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BIOMIMETICS DESIGN FOR TRIBOLOGICAL APPLICATIONS

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Abstract: *Biomimetics, biomimicry and bionics are synonyms for the scientific discipline of creating new structures inspired by nature. Biomimetics systematically analyses the evolutionary processes of living organisms, their structural relationships, the characteristics of natural materials and it studies how this knowledge can be used to create the optimal products and new sustainable materials. In the past decade, the biomimetics has received an incentive for the development by the technology modernization, and above all, by making it possible to study the micro- and nanolevels of biological structures. On the other hand, the miniaturization of technological devices has increased the need to understand the tribological phenomena on micro- and nanolevel, where is a huge potential for technological innovation. The integration of advanced research methods made it possible to discover new aspects in the structure and properties of biological materials and transfer that knowledge into new concepts or products. State-of-the-art of biomimetics progress is discussed, as well as, its goals and the potential to simultaneously achieve the financial and ecological contribution by realization of bio-inspired concepts. An overview of biomimetic researches is also provided, with special emphasis on the possibility of their tribological applications. The characteristic examples have been presented and those examples show how the structural and mechanical properties of the material were used as the basis for developing new creative solutions to solve the problem of friction in engineering applications.*

Keywords: *biomimetics, bionics, biomimicry, tribology, friction, nanotechnology.*

1. INTRODUCTION

Biomimetics is a science that is focused on solving technical problems through studying the imitation of nature's methods, mechanisms and processes [1,2]. It could be also defined as "biologically inspired design or adaptation or derivation from nature" [3]. The term biomimetics in the context of science was first introduced by Otto Schmitt in 1969 [4]. The term Biomimetics is derived from *bios*, meaning life, and *mimesis*, meaning to imitate [5]. The term biomimicry is also used in the literature, as a synonym for the term biomimetics. Janine Benyus in her book *Biomimicry: Innovation Inspired by Nature* defined biomimicry approach through three postulates, i.e. nature as a model, nature as a measure, and nature as a mentor. The nature as a model refers to the study and imitation of models from the nature. The nature as a measure means to apply ecological standards for evaluating the introduced innovations. The nature as a teacher means that we should not focus only on what we can extract from the natural world, but on what we can learn from it [6].

The development of biomimetics has intensified in the past few decades, primarily due to increased interest of scientists in finding efficient and environmentally friendly technical solutions [7]. The basic principles of green or eco-tribology have been defined and the need for the integration of the specific areas and biomimetics has been emphasized, as well as, the need for their use in sustainable engineering [8].

Historically, the inspiration by models from the nature for solving human problems exists much longer. Man has always been fascinated by the beauty and harmony of the natural forms, as well as, numerous advantages of principles of nature's system functioning. By careful studying and researching the nature, he was revealing the laws of nature, trying to imitate and implement them [2]. Through evolution, nature's solutions are tested by many challenges, resulting either in their disappearance or improvement to the maximum efficiency. Although many of the capabilities of living organisms are still unknown, or are inaccessible in terms of technical performance, there are also those capabilities that have already been adapted or are in the concept stage. One of the first known examples of biomimetic product is the hook-and-loop fastener known under the trade mark Velcro®, patented in 1958 by Swiss engineer George de Mestral inspired by burdock (Arctium) [3,9]. Superhydrophobicity and self-cleaning effect of the lotus leaf surface were used for the development of facade paints under the commercial name Lotusan® [9-12]. The specific hierarchical structure of toe attachment pads of various insects, amphibian and reptiles, such as geckos, frogs or salamanders, have become the subject of the research, because of their biomimetic ability to attach to and move over vertical walls and the ceiling, and wet or even flooded environments without falling [3,13,14]. The adhesive made by Sandcastle worm (Fig. 1) was the inspiration for the development of surgical glue [15,16]. In addition to medical applications, this viscous waterproof material, which is excreted by Sandcastle worm, can be a basis for the development of novel underwater paints and adhesives [17]. Scientific research of unique design of shark skin, which enables a very fast swim with minimum power consumption, led to the creation of a Riblet surface structure with reduced drag in the turbulent boundary layer [18,19]. Except the effect of drag reduction, shark skin has a feature of self-cleaning from the bacteria, i.e. inhibition of bacteria's attaching, colonizing and forming biofilms. This effect has been used in production of Sharklet™ surface textures [20,21].

Figure 1. Sandcastle worm and its tubular shell

In the past decade, biomimetics showed significant development due to the modernization of technology and above all the possibilities of studying the micro- and nanolevels of biological structures. On the other hand, the miniaturization of technological devices has increased the need for understanding of tribological phenomena at the micro- and nanolevel, which is the huge potential for technological innovation (Fig. 2) [22-25].

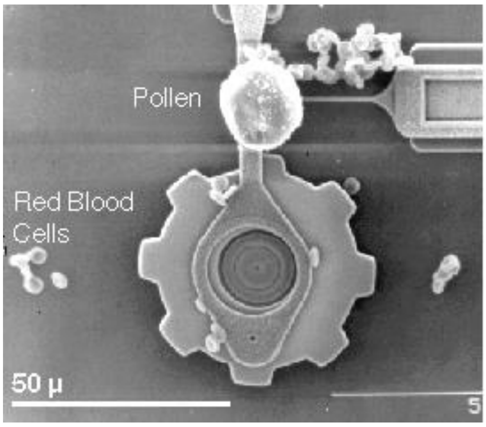

Figure 2. Drive gear chain and linkages [25]

Thanks to a better understanding of fundamental biological principles, biomimetic research activity has been directed increasingly toward the development of bioinspired materials [26-28]. One idea, which is in the development stage, is to make the geometrical texture of the material with the ability to retain the lubricant in the microgrooves. [18,29].

One of the important goals of biomimetic research is to obtain properties of the material optimized for different functions by applying interdisciplinary and holistic approach. In order to achieve that in the best possible way, it is necessary to apply the methodology of biomimetic design.

2. BIOMIMETIC DESIGN METHODOLOGY

Biomimetic design implies the study of biological processes, their abstraction and implementation in order to optimize the product in the functional and ecological sense. Biomimetics as a scientific discipline should formulate a theory to explain the relationship between nature and technology, and to develop a methodology that will facilitate the design process. In accordance with various aspects of biomimetics, different biologically inspired design methods are defined and described in literature [30,31].

Table 1. Biomimicry design method (adapted from [31])

Phase	Description
Identification of need	Defining the problem, including in-depth analysis of unmet needs, in order to identify what is the problem that must be solved
Selection and sampling	Selection of the samples from nature that fit the problem and current needs
Observation of the sample	Observation and analysis of the components of morphological structures, functions and processes; Sample classification
Analogy of the natural system with the product	Analysis of possibility and validity of the analogy between the studied sample and product design
Design implementation	Implementation of functional, formal and structural analysis of the system

In general, the application of biomimetic design principles can be achieved in one of two ways: by finding solutions to the problem in the nature (Biomimicry design method, Table 1) or by inverse design method, searching for a problem for which a solution already exists in the nature (Bio-solution and the search method of a problem, Table 2).

Table 2. Bio-solution in search of a problem method (adapted from [31])

Phase	Description
Biological solution identification	Observation of the nature in search of potential solutions that could be applied to some existing problem
Defining the biological solution	Identification of components or systems involved in the observed phenomenon, in order to extract a biological solution
Principle extraction	Extraction of basic principle solution from the analysis of biological solution in the schematic notation
Reframing the solution	Reframing solutions in a way that users can see the benefit of biological functions
Problem search	Search may include some new problems, which is a key difference from the problem-driven processes method, i.e. biomimicry design method
Problem definition	Definition of analogy between the system and the components of biological solutions and problems in the schematic notation
Principle application	Realization of bio-inspired solutions in technological product or system

The first approach begins with the identification of problem and then the inspiration for solution of the problem is searched in the nature. The second approach is based on the observation of nature and its structures in order to collect useful information that could be an inspiration for engineering or design solutions.

Significant achievements have been realized in solving many engineering problems by applying biomimetic design. Among others, many tribological problems have been solved but there are still many challenges and opportunities. So far, mainly surface texturing on the macro-, micro- and nanolevel have been used in solving the problems caused by tribological processes with the application of biomimetic design. The following examples show in more details the application of biomimetic design in solving some tribological problems. Most of the presented problems are associated with the increase/decrease of friction in tribological systems.

3. BIOMIMETIC DESIGN APPLIED IN SOLVING TRIBOLOGICAL PROBLEMS

3.1 Lotus effect

Sacred lotus plant in Asian religions is considered as a symbol for purity because its leaves cannot get wet and dirty, despite constant exposure to dust and rain [10]. After the rain, the drops of water roll-down picking-up all the dirt, and leaves remain dry and clean (Figs. 3a and 3b). A self-cleaning property of lotus leaves was discovered by Wilhelm Barthlott [10], who has extensively researched this complex biological phenomenon and has developed a colour facade StoLotusan® which has a surface microstructure similar to the lotus leaf. A high magnification image shows fine structure on the surface of lotus leaf (Fig. 3c). The area between the asperity peaks is too small for dust particles to reach it, and they stay at the asperity peaks. Similarly surface microstructure is obtained on the facade painted with StoLotusan® (Fig. 3d), providing the same self-cleaning effect (Fig. 3e).

3.2 Biomimetic tires

One of the aims of tire industry is to optimize the energy distribution between tires and road. Tires must fulfil several tasks simultaneously: during driving they should have a low rolling resistance to reduce fuel consumption; during braking they should have a high sliding resistance to shorten stopping distances; they should be durable and to ensure a silent drive.

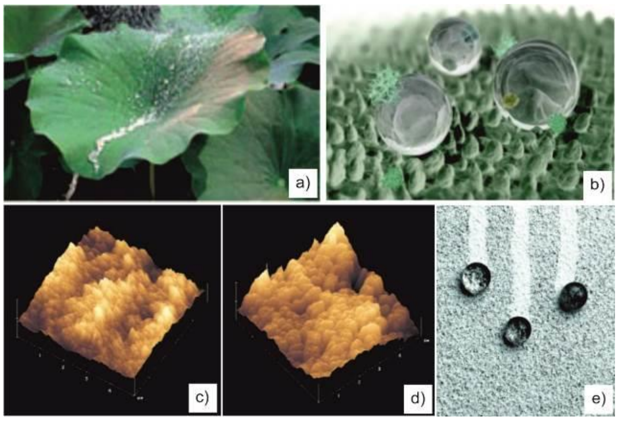

Figure 3. Lotus effect: (a) lotus leaf, (b) computer graphic of lotus leaf surface, (c) microstructure of lotus leaf surface magnified 7000 times, (d) microstructure on the surface of StoLotusan® magnified 7000 times and (e) self-cleaning effect on paint that makes use of Lotus effect

The model for solving these tasks was found with cheetah, which slowly stalks prey and attains a high speed for a short period of time. During running, the flat paws of cheetah are narrow, so they produce low friction in contact with the ground. This facilitates low energy consumption. On the other hand, during slowing down and changing the running direction, their paws broaden and increase the contact surface with the ground. Therefore, the force is transmitted to the larger surface, which increases stability. Thus, cheetah’s paws are optimized for the acceleration, efficient changing of the direction and high stability in curves (Fig. 4) [32].

Figure 4. Biomimetic tires inspired by cheetahs paw: Continental ContiPremiumContact™ summer tire

Applying this evolution strategy, the summer tire Continental ContiPremiumContact™ was obtained. This tyre has the same width as the conventional tire, but it widen during braking, thereby reducing the stopping distance of up to 10 %. This is achieved by appropriate choice of material and the profile of the tire (Fig. 4).

Biomimetic winter tire Continental ContiWinterContact™ TS 780 has a better performance on wet surfaces, the optimal grip and reduced stopping distance. These enhanced features enables the hexagonal tyre pattern (Fig. 5f), which is a replica of the surface structure of the toe pads of specific frog species (Figs. 5c, 5d and 5e): the tree frog (Fig. 5a), which lives on trees and is known for its climbing skills and the torrent frog (Fig. 5b), which is able to climb in wet conditions near waterfalls [33,34]. A V-shaped pattern of tire tread provides a quick evacuation of water from contact zone, thus reducing the risk of aquaplaning [35,36].

3.3 Riblet effect

Riblet effect is inspired by the unique structure of shark skin. Microscopic scales (dermal denticles) allow the water flow through the grooves without whirling and they effectively reduce the drag (Fig. 6a) [3,18]. Many materials applied in naval (Fig. 6b), aircraft and automotive industry are made by technical implementation of the shark skin structure [37].

Figure 6. Riblet effect: (a) microscopic image of shark skin morphology, (b) application in naval industry, (c) application in aircraft industry, (d) application in automotive industry, (e) and (f) application in making swimwear

Figure 5. Biomimetic tires inspired by frogs toe pads: (a) tree frog, (b) torrent frog, (c) microscopic surface morphology of tree frogs toe pad, (d) and (e) micrographs of toe pad epithelia in different frog species (white solid lines illustrate shortest routes to the edge of pad) and (f) biomimetic product: Continental Continental ContiWinterContact™ TS 780 winter tire

Riblet effect is indirectly used for the development of the wing skin of Airbus aircrafts (Fig. 6c). The effect of 6 % less air drag was achieved, which leads to significant fuel savings. The new polyurethane composite is developed inspired by the properties of shark skin within the project *FRIMO Street Shark*. The body components, hood and roof of modified car model *BMW Z4* are made of this bionic material (Fig. 6d) [38].

Speedo® also made a bionic swimsuit from the fabric with Riblet effect (Fig. 6e) [3]. On the underwater photography of swimsuits, there are air bubbles "trapped" in the fabric, which allows the swimsuit to stay dry for a longer time (Fig. 6f) [39]. Thanks to the innovative design, the water drag is reduced by 3 % compared to similar products [32]. At the Olympic Games in Beijing in 2008, two-thirds of the swimmers wore Speedo swimsuits, and a large number of world records were broken [3].

3.4 Gecko effect

Geckos are lizards that can easily climb on smooth vertical surfaces and even move along smooth ceilings without falling. The skin on their feet is comprised of a complex hierarchical structure of lamellae, setae (microscale hairs), branches, and spatulae [40]. There are about 1.5 million setae on each toe, that branch off into 100 to 1000 nanoscale spatulae [41]. This provides a large real area of contact and high adhesion with a variety of surfaces (Figs. 7a, 7b and 7c).

Adhesive tape Geckskin™ is made by simulation and modelling of the structure of the gecko toes. This tape sticks due to intermolecular forces between the large number of synthetic fibres and surface (Figs. 7d and 7e). The biomimetic gecko robot *Stickybot* (sticky robot) was made at Stanford University in order to demonstrate the gecko adhesion (Fig. 7f). It has the toe pads of urethane material with tiny bristles whose tops have a thickness of 30 microns, which is enough to keep him on steep surfaces, although gecko foot spatulae is much thinner (approximately 100 to 200 nanometres).

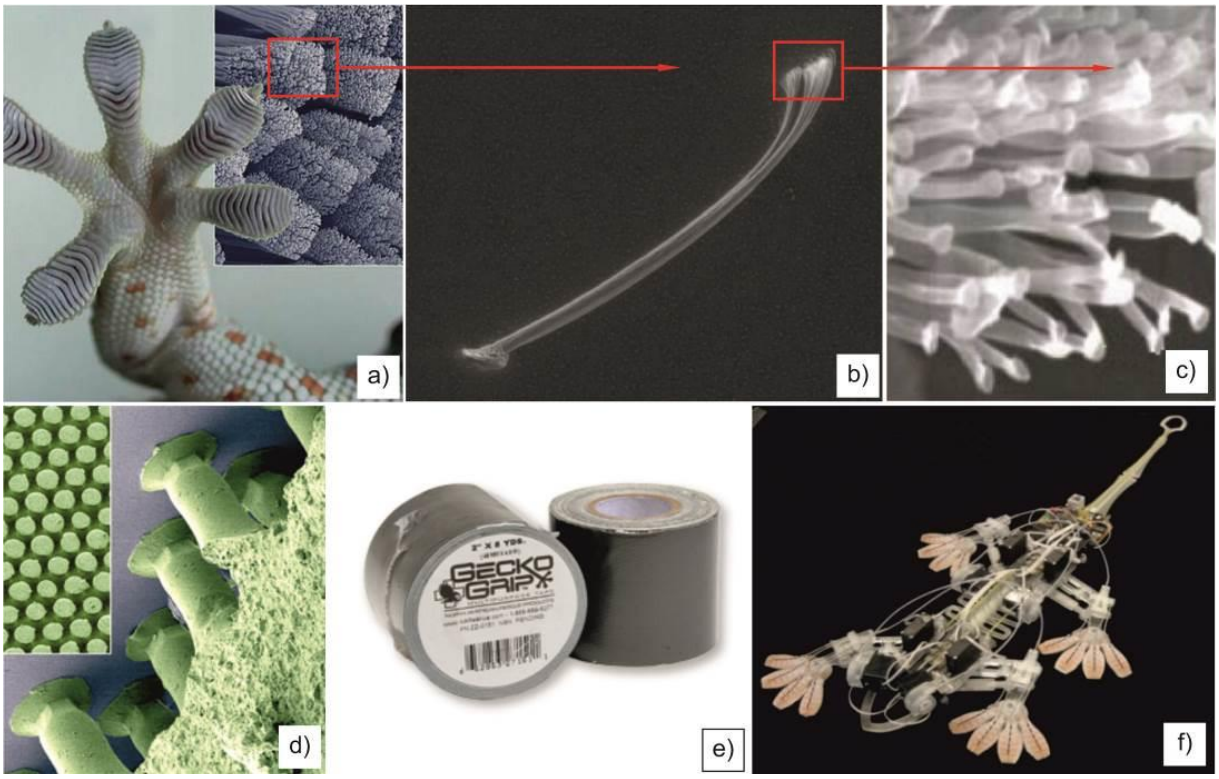

Figure 7. Gecko effect: (a) gecko feet structure with lamellae, (b) gecko foot setae, (c) gecko foot branches and spatulae, (d) millions of synthetic fibres in one square centimetre imitating gecko foot structure, (e) gecko adhesive tape and (f) biomimetic gecko robot *Stickybot*

3.5 Sandfish and snake scaled skin effect

More than 25 years professor Ingo Rechenberg from Berlin has studied the survival mechanisms of certain forms of life in the harsh desert conditions. One interesting example is a lizard *Scincus scincus* (Fig. 8). It is also known as a “sandfish”, since it dives into the sand and moves below the surface in a swimming-like motion. It usually goes to the depth of several centimetres, and it can “swim” at a speed of 10 to 30 cm/s [42]. By analysing the scaled skin of this reptile, it was found that it had even smaller coefficient of friction than those of polished steel, flat and smoother glass, PTFE, and high-density nylon surfaces, and showed hardly any sign of wear after it suffered abrasion with sand [43,44].

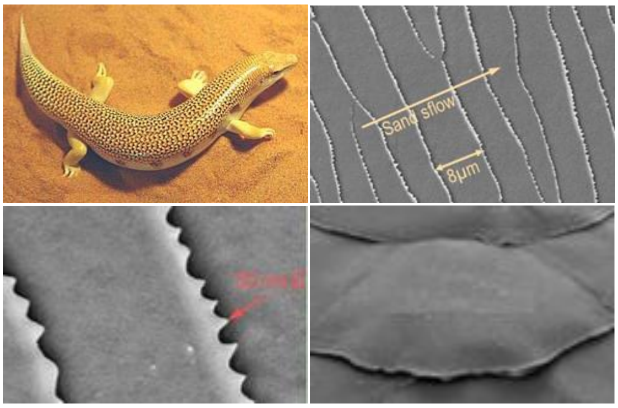

Figure 8. Sandfish (Scincus scincus) and microscopic images of its scaled skin

The shape and arrangement of scales of sand fish skin and certain types of snakes have inspired the scientists from Karlsruhe Institute of Technology to create a similar texture on bearing steel surfaces (Fig. 9), and test them in lubricated and unlubricated conditions [45].

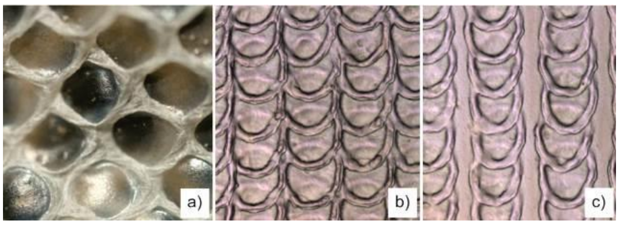

Figure 9. Surface texturing inspired by reptile scaled skin: (a) ball python (Python regius) scaled skin as inspiration, (b) artificial scales with vertically and horizontally overlapping scales and (c) artificial scale with horizontally overlapping scales; adapted from [45]

Two different surface textures were created in order to investigate the influence of scale distances on tribological properties. The first texture imitates scale skin arrangement on the stomach of one kind of a python (Fig. 9a). The artificial scales overlap in both directions, and they are very close to each other (Fig. 9b). The second texture consist of artificial scales arranged in vertical overlapping rows at a greater distance (Fig. 9c), similar to the structure of the sand fish skin (Fig. 8).

Tests in unlubricated sliding conditions have shown that the first texture (ball python) reduced friction by only 22 %, while the second texture (sandfish) reduced friction by more than 40 % in comparison to the untextured surface. On the other hand, for mineral oil lubricated sliding conditions scale-like textures seem not to be favourable, i.e. coefficients of friction were higher by 3 times with the first texture and by 1.6 times with the second texture [45].

The researchers’ opinion is that this discovery may help to reduce friction in the nano- and micromechanical devices that can not be lubricated. Potential applications also include the reduction of friction in artificial hips, machines which operate in a vacuum environment, sensors used in anti-lock brake systems of cars, in the operating elements of computer hard drives, etc.

4. CONCLUSION

The development of biomimetics encourages creative product development in various industries. From the initial inspiration with nature, the biomimetics has evolved into a general methodology for innovation. Although the product development process is very complex, from the concept inspired by nature, then its implementation in innovation, to its commercialization, there is a growing interest in the application of biomimetic design methods. At this point, many new ideas and concepts inspired by nature are researched in the academic and industrial research and development centres. One of the reasons is that many of the technological innovations could not be obtained by a traditional approach to the design. For a successful realization of the creative process, from inspiration by nature to engineering applications, it is first necessary to fully understand the behaviour of biological system, then establish an analogy with the technical problem, and finally realize the product by using modern technology.

This paper gives a broad overview of state-of-the-art of biomimetic research, while the examples developed for tribological applications are presented in more details. It is shown that the biomimetic design improves friction and generally properties of commercial products by applying the combination of unique characteristics of biomaterials, their excellent tribological properties and specific surface structures.

Many potential inspirations from nature for technological innovations is a good reason for more intensive development of biomimetic research.

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