Bioinspiration for Tribological Systems on the Micro- and Nanoscale: Dynamic, Mechanic, Surface and Structure Related Functions

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Abstract: Tribology deals with parts in relative motion, and related friction, adhesion, lubrication and wear phenomena. With our devices getting smaller and smaller, our understanding of tribology on the small scale has to increase. Micro- and nanotribology denotes tribology performed with micro- and nanotechnological instruments. This field is still in a developmental stage, and establishing the relation and interdependence between tribological knowledge and understanding on the macro-, micro- and nanoscales is a hot topic of research. Because of scaling and other issues, we cannot directly translate long-established tribological facts to small-scale technologies. However, we can immediately benefit from input concerning established 'best practice' systems in nature: organisms. Biological micro- and nanosystems show interesting tribological features, and furthermore can teach us novel aspects and possible approaches concerning our emerging technology that would not readily come to mind - here lies their enormous innovation potential. This manuscript introduces a new way to analyse best practice biological materials, structures and processes that were established *via* the biomimicry innovation method, by relating them to four main areas relevant for MEMS and related microsystems development: dynamic, mechanical, surface and structure related functions. Four representative examples for each of these four areas are presented, along with generated process and product ideas, in the concept stage or already on the market. Furthermore, this manuscript introduces reasons for a balanced mixture of problem-oriented and solution-oriented biomimetics innovation methods regarding tribology in technical micro- and nanotribological devices that ensures maximum benefit regarding revenue, innovation and sustainability.

Keywords: Bioinspiration, biomimicry innovation method, MEMS tribology, 3D MEMS, learning from nature, diatoms.

INTRODUCTION

Tribology is a system science. Dealing with friction, adhesion, lubrication and wear requires extensive knowledge and understanding of the respective tribosystem. This also holds for micro- and nanotribology [1] and for micro- and nanoelectromechanical systems (MEMS, NEMS). Major questions relating to current microsystems are how to cope with adhesion (because of the high surface to volume ratio compared to macroscopic systems), how to get rid of excess heat (because of low convection) and how to improve the functionality of emerging 3D MEMS (stiction, adhesion, material issues, quality issues). In the case of MEMS/NEMS, except for the digital micro-mirror device (that was already introduced by Texas Instruments in 1987), there is currently no other commercially available actuator-based MEMS/ NEMS device. The development of 3D MEMS is stuck, not moving as fast as it was envisaged some years ago, though ideas of using microorganisms to grow 3D components are being discussed [2,3]. More often than not, tribological issues prevent successful commercialization of 3D MEMS and are the reason why most of them are still in prototype stage. Impressive scanning electron microscopy images show complete micromotors, with gears smaller than a mite [4]. However, there are major issues with such devices concerning their reliability and quality [5]. We also need to address surface functionalization, surface texturing, and quality assurance. We cannot repair MEMS at the moment; we need to build them as functional, long lasting units. 3D MEMS would also present problems of access inside.

As can be seen from the examples given above we are in need of innovation regarding MEMS. We need new ideas, new approaches, new paradigms, new designs, perhaps unconventional, if we want to succeed in the miniaturisation of our electromechanical devices. Normally, in technology and innovation, inspiration comes from the technology of others. In the case of MEMS this is not possible, since we are still in an initial phase. However, if we look at nature, we find various interesting, functional micro- and nanosystems.

The view of engineers towards biology, towards biological materials, structures, processes and whole organisms has changed in the past decades [6]. Before the boom of nanotechnology, before we had instruments so strong that we can watch the micro- and nanocosmos with unprecedented resolution, biology used to be wet, unordered, scary, demanding and unintelligible with the long, complicated Latin names depicting organisms and the highly descriptive approach of most biologists. This has changed. The biologists have changed, and the way they approach their science is getting closer and closer to the world of engineers, in terms of concepts, language and methods [see e.g., 7-9]. So, joint

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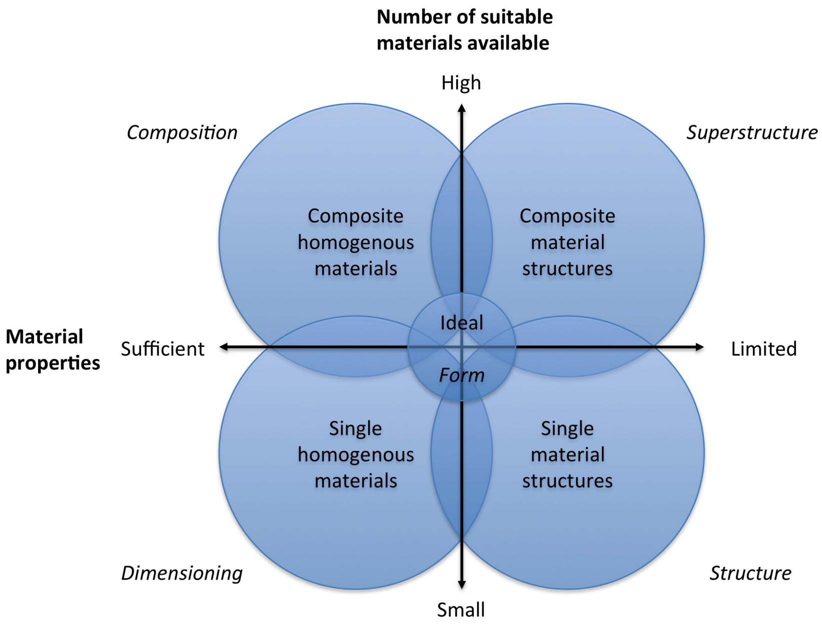

Fig. (1). In nature as well as in technology, the number of suitable materials available and the material properties determine the complexity of the approach. With our current MEMS technology we are still mainly in the region of limited material properties and small number of suitable available materials, resulting in single material structures determining the properties of the devices (bottom right corner of the figure).

approaches increasingly become possible, with benefit for both groups, the biologists and the engineers. In micro- and nanosystems, and with the boom of nanotechnology, the situation is changing even more – at the smallest scale, there is no difference anymore between the fields. The nanotechnologist is dealing with biology, chemistry, materials science, tribology, physics and engineering at the same time.

In line with this change of attitude, the field of biomimetics (and there are many more names for this and similar concepts: biomimicry, bioinspiration, learning from nature) has emerged and is getting more and more attention [10]. In biomimetics, not other technologies but nature, living nature, serves as inspiration. Two successful and widely known examples for biomimetics are the development of Velcro [11] and the self-cleaning surfaces inspired by the lotus leaf. Biomimetics is very positively viewed by the general public, and seems to be one of the few new or emerging technology fields that encounters little scepticism.

Learning from nature for design and optimization in engineering can happen in two different ways: the first is termed ‘biomimetics by analogy’ [6] and starts with the engineering problem. With a problem in mind, engineers and biologists, biomimetics specialists, address nature for analogous ‘solutions’ and ‘strategies’. Otto H. Schmitt, the inventor of the Schmitt trigger and the person who coined the term ‘biomimetics’ back in the 1980s, called this type of approach ‘problem-oriented biomimetics’ [12]. On the other hand, some of the most innovative inventions came from yet another approach: biomimetics by induction [6]. In this type of solution-oriented biomimetics, initially, basic research is performed, without any application, innovation or patent in mind. And just then, in a second step, research results leave the ‘ivory tower’ and are discussed related to application or innovation. Both approaches are important and useful, and care should be taken to keep them in balance. Concentrating solely on biomimetics by analogy (problem-oriented) might lead us to solving pseudo-problems (i.e., optimization along the wrong axis), and biomimetics by analogy (solution-oriented) is expensive and time-consuming, even though it often yields highly successful results. Wilhelm Barthlott, the botanist who contributed so much to the popularity of biomimetics *via* the lotus effect [13] (this paper is cited more than 1000 times in Google scholar), told one of the authors (ICG) at the founding meeting of the International Society for Bionic Engineering in China in 2010 that he went for more than 10 years from company to company, showing them lotus leaves, telling them about their self-cleaning properties and proposing technological R&D along these lines –to no avail; until finally he succeeded. Today he is well off, earning royalties from his lotus related patents.

There are various ways for an engineer to do biomimetics. You can sit in your room, read the literature, make the connections. You can watch nature movies, with your engineering problem in mind, and make the connections. You can talk to specialists from other fields and make your connections. The biological archival literature (journals, proceedings, books, book chapters) contains a huge body of knowledge related to biotribological systems on the micro- and nanoscale [14]. It is just hidden for the regular engineer, in terms of wording, concepts and language. A multidisciplinary team doing biomimetics can, however, mine such data, and utilize the information for innovation. But most fruitful of all is direct exposure. Leave your room, go to a place with high species diversity, take some specialists from biology with you who also understand, speak and appreciate the language of engineering, and wander about in the rainforest, go snorkelling, go diving. And in the afternoon, access databases and the Internet, and read up on the new things you learned about. This is, in a nutshell, the 3D tourism approach, with 3D standing for discover, determine and design [15].

The Relation of Structure and Function in Microsystems

The strong relationship between structure and function in organisms is one of the key reasons for the success of biomimetics. A SCOPUS search for TITLE-ABS-KEY(biomimetics) performed on July 17, 2011, shows that since the 1980s, 8938 papers with ‘biomimetics’ in the title or topic have been published, with the numbers of papers increasing every year. The less the number of different materials that are used (in technology as well as in biology), the more relevant becomes structure [8,16]. And since for MEMS just a limited number of materials are used, the relation of structure and function is of specific interest: if different functionalities cannot be accommodated by different materials, they have to be accommodated by different structures. Intriguing and beautiful examples of the concept of 'structure rather than material' are structural colours: by varying the size of minuscule structures of the order of the wavelength of visible light, colour can be tailored [17]. Examples of objects with structural colours include soap bubbles, iridescent insect wings and coatings in technical microsystems. And if the structures change their size triggered by certain signals, the results are reactive colours, responsive colours, smart colours [18].

The Biomimicry Inspiration Method

One successful methodology in biomimetics is the biomimicry inspiration method that was introduced by the US American Biomimicry Guild in 2008. This biomimetics-by-analogy method (solution-based biomimetics) starts by identifying the function the engineer want to have inspiration on. In the next step, this function is translated into wording accessible for a biologist. The more general this wording is kept, the more inspiring organisms, materials, structures and processes can be found (in the terminology of the biomimicry innovation method, they are called ‘best practises’). And finally, from the best practises in nature, possible technological processes or products are envisaged, and R&D along these lines can proceed. The biomimicry innovation method has been applied by various companies, such as Boeing, the City of Seattle, Ecotrust, General Mills, Georgia Tech, Hewlett-Packard, HOK Architects, Nike, Proctor & Gamble, Shell and Seventh Generation [19].

Especially today, learning from nature in all aspects can be beneficial. The negative influence of humans on the environment and on fellow humans cannot be ignored anymore. We need to turn towards sustainability, if we want to sustain. Nature shows us how complex ecosystems can be built with minimum effort and resources, but we have to admit that concerning our technologies we are still far from achieving sustainability. Note that biomimetics as a design method does not automatically yield sustainable solutions, and the question if values such as sustainability should enter biomimetics design concepts is an ongoing discussion.

BIOMIMECTICS BY ANALOGY REGARDING MEMS

Identifying the Functions and Asking the Relating Biologized Questions

Current issues regarding MEMS lie in four general areas: dynamic, mechanic, surface and structure. In each of these four areas, various functions that need to be optimized can be identified. A complete and clear list of related functions is the solid basis for comprehensive quality improvement for the technology of choice. Here we will introduce the method and the basics, and highlight some representative functions, biologized questions, best practises and generated product/process ideas (Table **1**).

The determination of the related biologized questions regarding each function is a creative process of paramount importance – it is similar to brainstorming – the more diversity is embraced, the more colourful and possibly inspiring are the answers, the best practises. The quality and usability of the best practices identified depend on the way the question is posed. Sometimes, it is interesting to find out how something is not done in organisms [20], to look at the opposite of what you want to deal with, to increase the band width of the results.

The best practises can be found in various ways, e.g. by accessing respective databases. For example, the Ask Nature database (http://www.asknature.org, last accessed July 17, 2011) by the Biomimicry Guild is freely accessible. Users can browse the strategies, can ask questions of the format “How would nature …”, can read about already commercialized bioinspired devices or processes, add their own strategies and much more.

Best Practices

Many of the best practices in Table **1** are diatoms (Fig. **2**). Diatoms are single celled algae that biomineralize silica parts of amazing variety, forms, structures and functions. There are tens of thousands of different diatom species. In a way one can view diatoms as algae living in nanostructured glasshouses [18] that they make themselves. Diatoms range in size from a few micrometers to a couple of millimeters, and some species build chain-like colonies. In the colonies the single cells are mechanically attached to each other by various mechanisms, from adhesives [21] to hinges [22] and nanozippers [23], curiously often permitting movement between cells without detachment [21]. There are several properties of the diatoms that make them interesting regarding MEMS and micro- and nanotribology [8,16,22,24-26]. For example they build their exoskeletons at the moment of cell division, and do not change the basic frustule after this. Repair does not take place on the hard silica parts. They use silica as material, and therefore accommodate various functions *via* structure alone. They are nanostructured, and their optical properties are interesting for nanotechnologists [18,27].

In the biomimicry innovation method, the biological best practices are viewed as solutions to engineering problems. Such a view of living nature is very single minded, and is used here just in the frame of the innovation method. We do

Table 1. Examples for Bioinspiration in MEMS Tribology and Related Fields

Area	**Function**	**Biologized Question:** How Does Nature ...	**Nature's Best Practice**	**Generated Process/Product Ideas**
Dynamic	Movable rigid parts	... optimize moveable parts?	The diatoms *Melosira* sp. and *Ellerbeckia arenaria*	3D MEMS with moveable parts
	Pumps	... move small amounts of fluids?	The diatoms *Rutilaria grevilleana* and *Rutilaria philipinnarum*	Micropumps for lab-on-a-chip applications
	Energy dissipation in microsystems	... dissipate mechanical energy in microorganisms?	The diatom *Solium exsculptum*	3D-MEMS
	Lubrication	... prevent wear?	Unknown diatom species	Preventing stiction
Mechanic	Hinges and interlocking devices	... mechanically connect hard single cells on the microscale?	Diatoms in chains (*Eunotia sudetica, Bacillaria paxillifer, Ellerbeckia* sp.)	Micromechanical optimization of 3D-MEMS structure
	Click-stop mechanism	... unfold microstructures and then irreversibly fix them?	The diatom *Corethron pennatum*	Obtain 3D structures from fabricated 2D structures
	Springs	... reversibly store mechanical energy?	*Rutilaria grevilleana* and *R. philipinnarum;* the spasmoneme of *Vorticella convallaria*	Energy storage in MEMS
	Parts connected in a chain with adjustable length	... provide stability to chains in turbulent environments?	The diatom *Ellerbeckia arenaria*	MEMS with moveable parts
Surface	Surface texturing	... structure surfaces?	The diatom *Solium exsculptum*	MEMS
	Photoprotective coating	... protect photo- sensitive plants?	The flowering plants *Begonia* sp., *Diplazium* sp., *Phyllagathis rotundifolia*	Coatings of containers for photosensitive reactions
	Photonic components	... make structural colours?	Peacock feathers, butterfly scales, iridescent plants, fruits, birds and mammals	Photonic micro- and nanodevices, MEMS, novel lasers
	Selective, switchable adhesion	... reversibly adhere to structures?	Immune system, gecko foot, insect attachment pads, plant wax surfaces	Lab-on-a-chip devices, reusable: trap, test and release and start again
Structure	Unfoldable microstructures	... generate 3D microstructures from rigid parts?	The diatom *Corethron pennatum*	Obtain 3D structures from fabricated 2D structures
	Stability (reinforcement)	... mechanically protect viable parts?	The diatom *Solium exsculptum*	Quality assurance of MEMS
	Mechanical fixation	... mechanically fix structures on the microscale?	The diatom *Corethron pennatum*	3D-MEMS, lab-on-a-chip
	Pressure resistant containers	... deal with high pressures?	*Euglena gracilis* pellicle, bacteria	Lab-on-a-chip

not understand life itself, its reason or its goal. Some people might attribute such questions rather to religion, some people might argue that such questions cannot be answered because our intellect is too limited, and we simply cannot grasp it all. Nevertheless, life itself shows us that is can sustain itself for billions of years. It shows us what is possible. Biomimetic design should also consider the sustainability of its solutions.

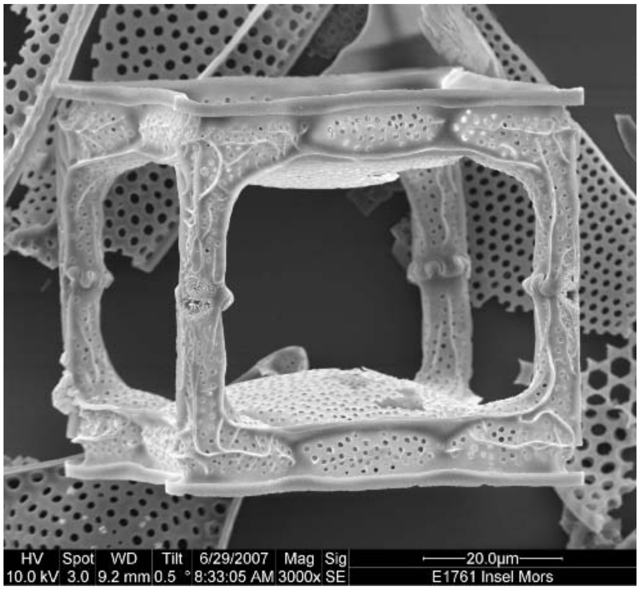

Fig. (2). *Solium exsculptum* is a diatom that lived 45 million years ago on the island of Mors in Denmark. This diatom is an example for nature's best practices concerning surface texturing and structure related functions (stability, reinforcement). Scale bar 20 µm. © F. Hinz, Alfred Wegener Institute Bremerhaven, Germany. Image reproduced with permission.

Transferring just the deep principles without having the whole system in mind, without considering the environment, without feeling responsible for future generations, might in the case of biomimetic design be even more dangerous than in 'normal technology inspired' human design approaches. Nature's solutions are seasoned, and powerful. And transferring just fractions might result in technological products and processes that are even more unsustainable than our previous ones.

The best practices and generated process and product ideas presented in Table **1** are aimed at stimulating engineers whose work is related to these functions in micro- and nanosystems. Behind each of the organisms given in the Table is a huge body of scientific literature and various experts, many of whom have devoted their whole life to studying one single genus or species. Detailed literature searches for archival scientific work and specialists in these fields can provide the starting points for further collaborative approaches. It is suggested that the engineers get in contact with the respective biologists working on the organism of interest, perhaps with the additional support of a person who is experienced in biomimetics and in speaking with representatives of both fields.

CONCLUSIONS AND OUTLOOK

Bioinspiration is a highly promising method in the design of emerging MEMS/NEMS with enhanced tribological properties. For maximum benefit, biomimetics by analogy and biomimetics by induction approaches should be balanced. Strong collaboration between biologists and engineers can yield new, sustainable approaches to emerging micro- and nanotechnologies and provide the basis for a new type of scientist/researcher/developer, who understands and feels at home in various fields, and who can transfer concepts and principles across fields. Such people are highly needed as counterpoles in our current time of increasing specialisation.

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