Material innovation – inspired by nature

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Material innovation – inspired by nature

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Abstract

This paper is about biomimetics which also is called biomimicry or bionics. Biomimetics means “copying nature” and during time many examples of successful copying has been seen. However there are at least 2 significant difficulties in learning and copying from nature. The first difficulty is about the complexity of nature and the many fantastic solutions we find here. It is often easy to recognise the splendour of a biological solution, but it can be much more difficult to understand the underlying mechanisms. As an example of this a case about optical properties in beetle shells will be described. The second difficulty lies in finding the biological solution that mach a given problem. A methodology that copes with this difficulty by using biological search will be discussed.

Figure 1. 2 examples of biomimetic (or biology inspired) design: Plant burrs that inspired Velcro and The human leg that inspired the artificial muscles in the prosthesis. Examples and pictures are from University of Maryland [1].

Biomimetic design

Biomimetic design uses biological phenomena to inspire solutions for engineering problems. There are many examples of biomimetic design that originate from interesting biological phenomena, which were subsequently developed into engineered products. Examples include the invention of Velcro inspired by the way in which a common burr stuck to the clothes, flying machines modelled after birds, underwater machines modelled after fishes, and robotic grippers modelled after the human hand [1, 2]. Many of the examples of biomimetic designs that often are quoted in the literature are direct copies of principles found in nature. Seen from a design point of view this is similar to search for applications for a given technology. When George Mestral wondered about the burrs that stuck to his dog’s fur, nothing more would have happened if he hadn’t thought about the possible applications. Another type of fastener – the zipper – was patented in 1893 and mainly used in rubber boots and tobacco pouches but it was first in the 1930´s that the zipper became a commercial success [3, 4]. So a brilliant solution principle is not enough in it self.

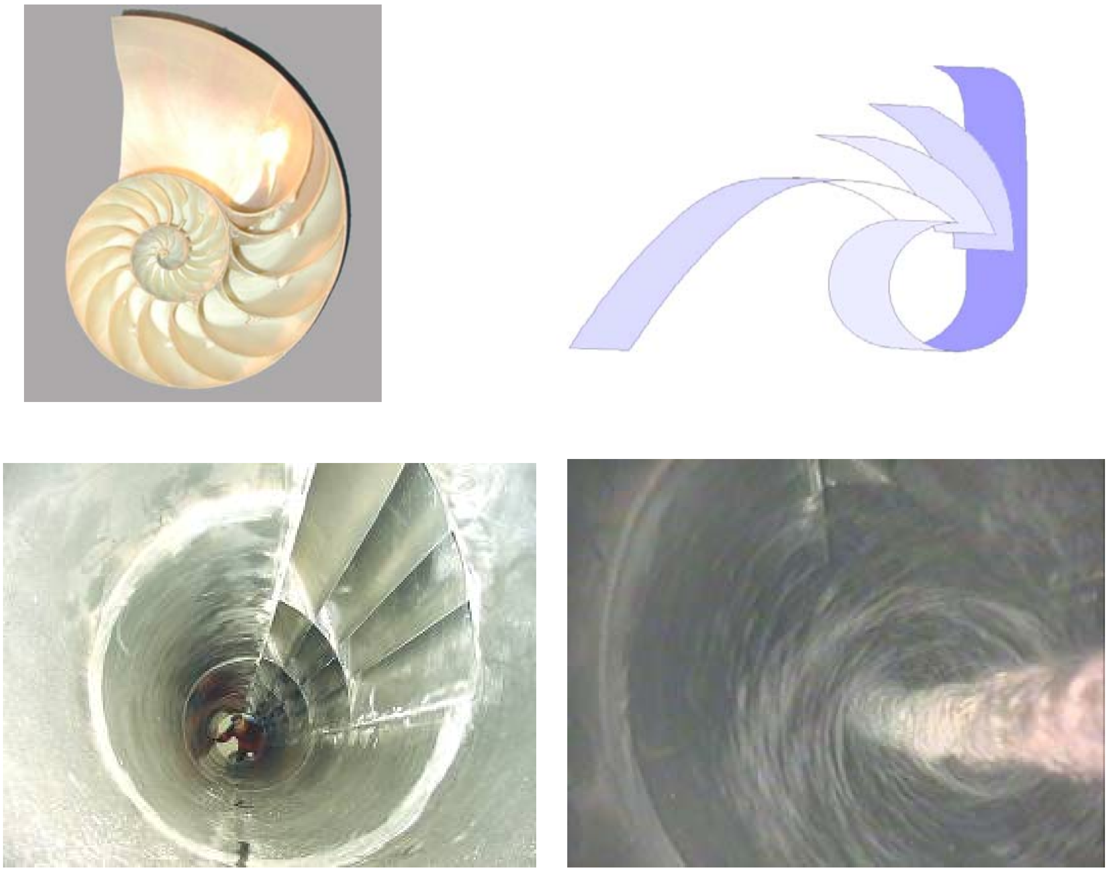

Figure 2. Biomimitics and wave energy. With inspiration from the snail a tube is made which cuts waves into slices that form a whirl that can be used to drive a turbine [8].

Another example of biomimetic designs is the self cleaning lotus flower. The basic mechanism in the leaf of the lotus flower is fairly easy to understand. The surface is highly hydrophobic and water will therefore easily glide off together with dirt particles. But the more detailed understanding of how to achieve the right hydrophobic surface required a more detailed understanding of the micro- and nanostructure in the lotus leaf.

Beetle-like optical reflectors

Another case illustrating the complexity difficulty in biomimetic design is the design of beetle-like optical reflectors. Inspired by the colourful and metallic look of beetles, 2 different basic principles for nano-structuring material surfaces were identified [5]. The first inspiration to the project was seeing metallic beetles from Central America similar to the ones shown in figure 3. The beetles looks like covered with shining metal, and many of them do not have the iridescent characteristic known from many other insects. Iridescence means that the reflected colour will change depending on the viewing angle. This was unexpected since the shining colours and metallic look found in nature is often explained with light interference. And light interference and iridescence normally goes hand in hand.

An interesting solution in nature was identified and the need it should satisfy was more environmentally friendly and aesthetically more diverse types of coatings that could replace paint and conventional metal plating.

Figure 3. Two beetles with metallic green (Sagra femorata) and gold appearance (Plusiotis resplendens).

But what was the explanation of the beetle reflectors? In order to get insight into this question a comprehensive search of biological, optical and material science literature was required. Particularly the biological literature was a challenge since a basic understanding of biochemistry and biological microscopy was required, not to mention the terminology. Another minor difficulty was that the required literature was placed on two different libraries geographically apart. DTV, the engineering technical library, has online access to many different relevant scientific journals – but not to the biology related journals. The literature search therefore resulted in many small trips to the DNLB Copenhagen University natural science library. Not a big problem – but clearly an obstacle that prevents many researchers from doing such searches.

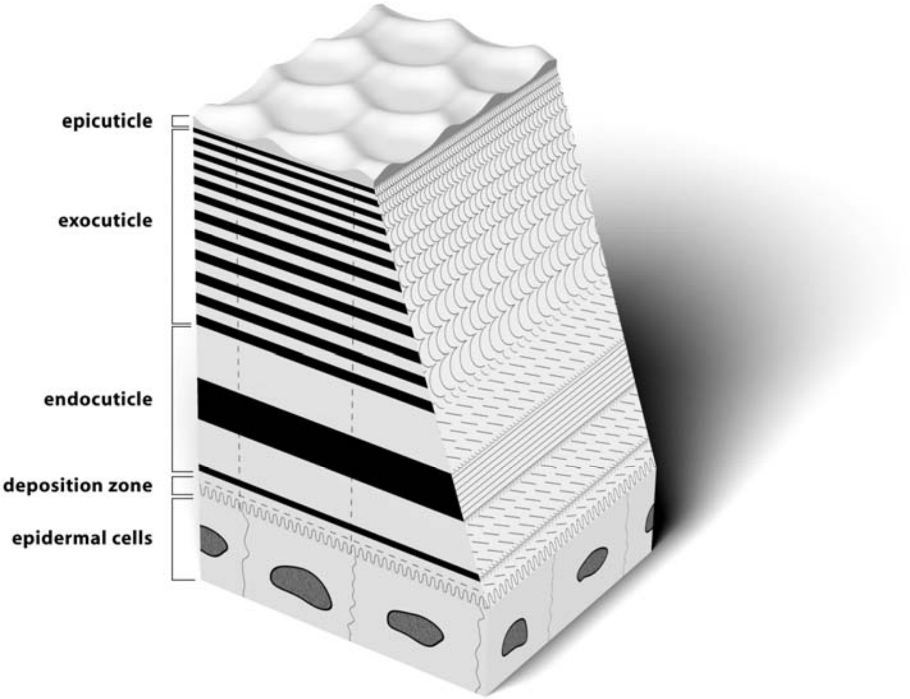

Figure 4. A cross section of the insect shell (The cuticula). The figure is based on Nevilles description of an adult Tenebrio beetle [10].

Our search was concentrated on four areas: light reflection principles, the build up process of biological reflectors, materials and composite structures.
The first part, that layers with different refraction would give structures that could reflect interference colours, became obvious through optics literature and mathematical models of multiple layer reflection. Micrographs of cross sections from beetle shells showing layers of appropriate thickness confirmed this principle. The missing iridescent effect could be explained with a clever optical design. The angle dependency becomes smaller the more layers there are in a multilayer reflector. Furthermore the reflector can be made so it also reflects the near infrared and ultraviolet light. When moving the spectrum due to different viewing angles the reflected spectrum within the visible area will look the same to the human eye.

But the next parts where far more difficult. How do you “see” structures smaller than what is possible to see with visible light?

The chemical or biochemical method to break down the structure to basic entities and then use these vast quantities of substances to synthesise products and then finally make a chemical analysis of these products gives some evidence of a structure, but only some. We found that two major substances of the beetle shell where chitin and protein and further that chitin formed rods and bundles of rods seemed to be wrapped in proteins. It did not seem feasible to go much further this way. To our purpose it was essential to look at methods where the structure was preserved.

We chose electron micrographs. However it soon became clear that when you look at an electron micrograph you do not se the “reality” but an interpretation of “reality”. In order to make the pictures it is necessary to colour the preparations with chemicals that react with the preparation. These reactions change the substrate. When the substrate eventually is bombarded with electrons, this also changes the structure and the distances between structural units. For example do some authors add 10-15% to the measured thicknesses in order to be able to calculate the expected colour reflection.

Figure 5. Electron micrograph of inner shield layers in a grasshopper illustrating the arcs from the bouligand structure. Kindly provided by Prof. Svend Olav Andersen, Copenhagen University.

One simple structure demands dozens of electron micrographs. We have a whole wall plastered with these pictures just to get two simple structures. Time and time over we look at the different pictures to convince our self that what we se actually is the same thing but from different angles. This mental process is more craving than it sounds. For decades electron pictures of organic substances from trees, bones, fish shells and insect shields showed arced patters. In the insects it was inferred that these where formed by chitin (see figure 5). In 1971, Yves Bouligand made his doctoral thesis where he clearly demonstrates, that the apparent arcs do not need to be arcs, but actually can be the united image of a lot fibril endings placed in twisted layers (see figure 6).

When long molecules form fibres in organisms in water solutions they tend to form clusters and layers. If the molecules have groups with charged atoms and these are unevenly distributed through out the fibre these layers further tend to twist. The two models we arrived at in our research, seems to be in agreement with the general shape fibres reach as a result of the natural processes of self assembly. We have confidence that we here have a biomimetic key that further can help to achieve the goals set for the beetle project.

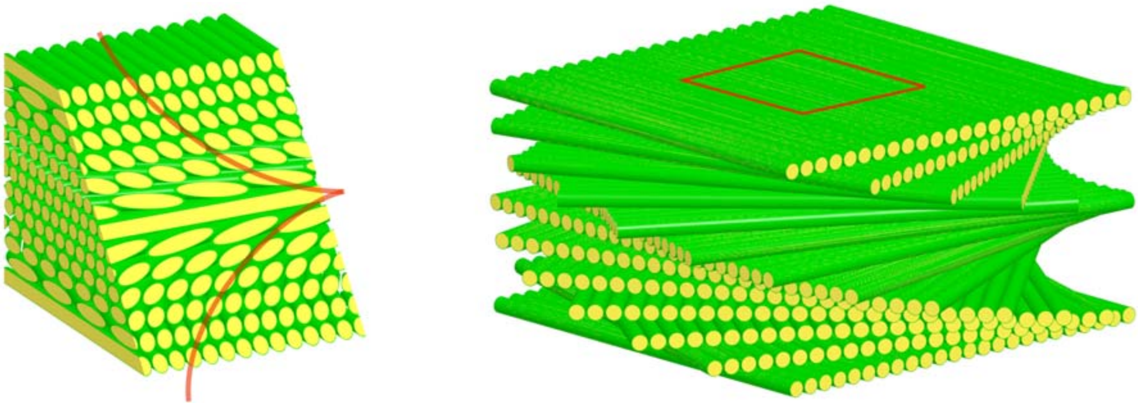

Figure 6. Model illustrating helical Bouligand structure. The left picture illustrates the arcs seen in micrographs of oblique cut sections. The red square in the picture at right shows where the cut out is made.

Biomimetic concept generation

Much of the biomimetic design seen until now is initiated by a fascination of solutions found in nature. However design work is often made the other way around: Solution principles are sought for a given engineering problem. To use biomimetic design at its full potential a methodology for identifying relevant solutions is required.

To make biomimetic design more accessible to engineers, a generalized method is required by which one can identify relevant biological analogies for a given engineering problem in an objective and repeatable manner. Such a method has been developed at the University of Toronto [6]. An example of the use of this method is the design of a microgripper inspired by the centering mechanism found in biological cells.

While a clear obstacle to find suitable biological analogies is the knowledge of biological phenomena, a less apparent obstacle is the tendency to use only the most superficial or direct analogies, e.g., modeling a robotic gripper after a hand. A way to achieve this goal is to identify biological analogies in a systematic manner by a computerized search through biological texts for instances of functional keywords.

The process of finding and using an analogy involves a number of steps. The first is the retrieval of potential analogies in the source (biological) domain. The best analogies may not be identified directly from the designer’s memory because of lack of knowledge or immediate access to only the most obvious or superficial examples. Therefore a biology text in computer-searchable format serves as the source. Text strings used in searches are functional keywords, to increase the chances of finding deep, rather than superficial analogies that contain functional similarities. Next, the search results are sifted through for relevant matches. The most common type of irrelevant matches occurs when the keyword is used in a meaning different from the target (engineering) domain. For example, the functional keyword “seal”, or to close, will locate matches with seal, the marine mammal. The remaining discernment between relevant and irrelevant matches is much more subjective, since even the most objectively irrelevant match may be used by the highly motivated to derive a solution to the target problem. After relevant matches are selected, the fundamental essence of the analogy must be extracted and applied to the target problem. This is also a subjective process, as different people reading the same text passage will have different interpretations of what the most useful principle is, as well as how best to implement that principle in the target, engineering, domain.

An example of how the method is performed is the search for centering principles for use in microgrippers. Using the search word “center” a larger number of occurrences were found in [7]. Three of these were considered to be relevant. The first phenomenon of interest was the mechanism in plant cells where light was concentrated prior to photosynthesis. Another phenomena was how retinal ganglion cells in the eye sense center versus off-center light stimuli. The third phenomenon was how the microtubule-organizing center (MTOC) centers itself in certain types of cells. For each phenomenon the basic principles were identified and analogue solutions were sketched. As an example the MTOC analogy will be described

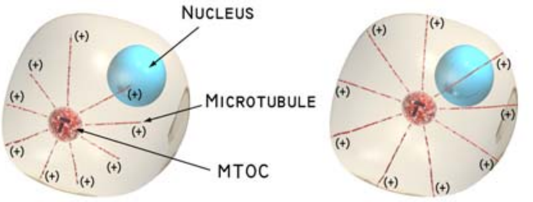

Figure 7. Centering of MTOC by extension of microtubules towards cell boundary. Modified from [7].

Microtubules are minute tubular structures, about 25 nm in diameter and up to several micrometers long. These long hollow cylinders are found in eukaryotic cells (those that contain genetic material within a nucleus) and play roles in cell motion and shape maintenance. Many microtubules radiate from a region of the cell called the microtubule-organizing center (MTOC) as shown in Figure 7. In certain types of cells, the MTOC is strikingly at the center of the cell. It is suspected that the centering mechanism involves microtubules that “scout out the cell periphery”.

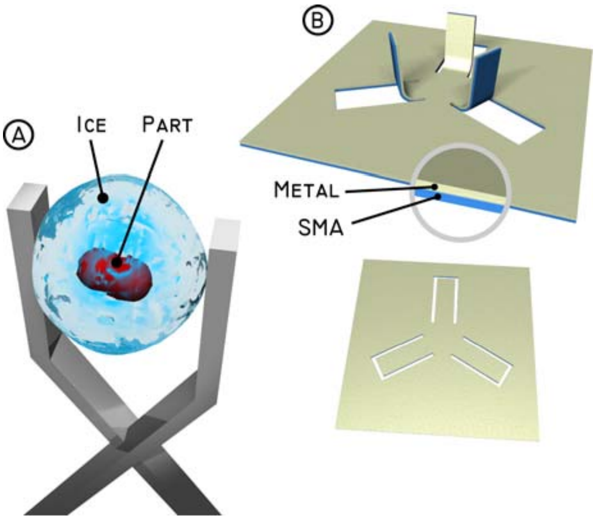

Figure 8 Possible implementations of MTOC-centering principle: a. Micro-object made bigger using CO2-ice and therefore easier to handle, b. a 3-finger microgripper using memory alloy.

A possible implementation of the MTOC-centering strategy of extending temporary spines may be accomplished using a substance like CO2-ice, shown in Figure 8a. After positioning, the temperature is increased and the ice surrounding the part sublimates.

A more abstract interpretation could be to have the spines extend from the gripper instead of the object. After positioning the gripper close to the part, the spines extending from the gripper will push the part into a known position and handling can be carried out. A possible configuration is a flat gripper with a number of flaps as shown in Figure 8b. The gripper can be fabricated with a base plate of elastic material (metal) and a plate of shape memory alloy (SMA) e.g. Ni-Ti. The SMA can be configured to seek a specific position when heated to a specific temperature. The elastic material will then return the flaps to the pre-heated position when the temperature is decreased.

Synonyms in biological search

The biological search tool just described involved searching the biological text-book: “Life the Science of Biology” [7]. The method has successfully been used in a number of cases. A similar search process was used in “The beetle project”. It became clear early in the project, that a literature search based on a few keywords came short, both within the same scientific discipline as well as within other areas. A discipline often uses its own terminology and has its own systematic ordering principles. This means that keywords relevant within one discipline might not be used within other disciplines.

In the beetle project none of the words “metallic” or “sheen” and “beetles” gave usable search results, neither within biology, chemistry, or physics. In order to make the search tools more efficient or better fitting, a new element has to be elaborated that incorporate more knowledge. The search words “Colour/color” and “cuticle” resulted in papers and books on the exoscelleton of insects and other arthropods. In here we then could find more precise terms for the continued search. New search words emerged: “chitin rods, multiple layers, Bouligand, twisted plywood, liquid crystals etc”. Some of these words are domain specific while others are understood across disciplines. E. g. liquid crystal also figures in chemistry and optical physics.

A more effective search could be made with access to a domain-specific thesaurus (synonym book). For example knowing that a beetle shell is described with words like cuticle, exoscelleton and elytra makes an effective search more straight forward.

Understanding knowledge organisation within a scientific discipline.

Within every scientific discipline, different topics are grouped and structured totally different. Insight into the knowledge organisation within a discipline makes it much easier to find “looks alike” or “functions alike”.

In the area of biology the principal knowledge organisation is based on familiarity or genealogy. All organisms are grouped after when they have formed a branch in the universal developmental tree. This approach is very efficient to find similar structures in different organisms. Often structures found in one organism also occur in other related organisms.

In the beetle project this meant, that when we first knew that the Plusiotis resplendens beetle reflected circular polarized light, we would expect similar structures to be found among close relatives. At the Zoological Museum in Copenhagen we tried to go even further in our search for beetles reflecting circular polarized light. As the Plusiotis genus belongs to the family of Scarabidae, we picked ten bright beetles among these. When we later made an optical test of these, none of them showed the desired characteristic. The unlikely happened, although about 85 % of all Scarabidae reflects circular polarized light, all ten beetles picked by chance, where of another kind. The next time we knew that picking by chance is not the most goal directed method. By bringing a filter which can block the circular light, it was easy to pick the Scarabidae who turned black when seen through the filter. It was amazing to discover how close and yet far away we were in our first attempt.

The example taken from the realms of biology, showed what the knowledge of the scientific discipline could do, this certainly also applies to other disciplines.

Conclusion

We have shown how biomimetic designs copy desired principles found in nature and implement them in artificial applications. Applications could be products we use in our daily life but it can also be used to inspire material innovation. Using the beetle project as an example we illustrated that understanding the complexity in nature is not necessarily an easy task, but involves understanding knowledge from other scientific domains including terminology and knowledge organisation. We also showed how relevant solutions in nature can be found using a biology search method. Inspired by the search process in the beetle project we propose the use of domain specific synonyms in order to make the search process more efficient.

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Links:

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http://www.rdg.ac.uk/Biomim/ Centre for Biomimetics at University of Reading
http://www.bioinspired.umd.edu/ University of Maryland
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