Biological and Medical Physics, Biomedical Engineering

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Biomimetics – Materials, Structures and Processes

Examples, Ideas and Case Studies

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With 122 Figures

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Biological and Medical Physics, Biomedical Engineering ISSN 1618-7210
ISBN 978-3-642-11933-0 e-ISBN 978-3-642-11934-7
DOI 10.1007/978-3-642-11934-7
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2011929499

Cover design: eStudio Calamar Steinen

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.spinger.com)

Preface

It is said very often that humankind should learn from nature. This means that some sort of technology transfer from biology to engineering has to be established. Nowadays, terms such as bionics, biomimetics, or bio-inspiration have been introduced to describe the concepts by which ideas of technology are derived from nature. One of the most important insights so far is that it is not feasible to try to copy nature. As many examples have shown, it makes sense to start with a careful analysis and abstraction of biological processes and structures. The implementation process itself requires substantial adaptation using common engineering knowledge to guarantee successful solutions. It is not surprising that in the field of biomimetics/bionics, principles of evolution or strategies of evolution have gained much attention. The primary goal often lies in surpassing "Nature" and thus achieving outstanding results. All these aspects are to a considerable extent taken into account and covered by the various topics of the contributions in this book. The main aim of this book is therefore to provide the reader with essential information on how biomimetic/bionic working principles are identified and also brought to technical implementation in various engineering disciplines.

Vienna
June 2011

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Part III Information and Dynamics

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Chapter 1
Biomimetics: Its Technological and Societal Potential

Herbert Stachelberger, Petra Gruber, and Ille C. Gebeshuber

Abstract This introductory chapter contains a short discussion of the topic of biomimetics with special emphasis on background and goals together with an overview of the book. Biomimetics is described as information transfer from biology to the engineering sciences. Methods and preconditions for this interdisciplinary scientific subject are mentioned briefly focusing on the educational issues and the pathway to product development. To provide the reader with a preliminary information, an overview of the book is given devoted to a brief description of the remaining chapters which are allocated to three main sections "Material & Structure", "Form & Construction", and "Information & Dynamics".

The process of evolution on earth during the last approximately 3.4 billion years resulted in a vast variety of living structures. Most recent findings suggest that multicellular organisms could have been around for 2.1 billion years [1, 2]. At any time, organisms were able to adapt dynamically to various environmental conditions. It is therefore the principal goal of biomimetics to provide an in-depth understanding of the solutions and strategies having evolved over time and their possible implementation into technological practice. Very often biomimetics must reach down to the microscopic and ultimately to the molecular scale. Some of nature's best tricks are conceptually simple and easy to rationalize in physical or engineering terms, but realizing them requires machinery of exquisite delicacy [3].

The routes of technology transfer from biology to the engineering sciences are normally not too clearly drawn. There is no doubt about the outstanding innovative

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P. Gruber et al. (eds.) *Biomimetics – Materials, Structures and Processes*, Biological and Medical Physics, Biomedical Engineering, DOI 10.1007/978-3-642-11934-7_1,

potential of the biomimetic approach. Yet there is no guarantee that a technical solution based on biomimetics will be ecofriendly. This has to be proven separately in any case.

There is a tremendous scope of research topics in the field of biomimetics (bionics) that – according to Rick [4] – could be roughly assigned to either construction bionics (e.g. materials, prosthetics, and robotics), procedural bionics (e.g. climate/energy, building, sensors, and kinematics/dynamics), or information bionics (e.g. neurobionics, evolution bionics, process bionics, and organization bionics).

Biomimetics is therefore an innovation method being applied in a multitude of technological fields. The realization of biomimetic innovation can be done either from the technological point of view (problem-oriented) or from the biology point of view (solution-oriented). These basically different approaches are therefore called top-down (biomimetics by analogy) or bottom-up (biomimetics by induction) approaches. They can also be distinguished by their differing time of development and other requirements.

To some extent biomimetics as an interdisciplinary scientific subject is thought to contribute to sustainable innovation [5]. Complex systems and patterns arise out of a multiplicity of relatively simple interactions in a hierarchically structured world. This phenomenon is called *emergence*. According to systems theory, it is necessary to go well beyond the frontiers of classical disciplines, thought patterns, and organizational structures in order to accomplish sustainable innovation.

Comprehensive knowledge as an asset is one of the most important preconditions for innovation within knowledgeable societies (Lane 1966 cited by Jursic [6]). Applied curiosity about everything's working principles requires a profound preoccupation with the technical foundations. Biomimetics is thought to facilitate the approach to technological developments and to foster scientific basics.

Advanced training in the fields of interdisciplinary research and development is a challenge that has to be met using novel concepts of teaching and training. Training is therefore a key to the expansion of biomimetics. It should be included in the training syllabus of engineers and designers to make them aware of the potential of the approach. The biological sciences should be made aware of the commercial applications of their knowledge. In order to introduce innovation principles into societal practice, there is need for ingenious and well-educated people and a proactive environment. For the education of highly qualified scientists and engineers, open access to scientific fields and domains is indispensable. Interdisciplinary activities in research units such as universities need to be initiated and supported internally (executive level) and externally (research grants). Close cooperation is necessary between R&D units and industry and economy in order to promote inventions. The formation of biomimetics networks currently taking place in Europe can be seen as the core event in the formation of a dynamic developmental area [7, 8].

The main aim of this book is to provide the reader with a collection of chapters that review the actual R&D activities at Vienna University of Technology with respect to topics in biomimetics. The three main sections "Material & Structure", "Form & Construction", and "Information & Dynamics" cover a wide range of topics.

"Material & Structure" contains five chapters. Matovic and Jakšić start this section with a chapter on "Bionic (Nano)Membranes" [9]. The authors offer a concise and clear picture of the most important artificial nanomembrane-related procedures and technologies, including those for fabrication and functionalization, and present the main properties and potential applications, emphasizing recent results in the field contributed by the authors. Bionic nanomembranes have a potential to improve environmental protection, to bring breakthroughs in life science, to enable the production of clean energy, and to contribute in numerous other ways to an enrichment of the overall quality of life.

Tribology, the science of friction, adhesion, lubrication, and wear, is the focus of the next two chapters. Tribology is omnipresent in biology, and various biological systems have impressive tribological properties. In "Biomimetics in Tribology" [10], Gebeshuber, Majlis, and Stachelberger investigate a large hitherto unexplored body of knowledge in biology publications that deals with lubrication and wear, but that has not before been linked extensively to technology. Best practices presented comprise materials and structures in organisms as diverse as kelp, banana leafs, rattan, diatoms, and giraffes.

In "Reptilian Skin as a Biomimetic Analogue for Design of Deterministic Tribo Surfaces" [11], Abdel-Aal and El Mansori investigate the multiscale structural features of reptilian skin. Shed skin of a Ball Python is chosen as the bioanalogue. Snakes have surface features that contribute to excellent wear resistance and tunable frictional response in demanding environments. The results are translated to enhance the textural design of cylinder liners in internal combustion engines.

Hellmich, Fritsch, and Dormieux subsequently investigate multiscale homogenization theory, an analysis tool for revealing mechanical design principles in bone and bone replacement materials [12]. Multiscale poromechanics recently became a key tool to understand "building plans" inherent to entire material classes. In bone materials, the elementary component "collagen" induces, right at the nanolevel, the elastic anisotropy, while water layers between stiff and strong hydroxyapatite crystals govern the inelastic behavior of the nanocomposite, unless the "collagen reinforcement" breaks. Mimicking this design principle may hold great potential for novel biomedical materials and for other engineering problems requiring strong and light materials.

In the final chapter in the section on materials and structure, Stampfl, Pettermann, and Liska report on "Bio-inspired cellular structures: Additive manufacturing and mechanical properties" [13]. Many biological materials (wood, bone, etc.) are based on cellular architecture. This design approach allows nature to fabricate materials that are light, but still stiff and strong. Using finite element modeling in combination with additive manufacturing, it is now possible to study the mechanical properties of such cellular structures from a theoretical and experimental point of view. Stampfl, Pettermann, and Liska give an overview of currently available additive manufacturing technologies, with a focus on lithography-based systems.

Additionally, numerical methods for the prediction of mechanical properties of cellular solids with defined architecture are presented.

The section on “Form & Construction” contains three chapters. Gruber introduces the emerging field “Biomimetics in Architecture” [14] and presents various case studies that exemplify the innovational potential of structures, materials, and processes in biology for architecture and emphasize the importance of the creation of visions with the strength to establish innovation for the improvement of the quality of our built environment.

Kuhlmann deals in her chapter “Biomorphism in Architecture – Speculations on Growth and Form” [15] with the essence of nature, nature as source for form and ecology, touches upon cyborgs and the concept of organic unity, and reaches the conclusion that despite many authors’ claims of producing something radically new, many of the design strategies applied by the current architectural avant-garde can be traced back to one of the oldest and most influential ideas in architectural history: the concept of organicism in its various guises.

In the final chapter of this section, “Fractal Geometry of Architecture – Fractal Dimension as a Connection Between Fractal Geometry and Architecture” [16], Lorenz introduces fractal concepts in nature and architecture, and defines them from mathematical and architectural points of view. The fractal concept of architecture means that details of different sizes are kept together by a central rule or idea: avoiding monotony by using variation. The author concludes that this concept is the reason why Gothic cathedrals and examples of the so-called organic architecture are so interesting and diversified.

The three chapters in the section “Information & Dynamics” deal with sensors and actuators, electrostimulation of muscles, and improved strategies for auditory coding in cochlear implants. Automation, dealing with the utilization of control systems and information technology to reduce the required human intervention, mostly in industrial processing systems, but more in all kinds of daily human activities for instance driving a car in the near future, faces the problem of increasing complexity through the incorporation of dramatically increasing amounts of details in sensory systems.

In “Biomimetics in Intelligent Sensor and Actuator Automation Systems” [17], Bruckner, Dietrich, Zucker, and Müller present an approach to use biomimetics as the promising method for overcoming this problem. They argue for careful application of the biomimetics approach in various respects in order to develop a technically feasible model of the human psyche and hence redeeming one of the big promises of artificial intelligence from the early days on.

The next chapter is “Technical Rebuilding of Movement Function Using Functional Electrostimulation” by Gföhler [18]. To rebuild lost movement functions, neuroprostheses based on functional electrical stimulation (FES) artificially activate skeletal muscles in corresponding sequences, using both residual body functions and artificial signals for control. Besides the functional gain, FES training also brings physiological and psychological benefits for spinal-cord-injured subjects. Current stimulation technology and the main components of FES-based neuroprostheses including enhanced control systems are presented. Technology and application of

FES cycling and rowing, both approaches that enable spinal-cord-injured subjects to participate in mainstream activities and improve their health and fitness by exercising like able-bodied subjects, are discussed in detail and an overview of neuroprostheses that aim at restoring movement functions for daily life as walking or grasping is given.

In the final chapter of this book, "Improving Hearing Performance Utilizing Natural Auditory Coding Strategies", Rattay deals with cochlear implants, the most successfully applied neural prostheses [19]. Cochlear implants have still deficits in comparison with normal hearing. The author argues that in contrast to nature, spiking patterns generated artificially in the auditory nerve via actual implants are based on the frequency information alone, whereas the natural method makes use of two additional principles. One of these principles, based on stochastic resonance, is especially spectacular as it uses noisy elements of the sensory system in order to amplify weak auditory input signals. The design of the next generation of cochlear implants should therefore include noisy elements in a concept similar to that shown by nature.

Not surprisingly, the Section "Material & Structure" by comparison is more extensive than "Form & Construction" and "Information & Dynamics". This reflects a big focus on material science and related fields. But nevertheless one can find true international reputation and competence also in the other areas cited here.

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Part I
Material Structure

Chapter 2
Bionic (Nano) Membranes

Jovan Matovic and Zoran Jakšić

Abstract The goal of this chapter is to offer a concise and clear picture of the most important artificial nanomembrane-related procedures and technologies, including those for fabrication and functionalization, and to present the main properties and potential applications, stressing recent results in the field contributed by the authors. Nanomembranes are probably the most ubiquitous building block in biology and at the same time one of the most primordial ones. Every living cell, from bacteria to the cells in human bodies, has nanomembranes acting as interfaces between the cytoplasm and its surroundings. All metabolic processes proceed through nanomembranes and involve their active participation. Functionally, the man-made nanomembrane strives to mimic this most basic biological unit. The existence of the life itself is a proof that such a fundamental task can be performed. When designing artificial nanomembranes, the whole wealth of structures and processes already enabling and supporting life is at our disposal to recreate, tailor, fine-tune, and utilize them. In some cases, the obstacles are formidable, but then the potential rewards are stunning.

There is an additional advantage in bionic approach to nanomembranes: we do not have to use only the limited toolbox of materials and processes found in nature. Instead we are free to experiment with enhancements not readily met in natural structures – for instance, we may utilize nanoparticles of isotopes emitting ionizing radiation, even at lethal doses. We can introduce additional structures to our bionic nanomembranes, each carrying its own functionality, for instance nanoparticles or layers with plasmonic properties (e.g., to be used in sensing applications), target-specific binding agents (to improve selectivity) and carbon-nanotube support (to enhance mechanical strength). In this way, we are able to create meta-nanomembranes with properties exceeding the known ones (Jakšić and

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Matovic, Materials 3:165–200, 2010). In this chapter, we present some small steps toward that goal.

2.1 Artificial Nanomembranes

Artificial nanomembranes are a very recent concept in micro and nanotechnologies [1, 2]. They may be defined as free-standing (self-supported) planar structures ranging 5–100 nm in thickness. A thickness of 5 nm corresponds to 15–20 atomic layers of silicon, which approaches the fundamental limits. Because of their unique structure, man-made nanomembranes with areas of several cm^2 and giant aspect ratios exceeding 1,000,000 are sufficiently robust to withstand laboratory handling without any special equipment and with only a modest degree of precaution [1,3,4]. Artificial nanomembranes simultaneously belong to two worlds: to that of the nanoelectromechanical systems (NEMS) because of their thickness and to that of the microelectromechanical systems (MEMS) owing to their area. They represent an artificial counterpart of the living cell membranes that divide the cytoplasm of the living cell from its environment and at the same time provide communication and enable their active interaction [3].

The most basic classification of man-made nanomembranes is inorganic and organic (macromolecular) ones. Early inorganic nanomembranes were in the form of homogenous (Cr, Pt) metallic films. Their areas were limited to about 1 μm^2 at a 6-nm thickness. These simple structures led to the next generation – the metal-composite nanomembranes. It is well known that composites can be tailored to have superior mechanical and thermal properties when compared with pure materials [5].

In a novel manufacturing process developed at Vienna University of Technology, metallic nanomembranes are modified by incorporating oxide and nitride nanoparticles within a metallic matrix [3]. The process is based on the standard MEMS technologies and does not require excessively expensive equipment and approaches. This technology combines reactive ion sputtering with simultaneous ion implantation into the substrate [3]. In this manner, nanoparticles are generated in situ during the deposition process itself. The result is a considerable enhancement of the mechanical properties enabling the fabrication of nanomembranes with areas 10^7-fold larger than previously possible (Fig. 2.1).

The second class includes organic (macromolecular) nanomembranes. This class is considerably greater than the inorganic structures, as there exists a plethora of organic molecules from which such nanomembranes may be assembled (see Fig. 2.3). There is also a wider choice of manufacturing processes available for organic nanomembranes compared with the inorganic ones.

During the 1930s, the Langmuir-Blodgett (LB) process was invented [6, 7]. LB nanomembranes are highly ordered. Being double-layered, they resemble biological membranes. Therefore, they were the first bionic membranes ever produced. Unfortunately, LB nanomembranes are very unstable and until now have found only niche applications [8].

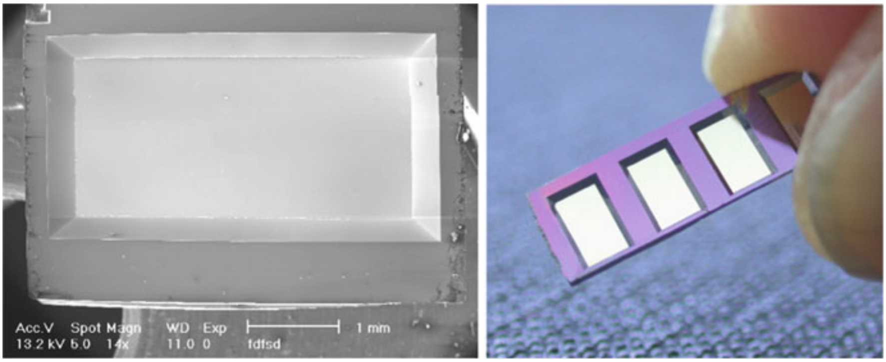

Fig. 2.1 *Left*. SEM image of a metal-composite nanomembrane with lateral dimensions of $1.5 \times 3.5\,\mathrm{mm}^2$. Full thickness of the nanomembrane is only 7 nm. *Right* A photo illustrating the mechanical robustness of the metal-composite nanomembranes: the dimensions are identical to those in the image on the *left*. Current research in TU Wien – ISAS

More recent production methods include spin coating or thermal deposition of macromolecules based on thiol or silane compounds onto a substrate. However, unlike the LB process, these methods do not allow the molecular order in the films to be controlled; therefore, those films are hardly appropriate for bionic structures [9].

Finally, there is a relatively recently introduced method for film self-assembly that makes use of the alternating adsorption of oppositely charged macromolecules (polymers, nanoparticles, and proteins) – the layer-by-layer (LbL) technique [10]. The assembly of alternating layers of oppositely charged long-chained molecules is a simple process, which closely mimics the natural self-organization in living cells. It provides the means to form 5–500 nm thick films with monolayers of various substances growing in a preset sequence on any substrate. These nanomembranes have lower molecular order than LB films, but they have the advantage of high strength and easy preparation [11].

The properties of inorganic and organic nanomembranes are fundamentally different, the only common trait being miniscule thickness and large aspect ratio. Inorganic nanomembranes are mechanically robust and stable in harsh environments, but largely lack functionalization possibilities. However, polymer nanomembranes provide a variety of functional advantages over inorganic nanomembranes because they can have a wide range of source materials, tunable surface, and structure functionalities.

The practical utilization of nanomembranes is still in its infancy; however, some application fields seem rather promising. Some examples include new generations of photonic and chemical sensors, fluid separation, and energy conversion. The function of most of them resembles the biological cell nanomembranes. The essential step toward wider applications of artificial nanomembranes is the combination of inorganic and organic materials into a single structure. This may be done by applying laminated inorganic and organic layers and by incorporating various functional groups.

2.2 Biological Nanomembranes

Biological nanomembranes consist of lipid bilayers incorporating proteins and carbohydrates and typically have a very complex internal structure. The biological nanomembranes are highly functionally ordered, not simply geometrically ordered, Fig. 2.2. Science still has a way to go toward full understanding of the structure and function of the cell membranes, even in the simplest cases. However, the phenomenological reactions of a cell membrane to stimuli are better known: the membrane actively alters its permeability to respond to the specific molecule concentrations inside or outside the cell. It can transport molecules symmetrically or asymmetrically, passively by diffusion or actively by various "pumps". The key to this complex behavior is the membrane functionalization, which appeared at the very beginning of life itself.

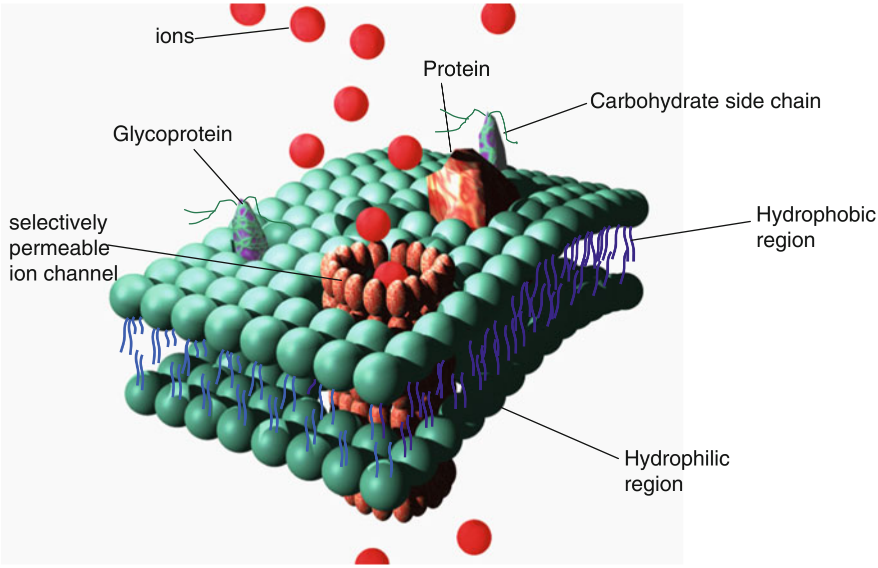

Fig. 2.2 Simplified representation of a lipid bilayer biological nanomembrane

2.3 Functionalization of Artificial Nanomembranes Toward Bionic Structures at ISAS: TU Wien

Bionic or biomimetic science may be defined as the study of biological systems as models for design and engineering of materials and systems. The model for the artificial nanomembranes, at least regarding their form and dimensions, are obviously the biological cell membranes. There is one fundamentally different trait of the artificial nanomembranes at their current state of development – their striking lack of complex functionalities. This is in stark contrast with the biological structures where such functionalities are not only common but also at the core of their function. This may appear like a very serious drawback of the man-made structures. However, one has to bear in mind that the research field of the artificial nanomembranes was conceived very recently, and the main body of literature being published within the last several years. Imparting complex biomimetic properties to nanomembranes is even more recent and is literally at its onset. Witnessing the present accelerating progress toward more complex functional structures, rapid advances may well be expected in the near future. The current research at the ISAS of nanomembranes with bionically enhanced functionality is directed exactly toward this goal [33]. Currently, it is proceeding along two main and seemingly disparate lines, fuel cell-based energy harvesting and detection of long wavelength infrared (IR) radiation.

2.3.1 Nanomembrane-Based Bionic Structures for Energy Harvesting

Stable and continuous energy supply is one of the very foundations of a peaceful and prosperous society. Considered from the thermodynamical point of view, the forms of energy currently used can be basically classified into two main groups: the low quality thermal energy, and the high quality energy like electricity or mechanical work.

Low quality energy (i.e., heat) is still mostly produced by burning accumulated fossil fuels. Other alternatives for obtaining thermal energy in large quantities and at high temperatures still fail from various causes. For instance, solar energy is highly dispersed (max. $2\,\mathrm{kW/m^2}$, rapidly declining at higher latitudes). Also, it is very difficult and technologically challenging to obtain high amounts of such energy in industrial plants and to further deliver it. Other energy sources such as biomass are helpful, but have many drawbacks and definitely do not suffice for the increasing energy demands of the modern society.

The situation with the production of electric power is even more complex. Nowadays the basic principles in power production remain unchanged when compared with those at the beginning of the industrial era. An energy carrier, typically fossil fuel, is used to generate heat, which is further transferred to a fluid.