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Bio-inspired textures for functional applications

Ajay P. Malshe (1)[a,b,*], Salil Bapat[b], Kamlakar P. Rajurkar (1)[c], Han Haitjema (2)[d]

[a] Department of Mechanical Engineering, University of Arkansas, Fayetteville, AR, USA
[b] Microelectronics–Photonics Graduate Program, University of Arkansas, Fayetteville, AR, USA
[c] Department of Mechanical Engineering, University of Nebraska, Lincoln, NE, USA
[d] KU Leuven, Mechanical Engineering Department, B-3001 Leuven, Belgium

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ABSTRACT

Textures are abundantly exploited in nature for securing superior functionalities including adhesion, color manipulation, anti-reflection, and drag management. Over millions of years, these advanced properties are endowed to various organisms on the planet to survive and adapt in harsh environmental conditions. Texture characteristics such as feature size, shape, periodicity, aspect ratio, orientation and hierarchy are critical in nature's 'tool-box'. Manufacturing of cutting-edge products require multi-functionalities for efficiency, durability and sustainability for improving the quality of life of growing population. This paper analyzes and discusses *convergence* and underlying science and engineering of well proven natural strategies of surface textures and their effective synthetic implementation in engineered products.

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1. Introduction: bio-inspired surface textures-nature's tool for delivering functional surfaces

'It is not the strongest of the species that survives, nor the most intelligent, but the most responsive to change,' said Charles Darwin. Survival of the fittest is a famous phrase of Herbert Spencer, which describes the idea that, in nature, there is a competition to survive and reproduce. Survival and change are two critical terms, especially as species on earth over millions of years are in continuous combat with changing environments. These environments are typically harsh for organisms to live in, but despite these difficulties organisms have survived and thrived by building harmonic ecosystems within divergent environments including marshy and muddy; deep cold and snowy; hot, dry and desert; and more. Living organisms interact and interface with their surroundings through their outer layers, their surfaces which have adapted and evolved with novel but simple designs and functional properties in this process of combat and survival.

The surface (and sub-surface) of an organism, also called skin, is an important interface between an organism and its environment, serving a mission critical role in the process of adaptation and survival. Skin surfaces interact with aggressive environmental factors such as temperature, moisture, abrasive agents such as sand and ice, pH, bacteria and viruses, light, mating abrasive or super smooth surfaces, etc. and their combinations. To combat these aggressive factors, skins have evolved unique design architectures that achieve multifunctional properties including (but not limited to) adhesion, hydrophobicity, hydrophilicity, thermal-management, anti-reflection, structural colors, and spherical vision as highlighted in Fig. 1.

The skins of organisms, from here onwards called surfaces, deliver these environment-specific properties by combining textures and material chemistries to exploit classical laws of physics to achieve superior functional properties. The term surface texture captures various facets of a construct including the repetitive arrangement of features, the various shapes and sizes of features (in 2-D and 3-D), and the hierarchical distribution of quasi-periodic connected structures in a multi-dimensional space

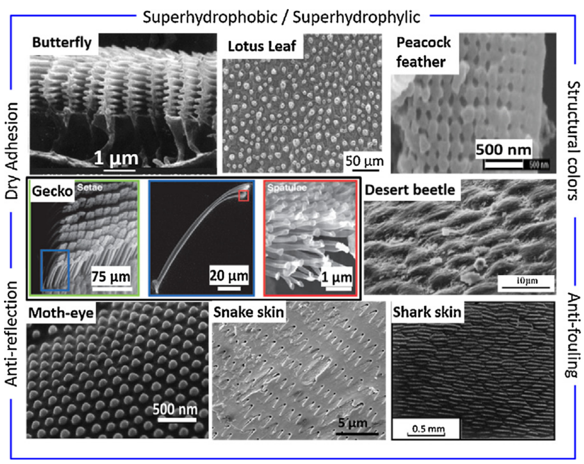

Fig. 1. Diversity in biological textures and their functions (images reproduced with permissions from [20,26,61,100,157,180,247]).

* Corresponding author.

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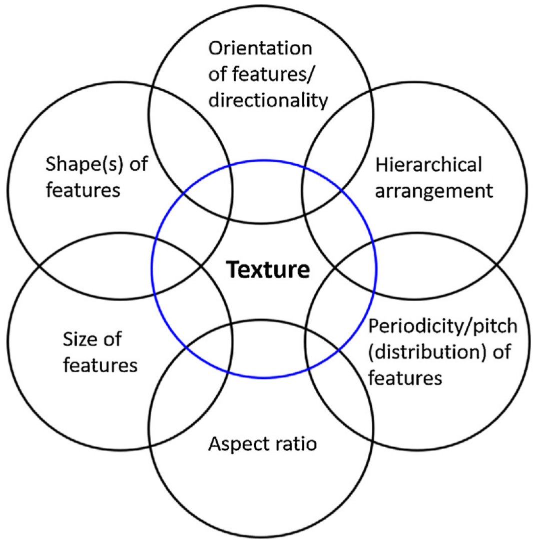

Fig. 2. Components that contribute to surface texture.

resulting in novel morphologies. Succinctly "surface texture is the geometrical irregularities present at a surface. Surface texture does not include those geometrical irregularities contributing to the form or shape of the surface" [168]. In other words, surface texture be seen as a design tool in nature's "tool box": they enable multi-functionality in many natural and biological surfaces [197]. Fig. 1 summarizes some of the commonly observed multi-functional textured surfaces in nature and the endowed functionalities of these surfaces.

To further understand texture as a design architecture or a construct, one needs to realize that all textures are convergence of construction features including the shapes of features, the sizes of features, their aspect ratio, their periodicity and pitch, their orientation and directionality, and their hierarchical arrangements (Fig. 2). As a result, there are more than 700 types of possible textures allowing a tremendous degree of freedom for surface manipulation. It is observed that these surface texture features converge to deliver a desired surface function (or multifunctions) to aid the organism's combat with the environment and survival.

Surface functions are also important for designing and manufacturing advanced products for growing populations. Furthermore, consumer demands are growing for higher efficiency and durability in products' performance and sustainability offered per unit currency of price. Also, demands are growing to deliver more functions per unit surface area per unit currency. Examples of such products are displays, personal data assistants (PDA), self-driving cars, sustainable buildings, clothing, cosmetics, and more. Last but not least, with a growing global population, natural resources are dwindling, and well-established strategies are needed to engineer the next generation of sustainable products that can be produced by using less resources. Bio-inspired texture strategies have been refined over millions of years by organisms on earth and are examples of efficiency, durability and sustainability. These properties have made them a recent focus of products and production engineering.

Functional surfaces have been a subject of extensive scholarly research for decades [78,91,161,173,230]. Some of the most notable contributions through the years are the CIRP keynote papers in the areas of structured surfaces, engineering of functional surfaces, surfaces in precision engineering and bio-inspired functional surfaces [44,64,77,197] along with notable contributions in surface metrology [65,99,106,145,171,186,219,257]. This paper builds upon these previous contributions and is unique in following discussion points on bio-inspired textures: (1) bio-inspired functional surfaces with an emphasis on specific design aspects of bio-inspired "textures"; (2) methodical analysis of texture into construction components; (3) biological texture characteristics classified into Tier I and Tier II characteristics for designing surfaces for specific functionality; (4) effective convergence and implementation of these characteristics for realizing product applications where these textures are utilized.

In the following sections, this paper discusses specific examples of surface textures and their resultant functionalities in nature and the fundamental science that is utilized through these texture constructs to achieve these functions. This is followed by the elaboration on metrological approaches, process methodologies and instrumentations used for studying complex surface textures. Further, it is discussed and highlighted for product systems where such functions are of major values and the manufacturing processes used to realize advanced products by corporations.

2. Understanding the science of surface textures in nature

The following section describes the construct of surface texture and the underlying science along with the design strategies for manufacturing via examples of multi-functional textures observed in nature.

2.1. Design components of surface texture

Surface texture can be further analyzed into multiple design components as shown in Fig. 2. These components, along with the specific material properties, deliver the desired functionalities upon interaction with the environment. Based on the extensive analysis of the literature for multiple bio-inspired textures, it is realized that for specific surface texture enabled functions, certain texture design components dominate over the others. These primary (dominant) component(s), along with complementary secondary component(s), lead to the desired functional effect as illustrated by following examples. Over time, researchers have studied textured metals, semiconductors, polymers, ceramics and composites for delivering variety of functionalities and product applications. Examples of different materials are demonstrated later in this paper. Typically, selection of material(s) is guided by the intended function, application environment and manufacturing process capabilities.

2.2. Natural examples of superhydrophobicity

Lotus leaf is well known for its superhydrophobic and self-cleaning properties those are enabled by random and hierarchical arrangement of nodules and hairs at micro and sub-micron scales. Apart from lotus leaves, rice leaves also show superhydrophobic effects. However, in case of rice leaves, the surface features are arranged in a periodic manner along the length of the leaf, leading to directional and anisotropic wettability [79]. Several other plants' surfaces as well as some animal skins (such as water strider legs, peacock feather and butterfly wings) also exhibit multi-functional superhydrophobicity [97,160,182,209,280]. Rose petals are particularly interesting as they exhibit superhydrophobicity owing to convergence of hierarchical micro-scale and submicro scale features. However, the water droplets on rose petals have high adhesion to the surface so no roll-off effect can be observed [25,180]. Fig. 3 shows some of the natural superhydrophobic surfaces and their diverse texture features.

The wetting properties of a solid depend on the interfacial energy balance between the solid–liquid–air interfaces as depicted

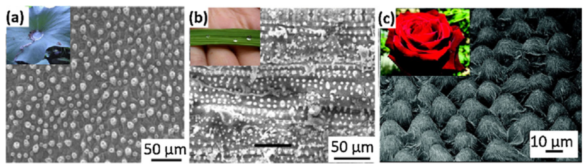

Fig. 3. (a) Surface structure of lotus leaf showing the micro-scale texture [180] (reprinted with permission from Elsevier); (b) photograph and SEM micrographs of rice leaf showing the directional micro-texture [96] (reprinted with permission from Elsevier); and (c) photograph and SEM images of rose flower and micro-texture [80] (reprinted with permission. Copyright 2008 American Chemical Society).

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