An attempt to reveal synergies between biology and mechanical engineering

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Abstract: Biomimetics is a continuously growing field. In this article specific examples for successful technology transfer among biology and engineering are classified along a newly proposed scheme of the field – biomimetics by analogy and biomimetics by induction – complemented by technical biology. Famous examples as well as niche applications are presented: winglets on airplanes, an optimized straw-bale screw, Velcro, and self-cleaning surfaces and paints, as well as investigations on spiders. The need of a common language for biologists and engineers, in which descriptions at different level of detail are more compatible, is stressed and general principles that can be applied by engineers who are not at all involved in biology are presented.

Keywords: biomimetics, bionics, new technologies, interface engineering biology, bioinspired technology

1 INTRODUCTION

This article aims at revealing synergies of biologists and mechanical engineers to further strengthen common approaches in the fields of biomimetics. This goal will be reached by pointing out the advantages of biomimetic work for both biology and engineering. Biomimetics is currently in a transition stage from being an exotic discipline, dealt with only by a few specialists, to an established field, appreciated by funding agencies as well as the general public. This is reflected by the ever-increasing number of publications on biomimetics (Fig. 1) [**1**]. With a special issue on biomimetics in engineering, this field is now attracting the attention it deserves in the *Journal of Mechanical Engineering Science* [**2**]. The ten articles in that special issue are a good introduction to those mechanical engineers and technologists not familiar with biomimetics, and also educate seasoned biomimeticists.

The high degree of specialization in current science and technology requires a cross-disciplinary dialogue to prevent re-invention of the wheel. Biologists as well as engineers can save a tremendous amount of work, money, and time while getting inspiration from the other field. However, there is still a cleft not only in the conceptual worlds of biologists and engineers, in many cases originating from early education, but also in attitudes and languages. In this article good reasons for starting a dialogue among biologists and engineers are given and the benefits for both groups are described in detail.

The concept of the article is as follows: The incentives for engaging with biomimetics are given along a newly proposed structure of the field. This structure is illustrated by examples of products and applications, some being widely known and used, others being used in highly specific areas.

2 MOTIVATION FOR A DIALOGUE

Biologists and engineers generally do not see many overlaps of their professions. A major basis for engineering is the understanding of the structure and

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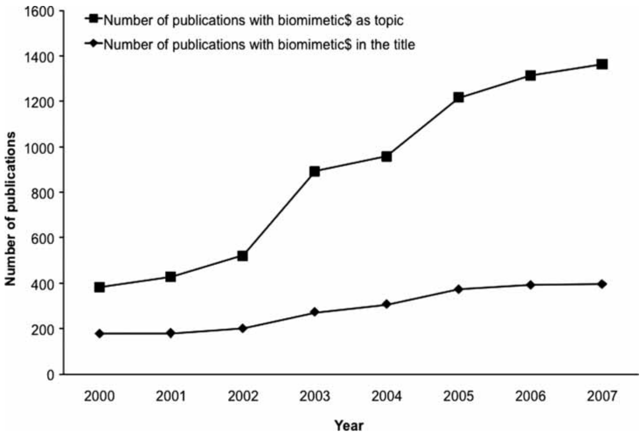

Fig. 1 Number of worldwide scientific publications containing the term biomimetic$ (i.e. biomimetic, biomimetics, biomimetical, etc.) within article topic or title. Source: ISI web of knowledge

function of materials and applying this knowledge to technological optimization (lighter, faster, and cheaper). Furthermore, tuning and controlling the properties of the components are prerequisites for sound engineering. Technological innovations, completely new ideas, and unconventional approaches are important for giant leaps in engineering. Biologists are not so much concerned with applications. They strive to gather basic knowledge to enhance the understanding of the principles of living systems.

However, both deal with constructions, processes, and developments. And here, the two professions meet: knowledge and understanding of the biologists can be applied for optimization as well as innovation in mechanical engineering, and biology with an engineering eye view has potential for broadening our understanding of the living. Fruitful cross-fertilization has already resulted in highly successful biomimetic products such as Velcro, winglets on airplanes, and self-cleaning surfaces and paints.

A good introduction to the mechanical worlds of biology and engineering is given by Vogel [**3**]. A handful of scientific journals is devoted to the field: *Applied Bionics and Biomechanics, International Journal of Design and Nature, Journal of Bionics Engineering,* and *Journal of Bioinspiration and Biomimetics*. Biomimetics can now be studied at various universities, and specific centres such as the 'Centre for Biomimetic and Natural Technologies' at the University of Bath in the UK advance the field (http://www.biomimetics.org.uk/). BIONIS, the Biomimetics Network for Industrial Sustainability, based at the University of Reading, UK, was set up in spring 2002, with the help of UK EPSRC funding to promote the application of biomimetics in products and services and its use in education and training (http://www.extra.rdg.ac.uk/eng/BIONIS/). In Germany, in 2001, the Bionics Competence Network (BIOKON, http://www.biokon.net/) was founded. It comprises 28 German major players in the field of bionics and biomimetics. The aim of BIOKON is to demonstrate the potential of biomimetics to business and industry, science, and the general public, and subsequently tap its full potential. A biomimetics/bionics cooperation network started in mid 2008 at the Vienna University of Technology in Austria. It was initiated by the authors of this article. The European Space Agency set up a project for 'development of a co-operation platform between space and biomimicry experts that will enable to bridge current gaps that exist for an effective application of natural mechanisms and phenomena in space system design and that will foster the development of a new generation of space systems' (http://www.bionics2space.org/).

2.1 Motivations for engineers: biomimetics

Biomimetics deals with the realization of processes and construction, as well as the development of principles of nature in technological applications and devices, i.e. there is a transfer (of knowledge) from biology to technology. It is worth noting that identical copies from nature to technology are not feasible in biomimetics. Instead, biomimetics encompasses a creative conversion into technology that is often based on various steps of abstractions and modifications, i.e. an independent successive construction that is rather a 'new invention' than a blueprint of nature [**4**]. The classification of the single subfields within biomimetics is not yet standardized. Based on the work of Nachtigall [**5**], the field can be subdivided as follows: construction biomimetics, process (or procedure) biomimetics, and information biomimetics.

The history of biomimetics can be traced back at least to the flying machines of L. da Vinci during renaissance times. The term biomimetics was coined by O.H. Schmitt in the mid-20th century. The word bionics was originally coined by J.E. Steele at about the same time and indicated a blend of biology and electronics. In the German speaking part of the world, the term 'Bionik' (blend of biology and technics) is used.

Based on the works of Nachtigall [**5**], Speck *et al.* [**6**], and Milwich *et al.* [**7**], a new categorization for the fields within biomimetics is proposed with the distinction between biomimetics by analogy and biomimetics by induction. In biomimetics by analogy, biological research is applied in order to find solutions to specific engineering problems. In biomimetics by induction, general principles derived from basic biological research are used for development of technical implementations. The two approaches entail different time frames and prospects.

2.1.1 *Biomimetics by analogy*

The methodology of biomimetics by analogy starts with the clear definition of the problem stemming from engineering. In the next step, analogous problems are sought in nature. This works by asking the question 'where in the living world do similar problems appear?'. The examples in nature are then analysed, and the specific findings are applied in the search of solutions to the engineering problem (Fig. 2). An example for successful biomimetics by analogy is the utilization of winglets in airplanes. Winglets minimize drag and are inspired by the wing tips of certain birds.

The advantages of this method are quick and effective solutions to the engineering problems. This directed method inherently provides a manageable number of examples from nature.

2.1.2 *Biomimetics by induction*

The basis for biomimetics by induction is fundamental biological research. Initially there is no aim towards specific applications. This method is inherently undirected. Abstracted from the biological realm and translated into non-specific language, the principle behind a phenomenon is unveiled and specified. Subsequently, possible technological applications are sought and developed in cooperation with engineers and designers (Fig. 2). A highly successful example of biomimetics by induction is the lotus effect [**8**], which is currently used in paintings, coatings, textiles, roof tiles, etc. and largely contributes to the positive public image of biomimetics.

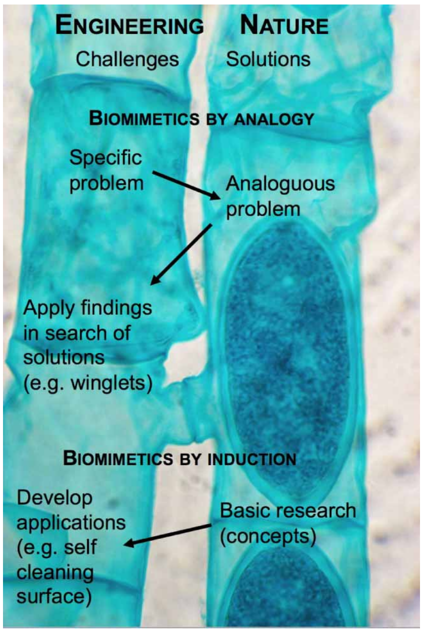

Fig. 2 Motivations for engineers to deal with biology: biomimetics by analogy and biomimetics by induction are two distinct research methodologies with different advantages. In both the cases information transfer is necessary. Background image: conjugation in *Spirogyra*, a genus of filamentous green algae. Two originally independent cells form a connection for 'fruitful exchange'. Image reproduced with permission ©David Polcyn, California State University, San Bernardino

2.2 Motivations for biologists: technical biology

Technical biology deals among other issues with the investigation of the correlation of form, structure, and function in living organisms using methods from physics and engineering, i.e. there is a transfer (of methods) from technology to biology. The term technical biology was popularized by Nachtigall to complement biomimetics.

The advantage of this method is that it can contribute to an understanding of basic principles. Additionally, in finding out how biological systems function, the technical biology approach can also yield biomimetic applications, which would then correspond to biomimetics by induction. An example for technical biology is the work by Barth [**9**] on spider mechanosensors, which is partly inspired by strain gauges.

3 EXAMPLES

3.1 Biomimetics by analogy: winglets on airplanes

The specific problem of large turbulences induced by the wingtips of airplanes prompted engineers to look for solutions to the analogous problem in biology. The wingtips of birds with their large variety in morphology are a promising biological example to look at. Especially, the wings of big gliders such as storks were found to be interesting by airplane constructors. The feathers at the wingtips of these birds are arranged in a way that the lift-induced drag caused by wingtip vortices is minimized by dividing the large vortex into several smaller vortices. Winglets are currently utilized on many commercial airplanes. By abstraction of the principle behind the winglets, the technological application improved even further in spiroids (split wing loops). Spiroids are winglets that loop back onto the wing to attempt to eliminate tip-induced vortices [**10**]. They considerably cut fuel consumption.

Bird wings are also investigated with regard to other technologically interesting features such as the variable geometry of their shape as they adapt to the velocity of flight and lift enhancement by self-actuating flaps. Biomimetic self-actuating flaps on a motor glider Stemme S10 cause improved flight performance as well as a reduction of the stall speed [**11**].

3.2 Biomimetics by analogy: bioinspired straw bale screw

Trees feature load-adaptive growth and maintain a uniform stress distribution at their surface. They grow in a way that the surface stresses, which arise from gravity and external sources (e.g. wind and snow), are kept constant. Therefore, the branching of trees has a characteristic shape. Changes such as cutting of large branches of the tree or tilt of the tree caused by hang-sliding induce morphological alterations by further growth according to the principle of minimizing surface stress peaks and result in regaining uniform surface stresses. Mattheck [**12**] has investigated shape optimization and fracture behaviour in trees for many years and introduced – based on his findings – a method to optimize workpieces.

A biomimetically optimized screw for mounting façades and other items to straw-bale buildings was developed by applying this method [**13**]. In this screw, the amount of material used is minimized and the toughness is increased in certain relevant cases of load by more than a third in comparison to a non-optimized geometry (Fig. 3). As opposed to conventional design principles (such as using simple arcs of a circle in transitions), this method allows for close to constant stress on the surface of the workpiece. The design principle based on the growth of trees was also applied to optimize an orthopaedic screw. The biomimetically optimized screw endured at least 20 times more stress cycles than a conventional orthopaedic screw, without showing cracks at the end of the test [**12**]. This drastically reduces the risk of an implant to rupture.

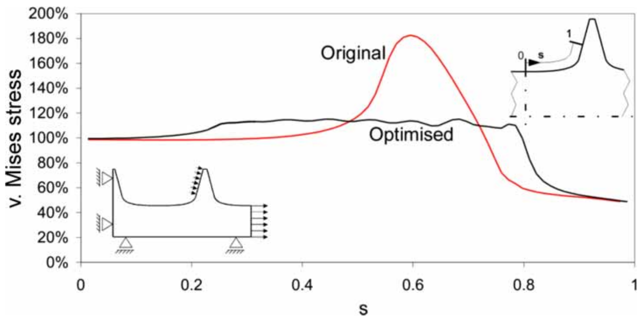

Fig. 3 Biomimetically optimized straw bale screw: The diagram shows the von Mises stress before and after optimization of the radius in the thread. The stress is reduced by more than one-third compared to a conventional radius for the case of load shown in the inset. Diagram and inset reproduced from reference [**13**] with permission ©Springer 2006

3.3 Biomimetics by induction: Velcro

Various plants utilize animals and people to disperse their fruits by transporting them in clothes, feathers, or furs. The Swiss engineer G. de Mestral investigated the fruits of a burdock using an optical microscope and discovered why they clung on so ardently: the fruits were covered by hundreds of tiny flexible but strong hooks and were thus able to reversibly attach themselves to textile and hairy structures. (see www.velcro.com).

Mestral realized the potential of this discovery and developed it into an idea that, with much time and effort, would become a revolutionary application: a hook and loop fastening system whose simplicity and strength superseded all previous systems. The patent was filed in 1951 (Swiss patent no. 295638). The brand name Velcro was created from the first syllables of the French words *vel*ours (loop) and *cro*chet (hook).

Mestral proposed several different reversible attachment systems in his patent application (Fig. 4). The attachment system as presented at the very bottom of Fig. 4 closely resembles a type of dragonfly head-arresting system, as reported by Gorb [**14**] in 1999. This design is currently being tested for use in low-wear reversible attachment devices.

3.4 Biomimetics by induction: self-cleaning surfaces and paints

The lotus plant has always been popular for its clean leaves. It is sacred for Buddhists because in their belief, impurities and sorrows roll off its leaves and thereby yield annihilation of suffering. Also, other plants such as cauliflower, cabbage, tulips, and bananas show self-cleaning effects.

Basic biological research showed that the key for understanding this phenomenon lies in the microstructure of the leaf surface: it is not smooth, but covered with microstructured wax [**8**]. This structure increases the contact angle of water droplets on the surface and causes them to roll off easily, taking surface debris with them. The microstructured wax is also the reason for the small contact area of debris with the surface, facilitating self-cleaning properties (Fig. 5). This principle has been used to develop technical surfaces with similar properties.

In 1997, W. Barthlott filed the US patent called 'Self-cleaning surfaces of objects and process for producing same' (US patent no. 6660363) and initiated worldwide activities on the production of self-cleaning surfaces and paints, leading to the development of a plenitude of applications. According to W. Cyrol from the Sto company, self-cleaning *Lotusan* paint for 40 million squaremetres was sold by the end of 2006.

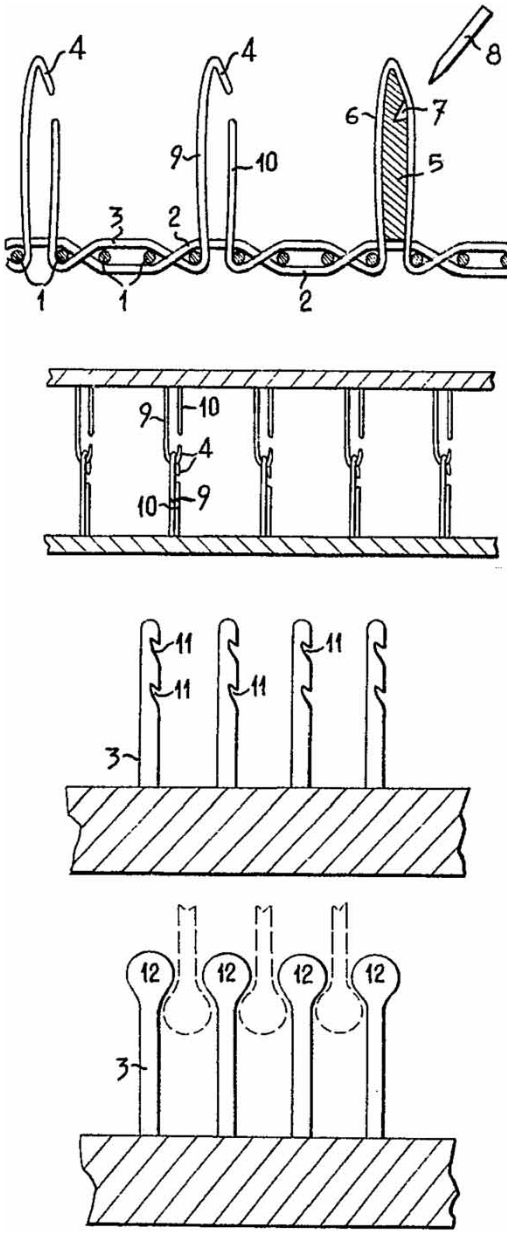

Fig. 4 Drawings from the 1951 patent application for a 'Velvet type fabric and method of producing same' showing different possibilities for reversible attachment systems. Source: http://v3.espacenet.com/origdoc?DB=EPODOC&IDX=CH295638&F=0&QPN=CH295638

3.5 Technical biology: investigations on spiders

Organisms have developed highly sensitive sensors such as single photon detectors [**15**] and mechanoreceptors with sub-nanometre sensitivity [**16**]. Such exquisite sensing asks for an explanation of the technical function. A good example for the cooperation between engineers and biologists is Barth and co-workers, who have been investigating the spider mechanoreceptive systems for several decades (for review, see reference [**9**]). They use methods that are generally applied in technology to understand biological systems.

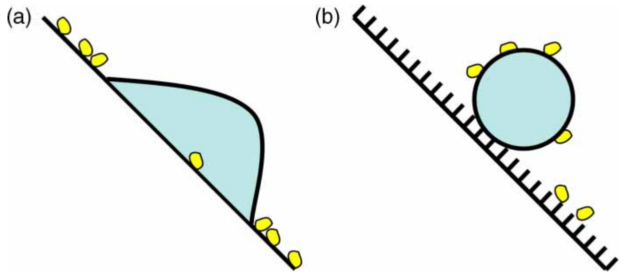

Fig. 5 Schematic diagram: (a) on a conventional flat surface, the liquid droplet slides over the dirt and only redistributes the particles; (b) on a self-cleaning surface, the dirt particles have only small contact area with the surface, and the large contact angle of the liquid droplet causes the droplet to roll over the surface, with the dirt particles adhering to the droplet

Spiders have a rigid outer chitin skeleton with embedded sensors. They perceive the world largely via mechanoreception of different kinds. Their highly developed sensory systems are the result of about 400 million years of evolution.

Slit sensilla organs on the legs act as biological strain gauges. Elongations of the tiny slits in the skeleton by some tens of nanometres induce nerve signals. This enables the detection of longitudinal vibrations that reach the spider legs by way of the radial threads of the net. The differences in the amplitude of arriving vibrations across the legs are used to determine the direction of the signal source.

Trichobothria are 'hairs' that measure medium flow. They respond to the slightest movement of the surrounding air, e.g. produced by a passing prey. At the threshold, the work driving a single hair over one oscillation cycle is 2.5×10^{-20} J [**9**].

Tactile hairs represent the majority of spider hairs. They are touch receptors. Tactile hairs are non-linear sensors in which the bending moment increases more slowly with increasing load than with small loads and reaches saturation at about 4×10^{-9} Nm. Thereby, the hair is protected against breaking, its measurement range is extended when compared with a rigid hair, and the measurement is more sensitive for small signals than for large ones.

Spiders extend their legs not with muscles and bones but with a micro-hydraulic system. A biomimetic application inspired by technical biology work of Blickhan and Barth [**17**] on pressure in the exoskeleton of spiders should lead to devices actuated by a pressurized fluidic system for space robots and clothing [**18**].

4 CONCLUSION AND OUTLOOK

Most of the biomimetic applications available today focus on constructions. Natural biotribological systems such as diatoms or biogenic switchable, dry and self-healing adhesives are examples in construction biomimetics and have inspired novel micro and nanotechnological devices (for review, see reference [**19**]). Also micro and nanostrucutured bioinspired surfaces exemplify constructions; they currently find widespread applications. Technological surfaces that reduce drag (inspired by shark skin) and structured surfaces based on the amazing construction that allows the Gecko to stick to walls are already on the way to mass production [**20**]. Processes such as photosynthesis and signal transduction in organisms bear enormous potential and are already under investigation for new process engineering solutions. A process that is also related to surface properties can be found in soil life: in earthworms, the process of forming a millimeter-thin liquid layer in the vicinity of a surface and the electro-osmotical flow contribute to adhesion reduction [**21**]. Rechenberg [**22**] in the 1960s and 1970s pioneered the use of evolutionary strategies for engineering. For a comprehensive introduction, see reference [**23**]. Evolutionary strategies are a part of information biomimetics that deal with principles of development, evolution, and data transfer. Established computational approaches such as neural networks and genetic algorithms can also be considered as a part of information biomimetics.

The examples presented above are the results of specific collaborations between biologists and engineers. Effective collaboration, as in the examples given, requires interdisciplinarity. However, with the huge knowledge in different fields, nowadays it is impossible for a single person to know and understand more than just a fraction. Nevertheless, the awareness and understanding of different approaches and concepts is a paramount prerequisite of interdisciplinary work. A common language of biologists and engineers, in which descriptions at different level of detail are more compatible, is desirable. Educating a number of persons in both engineering and biology is a promising first step towards reaching this goal.

Besides specific examples of the development of successful biomimetic devices and applications, general principles that can be applied by engineers who are not at all involved in biology have been distilled [**5**]. These basic principles comprise integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of mono-functionality, energy efficiency and development via trial-and-error processes. Systematic technology transfer from biology to engineering thereby becomes generally accessible.

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