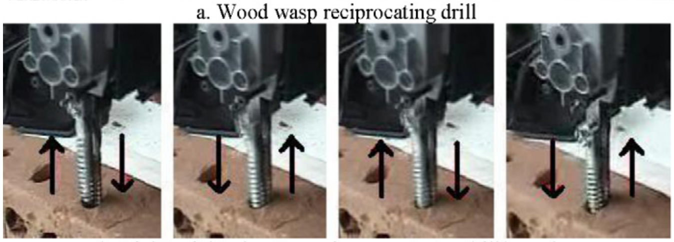


b. Self-sharpening shredder

Fig. 2. Rodent-teeth-based self-sharpening shredder [29,64]. Reprinted with permission from [64]. © Springer (http://www.springerlink.com/content/4270h20125600643/). (a) Self-sharpening rodent-teeth. (b) Self-sharpening shredder.



a. Wood wasp reciprocating drill



b. Lightweight planetary micro-penetrator drill/sampler

Fig. 3. Woodwasp-based drill/sampler by Gao et al. [30]. Reprinted with permission. Copyright IEEE 2007. (a) Wood wasp reciprocating drill. (b) Lightweight planetary micro-penetrator drill/sampler.

teeth that offer little resistance when moving downwards, but resist being moved upwards by engaging with the surrounding substrate. Once engaged, 'the tensile force that can be resisted, tending to pull the drill out of the substrate, allows the generation of an equal and opposite force' in the other half, tending to push it further into the substrate. Thus the drilling force is generated between the two halves, requiring no external force. The proposed biomimetic drill is lightweight (0.5 kg), operates on low power (3 W) and is able to drill 1–2 m deep. Tests using a simplified prototype, shown in Fig. 3, demonstrate the feasibility of this concept.

Kubota et al. developed another biomimetic drill design based on the movement of the earthworm [49]. Earthworm locomotion is known as peristaltic crawling and requires less space than other forms of locomotion. Nakamura et al. developed a robot based on earthworm peristaltic crawling, where locomotion is accomplished through varying the thickness of segments in the worm [67]. This is highly desirable in subterranean drilling and exploration when there is limited space. Additionally, Kubota et al.'s proposed drill design utilizes discharge substrate for propulsion, thereby not requiring much additional space to store the discharged material.

2.1.2. Forming

Freeze casting or 'ice templating' was first observed and studied by Bobertag et al. [7] and Lottermoser [58] who noted that freezing caused some materials to form highly regular honeycomb structures with pores of various sizes. Freeze casting relies on the regular dendritic growth of ice while carrying specific substrates during the freezing process. The ice is then sublimated after the shape is obtained, resulting in material with highly regular and structured pores. Freeze casting offers advantages because it is:

- Relatively inexpensive and straightforward to implement.
- Based on benign and biocompatible carriers, such as water.
- Easy to control pore properties, e.g., size, geometry, porosity.
- Suitable for many classes of materials, e.g., polymers, ceramics, metals and composites.
- Able to produce complex geometries with near-net shape.

Launey et al. and Wegst et al. applied freeze casting to achieve complex structures and required mechanical properties [51,114]. Wegst et al. fabricated biomaterials for therapeutic uses, exploiting freeze casting's inherently biocompatible nature. Koh et al. fabricated porous anode materials for use in solid oxide fuel cells, exploiting freeze casting's ability to control porosity and hence reaction sites and fuel transport [48]. Jones explored freeze casting's potential for automotive applications [45], and Tallon et al. applied freeze casting to produce filters, bioreactors and gas or chemical sensors [91].

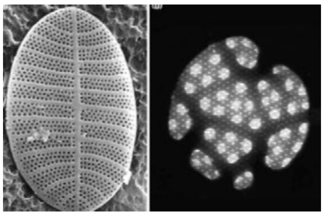


Fig. 4. Scanning electron micrographs of (left) a typical diatom frustule and (right) nanometer scale silica biopatterning [57].
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In biotemplating, materials are formed through complimentary interactions between oppositely charged entities such as ions and molecules. The biological inspiration derives from biomineralization processes that originated about 550 million years ago when organisms first began using available inorganic molecules to grow a hard mineral phase. For example, diatoms, which are unicellular photosynthetic organisms with genes derived from plant, animal and bacterial lineages, form silica shells for protection from the environment and predators [57]. Often, these structures are very complex and highly functional, motivating the growing interest in how biological systems incorporate inorganic elements. Lopez et al. note also the striking artistry of the amorphous silica shell, or frustule, shown in Fig. 4 (left), that results from biomineralization [57]. By incorporating diatom bioinspired molecules into a polymer hologram, Brott et al. achieved nanopatterning of silica spheres that formed a 2-D array with the periodicity of the hologram, shown in Fig. 4 (right) [8]. Hall noted that mimicking natural processes yields materials with structural similarities to those formed naturally, with some of the same desirable attributes, such as mechanical structure and properties, especially in the nano regime [34]. Luz and Mano reviewed natural mineralized structures to inform the design of new composite materials and biomaterials [59].

Biotemplating or biomineralization has applications in biomedical engineering, as well as electronics, ceramics and composites material fabrication. Porous ZnO films have desirable properties such as near-UV emissions, optical transparency, electrical conductivity and piezoelectricity, that make the films well suited to microelectronic devices, e.g., solar cells. Dong et al. initiated the forming of porous ZnO films utilizing eggshell membranes as a biotemplate to duplicate their protein patterns and relevant functional groups [25].

Fabrication of ceramics and ceramic composites through biotemplating is an alternative to conventional powder processing technologies. Sieber used bioorganic materials such as wood and other organic plants as a biotemplate to fabricate highly structured porous and cellular ceramics and ceramic composites [88]. These bioorganic materials are renewable, readily available, and offer cell diameters from micrometers (wood) to millimeters (preprocessed papers) that can be replicated in oxide/carbide based ceramics and composites. There are two biotemplating techniques. Molding reproduces the microstructure of the bioorganic template by coating internal surfaces with low viscous oxide sols, or colloidal solutions, followed by annealing for burn out of the biocarbon template and consolidation of the oxide layers. The second, reactive techniques involve conversion of the bioorganic preforms in biocarbon templates by pyrolysis and subsequent reaction of the char with Si or metals into carbide phases (e.g., SiC or TiC).

Similar to biotemplating, where natural structures are copied, Han et al. used a biomolding technique in the replication of sharkskin, shown in Fig. 5 [35]. Sharks and other aquatic animals, e.g., tuna, have skins with low friction properties that facilitate swimming speeds of up to 60 km/h [35]. Sharkskin was the inspiration for Speedo's FastSkin swimsuit, reported to reduce drag by 3% for women and 4% for men [112]. Drag reduction is

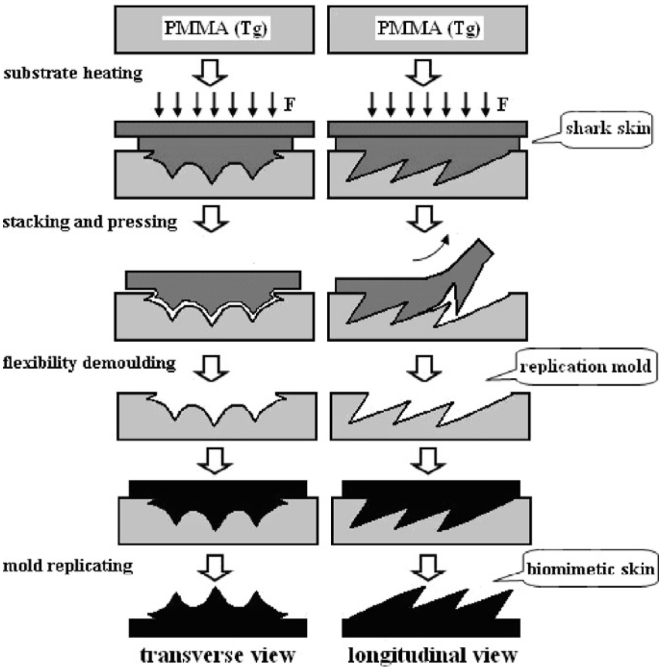

Fig. 5. Biotemplating of sharkskin by Han et al. [35].
Adapted with permission.

attributed to the diamond geometry of placoid scales on the sharkskin surface, and to tiny 50-micrometer grooves on the surface of the scales. However, conventional micro forming methods to replicate sharkskin have only been able to produce skins that reduce drag by up to 7%. Han et al. used actual sharkskin in a bioreplicated mold for the production of synthetic sharkskin. After preparing the sharkskin, they used hot embossing to replicate the external morphology including the surface of the placoid scales containing the grooves. Sharkskin produced in this manner was shown to reduce drag by 8.25%. Compared to other micro forming methods for sharkskin, this biomolding method demonstrates high forming efficiency, good maneuverability, and increased fidelity compared with live sharkskin, while being cost effective. Potential applications include drag-reduced hulls for ships and submarines.

Biomimetic forming also includes fiber manufacture, e.g., production of the spider silk that has inspired many with its strength and lightness. However, De Luca and Rey and Ellison et al. note that mechanical properties of spider silk are related to the spinning process in addition to the chemical composition of the silk [24,26]. Therefore, rather than relying on chemical or artificial synthesis (which cannot produce silk of the same quality as spinning in vivo), efforts are underway to understand and mimic the natural spider silk spinning process, which involves low temperatures and water-based solvents. Saravanan notes that mechanical spinning may offer a more economical method of production than even genetic recombination methods, where biological hosts such as hamsters and goats are implanted with silk genes to cause them to produce spider silk in bulk [79].

2.2. *Machines, surfaces, and precision engineering*

As noted, biomimetic methods of fabrication and manufacturing seem well suited to applications in the micro and nano regimes, and are also relevant to surfaces, precision engineering and micromachining. This section will present biomimetic surfaces and coatings, specifically silica coatings, superhydrophobic surfaces and wear resistant surfaces; precision machining and manipulation, alternatives to machining and manipulation; and biomimetic sensing and measurement. Biomineralization, previously discussed in the context of material formation, is described here in the context of coating production.

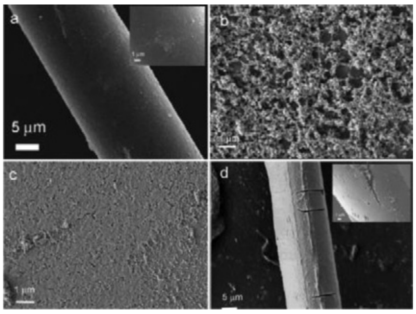

Fig. 6. Bioinspired silica coating of glass fibers by Pogula et al. [70].
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2.2.1. *Surfaces*

Uniform silica coatings can enable desired optical, electrical, chemical and mechanical properties for a multitude of applications. Pogula et al. initiated silica coating of glass using three different types of biopolymers, and demonstrated that each alone was able to catalyze the formation of silica films, and rapidly produce a uniform coating, shown in Fig. 6 [70]. Li et al. reviewed fabrication of biomimetic antireflective surfaces of silicon and fused silica substrates [53].

Interest in self-cleaning surfaces has motivated extensive research into the superhydrophobic phenomenon observed on biological surfaces. Most notably, the lotus effect has inspired several biomimetic surfaces and coatings, and refers to a hydrophobic self-cleaning property seen on lotus leaves. Although a lotus flower tends to grow in muddy water, lotus leaves always appear clean, and drops of water on the leaves appear crystal clear. Two levels of surface structure on the lotus leaf, micro scale mounds and nano scale hairs, shown in Fig. 7, cause water drops on the leaf to form high contact angles and minimal contact area with the leaf surface [6,14,55]. Thus water and any dirt in the drop rolls off the leaf easily, creating a superhydrophobic, self-cleaning surface. Mimicking the lotus leaf surface features, the lotus effect is commercialized in self-cleaning paints (Lotusan) and stain-repellant fabrics (NanoTex). Future applications could include self-cleaning medical devices, cookware, building materials and a myriad of other products that benefit from self-cleaning or self-decontamination.

A less well-known but also advantageous surface effect is observed in the dung beetle, which breaks up and compacts dung into balls with neither dung nor dirt sticking to its body or legs. Tong et al. noted that the specialized geometry of the dung beetle's various body parts and geometrical embossing, shown in Fig. 8, contribute to this surface effect [94].

Potential applications of dung beetle surface geometry include agricultural equipment, e.g., plows and tillers, and construction equipment, e.g., tunnel borers and excavators. After characterizing the geometrical features of dung beetle surfaces, Tong et al. molded the dung beetle surface features on the surface of a furrow opener, a type of plow [95], shown in Fig. 9. The biomimetic furrow opener demonstrated lower resistance and power requirements against soil.

Surface geometry rather than material can also reduce the wear on a surface exposed to abrasive substrates. Tong et al. studied and

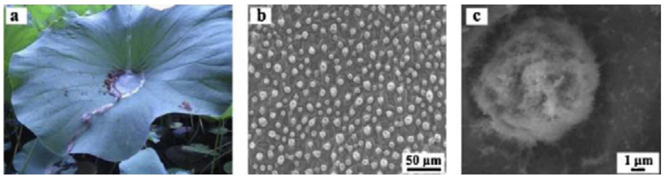
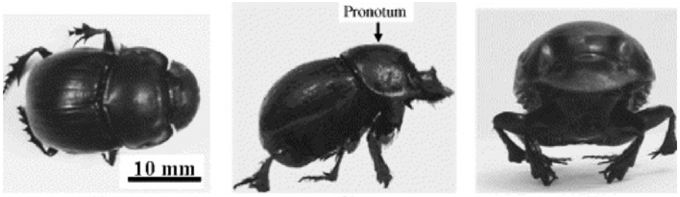
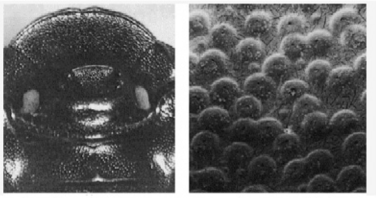


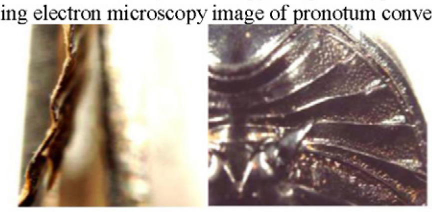
Fig. 7. Lotus leaf superhydrophobicity, from Liu & Jiang [55]. Reprinted with permission. Copyright Elsevier 2011. (a) Water drops roll easily across lotus leaf surface, picking up dirt particles, (b) SEM image of randomly distributed micropapillae on lotus leaf surface, (c) SEM image of cilium-like nanostructures on micrometer scale papillae.



a. Female dung beetle *C. ochus Motschulsky*, from Tong et al. [94]



b. Cuticle surface details: (left) stereoscopy image of clypeus and pronotum, (right) scanning electron microscopy image of pronotum convex domes. [94]



c. Ventral surface details: Stereoscopy photograph of: (left) ridges on longitudinal section of ventral surface, (right) ridges on ventral surface. [95]

Fig. 8. Details of female dung beetle *C. ochus Motschulsky*. a and b reprinted with permission from Tong et al. [94]. Copyright Elsevier 2005. c reprinted with permission from Tong et al. [95]. Copyright Elsevier 2009. (a) Female dung beetle *C. ochus Motschulsky*, from Tong et al. [94]. (b) Cuticle surface details: (left) stereoscopy image of clypeus and pronotum (right) scanning electron microscopy image of pronotum convex domes [94]. (c) Ventral surface details: stereoscopy photograph of: (left) ridges on longitudinal section of ventral surface (right) ridges on ventral surface [95].

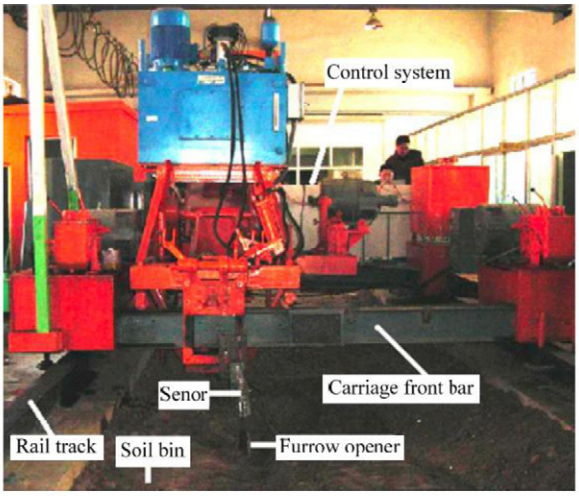
numerically modeled ridged surfaces like that of a Farrer's scallop, shown in Fig. 10 [96]. They found that similarly ridged surfaces resist abrasive wear better than flat surfaces. Experiments using a bioinspired, ridged surface in contact with quartz, the main abrasive material in soil, resulted in 63% less average mass loss than with a conventional flat surface. While Tong et al. proposed agricultural applications for bioinspired ridged surfaces, there are many manufacturing applications for surfaces that better resist abrasive wear, e.g., components for the automotive and aerospace industries.

2.2.2. Precision engineering and metrology

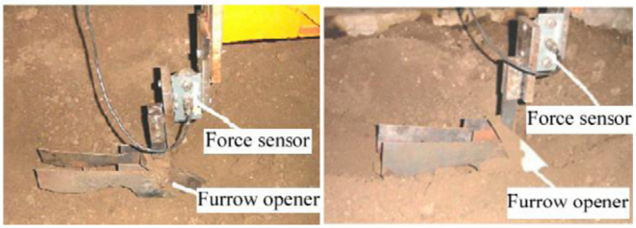
Limitations, such as resolution in the nano and micro scale, in conventional machining methods such as lithography, motivate the development of alternative fabrication techniques. Inspired by the development of complex biological structures through morphogenesis, Ross et al. fabricated nano components using soft and changing substrates consisting of active polymers instead of conventional rigid silica substrates [73]. Continuous morphogenesis occurs in the developmental lifecycle of many complex three-dimensional biological structures. For example, the fruit fly eye changes from an initial flat disc to its final complex three-dimensional geometry. Based on morphogenesis, active polymers were used to introduce and control deformations during the fabrication of complex three-dimensional structures. With this method, Ross et al. were able to produce a nano-prism lens array with much greater densities than those produced through conventional lithography.

Livingston et al. used a biomineralization method instead of solid-state reaction pathways and solution-based synthetic routes to produce precision patterned 2-D focal-plane arrays of pyroelectric perovskite-based materials [56]. These arrays would be used in passive and uncooled infrared sensor applications such as rifle sights, seeker munitions and unattended ground sensors.

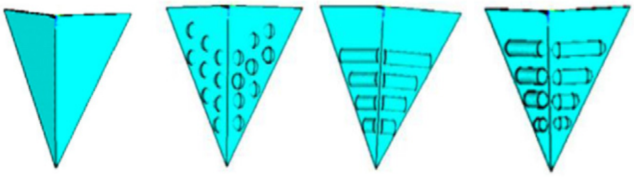
In biology, there are many different strategies for sensing and uses for the different types of sensory input. Controlling precision



a. Electric carriage used for soil resistance tests in operation.



b. Furrow opener and force sensor: (left) conventional furrow opener, (right) biomimetic furrow opener.



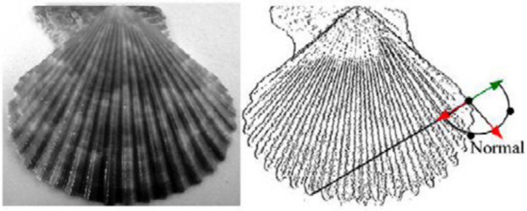
c. Furrow opener surfaces. Left to right: conventional smooth, biomimetic convex domes, biomimetic cylindrical section ridges, and biomimetic surface structure with tubular section ridges.

Fig. 9. Dung-beetle inspired plow by Tong et al. [95]. Reprinted with permission. Copyright Elsevier 2009. (a) Electric carriage used for soil resistance tests in operation. (b) Furrow opener and force sensor: (left) conventional furrow opener (right) biomimetic furrow opener. (c) Furrow opener surfaces. Left to right: conventional smooth, biomimetic convex domes, biomimetic cylindrical section ridges, and biomimetic surface structure with tubular section ridges.

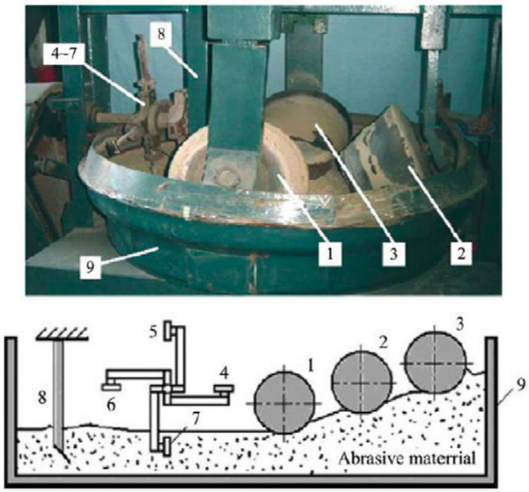
movement is a challenge that can potentially be addressed by development of biomimetic sensors and measurement. Jaax and Hannaford designed a sensor based on the muscle spindle of a cat soleus that senses muscle length and velocity for kinesthetic awareness and movement control [42]. They were able to capture the core functionalities of muscle spindles using mechanical filtering through electromechanical subsystems. Applications of their biomimetic sensor include real-time motor control, such as in prosthetics.

Wang et al. developed a dome-shaped sensor inspired by tactile sensor cells of the papillae from the inner surface cucurbitacea tendrils [113], shown in Fig. 11. Cucurbitaceae are plants, including cucumbers, pumpkins and watermelons, which send out shoots or tendrils that can cling to and climb obstacles. Cucurbitacea tendrils can sense 3-dimensional forces and provide a model for biomimetic mechanosensor arrays.

Hill et al. developed biomimetic sensors based on the ability of seal whiskers to detect hydrodynamic trails left by prey [39]. Chagnaud et al. and Yu et al. developed flow sensors, shown in Fig. 12, based on the ability of fish, such as salmon, to sense flow motion and detect turbulence [10,123]. Turbulence is difficult to measure as measurements may disturb flow conditions. Fish appear to sense the turbulence component of flow through an array of hair cells on their lateral line. A sensor design based on an



a. Shell and computer model of a Farrer's scallop.



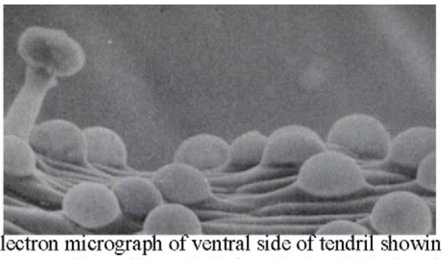
b. Abrasive wear tester using rotary abrasive disc: (top) photograph and (bottom) schematic diagram. Labels 1-3 indicate compacting wheels, 4-7 refer to test specimens, 8 indicates subsoiler and 9 is rotary abrasive disc.

Fig. 10. Scallop-based ridges to reduce wear/abrasion from Tong et al. [96]. Reprinted with permission. Copyright Elsevier 2010. (a) Shell and computer model of a Farrer's scallop. (b) Abrasive wear tester using rotary abrasive disc: (top) photograph and (bottom) schematic diagram. Labels 1–3 indicate compacting wheels, 4–7 refer to test specimens, 8 indicates subsoiler and 9 is rotary abrasive disc.

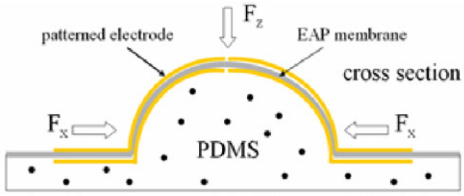
array of piezoelectric micropillars was prototyped and tested, demonstrating general ability to detect turbulence.

2.2.3. Machines

Biomimetic approaches can offer alternative methods to precision manipulation and machines, especially when conventional methods fail in the nano and micro range. Oh et al. developed biomimetic silicone cilia for microfluidic manipulation in biomolecular mixing and drug delivery [69]. Serving as their primary motivation is that the motion of biomimetic cilia should be compatible with biomedical applications, e.g., in vivo drug delivery. Effective micro scale manipulation has wider applications in microfluidics and MEMS, e.g., lab on a chip and cilia-based microactuators. However, Oh et al. reported that actual cilia manufacture is challenging [69]. Based on efficient movements of spermatozoa tail, Chen et al. proposed a biomimetic propulsion method for a micro robot for highly localized drug delivery and manipulation in minimally invasive surgical procedures [13].

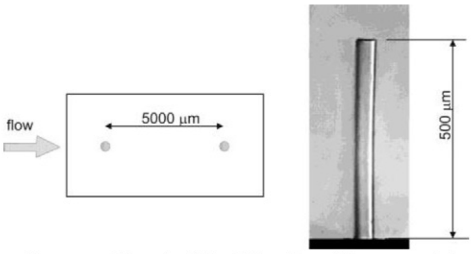


a. Scanning electron micrograph of ventral side of tendril showing a trichome and numerous tactile papillae. x 390 from Junker [43]. Reprinted with permission. Copyright John Wiley and Sons 1977.

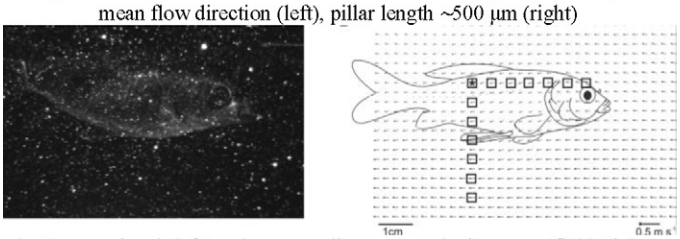


b. Cross-section view of sensor unit by Wang et al. [113]. Reprinted with permission. Copyright American Institute of Physics 2009.

Fig. 11. Tendril-based dome sensor. (a) Scanning electron micrograph of ventral side of tendril showing a trichome and numerous tactile papillae. ×390 from Junker [43]. Reprinted with permission. Copyright John Wiley and Sons 1977. (b) Cross-section view of sensor unit by Wang et al. [113]. Reprinted with permission. Copyright American Institute of Physics 2009.



a. Top view of sensor with pair of flexible micropillars spaced 5 mm apart in mean flow direction (left), pillar length ~500 µm (right)



b. Camera signal (left) and corresonding water velocity vector field (right).

Fig. 12. Fish-based turbulence sensor, by Chagnaud et al. [10]. Reprinted with permission. Copyright Society for Neuroscience 2008. (a) Top view of sensor with pair of flexible micropillars spaced 5 mm apart in mean flow direction (left), pillar length $\sim$500 μm (right). (b) Camera signal (left) and corresonding water velocity vector field (right).

2.3. Life-cycle engineering and assembly, design, production systems and organizations

The research and advances presented so far suggest that biomimetic manufacture may offer advantages because they are inherently more benign, and/or they overcome limitations associated with conventional methods. This section presents the final grouping of biomimetic manufacturing research and advances, summarizing work in biomimetic assembly and disassembly, and production systems modeling and control.

2.3.1. Assembly and disassembly

Assembly and disassembly are central to the product design and realization cycle. As products become more complex, new assembly techniques are required to enable efficient production. Legislation and increasing consumer consciousness of 'green' choices motivate research on product disassembly for efficient recycle, remanufacture and reuse. Highlighted below is some recent work on biomimetic assembly and disassembly.

Increasing miniaturization, e.g., in consumer electronics, motivates research on microassembly, where smaller components become more difficult to position and handle using conventional assembly tools. To address the positioning and centering problem, Shu et al. systematically searched biological literature for methods of 'centering' [84]. The search located a mechanism where a cell's microtubule organizing center (MTOC) centered itself within the cell by extending its microtubules to locate the cell walls. Collaborators at the Technical University of Denmark applied this centering strategy to develop a concept that uses temporary spines made of CO_2 ice, which is then sublimated after the centering is performed.

Another challenge in microassembly is the 'sticking' that occurs because surface tension, friction and van der Waals forces dominate gravity, complicating the reliable release of microparts.

In another collaboration between the Technical University of Denmark and the University of Toronto, Shu et al. described a method of microscrew 'release' based on abscission, which is involved in the release of fruit, petals, deciduous leaves in the autumn, etc. [86]. This case study will be discussed in detail as an application example of a generalized biomimetic design method in Section 5.2.

Lanzetta and Cutkosky exploit van der Waals forces to benefit assembly by fabricating biologically inspired hierarchical microstructures for synthetic dry adhesive applications [50]. Synthetic dry adhesives may be superior to mechanical gripping and suction in handling delicate materials such as glass, LCD panels and leather.

To facilitate macroassembly, snap fits are ideal because they do not require additional tools, and are generally time and cost efficient. However, challenges arise during disassembly for end-of-life, including failure in the parts to be reused, for example, during remanufacture. Detailed in another application example in Section 5.1, Hacco and Shu developed a repairable snap fit configuration with predetermined break points, based on two biological phenomena, including plants replacing rather than repairing parts such as leaves [33].

While snap fits facilitate assembly, during disassembly, they may present challenges in physical and visual access, or the need to release multiple snap fits simultaneously. Willems et al. developed snap fits where a single operation activated through a pressure trigger can disassemble multiple parts simultaneously [115,116]. One possible concept was inspired by a frog's foot, which contains both rigid and flexible parts in one structure. This combination allows multiple tight locking points through the rigid parts, and relative movement through the flexible parts during assembly and upon triggering the one-to-many disassembly operation. Two- and three-dimensional finite element analyses showed that active fasteners allowing for one-to-many disassembly achieved a 250% increase in efficiency, enabling faster and more economical end-of-life disassembly.

'Authorized' disassembly may be desirable when a product contains relatively new microchips and memory components, or large amounts of precious metals such as indium, platinum, and gold. To discourage third-party reclamation activities, the OEM may wish to render high-value components difficult to retrieve, such that only those authorized by the OEM can disassemble and reclaim them, e.g., with a disassembly 'key'. Saitou et al. developed a heat-reversible snap-locator joint system inspired by enzyme-substrate interaction [76]. This biological analogy was found by searching the biological literature with the term 'lock and key'. Based on the phenomenon that binding between the enzyme and substrate can be disabled by change in pH or temperature, Saitou et al. developed a locator-snap system in which strategic application of heat would cause thermal expansion only in one plane, resulting in the release of parts. As a further deterrent to unauthorized disassembly, simultaneous application of heat to specific areas could be required; with the application of heat in the wrong areas destroying the part rather than facilitating disassembly.

Other research on assembly envisions machines and robots that self-assemble in harsh or distant environments such as other planets. Bhalla et al. investigated self-assembling physical systems based on macro physical systems that only form under specific conditions, e.g., sand dunes and galaxies [4,5]. Because these are physical systems rather than biological systems, they take a bottom-up approach where information is encoded within the components and end environment of the system itself, rather than a top-down approach such as using DNA to encode information. The benefit of a bottom-up approach is that no knowledge of the end result is required, mirroring the bottom-up self-assembly process found in natural physical processes. To understand natural self-assembly, Bhalla et al. performed both virtual and physical modeling, and demonstrated that it is possible to create emergent systems by mapping virtual self-assembly rules onto physical systems. Bhalla and Bentley noted four requirements for artificial self-assembly: (1) components with shape, scale, material properties; (2) environment with boundary conditions, physical and chemical properties; (3) assembly protocol or methods, e.g., repulsion and attraction; and (4) energy, e.g., internal or transferred to the component through the environment [5]. Physical experiments involved placing magnetically encoded parts on a tray and assembling these parts into predetermined configurations through vibrations. These studies demonstrated feasibility of the self-assembly of mechanical parts, structures, and ultimately of machinery and robots.

2.3.2. Modeling and controlling manufacturing systems

Biological self-assembly and self-organization have also inspired much research into production-level application of these concepts. As manufacturing environments become more demanding, e.g., shorter lead times, reduced inventory, increased number of product lines and customization demands, researchers have aimed to better model, control and predict manufacturing systems with the aid of concepts from biology.

Evolutionary and self-organizational biomimetic models have been developed to create more dynamic and adaptive manufacturing systems that better address increasing manufacturing complexities. Ueda et al. have been a leading proponent of biomimetic modeling of manufacturing systems, developing the Biological Manufacturing System (BMS) [98–101]. The concept of BMS can be applied to the whole life cycle encompassed by a manufacturing system, from planning to disposal. As in biology, the concepts of self-organization and evolution are central to the BMS model, which is implemented through genetic algorithms, genetic programming, evolutionary strategy, cellular automatic, reinforcement learning and immune networks. Also as in biology, two types of information are found within the BMS, information passed from generation to generation (DNA-type), and individually acquired information based on learning (BN-type). In BMS, all entities such as work materials, tools, transporters, are autonomous organisms, with products from raw materials expressing DNA-type information, and manufacturing equipment creating the product through BN-type information. Self-organization within the BMS involves the use of attraction fields emanating from manufacturing cells to attract jobs. DNA-type information would encode product type, while BN-type information would include machine selection that could be based on past experience. Evolution with the BMS would involve DNA-type information directing work material to search for a work cell with a certain objective function, and occurs within the work material and work cell to meet the objective function.

Jin et al. described a model that mimics DNA-based capturing, representing and applying design information to functions and changing operational situations, and cell-based differentiating of function [44]. Jin et al.'s motivation is to enable large engineered systems to self-adapt to changes rather than to retool at a high cost. Tang et al. proposed a BioInspired Manufacturing System (BiMS) to respond rapidly to production changes based on the ultra-short feedback loop of the neuro-endocrine immunity system [92]. Unlike the work of Ueda et al. and Jin et al., BiMS is not based on DNA encoded information, but similar to the other two models, it incorporates the idea of autonomous cells to implement self-adaptive manufacturing control.

Another model borrows from concepts not only from evolution but the study of evolution itself. To examine changes undergone by products and associated manufacturing systems, ElMaraghy et al. used cladistics to model product evolution as well as the associated evolution of the manufacturing system [27]. Cladistics is a classification and modeling method that involves comparative studies to find similarities among entities. A cladogram is generated that hypothetically represents the evolutionary history of a group of entities, showing relationships and differences between the groups. The use of cladistics can provide a better way of organizing entities as well as predicting the future behavior of these entities. Further building on the use of evolutionary modeling of products and manufacturing systems, AlGeddawy and ElMaraghy hypothesized that like many species with a common evolutionary course, products and associated production systems also co-evolve [1]. Establishing this link between products and associated production systems may help prolong the life of manufacturing systems by predicting future behavior, thus facilitating decision-making. Tolio et al. reviewed and synthesized methods and tools that support the coordinated evolution (co-evolution) of products, processes and production systems [93].

In the area of biomimetic production system control and scheduling, recent research includes genetic approaches to scheduling by Chan and Chung [12] and pheromone-based scheduling by Yu and Ram [122], Scholz-Reiter et al. [82], and Zhu et al. [125]. Scholz-Reiter et al. explain that, in an ant colony, when given a choice of two paths between a food source and their nest, initially half the ants will take the shorter path, and the other half will take the longer path. During trips between the food source and the nest, ants deposit pheromones on the path, attracting other ants to the food source [81]. Since the pheromones on the longer path have more time to dissipate, over time, there is a weaker concentration of pheromones on the longer path and a stronger concentration of pheromones on the shorter path, thus attracting more ants to the shorter path. Many ant colony algorithms operate similarly to find the shortest scheduling route.

2.4. Conclusions for biomimetic manufacturing examples

This section presented a variety of biomimetic manufacturing research in three groupings, with some overlap between groups 1 and 2. Motivation common to much biomimetic research includes:

1. Increased potential for sustainable manufacture, e.g., from biomimetic forming processes in ambient environmental conditions to extending the life of manufacturing systems through biomimetic production systems modeling.
2. Ability to create 'self'-enabled manufacture, e.g., from self-sharpening shredders to self-assembly of components to self-organizing lineless production systems.

In many instances, more sustainable or self-assembling manufacture provides alternatives to conventional methods. In some cases, biomimetic means provide a method where none was easily accomplished or possible before, e.g., measurement of turbulence and fabrication of highly structured porous materials. Thus, biomimetic methods hold great potential for increasing manufacturing capability, sustainability and efficiency. However, not always available for the above examples are details on the process of identifying and applying relevant biological analogies. Therefore, the remainder of this paper will be devoted to general methods that support the identification and application of biological analogies to solve engineering problems.

3. Methods that support biomimetic design

Janine Benyus popularized the notion that humans emulate biological phenomena to design sustainable products and processes [3]. A biological sciences writer, she founded the Biomimcry Institute, a clearinghouse for biomimcry researchers. A resource supported by the Biomimcry Institute is an online database of nature's solutions, available at AskNature.org.

Julian Vincent, a biologist working in engineering, is developing TRIZ (the Russian system for creative solution of problems) as the main tool of biomimetics. Vincent et al. describe how TRIZ is adapted to support the transfer of knowledge from the biological to the engineering domain in a method called 'BioTRIZ' [109,110]. In TRIZ, problems are first expressed in terms of contradictions or conflicts. Next, 'inventive principles' that typically solve those conflicts are identified and applied. TRIZ was developed by analyzing over two million Russian patent certificates. Vincent et al. created BioTRIZ using the same inductive approach as for TRIZ, but based on over 500 biological phenomena instead of patent knowledge. BioTRIZ currently covers about 270 functions and 2500 conflicts and resolutions found in biology. The contradiction matrix for BioTRIZ is only 12% similar to the original TRIZ, suggesting that different principles are used to solve contradictions in biology. Notably, biological solutions rely less on energy, and therefore the use of biologically inspired design is promising for the development of new and sustainable engineering solutions.

Research on methods that support biomimetic design in general falls under the two high-level categories:

1. Methods to support search, retrieval and representation of biological phenomena for design.
2. Studies to better understand and therefore support the application of biological analogies to design.

Clearly the two categories are related and how the first category is implemented directly affects the second. Research under the above categories will be addressed in the order in which they are relevant during the biomimetic design process. Helms et al. [37] identify two directions in biomimetic design:

1. Solution driven, where an interesting biological phenomenon inspires the search for potential applications, and
2. Problem driven, where a given problem motivates the search for biological analogies that could help solve the problem.

The second direction, problem-driven is more widely practiced, as well as promoted. Much of the general methods on biomimetic design support this approach, and thus Section 4 is devoted to the problem-driven approach. However, many commonly cited as well as commercially available examples of biomimetic design, e.g., Velcro, are reported as solution driven. Therefore, the solution-driven approach deserves some mention, and comprises the rest of the current section.

Finally, one of the recurring messages of this paper is that there are several levels of biological organization, from the molecular, e.g., DNA, to the ecosystem/biosphere that can be exploited for biological analogies. Table 1, taken from Vakili and Shu's initial work [102] towards developing a natural-language approach to identify biological analogies, lists these levels, as well as possible applications for these levels. Biological analogies are often recalled from the organ (e.g., lung, leaf) to organism (e.g., animal, plant) levels, supported by the many instances of existing biomimetic design based on organs and organisms. However, biomimetic design is more fully exploited by identifying analogies beyond the obvious ones that come to mind, which motivates more objective search approaches.

3.1. Solution-driven approach

Helms et al. identify the following steps observed in students using the solution-driven approach, where designers start with a particular biological phenomenon in mind [37]. While many of the below steps are also involved in the problem-driven approach, definitions given here will be based on those by Helms et al., whereas the section on the problem-driven approach will contain more perspectives on what constitute each step.

1. *Biological Solution Identification*: Designers start with a biological phenomenon of interest in mind.
2. *Define Biological Solution*: This step involves designers moving from structures and superficial mechanisms to a deeper understanding of the biological system. The example used involves progressing from the initial understanding that abalone shell is hard, lightweight, resists impacts, into an understanding of the complex interactions of composite materials that are responsible for this behavior. Functional decomposition typically used for engineering problem definition can also assist in understanding the biological solution. In addition, Helms et al. define functional optimization as expressing functions in an optimization problem or equation. As an example, the func-

Table 1
Levels of biological organization and possible applications, adapted from Vakili and Shu [102].

Level	Intermediatelevels	Possible applications
Molecule		Chemical processes, catalysis, nanosystems
	Protein	
Organelle One of several formed bodies with specialized functions suspended in the cytoplasm found in eukaryotic cells.		Components, single function systems, microsystems
	Virus	
Cell The lowest level of organization where all the properties of life appear.		Microsystems
Tissue An integrated group of cells with a common structure and function.		Materials, composites, smart materials
Organ A specialized center of body function composed of several different types of tissues.		Single function systems, sub-systems
Organ system An organized group of organs that carries out one or more body functions.		Multi-function systems, information systems
Organism A complete living being composed of one or more cells.		Autonomous systems, multi-function systems
	Family unit	
Population A group of individuals of one species that live in a particular geographic area.		Self-organizing systems
	Host–parasite symbiosis	
Community All the organisms that inhabit a particular area; an assemblage of populations of different species living close enough together for potential interaction.		Competing systems, co-operative systems
Ecosystem A level of ecological study that includes all the organisms in a given area along with the abiotic factors with which they interact; a community and its physical environment.		Complex systems, macrosystems
	Biome	
Biosphere The entire portion of the earth that is inhabited by life. The sum of all the planet's ecosystems.		Macrosystems, isolated systems

tional goals of moss, which are to reduce water loss and protect reproductive structures from environmental stress, contradict the desire to increase surface area and position relative to the sun for photosynthesis. Thus, the structure and placement of moss optimize between these opposing sets of functional goals.

3. *Principle Extraction*: After the biological phenomenon is sufficiently understood, principles are extracted into a solution-neutral form, which involves removing reference to structural and environmental entities of the biological domain. For example, instead of describing the abalone shell as ‘interactions between flexible proteins and hexagonal calcium carbonate deposits’, the principle is expressed as ‘tightly coupled composite material formation by alternating flexible and rigid structures for resisting impact.’
4. *Reframe Solution*: Reframing the solution involves considering how humans would view the usefulness of the function achieved by the biological phenomenon.
5. *Problem Search*: After reframing the biological phenomenon as usefulness to humans, human problems to which the principle can be applied are identified.
6. *Problem Definition*: An identified problem is defined using tools such as functional decomposition and optimization.
7. *Principle Application*: The biological principle is translated into the engineering domain by introducing new constraints (and affordances), e.g., weight, flexibility, impact resistance and manufacturing process criteria. Then, the principle is applied to develop a solution to the identified problem.

As could be expected, Helms et al. [37] observed a tendency in students to fixate on the initial biological phenomena selected in solution-driven processes. This fixation is not ideal, as other potentially more suitable biological phenomena may thus be overlooked.

Lindemann and Gramann [54] also conducted a case study where they first studied a selected biological phenomenon, and then looked for technical transfer opportunities. While they were able to generate multiple concepts after studying the selected biological phenomenon, they observed that selecting a ‘nice’ phenomenon in the first place requires some knowledge of biology, and that successful technical transfer may be an even more challenging task.

4. Problem-driven approach

4.1. Problem definition

The problem-driven approach requires that a problem be defined sufficiently to enable a meaningful search for biological analogies. The majority of work in biomimetic design suggests that functions are identified in this step. Functional modeling in engineering typically involves expressing the desired function to be fulfilled by a design solution. Complex high-level functions are decomposed into simpler functions, any one, or combination of which can be solved using biological analogies. A primary goal in functional description is to avoid limitation to specific physical solutions for as long as possible. Functions are typically represented by verbs. The use of nouns, except as objects of functional verbs, is typically discouraged as this may indicate that a physical solution is already in mind, and not give other potential solutions fair consideration. However, the use of adjectives also has potential, as adjectives may describe desired qualities of the solution, e.g., flexible, transparent, etc. Although to some extent, the use of adjectives also assumes certain physical entities, e.g., surfaces that are flexible or transparent, versus the need to transmit light or allow for deflection.

In an example given by Helms et al., students began with the problem of preventing shark attacks on surfers, and redefined their desired function as camouflaging a surfboard. Here, camouflage is the functional verb selected, and surfboard’, the object of the verb, identifies the object to be camouflaged, and already limits the solutions to those applicable to surfboards, as well as specifies *camouflage* as a specific manner of protecting.

Other approaches may require redefining the original problem. In TRIZ and BioTRIZ, the problem is first reformulated as a conflict. Vincent et al. [110] give an example where tire chains are needed on icy roads during winter to increase friction for safe driving. However, chains will damage ice-free road surfaces, and conventional alternatives such as changing between winter and summer tires are inconvenient. Therefore, a tire that can instantly adapt to road conditions is desired. The conflict becomes, ‘How can friction between the tire and road increase, without increasing the weight (normal force) of the vehicle?’

Helms et al. and others suggest as a step between problem definition and solution search, to reframe or ‘biologize’ the problem. This is done by redefining problems in biological terms, often in the form of a question, e.g., ‘How do biological solutions accomplish the desired function?’ The example given reframes or biologizes the function of ‘stopping a bullet,’ into considering how biological entities ‘prevent, withstand and heal damage.’ However, this step must be undertaken with some caution, as it may predispose the designer to specific solutions, e.g., biological phenomena, and levels of biological organization.

4.2. Search for biological analogies

There are a number of ways to search for biological phenomena that are relevant as possible analogies to a given problem, each with associated benefits and challenges. While the final goal is to identify an analogy that provides a working solution, the initial goal, ought be to identify a large variety of potential biological analogies in an objective manner.

Lindemann and Gramann propose a checklist of associations to translate between technical functions and biology terms [54]. For example, the technical functions of 'change of the state of aggregation' and 'condense a gas' are associated with biological terms: nose passages, desert plants/animals, and leaves.

Helms et al. [37] describe the following solution search heuristics, relevant to several of the below methods as:

1. *Change Constraints* – For example, generalize 'keeping cool', to 'thermoregulation'.
2. *Champion Adapters* – Identify organisms or systems that survive in extreme environments relevant to the problem, e.g., consider organisms living in desert or equatorial climates to find biological methods of 'keeping cool'.
3. *Variation within a Solution Family* – Examine how different organisms solve a common problem, e.g., hearing, in different ways, e.g., bats and echolocation, and how different solutions correlate with differences in the problem domain.
4. *Multi-Functionality* – Identify organisms or systems that solve multiple problems simultaneously with single solutions.

One limitation of the above is a bias towards 'organisms', as opposed to biological phenomena at any level, from the molecular to the ecosystem. With or without incorporating the above, below are approaches for finding biological analogies.

4.2.1. Ask biologists directly

Certainly one obvious way of identifying potential biological analogies for engineering problems is to ask biologists. AskNature (http://www.asknature.org/) provides a social network of biologists specifically for this purpose. The advantage of simply asking biologists is that the engineer, generally untrained in biology, does not have to search for and interpret the relevance and potential application of information that may be unfamiliar. The disadvantage of this approach is that one must have access to biologists. In addition, biologists, as humans, may be biased towards their areas of expertise, rather than objectively recall and present a variety of phenomena as potential analogies.

4.2.2. Search through database

An obvious approach to address the limitations of asking biologists directly is to attempt to capture their knowledge in a database. The advantages include more focused search results. Frequently, the same keywords used to categorize biological phenomena, and often, past engineering solutions developed based on them, are presented as search keywords. Therefore, the 'relevance' of information found is guaranteed since the same keywords used to categorize and enter information are used to then search the database.

Chakrabarti et al. developed a model to represent causality of natural and artificial systems, and used it to structure information in a database of systems from both natural and artificial domains [11]. Bar-Cohen suggested the need for a documented database to support biomimetic design [2]. Bruck et al. created a design repository of bioinspired products and concepts to support bioinspired robotic projects for senior mechanical engineering students [9]. They also include a concurrent fabrication and assembly technique to manufacture bioinspired designs. Wilson et al. propose the use of reverse engineering and ontology to structure a database to support biomimetic design [117,118]. Vattam et al. constructed a functionally indexed knowledge base of structures and behaviors of biological and technological systems [106]. Nagel et al. used functional modeling and a design repository to connect biological and engineering solutions, and suggest two approaches. The first functionally models a biological system, and then seeks existing designs in a repository that can be improved based on the biological system. The second models a desired design based on customer needs, and looks for possible elements of biological solutions from a repository [66].

The main disadvantage of searching through a database specifically developed to support biomimetic design is that the search results are limited to what was entered into the database. Depending on how the database is structured, bias may be imparted during the categorization of information as it is entered. A simple example is that while Velcro was developed from burrs, should the biological entity of a burr be categorized under the engineering function of fastening? If so, other potential functions or strategies that can be extracted from the burr may be lost.

4.2.3. Natural-language based search

In addition to building a database of biological phenomena categorized for engineering use, another approach takes advantage of the abundant biological information already available in natural-language format (e.g., texts, papers) by searching them directly for relevant phenomena. This approach also avoids the subjective and enormous task of cataloguing all of biological phenomena for engineering, and is summarized by Shu [87]. The natural-language approach is supported by Vandevenne et al., who propose a scalable approach for the integration of large knowledge repositories in the biologically inspired design process [104]. While the natural-language approach overcomes the many limitations of other approaches, there are also more complex challenges, as detailed below.

4.2.3.1. Natural-language sources. The initial source of natural-language information is critical. This source should be written at a level that can be easily understood by engineers with little or no background in biology. Life, the Science of Biology, by Purves et al., a reference text for an introductory-level university biology course, is an example of a suitable text [71]. In addition to ease of comprehension, introductory-level texts tend to be general and cover a wide range of organizational levels, from the molecular and cellular to the ecosystem, such that potential solutions are not limited to one or two familiar levels.

Since a suitable search tool can be used to search any corpus, or body of text, other texts can be substituted or added as required for the initial or subsequent search. The challenging task is the initial identification of relevant biological phenomena. Once relevant phenomena are identified, further details can be found through more advanced texts, research papers and traditional research methods. However, searching through more advanced sources initially will generate results that are in more technical language and thus more difficult to understand. Due to the designer frustration this may cause, such results are more likely to be overlooked even if they are relevant. Therefore, initial results from a more basic text may be more effective for introducing the subject and confirming relevance to the design problem. An understanding and confirmed relevance of the subject then motivates further research and effort to understand the possibly complex details needed to develop a solution.

4.2.3.2. Natural-language search keywords. As the same keywords used to categorize phenomena are often presented as possible search keywords, searching databases specifically created to support biomimetic design tends to be more straightforward than searching natural-language sources. Unlike with databases, finding relevant analogies in natural-language text is subject to the word choices made by authors of the various natural-language sources. That is, multiple terms can describe and thus locate the same concept.

Vakili and Shu noted that synonyms are an obvious means to increase the number of matches for a given functional keyword [102]. Chiu and Shu noted that troponyms, verbs that describe specific manners of another verb, e.g., 'ambling' is a troponym of 'walking' as it is a particular manner of walking, also represent suitable alternative keywords [19]. Keywords used to search for biological analogies are verbs that describe the intended effect, or function, of desired solutions. Consistent with functional description, verbs are strongly preferred over nouns as keywords to initiate searches. Searching with nouns suggests pre-conceived analogies or solutions, while searching for verbs that describe the desired action is more likely to objectively identify a wider range of biological forms that perform that action. For example, searching with the verb keyword 'protect' will identify several biological phenomena that involve protection. However, searching using the noun keyword, 'cuticle', will only identify information related to cuticles, thereby limiting potential protection solutions to those that are based on cuticles. Ke et al. examined as keywords, the use of adjectives that describe a desired characteristic, and confirmed that adjectives can locate biological phenomena related to that characteristic [47].

Different lexicons, or vocabularies, between engineering and biology to describe the same phenomena motivated the identification of what Chiu and Shu refer to as biologically meaningful keywords [20]. The motivating example involved the keyword 'clean', which did not locate many useful matches for a problem involving cleaning. The advice of a domain expert was sought, who suggested 'defend' as an alternative keyword, since some organisms clean as a defensive mechanism. However, 'defend' is not intuitively related to 'clean' for most engineers, and has no documented lexical relationship with 'clean,' e.g., as a synonym. Therefore, Chiu and Shu developed a bridging method that identifies such highly relevant, but non-obvious, biologically meaningful keywords objectively and in a repeatable manner, without the need for domain experts [20,21].

The method uses word collocation and frequency analysis, and is summarized in Fig. 13 for the 'clean/defend' example. First, hypernyms of 'clean' are found using the lexical resource WordNet [120]. A hypernym is a more general form of a word, e.g., 'plant' is a hypernym of 'tree', and 'remove' is a hypernym of 'clean'. WordNet is also used to identify related words, such as hyponyms/troponyms, of 'remove', e.g., 'eliminate' and 'kill'. 'Eliminate' is a hyponym/troponym of 'remove', as eliminating is a specific manner of removing. The original and additional keywords are then searched in the corpus, in this case, the Purves et al. text. Resulting text excerpts that contain these words are assessed for relevance using metrics that are described below.

Within the relevant matches, words, typically nouns, e.g., cells, plants, and disease, which frequently occur, are then identified, along with the verbs that act on them. These verbs are then searched for in a biology dictionary. Verbs that are defined or part of a defined term are categorized as 'biologically significant'. For example, 'abscise', meaning to naturally separate or fall off, e.g., by a dead leaf or ripe fruit, is part of the defined term 'abscission', and therefore a biologically significant verb. Verbs that appear in the definition of terms, but are not defined themselves, are categorized as 'biologically connotative'. An example of a biologically connotative word is 'defend', since it occurs in several definitions, but is not a defined term itself. Biologically significant and biologically connotative words combined are termed 'biologically meaningful'. Biologically meaningful keywords are then sorted by frequency of occurrence in the biology dictionary. Most useful bridge words are observed to occur between certain frequency cut-offs. Words that occur very infrequently tend to be fairly specific technical terms that locate limited phenomena. Words that occur too frequently are not useful keywords as they locate an unmanageable number of matches. Such words are common in the English language, and include the forms of 'to be' or 'to have.' Fig. 13 shows schematically that 'defend' is located within certain frequency cut-offs. This method was able to identify 'defend' and other biologically meaningful keywords for 'clean'. Chiu and Shu used the method to also identify 'survive' as a biologically meaningful keyword for 'encapsulate' and 'break' or 'breakdown' as a biologically meaningful keyword for 'release' [21]. A more obvious and straightforward approach to identifying biologically meaningful keywords was to simply collect all verbs in the vicinity of the search verb. However, this method yielded far fewer useful, biologically meaningful words.

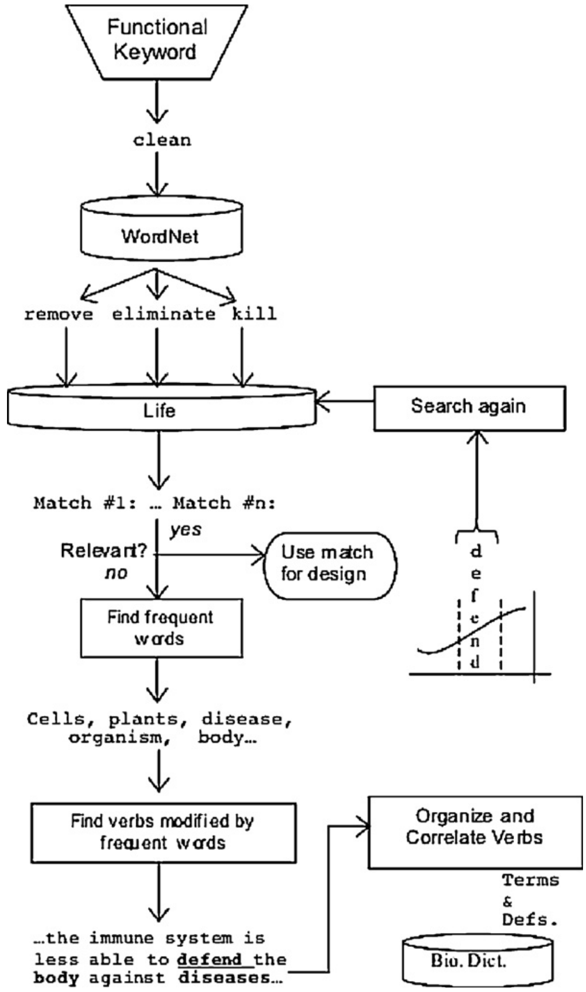


Fig. 13. Flow chart of method bridging 'clean' to 'defend' by Chiu and Shu [20]. Reprinted with permission. Copyright ASME 2005.

Cheong et al. used the bridging method to identify biologically meaningful keywords for functional terms of the functional basis [15,18]. The functional basis contains verb-object pairs intended to comprehensively represent the functionality of mechanical devices [89]. During the translation from functional to biologically meaningful keywords, Cheong et al. identified four categories, where most biologically meaningful keywords appear [18]. Excerpts by Purves et al. [71] illustrate these cases.

1. *Synonymous pair*: This case refers to groups or pairs of words that are used synonymously in the biology text, frequently in the same phrase or sentence. For example, 'convert' and 'transduce' are a synonymous pair in 'This information is received and converted, or transduced, by sensory cells into electric signals. . .'
2. *Implicitly synonymous pair*: This case refers to synonymous words that appear in a separate phrase or sentence. Most synonyms appear in this manner. For example 'conduct' and 'transport' are implicitly synonymous in, 'the xylem of tracheophytes conducts water from roots to aboveground plant parts. It contains conducting cells called tracheary elements, which undergo programmed cell death before they assume their function of transporting water and . . . minerals.'
3. *Biologically specific form*: This case refers to words that are biologically specific forms of engineering words. For example, 'photosynthesize' is a biologically specific form of 'convert', and 'mutate' enables 'transform' in, 'Mutations of one of the homeotic genes, bithorax, transform the third thoracic segment into . . .'
4. *Causal relation*: This case refers to a relationship where one action is performed to enable another action. For example,

‘break down’ enables ‘absorb’ in ‘Humans absorb amino acids by breaking down proteins from food’.

Cheong et al. applied the above cases to identify biologically meaningful keywords for function set verbs of the functional basis [18]. Other translators were also asked to identify biologically meaningful keywords using the same cases as criteria, and confirmed the objectiveness and repeatability of the criteria.

4.3. Assessing biological analogies

Another challenge in using biological analogies for design involves the human process of extracting relevant strategies from the biological phenomena and applying these strategies to design problems. As explained above, the challenge of assessing biological analogies for relevance to the engineering problem is most relevant to the natural-language search approach. Biologists pre-assess relevance before or while presenting potential biological analogies. Relevance of biological phenomena is determined as they are entered into databases.

In the natural-language search approach, the evaluation of biological analogies affects the very selection of what is considered relevant. The perception of relevance is very important, since, like with traditional search engines, search results may be presented as a list of text excerpts.

4.3.1. Categorization of search results

A significant challenge in searching natural-language knowledge sources to identify biological analogies is the quantity and quality of matches that may result. Depending on the keyword, there can easily be an unmanageable quantity of matches. Below are strategies to address this challenge, while minimizing the loss of relevant information.

Words that frequently collocate with, or occur in the vicinity of, sought keywords can often summarize dominant biological phenomena related to these keywords. For example, Chiu and Shu found that high frequency words, ‘predator’, ‘prey’ and ‘species’ for the keyword ‘eliminate’, describe how interactions between prey and predator species lead to one another’s elimination [19].

Ke et al. explored the use of Wikipedia categories to categorize search results [46]. Also investigated were other means for categorization so that search results can be more quickly summarized and skimmed. The most promising method is to sort by the subject acting on the keyword verb, and/or by the object that the keyword verb acts upon.

4.3.2. Evaluation and selection of biological analogies

Evaluating the relevance of potential analogies across domains is a more complex process than evaluating the relevance of matches to specific information sought. For example, in a traditional web search for ‘map of Paris’, it is far more obvious which matches actually contain the map sought. However, with cross-domain analogies, the physical entities involved are likely to be different between analogy and problem. Thus it is less straightforward to determine the relevance, as well as usefulness of a given match. Described below are challenges involved from the evaluation to the application of matches, and known ways of addressing these challenges.

Hacco and Shu noted that matches with the following characteristics could be eliminated right away [33]:

1. Matches may contain the sought keyword in a different sense, or meaning. For example, when searching for ‘conduct’ as in conducting energy, some matches contained ‘conduct’, as in conducting a study. Clearly, these matches are not relevant and were therefore eliminated.
2. Matches may contain the sought keyword acting on abstract, instead of physical objects. For example, when searching for ‘support’, matches regarding supporting a weight may be more useful than those regarding supporting a theory. For mechanical design problems that involve physical objects, matches that contain abstract entities, e.g., interest, equation, theory, etc., as the objects of search keywords are generally less applicable and therefore not further considered.

Ke et al. implemented the tagging of each word in a corpus with metadata such as: its part of speech, and if a noun, whether it is an abstract or physical noun, and possible senses. This information can be exploited to enable automatic hiding of matches that are unlikely to be relevant [47].

Mak and Shu observed that text descriptions of biological phenomena that describe principles and behaviors in addition to forms, tended to be more easily used by students as design stimuli [60]. In addition, Cheong et al. noted that text descriptions of biological phenomena that contain causal relationships, where one action enables another action, are more likely to serve as useful analogies for design problems [16,17]. Causal relations often explain how functions are achieved by behaviors. For example, in the text excerpt, ‘Lysozyme is an enzyme that protects the animals that produce it by destroying invading bacteria’ [71], the function of ‘protecting’ is, perhaps, counter intuitively enabled by the behavior of ‘destroying’.

4.4. Applying biological analogies

Mak and Shu observed that awareness of specific difficulties that could occur when generating engineering concepts from biological analogies reduced their occurrence [62]. Therefore, this section presents categories of difficulties experienced by students in detail rather than in summary.

4.4.1. Types of similarity

Mak and Shu investigated how students applied descriptions of biological phenomena functionally related to a given problem to solve that problem [60]. Specifically, students were asked to develop concepts that result in ‘clean clothes’, by using the following description of a biological phenomenon by Purves et al. [71]:

> Barriers and local agents defend the body – skin is a primary innate defense against invasion. The bacteria and fungi that normally live and reproduce in great numbers on our body surfaces without causing disease are referred to as normal flora. These natural occupants of our bodies compete with pathogens for space and nutrients, so normal flora are a form of innate defense.

Four similarity types were observed between the description of the biological phenomena and the concepts developed using them as stimuli. These similarity types are shown with examples in Fig. 14, whose axes are strategic accuracy and abstraction of biological entities. Details on the four similarity types are as follows. In addition, related errors observed by Helms et al. [37] are identified under the corresponding categories, and indicated in Fig. 14.

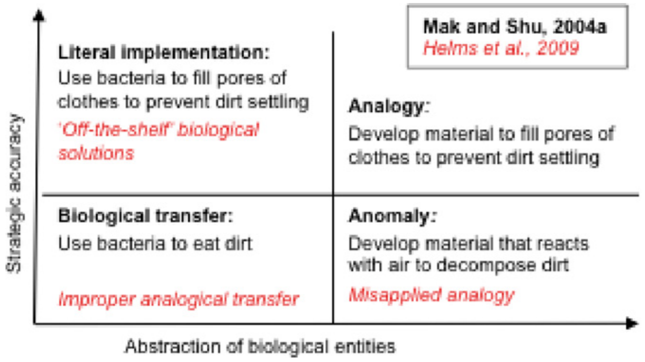


Fig. 14. Types of similarities between biological phenomena and developed concepts, adapted from Mak and Shu [60].

1. *Literal implementation*: A literal implementation involves using biological entities, e.g., bacteria, directly to solve the engineering problem, e.g., by filling clothing pores to prevent dirt from settling. Here, the biological entities are not abstracted, but rather, used directly, with the same strategy between source and problem domains. Of relevance are the terms bioutilization and bioassistance – the use of biological entities directly as solutions. Bioutilization refers to the use of biological materials, e.g., bamboo in floors, plant extracts in drugs, etc. Bioassistance refers to using the actions of biological organisms to enable solutions, e.g., plants to clean air, leeches to reduce blood coagulation, etc.

   This category is most related to the Helms et al. identified behavior that designers use 'off-the-shelf' biological solutions to 'do what it does' instead of abstracting and applying the principles of the biological entity. The example given involves using fireflies directly to emit light, instead of applying the principles that enable bioluminescence.
2. *Biological transfer*: A biological transfer involves transferring the biological entities, e.g., bacteria, into the solution domain, but without applying the strategy presented in the biological domain. For example, bacteria are used to provide the solution of clean clothes by eating dirt.

   This category is most closely related to Helms et al.'s 'improper analogical transfer,' where mechanisms important in the inspiration source, but not relevant to the problem, were transferred to the problem. The example given describes how filters in a dog's nose well suited for sorting through and identifying several different scents are unneeded for a single scent, but still transferred to the solution.
3. *Anomaly*: An anomalous solution involves neither the entities nor the strategy from the biological phenomenon. Some anomalous concepts are due to lack of understanding. Other anomalous concepts are likely due to fixation on a few words in the text description while disregarding the overall strategy or principle presented. Mak and Shu noted that the appearance in a text excerpt of any word that is commonly used in engineering, e.g., 'motor' in motor proteins, tends to result in concepts that involve motors, whether or not motors are relevant to the phenomenon presented [61]. Although anomalous concepts can be novel as well as practical, they are not based on the biological phenomenon, except perhaps as a source of random stimuli.

   The error Helms et al. observed that most closely relate is 'misapplied analogy', where matches were often forced into flawed solutions. The example given involves a two-way traffic optimization algorithm derived from ant foraging behavior, resulting in an inaccurate model when applied to a throughput traffic optimization problem.
4. *Analogy*: The intended analogous solution accurately applies the strategy from the biological phenomenon to the concept without transferring the biological entities, e.g., bacteria, into the solution. Gentner and Goel established foundations for analogical reasoning relevant to this work [31,32]. More recently, Vattam et al. developed a conceptual framework for compound analogical design [105], studied the content of different types of analogy in biomimetic design [106], and analyzed different kinds of analogies that occur at different stages in biomimetic design [107]. Sartori et al. implemented a SAPPhIRE model to describe a biological system at various levels of scale and abstraction, and suggest that this specific representation may support transfer at a particular level [80]. Yen and Weissburg support that the success of biologically inspired design depends most critically on establishing an analogy at the appropriate level of abstraction [121].

4.4.2. Additional errors observed in biomimetic design

In addition to the errors identified by Helms et al. already categorized under the Mak and Shu's [60] observations above, are the following remaining errors [37].

4.4.2.1. Vaguely defined problems. Not unique to biomimetic design, problems that are vaguely defined, e.g., 'lowering our dependence on oil,' or 'protecting a cell phone,' are either too vague for functional modeling or do not limit the search space enough. Helms et al. present the above examples improved as 'more efficient allocation of resources to reduce energy consumed in transportation' and 'forming a scratch-resistant coating for cell phones.'

4.4.2.2. Poor problem-solution pairing. Designers were observed by Helms et al. to match problems to biological solutions based on superficial as opposed to functional similarity. The example given involves matching 'making a better dishwashing detergent' with the 'cleaning properties of the lotus leaf.' While 'cleaning' is common between problem and solution, the lotus leaf self-cleans due to its surface structure, which typically cannot be changed by a detergent.

Lindemann and Gramann also suggest an iterative approach to bionics where failure to realize a solution based on a specific associated biological term requires abstracting the problem to a different level, exploration of a different biological system, or both [54].

4.4.2.3. Oversimplification of complex functions. Helms et al. observed that designers tend to miss the significance of an underlying principle due to simplifying assumptions. The example given involves using the term 'simply writhing', which oversimplifies the deliberate, complex motion involved in writhing.

4.4.2.4. Simplification of optimization problems. Helms et al. observed that designers tend to fixate on a single biological function instead of examining complex and competing biological functions in forming optimization problems. The example given has designers expressing the structure of moss as optimizing surface area to gather sunlight, and ignoring the requirements of the plant for protection and water conservation.

Mak and Shu also noted that students tend to apply only one of several interacting strategies present in descriptions of biological phenomena [62].

4.4.2.5. Solution fixation. Designers were often observed by Helms et al. to fixate on the first biological phenomenon identified, exclude consideration of other phenomena, and prefer the initial phenomenon to subsequent phenomena when comparative evaluations were required. Only one out of nine teams was observed to replace their initial biological phenomenon with another. As biological phenomena were provided to students by Mak and Shu [61,62], the fixations observed involved fixating on particular solution modes as well as on irrelevant aspects of the biological phenomena [61,62].

Santulli and Langella examined how students used biological analogies to design sports equipment. They observed that most projects were based on (1) animals, as opposed to plants, (2) simple mental associations (e.g., jumping and frogs or grasshoppers, or light and fireflies), without necessarily a sound rationale, and (3) that formal imitation of structure was prevalent without necessarily matching the conditions between the engineering and biological environment for which the structure is suited [78]. Wilson et al. also studied students using biological analogies as stimuli and report that exposure to biological examples increased design novelty without decreasing concept variety [119].

4.4.3. Analogical mapping tool

Although identifying the undesired categories of similarity reduced the quantity of misapplied biomimetic design, two persisting difficulties observed by Mak and Shu in students using descriptions of biological phenomena were: inability to transfer information from biology to engineering; and fixation on specific phrases of the description of biological phenomena [62]. This motivated further studies where students were provided outlines of strategies to be applied to both biological and engineering domains to facilitate analogical mapping. Compared to results without the mapping tool, the quality of generated concepts improved. However, although participants who used the mapping tool extracted strategies consistent with the biological phenomena presented, they continued to apply strategies to specific attributes of the given problem. For example, participants tended to apply strategies to only one attribute of the problem domain, particularly 'clothing' in the clean-clothes problem, even though the resulting concepts were not necessarily feasible. Because generated concepts varied with selected attributes, a possible method to reduce fixation and increase the variety of solutions developed, is to instruct the designer to list the problem attributes, e.g., 'clothing', 'dirt', 'detergent', and then develop ways in which the biological strategies can be applied to each item in the list of attributes.

Further work by Cheong and Shu and Cheong et al. support the idea that a template would be particularly helpful for descriptions of biological phenomena that contain a causal relationship that must be recognized and transferred across domains [16,17].

4.4.4. Functional models to aid comprehension

Vakili et al. performed a preliminary study examining the role of functional models in presenting biological phenomena as stimuli [103]. Study participants were asked to solve a micro-assembly problem using a set of biological representations, including functional models, of leaf abscission for inspiration. The visual aids provided to the designers were examined, and the use of functional models of biological phenomena in particular was critiqued. Solutions developed from the study were classified and theories drawn on potential influences of the biological representations. Observations, retrospective conversations with participants, and analogical reasoning classifications were used to determine positive qualities as well as areas for improvement in representation of the biological domain. Results suggest that designers require an explicit list of all possible biological strategies.

Nagel et al. explored the role of functional modeling to support biomimetic design [65]. Helms et al. studied how functional representations of biological systems using the Structure-Behavior-Function model facilitate understanding of biological systems. They conclude that multiple representations, e.g., text, diagrams, and SBF models, should be provided to designers because each representation is effective at facilitating the comprehension of different types of biological knowledge, e.g., spatial, functional, causality, etc. [38]. While functional models may help engineers understand biological phenomena, Section 6 will submit that function may not be sufficient to identify the most suitable biological analogy.

5. Examples

Because the most detail is available for each, but especially for the analogy identification, step of the biomimetic design process, examples detailed in this section are from the natural-language approach. Most other published examples of biomimetic design tend not to specify how the biological analogies were identified. Case studies using the natural-language approach include those in: design for remanufacture [33,85,102], authorized disassembly [76], micro-assembly [84,86], sensing [52], redesign of fuel cells [22,47], protection during hobbies [15], and protection from lunar regolith [23].

Summarized below are three case studies executed in chronological order over the span of nearly a decade, and research results were applied to the case studies as they became available. Parts of the examples are presented in detail below to provide better context for more recent insights developed from them, which are presented in Section 6.

5.1. Design for remanufacture

5.1.1. Introduction and problem definition

Remanufacture is a product end-of-life process that enables the reuse of product components. Over scrap-material recycling, remanufacture offers advantages that include conservation of resources needed to melt and reform components. To facilitate remanufacture, an identified design guideline is that product features prone to failure should be made separable [83]. This separation enables the replacement of failed features and the reuse of a component without labor- and capital-intensive repair. This guideline however, contradicts design for assembly guidelines, since making failure-prone parts separate increases part count and assembly cost. This apparent contradiction between ease of assembly and ease of remanufacture motivated the search for potential biological analogies [102].

5.1.2. Keyword and analogy identification

Not surprisingly, searching for the keyword 'remanufacture' did not result in any matches in the biology text. Therefore, synonyms and related words were required to find any matches. Other keywords used include 'repair' and 'correct.'

5.1.2.1. Organ/organism level analogy. The keyword 'repair' located a biological phenomenon at the organ to organism level in the Purves et al. text [71]:

> The defense systems of plants and animals differ. Animals generally repair tissues that have been infected. Plants, on the other hand, do not make repairs. Instead, they seal off and sacrifice the damaged tissue so that the rest of the plant does not become infected. This approach works because most plants, unlike most animals, can replace damaged parts by growing new stems, leaves, and roots.

The strategy derived from this phenomenon involves adding new parts to replace damaged ones, rather than expending resources in repairing damaged parts, or sacrificing the entire organism. Applied to products, this strategy could involve planning for parts to replace features that are likely to break, without repairing the broken feature or replacing the entire part that contained the feature.

5.1.2.2. Organ-system level analogy. A match found using the keyword 'correct', that describes fainting, follows [71]:

> Blood must be returned from the veins to the heart so that circulation can continue. If the veins are above the level of the heart, gravity helps blood flow, but below the level of the heart, blood must be moved against the pull of gravity. If too much blood remains in the veins, then too little blood returns to the heart, and thus too little blood is pumped to the brain; a person may faint as a result. Fainting is self-correcting: A fainting person falls, thereby moving out of the position in which gravity caused blood to accumulate in the lower body.

The strategy derived from this analogy is to use preemptive, defensive failure to prevent more serious failure.

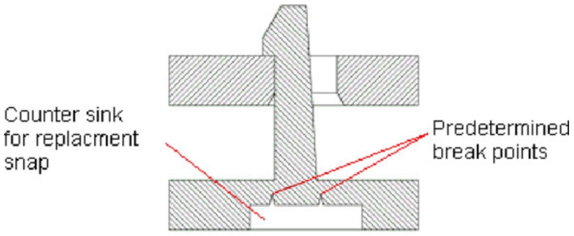
5.1.3. Selected analogies and implementation

Fastening and joining are highly relevant to life cycle considerations, as they clearly affect required assembly and disassembly. Snap fits are often used as a fastening method due to their ease of assembly. However, snap fits frequently break and are difficult to repair during remanufacture.

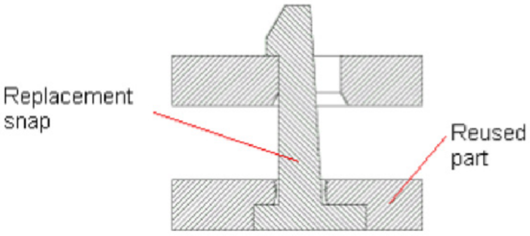
Incorporating the preemptive failure strategy to the redesign of snap fits, Hacco and Shu specified predetermined breakpoints, shown in Fig. 15a, that may cause earlier failure, but the part containing the snap fit feature can be more easily reused. Incorporating the strategy to sacrifice and replace parts, a possible planned replacement part is shown in Fig. 15b that can be used once the sacrificial feature in Fig. 15a fails [33].

5.1.4. Conclusions for remanufacture example

This initial case study was performed to confirm that the natural-language text search approach is able to identify relevant



a. Snap fit redesigned with counter sink and break points.



b. Redesigned snap fit after failure and refurbishment

Fig. 15. Redesigned snap fit to facilitate repair by Hacco and Shu [33]. Reprinted with permission. Copyright ASME 2002. (a) Snap fit redesigned with counter sink and break points. (b) Redesigned snap fit after failure and refurbishment.

and novel analogies to solve engineering problems. Analogies were found at several levels of biological organization, from the molecular to the ecosystem, with only two detailed above. For both analogies, strategies were abstracted from the biological phenomena for implementation in engineering solutions.

5.2. *Overcoming sticking in microassembly*

5.2.1. *Introduction and problem definition*

Size effects complicate the handling and assembly of micromechanical parts. Specifically, surface-related forces, e.g., electrostatic, van der Waals and surface tension forces dominate gravitational forces. As a result, sticking between the micropart and the gripping device during release hinders the automation of microassembly operations.

Shu et al. [86] describe the identification and use of biological analogies to address the problem of 'sticking' during microassembly [86]. Biological analogies were sought to develop concepts that enable the controlled removal of a microobject from a gripping device. Release techniques based on DNA transcription and abscission in plants led to concepts enabling the automated handling of microobjects. Described below is a concept implemented at the Technical University of Denmark.

5.2.2. *Keyword and analogy identification*

The initial functional keyword identified for this problem is 'remove'. The processes Chiu and Shu had developed were used to identify alternative keywords. In addition to synonyms, these include troponyms, or more specific manners of a functional verb [19–21]. Alternative search words also include biologically meaningful keywords, i.e., words relevant to the desired function in biology whose relationship may not be documented in lexical references, e.g., dictionaries and thesauri.

One biologically meaningful keyword for 'remove' is 'defend' since entities are sometimes removed in biological systems as a defensive mechanism. The keyword 'defend' led to a match with DNA transcription as the basis for how proteins are selectively synthesized to defend against infections, which led to a concept where features with different geometries would be used to maximize or minimize surface contact with the microobject as needed. However, this solution is relatively complex compared to one that was developed based on the abscission principle as described below.

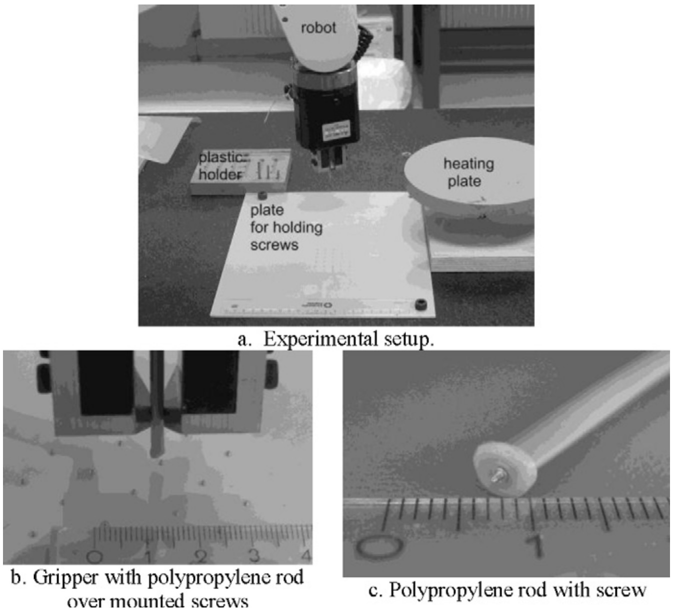
Multiple keywords, including 'defend', 'remove' and 'release' led to the biological phenomenon of abscission. Abscission is the process by which leaves, petals, and fruits separate from a plant. A hormone called auxin is strategically released in plants to direct growth. When auxin is no longer produced, other hormones are released. The combined effect of these hormones breaks down parts of plants, e.g., stalks of leaves damaged through infection, or are no longer needed, as in the winter season, such that they become completely detached from the plant. The base of some leaves contains the abscission zone, which is a special layer of cells. Without auxin, these cells swell and form a cork-like material, which cuts off nutrients to the leaf, forms a seal between the leaf and the plant, and protects the plant once the leaf separates [71].

5.2.3. *Implementation*

The abscission principle was applied abstractly to overcome difficulties associated with 'sticking' as follows. The microobject is released together with a part of the tool designated as sacrificial, which can be of significant mass to take advantage of gravity. The object can thus be easily released, and the sacrificial part of the tool can then either remain with the microobject or be subsequently removed.

For the specific application of inserting a 0.6 mm metallic microscrew into a plastic counterpart, the abscission zone is physically implemented as a polypropylene rod of 4 mm diameter that is easily gripped and positioned by a small industrial robot with six degrees of freedom and a specified repeatability of ±0.02 mm (see Fig. 16). The tip of the polypropylene rod is locally melted by heating, and then pressed over the head of the screw. The contact with the screw results in solidification of the polypropylene, and a solid bond between the rod and the screw is formed. The robot can now manipulate the screw into the plastic counterpart. Once the screw is tightened into its final position, the resulting increased torque will break the bond between screw and rod.

Other concepts considered for the abscission principle included the use of ice or other intermediate material that could be chemically dissolved. This however would introduce possible contaminants that are clearly undesirable. The abscission principle is more broadly interpreted as a physically weaker zone between the plant (gripper) and the leaf (screw). Gravitational, torsional or other forces can be used to break this zone to separate the gripper and screw. In addition to relative 'weakness', a polymer was chosen as the intermediate-zone material due to its ability to form the very small geometric features that mate with and thus handle the microscrew.



a. Experimental setup.

b. Gripper with polypropylene rod over mounted screws

c. Polypropylene rod with screw

Fig. 16. Implementation of abscission principle for micropart release [86]. Reprinted with permission. Copyright ASME 2006. (a) Experimental setup. (b) Gripper with polypropylene rod over mounted screws. (c) Polypropylene rod with screw.

5.2.4. Conclusions for microassembly example

Previous work conjectured that biological analogies at smaller scales comparable to the microassembly scale could be directly implemented with less need for abstraction [84]. However, physical implementation of the biological strategy in a solution for this case study highlighted the difficulty of emulating the complex and tightly controlled biological processes identified at the micro scale, only one of which was mentioned for this case study. Thus, the far simpler, albeit abstract rather than literal, implementation of an intermediate zone that could be broken down, thermally, chemically or mechanically, was chosen. This example supports the abstraction of biological principles for implementation in engineering, since it may be neither possible nor desirable to literally emulate analogous biological processes.

5.3. Protection from lunar regolith

5.3.1. Introduction and problem definition

In a collaborative project between the Canadian Space Agency, Dalhousie University and the University of Toronto, biomimetic concepts were developed to protect a Light Detection And Ranging (LIDAR) device from lunar regolith, or moon dust. Davidson et al. report the use of biologically meaningful keywords to identify biological analogies to generate solutions for protection required during lunar exploration [23].

In lunar exploration, regolith, or dust, is a significant problem due to its pervasiveness, adherence, and abrasiveness, causing premature failure of space suits, mechanisms, and scientific instruments used on the moon. Unique characteristics of both the lunar environment and lunar regolith prevent implementation of most obvious solutions. Therefore, biological analogies were sought to expand the range of possible and feasible solutions.

Two components of the lunar environment limit the choice of materials. First, the thin lunar atmosphere approximates a hard vacuum, and eliminates the specification of materials such as polymers, which will outgas in a vacuum and result in severe physical degradation. Second, in the most common lunar exploration areas, temperatures range from 120 °C during the day to −150 °C at night. Solutions therefore must accommodate large and rapid temperature swings that occur during the change from day to night and vice versa, further limiting the selection and arrangement of materials.

Both mechanical and electrostatic aspects contribute to lunar regolith adhering strongly to all surfaces. Without an atmosphere, no wind rounds regolith particles. The sharp, jagged edges of regolith cause the mechanical aspect of adhesion, as well as the abrasion of mechanical seals. Furthermore, the small size of most regolith particles (below 70 μm), leads to infiltration of almost all mechanical systems. Positive charging of particles by solar wind during the lunar day and negative charging by plasma electron currents at night enable particles to cling to ungrounded conductive surfaces and nonconductive surfaces. Finer regolith grains will levitate under this electrostatic charging and thus, dust is present at the instrument level, even without mechanical disturbance of regolith.

The LIDAR device, shown in Fig. 17, is an optical instrument that can detect particle concentrations kilometers above the instrument itself. A LIDAR consists of a high-powered laser that points upward and an optical receiver. A cover, when closed, protects both the laser beam canister and the receiver lens. Improved protection is sought for the lens both during operation (when the cover is open) and while idle.

5.3.2. Keyword and analogy identification

The engineering keyword ‘protect’ is identified directly from the problem statement. In the translation from engineering to biologically meaningful keywords, Cheong et al. grouped ‘protect’ with the functional basis words: ‘prevent’, inhibit’, and ‘shield’ [18]. Corresponding biologically meaningful keywords are: ‘cover’, ‘surround’, ‘inhibit’, ‘destroy’, ‘change shape’, ‘bind’, ‘release’, ‘attach’, ‘protect’, ‘repel’, ‘push away’, ‘shield’, and ‘defend’. The more promising biologically meaningful keywords were selected and used to identify the below matches.

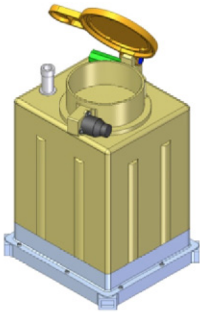


Fig. 17. LIDAR (~20 cm high), from Davidson et al. [23]. Reprinted with permission.

1. *Matches for ‘protect’*: Most matches located with the keyword ‘protect’ involve some physical protection and/or covering, e.g., for embryos, seeds, etc. One match was not used entirely analogously, but did inspire a simple reconfiguration of the lens cap that would reduce the amount of regolith falling onto the lens during opening. This match involved a ‘clam’, inspiring a lens cap configured as two halves of a bivalve that opens from the top, such that regolith that has collected on top is less likely to fall onto the lens than from a single hinged cap, the current configuration, shown in Fig. 17.
2. *Matches for ‘repel’*: The keyword ‘repel’ identified concepts that use coatings, e.g., waxy coating on hair that repels water. One match, involving the use of like charges to repel versus opposite charges to attract, may be more conceptually novel than the use of coatings, and led to the idea of using charge to manipulate regolith away from LIDAR parts.

5.3.3. Selected analogies

The biological analogies introduced above are detailed below. An additional, more obvious biological analogy, not identified in the manner described above, is also explored.

1. *Bivalve class*: Davidson et al. further investigated the bivalve class of mollusks, which include scallops, clams, oysters, and mussels, and revealed the following relevant details. These organisms, evolved in particulate-laden environments, ‘protect’ themselves from both predation and excessive particle intrusion with their shells. Bivalve shell geometry affords easy travel through sand and mud, as well as protection from hazards. The two shell halves meet at a 10–20° angle, which deflects sand away from mating surfaces, while the curvature of the shell sheds passing sand particles. Furthermore, the two halves of the bivalve pivot to open and close using a flexible ligament, which is more resistant to particle fouling than standard mechanical hinges that require rotational sliding motion.
2. *Charge*: The strategy of using like versus unlike charges identified by the keyword ‘repel’ led to the idea of moving and keeping particles around the perimeter of the LIDAR receiver using high-voltage direct current (DC) electromagnetic fields. This method makes possible active dust protection with the cover opened during operation, and exploits the electrostatic charge always present on lofted lunar dust that is not mechanically disturbed.
3. *Human eye*: Davidson et al. identified the human eye as an obvious biological analogy for the protection of an optical sensing system from dust. Tears not only hydrate the eye, but also provide a barrier between dust and the sensitive tissues of the eye. The eyelid sweeps and actively transports foreign particles to the perimeter of the eye, where they are flushed from the eye with tears. However, directly implementing many parts of the human eye analogy is not appropriate for this

problem. Use of fluids in the lunar environment is inappropriate because of the hard vacuum and large temperature ranges. The use of a mechanical wiper is not suitable because of the abrasiveness of the particles and the sensitivity of the protected optical surfaces. However, suitable strategies include transporting particles to the perimeter of sensitive surfaces, and actively protecting these surfaces while in operation, which is accomplished by the charge-inspired concept.

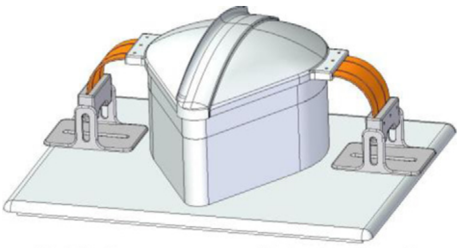
5.3.4. *Implementation*

A dust protection system was prototyped based on the two suitable analogies, and corresponding concepts are shown in Fig. 18. The system is comprised of two protection mechanisms: a Shape Memory Alloy (SMA) actuated, bivalve-inspired lid assembly that protects the LIDAR device when not in use, and an integral DC field generator in a circular collar that protects the LIDAR device during use.

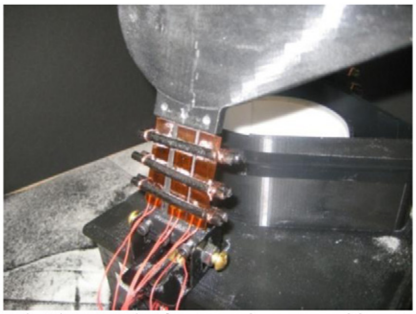
5.3.4.1. Bivalve inspired lid-assembly. Both the geometry and the joint of the bivalve shell were incorporated into a two-piece cover system for the LIDAR device. The curvature of the lids facilitates shedding of regolith and reduces regolith falling onto the lens area during opening. The bivalve ligament joint led to development of an SMA hinge that also avoids the relative motion found in traditional rotating joints, increasing resistance to particle fouling. Thin-film surface heaters supply heat to SMA actuators, which move each of the two lid sections. Davidson et al. provide further details of this implementation [23].

5.3.4.2. Particle management using charge. The receiver section of the base contains two semi-cylindrical insulated aluminum sheets, which, oppositely charged, deflect charged particles away from the lens face. This solution works particularly well in the lunar environment because of a weaker gravitational field compared to earth. A charged particle that enters the electric field is drawn towards the oppositely charged plate, and is held at that plate upon contact.

5.3.4.3. Prototype test results. Davidson et al. report that the SMA actuation system achieved more than 100 repeatable lid-opening and closing cycles, and the high-voltage DC field controlled and deflected 98% of incoming charged polystyrene particles, with an average size of 1 mm, away from a representative surface.



a. Model of prototype assembly in closed position.



b. Photograph of actuator in open position.

Fig. 18. Clam-based LIDAR protection by Davidson et al. [23]. Reprinted with permission. (a) Model of prototype assembly in closed position. (b) Photograph of actuator in open position.

5.3.5. *Conclusions for LIDAR protection example*

This case study supports a number of conclusions for biologically inspired design. First, obvious biological analogies that come to mind, e.g., human eye protection, may not be the most suitable for a given problem. Second, biologically meaningful keywords, including those that are not obviously related to the engineering function, e.g., 'destroy' (which was retrieved by protect), may lead to novel analogies and thus concepts. Finally, although the clam analogy was not initially identified by a functional link, the clam operates in a particle-laden environment similar to the lunar environment. Therefore the initial concept of two halves of a clamshell opening from the top was further improved with additional characteristics, e.g., shell geometry and ligament joint, of the clam that enable it to better cope with such an environment.

6. Summary, observations and conclusion

This paper presented several specific instances of biomimetic design and manufacturing. However, not always available is how the biological analogy was identified or selected. Therefore, general methods, which support the identification and application of biological analogies to any given problem, were described. One such general method, the natural-language approach to biomimetic design was illustrated through three examples involving a variety of applications. This section presents observations and insights based on the specific instances of biomimetic manufacturing in Section 2, as well as the application examples in Section 5.

6.1. *Observations from biomimetic manufacturing examples*

6.1.1. *Incorporate features on smooth surfaces*

A review of the examples presented in Section 2 reveal that many biomimetic surfaces incorporate features that give them advantages over 'smooth' surfaces. Serrations on the mosquito proboscis and its bioinspired syringe needle reduce compression and nerve stimulation. Micro grooves on sharkskin scales and its bioinspired surfaces reduce drag. Micro mounds and nano hairs on lotus leafs and their bioinspired products enable them to stay clean. Geometrical embossing on surfaces of the dung beetle and its bioinspired furrow opener offer lower resistance and power requirements. Ridges on scallops and the corresponding bioinspired surfaces better resist abrasive wear.

While these phenomena were likely identified or recalled as relevant based on observations at the organ to organism level, the mechanisms that enable the phenomena of interest are generally at much smaller scales. Therefore, there may be value in searching directly for relevant phenomena at these scales, demonstrated possible in the natural-language search approach to biomimetic design. As engineering operates at increasingly smaller scales, not only can these surface features be better observed, studied and modeled, but they may also be better replicated in engineered surfaces to confer similar advantages. This view is supported by recent review papers on hierarchical features at the micro and nano scales in natural and biomimetic surfaces, e.g., by Bhushan and Jung for superhydrophobicity, self-cleaning, low adhesion, and drag reduction [6], Sameoto and Menon for dry adhesion [77], as well as Vincent [111] and Liu and Jiang [55]. Raibeck et al. point out that while biologically inspired self-cleaning surfaces offer obvious environmental advantages during use, environmental burdens associated with current production techniques may offset these advantages [72]. Therefore, there is likely potential for improving techniques that produce biomimetic surfaces with respect to environmental burden, perhaps by studying the corresponding biological processes.

6.1.2. *Make homogenous characteristics heterogeneous*

Many examples that involve self-enabling features incorporate heterogeneous rather than homogeneous characteristics. For example, the combination of soft dentine and hard enamel enables self-sharpening in rodent teeth and corresponding shredder blades. Gradients in attraction fields from manufacturing cells attract jobs in the self-organizing Biological Manufacturing System (BMS). Gradients in pheromone concentration allow ants and their bioinspired scheduling approaches to self-align to the shortest routes. The identification and exploitation of other possible gradients can be used to realize other self-enabling activities in engineering solutions. For example, Trask et al. propose biomimetic self-healing polymer composites [97]. Furthermore, McKittrick et al. studied mammalian structural materials including bones, teeth and tusks, horns and hooves for energy absorption mechanisms, and identify gradients in density as well as Young's modulus as possible biomimetic design strategies [63].

6.2. Observations from biomimetic method application examples

Below are retrospective observations from first-hand experience in the selection of biological analogies, extraction of biological strategies and their application in engineered systems, as described in Section 5.

6.2.1. Consider analogies by environment in addition to function

In addition to the search for and selection of biological analogies based on functional similarity, as suggested by the majority of biomimetic design researchers, the lunar regolith example also highlights the role of environmental similarity. Specifically, while the clam was identified more by superficial than functional characteristics, it turned out to provide a wealth of transferable strategies. The clam's physical characteristics that are suited to its particulate-laden environment, e.g., shell shape that sheds sand and ligament hinge less susceptible to particle fouling, are also well suited to protection from lunar dust. Conversely, strategies from the more obvious eye protection analogy, though more functionally similar, turned out to be much less directly transferable to the lunar environment.

Helms et al. indirectly refer to the identification of biological analogies by environment as well as function through champion adapters – organisms that survive in the most extreme of the environment of interest [37]. Ke et al.'s use of adjectives in addition to verbs to search knowledge in natural-language text can be applied to facilitate finding analogies by environment [47].

6.2.2. Implement strategies passively to enable/replace active solutions

Although not detailed in this paper, earlier reports of both the remanufacture and microassembly examples include biological analogies that were not as obviously or successfully implemented in the engineering solution. For example, identified using the keyword 'repair' for the remanufacture problem are DNA repair mechanisms. Specifically, excision repair targets damaged sections of a DNA molecule, including that which occurs during the life of the cell. Chemically damaged abnormal bases are excised and replaced with functional bases. Clearly, this phenomenon is highly analogous to the repair of damaged parts during remanufacture. The text on excision repair by Purves et al. follows [71].

> For example, in excision repair, certain enzymes 'inspect' the cell's DNA. When they find mispaired bases, chemically modified bases, or points at which one strand has more bases than the other (with the result that one or more bases of one strand form an unpaired loop), these enzymes cut the defective strand. Another enzyme cuts away the bases adjacent to and including the offending base, and DNA polymerase and DNA ligase synthesize and seal up a new (usually correct) piece to replace the excised one.

While the above description confirms relevance, it is difficult to apply the active strategies given. For instance, who or what can be used in place of enzymes in an engineering solution to 'inspect, find, cut, synthesize, seal up, and replace' the defective parts, activities needed in excision repair? Relegating these duties to a human repair technician confers no improvement over the current situation in remanufacture. Further details on excision repair from a more advanced source mention conformation changes that result from the interaction of enzymes and contribute to the above activities in the repair sequence. The conformation-change strategy was then matched to the engineering strategy where failure induces a conformation change that helps release the part for replacement, e.g., self-removal during failure, somewhat implemented already in the solution described in Section 5.

Another biological analogy identified for the microassembly example also involves complex molecular interactions. This phenomenon was developed into a potentially feasible physical concept, but was far more complex to implement than the polypropylene rods used to represent the abscission zone in the solution described. Again, as engineering operates at increasingly smaller scales, it is possible that these molecular strategies can be better implemented directly.

In the lunar regolith example, the charge-based solution, although also 'active' in that energy is required, can be implemented without the need for a physical actor, e.g., an astronaut, a robot or a wiper to clear the lens of regolith while the LIDAR is being used, all of which would be more complex as well as potentially unsafe.

6.2.3. Identify other preventive solutions in biology

Many of the biological analogies discussed in Section 5 are based on preventive strategies in biology. For the remanufacture and LIDAR protection example, this is not surprising because of the nature of the problems and the keywords used for the searches. On the other hand, it is interesting that a preventive strategy, i.e., abscission in plants, was also identified and finally chosen to address the microassembly release problem.

In biology, the consequence of failure or damage may be dire. Therefore, strategies such as abscission and fainting are used before more critical damage to the organism occurs. There is likely an abundance of preventive strategies in biology that are highly relevant to engineering, particularly the development of more sustainable products and processes.

6.3. Explore the applicability of ubiquitous biological phenomena to engineering

Many of the biomimetic manufacturing examples in Section 2 were based on characteristics of organs or behaviors of specific organisms, e.g., mosquito proboscis serrations, self-sharpening rodent incisors, wood wasp reciprocal drilling, self-cleaning lotus leaf, drag-reducing sharkskin, wear-reducing ridges on scallops. However, in addition to the mosquito proboscis, serrations in piranha teeth also confer similar advantages in cutting efficiency. In addition to the well-known lotus effect, dung beetles also have surface features that enable self-cleaning. Other biomimetic manufacturing examples are based on biological phenomena that are common to many different organisms. For example, not only does biomineralization enable diatom silica shells, but biomineralization in mammals and birds forms bone, and some bacteria biomineralization involves iron and other metals to enable magnetic and gravity sensing, and iron storage. Therefore, it is not surprising that biomineralization is used for two classes of applications (forming and coating) included in this paper alone. Hoeller et al. propose that capturing recurring solutions from nature would support the design of sustainable products or services [40]. Yen and Weissburg also support that the generality and robustness of a particular biological strategy may be examined by how the strategy is implemented across many organisms [121]. An example of a ubiquitous biological phenomenon already successfully used in several fields of engineering is the optimization method of genetic algorithms. Roy et al. note that while genetic algorithms represent the most popular technique for design optimization, swarm intelligence, also biologically inspired, demonstrate potential for further application in design optimization [75].

Towards the goal of identifying other ubiquitous biological phenomena in a systematic manner, Cheong et al. are using natural-language processing to automatically identify strategies common to multiple biological units, e.g., biomolecules, organisms, etc. This work may enable some common ground between the natural-language search and database approaches to support biomimetic design. Some phenomena have already appeared as results to multiple natural-language searches for different applications, e.g., abscission and plants sacrificing leaves for remanufacture and microassembly. Such repeatedly relevant phenomena may warrant additional modeling to facilitate understanding, as well as be stored with past application examples.

6.4. Conclusion

Biologically inspired design holds much potential for engineering that is yet to be fully realized. Specifically, systematic access to biological information that is not limited to: 1. Obvious or chance analogies, 2. Well-known analogies already documented for biomimetic design, and 3. Analogies at the organ-to-organism scale, is a first step towards better exploiting biological phenomena for engineering design. This paper described how the natural-language search approach has been successful in identifying non-obvious analogies, from multiple levels of organization and scale, for a number of case studies. However, this approach also presents challenges that require further efforts.

To best support the process of biomimetic design, it is vital to objectively and systematically determine the needs of those using biomimetic design, including both novice and expert designers from a variety of fields and backgrounds. Support tools should then address these needs, rather than be based on obvious solutions that already exist or approaches that first come to mind. Biologically inspired design should not be limited to obvious biological phenomena and solutions already known to the designer, but a systematic identification and application of biological analogies. Similarly, research and tools that support the process of biomimetic design should not be limited to researchers' personal knowledge and experience, but aim to best address needs that are systematically identified from multiple perspectives of biologically inspired design.

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