BIOMIMETIC COMPUTER-AIDED DESIGN AND MANUFACTURE OF COMPLEX BIOLOGICAL SURFACES

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Abstract: Conventional computer-aided design software does not yet provide special tools oriented to modeling the complexity of biological systems, as such programs are mainly developed for promoting information exchange in tasks related to industrial design and to parts with regular smooth surfaces. The process explained in this study allows defining and precisely controlling the topography of surfaces from the design stage, with help of computer-aided design tools. Its application to obtaining a biomimetic surface based on the leaves of the Lotus flower (*Nelumbo nucifera*), renowned for its outstanding self-healing and tribological properties, is shown as example. Some reflections on potential remarkable applications, linked to the development of implants and prototypes with applications in several industries, have also been included.

1 INTRODUCTION

Several studies have focused on the importance of surface topography and microtexture for promoting positive effects in all kinds of biomedical devices, from implantable prosthesis to extra-cellular matrixes and scaffolds for cell growth and tissue engineering. These textures have a significant influence in osseointegration of prosthesis, cell proliferation and tissue growth given that those cells and tissues seem to be more "comfortable" and spread more quickly when faced with biodevices with similar surface properties.

In addition the use of biomimetic surfaces can help to introduce numerous desirable phenomena in machine, mechanical and structural elements, thus improving contact between parts, reducing wear or even obtaining self-cleaning objects. However, the process of introducing desired roughness on the surfaces of man-made objects is still mainly linked to carrying out machining operations, laser processing or chemical attacks. In all these cases, post-processing operations can be difficult to control and it would be very positive to directly impose special topographies from the design stage.

The use of fractal models for mimicking such natural surfaces can prove to be useful for design tasks. Fractals are rough or fragmented geometric shapes that can be split into parts, each of which is (at least approximately) a reduced-size copy of the whole. The term *fractal* was coined by Benoît Mandelbrot in the late 1970s / beginning of 1980s and derives from the Latin *fractus* meaning "broken" or "fractured" (Mandelbrot, 1982). The term is used to describe complex geometries that are too intricate to be formulated in conventional Euclidean terms, with properties like self-similarity and defined usually with simple recursive procedures.

Since the early works linked to fractal geometry, it became clear that they could be used for describing the geometries, patterns and roughness of natural objects. Although fractals are commonly considered to be infinitely complex (due to their usual recursive definitions) "approximate fractals" are easily found in nature, which usually display self-similar structure over an extended, but finite, scale.

By limiting the steps applied in a recursive definition of a conventional fractal, approximate fractals can be obtained, which mimic complex natural geometries. Natural objects that are approximated by fractals include clouds, mountains,

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lightning bolts, coastlines, snowflakes, various vegetables and several corporal and animal geometries (Mandelbrot, 1982, Falconer, 2003).

During the last decade, increasing attention has been paid to using fractals for promoting modeling, design and simulation tasks in several areas of Bioengineering. The most remarkable ones include “modelling the behaviour of microorganisms” (Tsyganov, 2007), “modelling complex organisms and their systems (including human anatomy)” (Lin, 2004) and “modelling the surfaces of organs and tissues” (Longoni, 2010).

In fact, very recent interest has appeared in the use of fractals for mimicking the surfaces of organs and tissues and thus improving the designs and *in vivo* performance of several prosthetic devices, although some limitations linked to the design procedure still have to be overcome.

The process explained in this study allows defining and controlling the texture and roughness of surfaces from the design stage, with help of computer-aided design tools. Its application to obtaining a biomimetic surface based on the leaves of the Lotus flower (*Nelumbo nucifera*), famous for its remarkable tribological properties, is shown as example (Barthlott, 1997).

The mentioned computer-aided design, calculation and manufacturing technologies (CAD-CAE-CAM), have become essential tools for developing products. They allow 3D geometries and alternative designs (to which calculations of stress, deformations, ergonomics, dynamic response can be applied) to be rapidly manufactured.

Moreover, these technologies can also be employed to test materials and designs. They can also prove to be extremely beneficial when applied to the development of biomimetic devices with advanced properties, even promoting personalization of devices and special contact phenomena.

2 DESIGN PROCEDURE: FROM MATHEMATICAL SURFACE MODEL TO SOLID CAD FILE

2.1 Combining Euclidean and Non-euclidean Geometry

We propose and explain in this section the use of mathematical fractal models for designing the complex and highly irregular surfaces of biomimetic objects. In this way, parameters such as roughness, waviness, skewness can be controlled from the design stage and adapted in a more efficient way to the requirements of final application.

Final multi-scale surface z(x,y) can be considered as the sum of two different surfaces (z_m (x,y) and z_n (x,y)), each providing a relevant component at a different scale level. In our case, the microscopic bump-like behavior of the Lotus flower leaves can be approximated by using a regular surface defined by $z_m(x,y)$, for obtaining 10 μm size details. For introducing an additional level of precision (irregularities in the range of hundreds of nanometers) $z_n(x,y)$ proves to give positive results if based on fractal models.

In this study we have selected a fractional Brownian fractal surface model for $z_n(x,y)$, which has previously proved to be useful when carrying out designs of natural surfaces (Falconer, 2003). The following equations give the height “z” of the surface, when assessing the function over a grid of points given by their (x,y) coordinates.

The model uses several random functions (A_k, B_k, C_k), several control constants (λ, α, k) and an initial height function “z_0” can also be introduced. According to the model, fractal dimension “D” of the generated surface can be obtained from the expression “$D = 3 - \alpha$”, for having an indication on how completely the fractal appears to fill space.

$$z(x,y) = z_m(x,y) + z_n(x,y)$$
$$z_m(x,y) = z_0 + 10\left|\sin(\pi x/10)\cdot\sin(\pi y/10)\right|$$
$$z_n(x,y) = \sum_{k=1}^{\infty} C_k \cdot \lambda^{-\alpha k} \cdot \sin(\lambda^k [x\cdot\cos(B_k) + y\cdot\sin(B_k) + A_k])/10$$

2.2 Surface Generation

The calculations have been carried out with help of Matlab software (Mathworks, version R2009) and the data obtained have been stored in three-column matrixes [X, Y, Z].

The command “surf” helps to represent the surfaces linked to the mentioned matrixes. Figure 1 shows the result of evaluating function z(x,y) over a grid of 300 x 300 points (corresponding to 30 μm x 30 μm). Consequently, distance between points of the grid is similar to the scale of irregularities (around 100 nm size) introduced by $z_n(x,y)$. Number of iterations “k” has been limited to 10, enough for introducing the fractal random-like irregularities, and the following design values have been used:

$$\lambda = 1.5;\ \alpha = 0.4;\ z_0 = 0.$$

Similarity with original topography of the Lotus flower leaves is noteworthy, as can be seen if compared with the photos from references

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(Barthlott, 1997) or with the results from alternative biomimetic manufacturing approaches (Groenendijk, 2007).

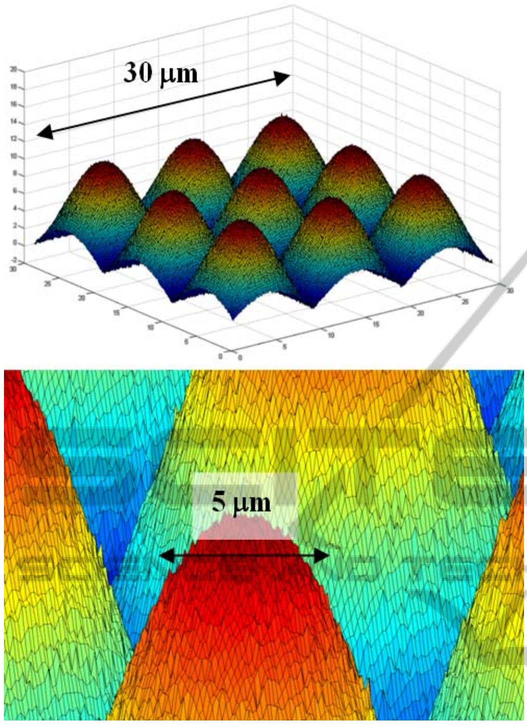

Figure 1: Mathematical surface mimicking the micro- and nano-topography of the Lotus flower leaves.

2.3 Exporting Geometry to CAD Software

Once the mathematical surfaces have been obtained, the information stored in the form [X, Y, Z] can be converted into .stl universal format, so that the surface can be recognized and imported with a CAD program, for additional design operations (i.e. providing the surface with a thickness, copying the surface atop a previously designed geometry…).

Different special software packages and “mesh to solid” tools can be used for directly handling data in .stl and enabling subsequent CAD operations. Figure 2 shows below the surface after importing the .stl file with the help of NX-7.5 (Siemens AG) and the solid body obtained after applying standard Boolean design operations, for launching manufacture through the 3D Lightyear™ software (3D Systems).

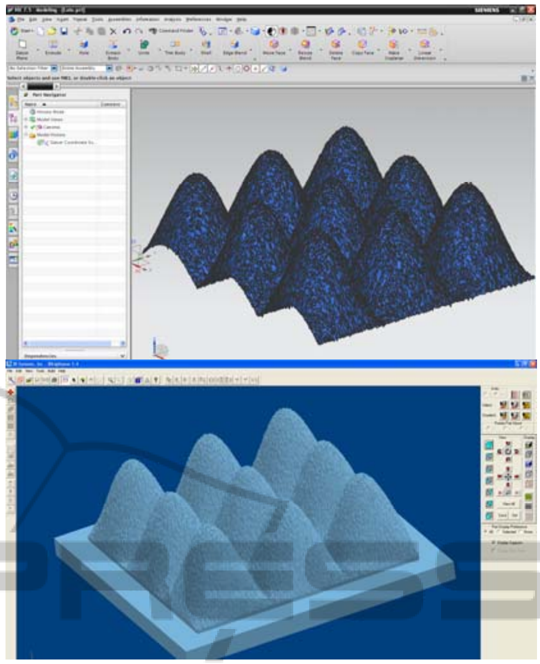

Figure 2: Handling the surface with CAD software for obtaining a solid model.

2.4 Process Summary and Actuations regarding Computer-aided Engineering & Rapid Manufacturing

Once obtained, CAD files enable the development of several kinds of design validations (assembly, relative movements…) and simulations (mechanical, thermal, fluidic…) with the help of computer-aided engineering resources, especially based on the use of F.E.M. calculations.

Additionally the use of CAD tools can be very beneficial when combined with a new set of manufacturing techniques and technologies that have appeared in the last two decades called “Rapid prototyping and manufacturing technologies”.

These technologies help to address market requirements in an ever more customized way, as well as optimized in terms of time and cost, and provide support for research work where physical models (or prototypes) are needed for tests and trials.

They are usually based on automatic “layer manufacturing technologies” (like “laser stereolithography”, “3D printers” or “selective laser sintering”), rapid shape-copying processes, or manufacturing processes through the elimination of material (such as in computer-driven high speed numerical control machining).

The different technologies available allow prototypes to be obtained rapidly in a wide range of metallic, ceramic or polymeric materials with remarkable precision. The whole proposed design, simulation and manufacturing process is summarized in Figure 3.

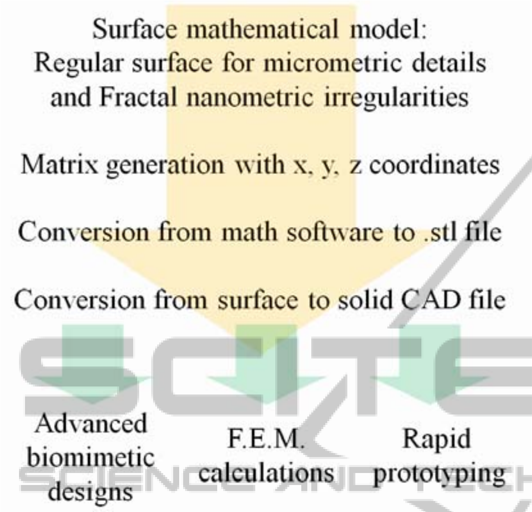

Figure 3: Process scheme. OEPM P20103947 (Díaz Lantada, 2010a).

Regarding the manufacture of fractal surfaces, our previous research has helped to validate the use of rapid prototyping for obtaining physical prototypes with details in the range of 0.4 to 4 mm (Díaz Lantada, 2010b).

The manufacture of more precise geometries, such as the examples shown in this study, can be accomplished by using some technologies such as two-photon polymerization (Inführ, 2007), micro-stereolithography (Choi, 2009), digital light processing (Stampfl, 2007) and X-ray based micromachining (Gad-el-Hak, 2002), for details even down to hundreds of nanometers.

In any case Figure 4 provides an example of prototype (30 x 30 mm^2) manufacture through laser stereolithography with a magnified scale due to precision limitations. Further miniaturization can be accomplished by using some of the aforementioned technologies.

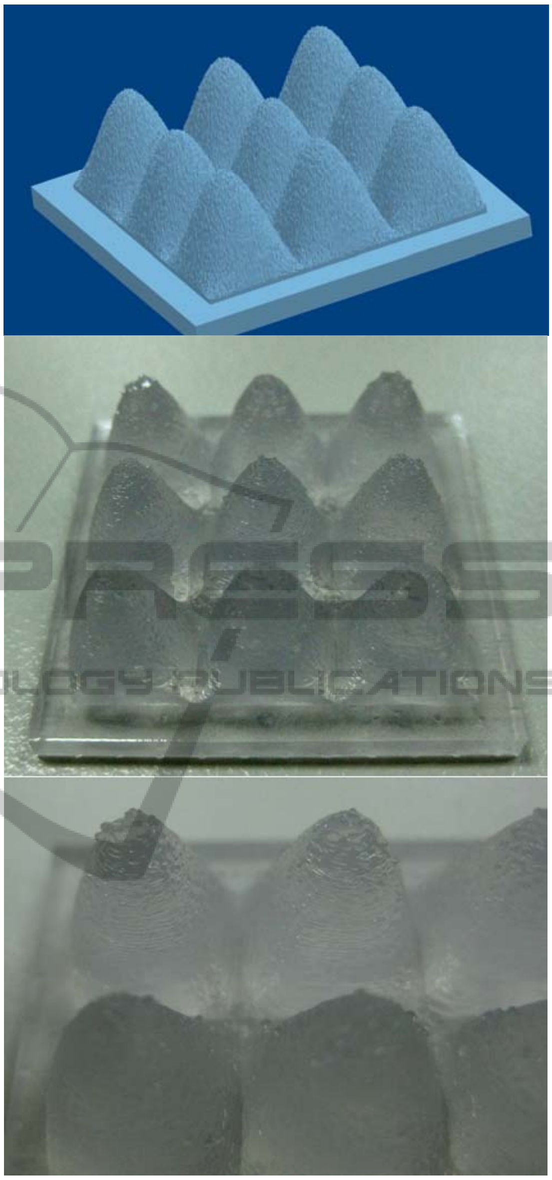

Figure 4: Design and prototype manufactured using laser stereolithography.

3 BRIEF DISCUSSION OF POSSIBLE APPLICATIONS

The possibility of designing parts with surfaces mimicking those from natural organisms can prove to be of great value for incorporating advanced contact phenomena into devices for several industries, thus promoting interactions with surrounding elements (if the part is integrated within a complex device) or tissues or organs (in the case of an implant).

Among most promising applications we would propose to focus in the near future on the design of implants with optimized biocompatibility, devices with self-cleaning properties, devices with *ad-hoc* improved hydrophobicity or hydrophilicity, scaffolds for cell and tissue growth and prototypes for research linked to tribological phenomena, including adhesion, lubrication, friction and wear.

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In addition, combining novel advances in micro-CT and medical imaging software (i.e. Mimics, Materialise NV) for obtaining precise CAD data of organs and biostructures (Shi, 2008, Guo, 2010), with the possibility of incorporating even nanometric features in a similar way to the presented study, can be of great help for research linked to enhanced modelling of biosystems.

4 CONCLUSIONS

A novel method for defining and controlling the topography of surfaces from the design stage, even mimicking the characteristics of biological systems, has been presented. It is based on the combination of regular surfaces for describing the micrometric structure and additional fractal components for providing the final nanometric details. As application example a biomimetic design of the surface of the Lotus flower leaves has been explained.

Manufacture of such complex geometries can be directly accomplished with help of additive rapid prototyping technologies, what supposes a focus change, from a more conventional "top-down" (micro-machining, chemical etching, laser ablation), to a more versatile "bottom-up" approach. The flexibility of additive manufacturing also enables the application of similar surface microtextures to the complex geometries of prostheses and biodevices, thus helping to introduce beneficial contact properties for enhancing aspects such as wear endurance or biocompatibility.

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