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TRIBOLOGY IN BIOLOGY: BIOMIMETIC STUDIES ACROSS DIMENSIONS AND ACROSS FIELDS

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ABSTRACT

Biomimetics is a field that has the potential to drive major technical advances. It might substantially support successful mastering of current tribological challenges, i.e., friction, adhesion and wear in machines and devices from the meter to the nanometer scale. Science currently goes through a major change, with biology gaining increasing importance. Indeed, biology is becoming the new Leitwissenschaft. Tribology is omnipresent in biology. Various examples for biological tribosystems across dimensions are introduced to the reader, exemplifying the hierarchical nature of biomaterials, and concepts such as integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of mono-functionality and development via trial-and-error processes. The current state of biomimetics in tribology is reviewed, and possible biomimetic scenarios to overcome current tribological challenges are suggested (switchable adhesives, micromechanic devices, novel lubricants and adhesives).

Keywords: biotribology, biomimetics, learning from nature, multidisciplinarity

1. INTRODUCTION

Biomimetics is a growing field that has the potential to drive major technical advances (see Figure 1). It might substantially support successful mastering of current tribological challenges, i.e., friction, adhesion and wear in machines and devices from the meter to the nanometer scale. In biomimetics, materials, processes and systems in nature are analysed, the underlying principles are extracted and subsequently applied to science and technology (Bhushan, 2009; Bar-Cohen, 2005; Gebeshuber and Drack, 2008). This approach can result in innovative new technological constructions, processes and developments. Biomimetics can aid tribologists to manage the specific requirements in systems or product design, especially to create products and processes that are sustainable and perform well (e.g. to overcome stiction), to integrate new functions, to reduce production costs, to save energy, to cut material costs, to redefine and eliminate "waste", to heighten existing product categories, to define new product categories and industries, to drive revenue and to build unique brands (Gebeshuber, Pauschitz and Franek, 2006; Gebeshuber, Stachelberger, Ganji, Fu, Junas and Majlis, 2009; Gebeshuber, Stachelberger and Drack, 2005; Gebeshuber, Majlis, Neutsch, Aumayr and Gabor, 2009). Recurrent principles in biological materials and systems are hierarchy and multi-functionality (Fratzl and Weinkammer, 2007; Vincent, 2005).

Science currently goes through a large change: in biology more and more causation and natural laws are being uncovered (Gebeshuber, Gruber and Drack, in press). Biology has changed from being very descriptive to a science that can be acknowledged and understood (in terms of concepts) by tribologists. The amount of causal laws in this new biology (indicated by the ratio of causal versus correlational knowledge, or the ratio of explanatory versus descriptive knowledge) is steadily growing and a new field that can be called "biological engineering" is emerging. The languages of the various fields of science increasingly get compatible (see Figure 2), and the amount of collaborations and joint research projects between tribologists and biologists have increased tremendously over the last years.

Tribology is omnipresent in biology (Gebeshuber, Drack and Scherge, 2008). Examples for biological tribosystems across dimensions are the crack redirection in the horse hoof (Kasapi and Gosline, 1997; Kasapi and Gosline, 1999), biological tribosystems on the micrometer scale (Gebeshuber, Pauschitz and Franek, 2006; Gebeshuber, Stachelberger and Drack, 2005; Crawford and Gebeshuber, 2006; Gebeshuber and Crawford, 2006; Gebeshuber, Stacheleberger and Drack, 2005; Gebeshuber, Kindt, Thompson, Del Amo, Stachelberger, Brzezinski, Stucky, Morse and Hansma, 2003; Gebeshuber, Thompson, Del Amo, Stachelberger and Kindt, 2002), plant wax structures preventing herbivores to adhere to plants (Gorb and Gorb, 2002; Gorb, Haas, Heinrich, Enders, Barbakadze and Gorb, 2005; Koch, Dommisse, Barthlott and Gorb, 2007) and single switchable adhesive molecules that enable the rolling adhesion of red blood cells on the endothelium (Popel and Pittman, 2000; Patrick, Sampath and McIntire, 2000, Orsello, Lauffenburger and Hammer, 2001).

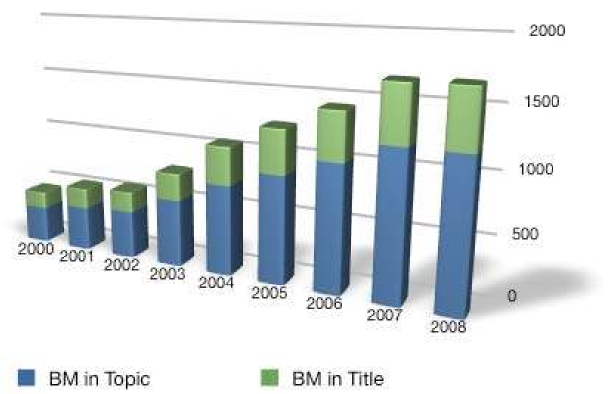

Figure 1 The number of scientific publications with "biomim*" as topic or in the title. Source: ISI Web of Knowledge, Thomson Reuters. http://www.webofknowledge.com

Recurrent concepts in all these examples are integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of mono-functionality and development via trial-and-error processes. Such concepts can easily be transferred to technology, and can be applied by engineers with no knowledge of biology at all (Gebeshuber and Drack, 2008; Gebeshuber, Majlis, Neutsch, Aumayr and Gabor, 2009; Gebeshuber, Gruber and Drack, in press). Biotribological systems can inspire novel tribological approaches (Gebeshuber, 2007). First devices based on bioinspired materials are a technique for cell separation inspired by adhesion of white blood cells (Li, 2005; Sakhalkar, Dalal, Salem, Ansari, Fu, Kiani, Kurjiaka, Hanes, Shakesheff and Goetz, 2003), devices inspired by the hierarchical dry adhesive in the Gecko's foot (Northen and Turner, 2005; Shah and Sitti, 2004), such as wall-climbing robots; and artificial hierarchical as well as novel adhesives (Hansma, Turner and Ruoff, 2007).

In this paper, for the first time, the Biomimicry Innovation Method is applied to current tribological challenges comprising MEMS, micropump and lab-on-a-chip research and development, as well adhesives and lubricants and functional materials with crack redirection properties.

2. METHODOLOGY

2.1. Biomimicry Innovation Method

The Biomimicry Innovation Method is applied to identify biological systems, processes and materials that can inspire novel technological approaches concerning tribological issues. Biomimicry is an innovation method that seeks sustainable solutions by emulating nature's time-tested patterns and strategies. The goal is to create products, processes, and policies - new ways of living - that are well adapted to life on earth over the long haul.
The Biomimicry Innovation Method (© Biomimicry Guild, Helena, MT, USA 2008, http://www.biomimicryguild.com/) involves specifically trained biologists as well as engineers, natural scientists, architects and/or designers from universities or companies. The Biomimicry Innovation Method is for example used in the rainforest (high species variety, high innovation potential) to learn from and emulate natural models).
The steps in the Biomimicry Innovation Method are as follows:

- Identify Function,
- Biologize the Question,
- Find Nature's Best Practices and
- Generate Product Ideas.

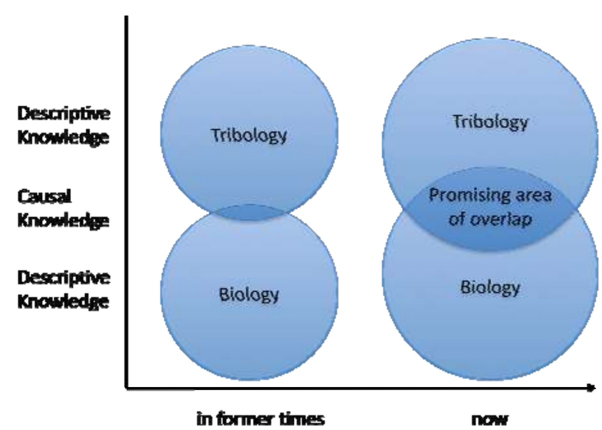

Figure 2 The increasing amount of causal laws in biology generates promising areas of overlap with mechanical engineering

Identify Function: The biologists distil challenges posed by engineers/natural scientists/architects and/or designers to their functional essence.
Biologize the Question: In the next step, these functions are translated into biological questions such as "How does nature manage lubrication?" or "How does nature bond parts together?" The basic question is "What would nature do here?"
Find Nature's Best Practices: Scientific databases as well as rainforest and marine habitats are used to obtain a

compendium of how plants, animals and ecosystems solve the specific challenge.

Generate Process/Product Ideas: From these best practices (90% of which are usually new to clients), the scientists and engineers generate ideas for cost-effective, innovative, life-friendly and sustainable products and processes.

2.2. Tribological Challenges Investigated

Tribology is a huge field, so only selected current tribological challenges can be dealt with in this paper. Areas that are treated here comprise the need for optimally designed rigid micromechanical parts (for 3D-MEMS), pumps for small amounts of liquid (for lab-on-a-chip applications), novel dry and wet adhesives and lubricants (for various applications) and functional material with crack redirection properties (for mechanical protection of viable parts in machinery).

3. RESULTS

3.1. Optimally Designed Rigid Micromechanical Parts

Identified Functions:
1. Hinges and interlocking devices
2. Click-stop mechanism
3. Springs
4. Parts connected in a chain with adjustable length
5. Movable rigid parts
6. Unfoldable structures
7. Energy dissipation
8. Pressure resistant containers
9. Stability (reinforcement)
10. Fixation

Relating Biologized Questions:
1. How does nature mechanically connect hard single cells?
2. How does nature unfold structures and then irreversibly fix them?
3. How does nature reversibly store mechanical energy?
4. How does nature provide stability to chains in turbulent environments?
5. How does nature optimize moveable parts?
6. How does nature generate 3D-structures of rigid parts?
7. How does nature dissipate mechanical energy?
8. How does nature deal with high pressures?
9. How does nature provide mechanical stability?
10. How does nature mechanically fix structures?

Nature's Best Practices:

1. Diatom chains with mechanical connections between the single cells. Diatoms are unicellular microalgae with a cell wall consisting of a siliceous skeleton enveloped by a thin organic case (Round, Crawford and Mann, 1990). The cell walls of each diatom form a pillbox-like shell consisting of two parts that fit within each other. These microorganisms vary greatly in shape, ranging from box-shaped to cylindrical; they can be symmetrical as well as asymmetrical and exhibit an amazing diversity of nanostructured frameworks. These biogenic hydrated silica structures have elaborate shapes, interlocking devices, and, in some cases, hinged structures. The silica shells of the diatoms experience various forces from the environment and also from the cell itself when it grows and divides, and the form of these micromechanical parts has been evolutionarily optimized during the last 150 million years or more (see Figure 3).

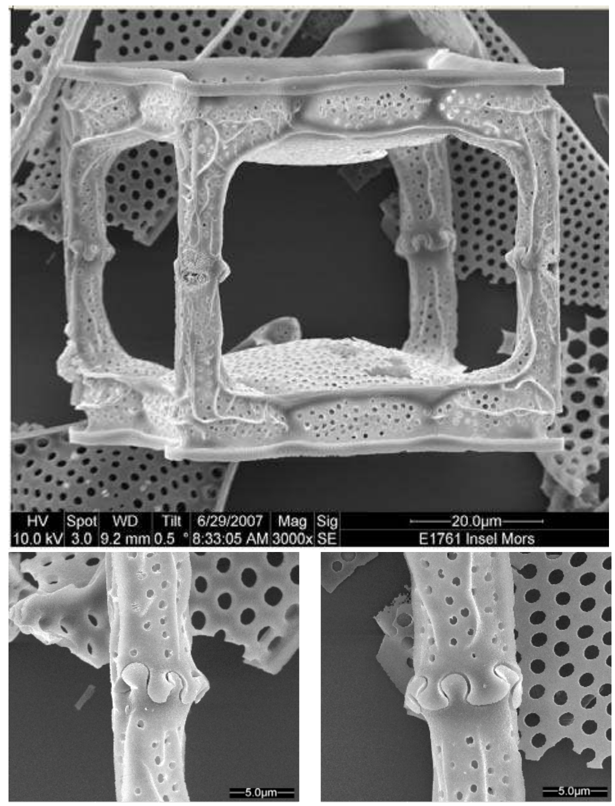

Figure 3 Biological example for optimally designed rigid micromechanical parts. The sample is from the Hustedt Collection in Bremerhaven, Germany, # E1761. © F. Hinz and R. M. Crawford, reproduced with permission.

2. The diatom species *Corethron pennatum* and *Corethron criophilum* are excellent examples for unfolding structures (Crawford and Hinz, 1995; Crawford, Hinz and Honeywill, 1998; Gebeshuber and Crawford, 2006).

3. The diatom species *Rutilaria grevilleana* and *Rutilaria philipinnarum* have structures that might be interpreted as springs (Gebeshuber, Stachelberger, Ganji, Fu, Junas and Majlis, 2009; Srajer, Majlis and Gebeshuber, 2009). However, more detailed investigation is needed to confirm this.

4. *Ellerbeckia arenaria* is a diatom that lives in waterfalls. *E. arenaria* cells form string like colonies which can be several millimeters long and can reversibly be elongated by

one third of their original length (Gebeshuber, Stachelberger and Drack, 2005).
5. The diatoms *Melosira sp.* (Gebeshuber and Crawford, 2006), *Solium exsculptum* (Figure 3) and *Ellerbeckia arenaria* (Gebeshuber and Crawford, 2006) are interesting best practices for optimization of moveable parts in nature. The diatom species *Solium exsculptum* lived 45 million years ago. Scanning Electron Microscopy images of this Eocene fossil from a deposit at Mors, Denmark reveal that the connections between sibling cells are still in good condition (Figure 3).
6. *Corethron pennatum* and *Corethron criophilum*. The process of new cell formation in these species is highly complex, and involves elaborate mechanisms (Crawford and Hinz, 1995; Crawford, Hinz and Honeywill, 1998).
7. The diatoms *Solium exsculptum* (Gebeshuber, 2007; Gebeshuber, Aumayr, Hekele, Sommer, Goesselsberger, Gruenberger, Gruber, Borowan, Rosic and Aumayr, in press) and the diatoms *Melosira sp.* (Gebeshuber, Stachelberger, Ganji, Fu, Junas and Majlis, 2009; Gebeshuber and Crawford, 2006) and *Ellerbeckia arenaria* (Schmid and Crawford, 2001).
8. The green alga *Euglena gracilis* is a single-celled algal species that performs tasks as diverse as sensing the environment and reacting to it, converting and storing energy and metabolizing nutrients, living as a plant or an animal, depending on the environmental constraints.
The striated pellicle covering the whole cell is a distinct exoskeletal feature of the *Euglena* species. The pellicle is a proteinaceous structure that provides mechanical stability to the cell, yet it is flexible. Its single strips are connected via interlocking ridges that can slide against each other and are lubricated via biogenic lubricants excreted from pellicle pores.
Internal pressures up to several bar cannot break the exquisite pellicle arrangement in these algae (see Gruenberger, Ritter, Aumayr, Stachelberger and Gebeshuber, 2007 and references therein).
9. Reinforcement ribs on the diatom *Solium exsculptum* (Figure 3): Between the main ribs the silica structure is extremely thin and interspersed with pores. In these fragile plate-like structures, secondary stiffening by small, undirected ribs can be observed. These reinforcement structures prevent the buckling that flat shells are prone to. The flange structure around the rim, which obviously belongs to the primary structure, is also interesting – perhaps it helps in the attachment of the valves or serves as an attachment structure for the cell membrane (Gebeshuber, Aumayr, Hekele, Sommer, Goesselsberger, Gruenberger, Gruber, Borowan, Rosic and Aumayr, in press)
10. The mechanical click-stop mechanism in *Corethron* is an excellent best practice showing how nature deals with the task to mechanically fix structures (Crawford and Hinz, 1995; Crawford, Hinz and Honeywill, 1998; Gebeshuber and Crawford, 2006).
Generated Product Ideas: Generated product ideas comprise micromechanical optimization of 3D-MEMS structure, methods to obtain 3D structures from fabricated 2D structures, novel methods for energy storage in MEMS, development of (3D) MEMS with moveable parts, methods to obtain 3D structures from fabricated 2D structures, quality assurance of MEMS and novel methods to preventing stiction.

3.2. Pumps for small amounts of liquid

Identified Function: Pumps for small amount of liquids as they are needed in lab-on-a-chip devices and in microchemical reactors.
Biologized Question: How does nature move fluids?
Nature's Best Practices: *Rutilaria philipinnarum* is a fossil colonial diatom thought to have lived in inshore marine waters (Crawford, pers. comm. 2008). In this species, the single diatoms connect by linking spines and by a complex siliceous structure termed the periplekton. These linking structures on the one hand keep the cells together, but on the other hand also keep distance between the cells. The shape of the spines allows expansion of the chain to a certain maximum distance and compression to a minimum distance, in which case there is still some fluid between the cells. The links allow movement of single cells in the chain against or from each other in a rather one-dimensional way (Gebeshuber and Crawford, 2006).
Such elaborated linking mechanisms, inspired the question what would happen to such a diatom colony when subjected to water flow. Computer simulations published by Srajer, Majlis and Gebeshuber in 2009 suggest that a diatom colony subjected to water flow exhibits some kind of oscillatory movement. This movement might facilitate nutrient uptake of a diatom colony. The inspiring organisms for the computer simulation study are *Rutilaria grevilleana* and *Rutilaria philipinnarum* (Srajer, Majlis and Gebeshuber, 2009). Oscillatory movement increases the advective diffusion through the surface of the diatoms and therefore increases nutrient supply in a homogeneous nutrient solution (Pahlow, Riebesell and Wolf-Gladrow, 1997).
Generated Product Ideas: Generated product ideas comprise the development of micro- and nanopumps for lab-on-a-chip applications and emerging technologies.

3.3. Novel Dry and Wet Adhesives and Lubricants

Identified Functions: Various types of adhesion (wet, dry, reversible, switchable, selective, underwater) and lubrication (wet, dry).
Biologized Questions: How does nature prevent wear? How dies nature reversibly adhere to structures?
Nature's Best Practices: Articular cartilage, the bioactive surface on synovial joints (like the hip, the knee, the elbow, the fingers, the shoulder or the ankle) has a very small friction coefficient. Some groups report friction coefficients for normal synovial joints as low as 0.001 (Linn, 1967; McCutchen, 1959; Unsworth, Dowson and Wright, 1975). Identifying the mechanisms responsible for the low friction

in synovial joints has been an area of ongoing research for decades. Furey lists more than 30 theories that have been proposed to explain the mechanisms of joint lubrication (Furey, 2000). In summary, articular cartilage provides an efficient load-bearing surface for synovial joints that is capable of functioning for the lifetime of an individual.

Generated Product Ideas: Generated product ideas comprise improved hip, shoulder and knee implants, as well as improved lubrication strategies in various further cases where moveable hard parts have to be interconnected.

3.4. Functional Material with Crack Redirecting Properties

Identified Functions: Fracture control, crack redirection

Biologized Question: How does nature tailor-shape wear particles and thereby protect viable parts?

Nature's Best Practices: The horse hoof is a system that can tailor the shape of its wear particles. Hoof is an excellent example for a tough natural material that increases the energy required for tearing by diverting cracks away from their preferred directions of propagation. Macroscopic wear particles from horse hoofs are more often than not of rectangular shape. A horse's hoof is difficult to split vertically. In the hoof, the keratin is arranged in an ordered three-dimensional array such that a crack initiated by a vertical cut will turn and split the material at right angles to the vertical direction (Kasapi and Goslin, 1997; Kasapi and Goslin, 1999).

Generated Product Ideas: Studies of the mechanisms of synthesis of hoof material in the horse can be expected to provide hints for the industrial fabrication of such complex three-dimensional fibrous materials.

4. CONCLUSION

Current mechanical systems, synthetic adhesives and lubricants are not perfect, and the low friction coefficients in many natural systems are yet to be achieved in artificial systems. Technological innovations, completely new ideas, and unconventional approaches can all be learned from nature. These approaches have been tested and improved upon for millions of years; they are continuously being optimized with respect to their function and environment.

Tribology always has to do with applications and devices. For accelerated scientific and technological breakthroughs Gebeshuber and co-workers proposed in 2009 in a paper that deals with the future of biomimetics the "Three-gaps-theory" (Fig. 4; Gebeshuber, Gruber and Drack, in press): the inventor gap, the innovator gap and the investor gap have to be bridged. Since development always takes a path from the primitive over the complex to the simple, effective or efficient solutions can be envisaged, depending on the time frame provided and the acceleration wanted.

In nature, there is equilibrium between generalists and specialists; there are sources and drains, with natural flow between them. The whole system grows via evolution; there is no static natural system. In humans the necessities are shifted. To advance our system, more visions and a platform for "evangelists" are needed. Interdisciplinary working groups with generalists as heads, coordinating the specialists, are needed.

At the moment, we do not have such structures. Our scientific system fails because of a lack of competition, the "pull" is missing, we "push", but industry does not want. Industry does not "pull", because it needs products and no solutions. Economy needs a vision. Steve Jobs from Apple with the vision of making technology simple is a rare example for successful "pull". Generally, current economy loses itself in details. Industry lacks visions, science cannot promote its knowledge, and there is no platform.

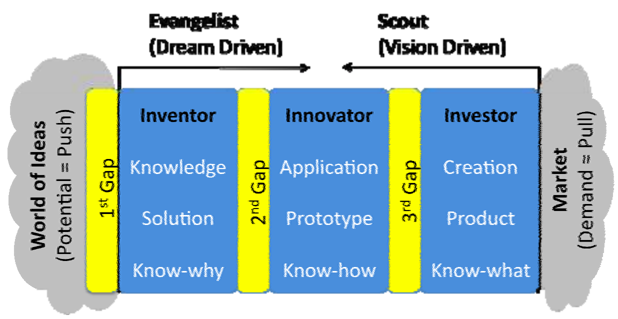

Figure 4 The Three-Gaps-Theory as proposed by Gebeshuber, Gruber and Drack, in press. Image © Professional Engineering Publishing, UK. Image reproduced with permission.

To prevent being trapped in the inventor, innovator or investor gap, a cross dialogue is necessary, a pipeline from "know-why" to "know-how" to "know-what", from the inventor who suggests a scientific or technological breakthrough to the innovator who builds the prototype to the investor who mass produces the product and brings the product to the consumer. Currently, and this is the main problem, at universities worldwide huge amounts of knowledge are piled up with little or no further usage. We know a lot, we can do relatively little. We need a joint language and a joint vision.

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