

Application of Reaction-Diffusion Mechanism in Parametric Design of Product Surface Textures

Jingxu Yao^{1,2,a}

¹Wuhan University of Technology, Wuhan, Hubei, China

²Shandong University of Arts, Jinan, Shandong, China

^a22073168@qq.com

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Abstract: The current trends in the product design have a tendency to create designs that are more personal and biomimetic, but the traditional methods of geometric modeling can not satisfy the needs of creating natural textures. In this paper, the theory of reaction-diffusion (RD) process has been used to generate the surface texture on products as well as their practical design. By examining the model of Gray-Scott, the paper creates a parametric design procedure that encompasses two-dimensional patterns creation, three-dimensional surfaces alteration, and physical manufacturing. It is shown that interference fields allow localized control of parameters that can be used to maintain the system of texture with both visual gradients and functionality. This technique presents a new digital avenue towards industrial development of color, material and finish (CMF), which is an improvement over the conventional texture mapping approach.

1. Introduction

1.1. Design Transformation: From Standard Geometry to Bio-inspired Algorithms

The design of the industrial products is not mass customization anymore. The application of the additive manufacturing has been so common that it has made the traditional mold method to be less used and designers can now make new forms easier. Moreover, biomimetic design was more widely accepted in the culture and market place as well as people were more willing to buy things with natural shapes, natural growths and even a surface with unevenness. SolidWorks and Rhino are two relatively old modeling software packages on CAD modeling, but they are not able to produce irregular geometry. But when it comes to creating biomimetic shape (the creation of coral-like structures or animal pattern) which requires the creation of an irregularly shaped form with a high density of different textures, the process of modeling becomes extremely inefficient and impossible to alter parameters later on.

1.2. Significance of the Reaction-Diffusion Mechanism

Since the 1952 paper by Turing, reaction-diffusion (RD) mechanism has offered a theoretical explanation of pattern generation based on self-organizing processes in chemical reactions. The mathematical representation of this process can be used to generate surface textures that are not typical and can be adjusted by altering the parameters involved in the calculations to achieve different levels of density in the texture. It is worth noting that RD can be implemented into product design as it allows the designer to simulate the process and apply the results to the design of the product.

2. Theoretical Basis of the Reaction-Diffusion Mechanism and Its Digital Translation

The Reaction-Diffusion (RD) model as one of the main theories of complexity science in morphogenesis is a design product theory which offers an alternative to Euclidean geometry, and can be used to create new designs.

2.1. Turing Patterns and Self-Organized Emergence

In 1952, Alan Turing wrote *The Chemical Basis of Morphogenesis*, in which he described a mathematical explanation for biological pattern such as zebra stripes, leopard spots, and patterns on tropical fish. His thesis was that such patterns do not arise from a predetermined blueprint, but rather from interactions between chemical substances in a medium.

2.1.1. Antagonistic Mechanism of Activator and Inhibitor

The RD system is based on the dynamic equilibrium between two hypothetical morphogens, which are typically referred to as an activator and an inhibitor:

(1) The activator is autocatalytic. It promotes its own production and creates local positive feedback as it diffuses.

(2) The activator is inhibited by the inhibitor. Its rate of diffusion should be significantly increased, such that it may exert control over a greater distance.

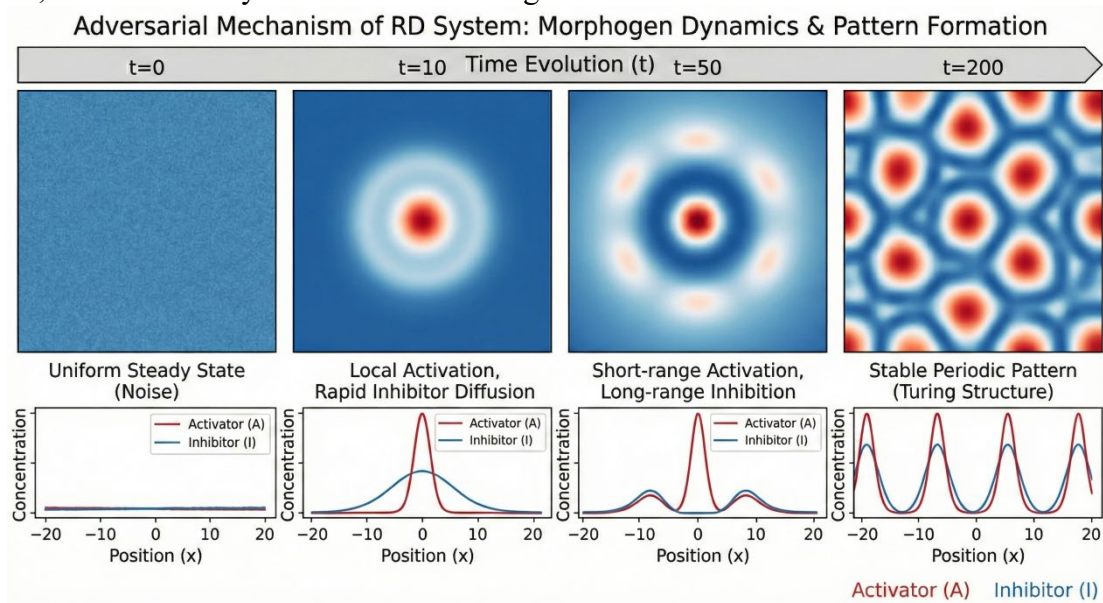


Figure 1. Interaction of two chemical substances in the RD system (Drawn by the author)



Figure 2. Surface texture of a fish (Drawn by the author)

The interaction of the two substances is responsible for keeping the system in equilibrium and in a suitable way, it results into the formation of patterns that are visible. It is the classic process of

short-range activation and long range inhibition as shown in Figure 1. On a small scale, activator builds up rapidly and forms spots with high concentration. The inhibitor diffuses faster so it can quickly encircle such regions and inhibit the expansion of such regions to any further outward direction resulting in a blank space surrounding each spot. This antagonistic action will be repeated on the medium until the homogeneous state is destabilized and broken symmetry occurs. These surface patterns are stable and periodic and slowly develop as illustrated in Figure 2.

2.1.2. Paradigm Shift in Design: From "Top-Down" to "Bottom-Up"

In the conventional product design and CAD modeling, designers tend to use a top-down logic; they pre-conceive the form and then define geometric features explicitly with drawing tools (e.g., NURBS curve drawing). This method is very effective in working with regular geometries but ineffective when it comes to highly complex, non-repetitive, and anisotropic organic textures that are found in nature.

In the opposite, the design of RD mechanism is a kind of bottom up logic in its generative character. The artist does not create the form itself, but only the designer as the gardener of the system that sets the conditions and reactions to produce the texture automatically through algorithms. It has two advantages that are superior to those of conventional texture mapping due to this property of Emergence of RD textures. First, it is continuity: it is continuous with respect to the computational mesh, thus, the problem of seam and stretching distortion will be eliminated. Second, organic adaptability: the texture would be able to self-adapt its distribution depending on the topology of the surface having an innate feel of adaptation which is similar to skin of a biological being.

2.2. Parametric Logic of the Gray-Scott Model

Even though the equations of Turing have been the basis of the theoretical study, it is the model that has been developed by Pearson et al. which is the most popular in computer graphics and generative design^[1]. It is a particular simplification of the overall RD equations. The introduction of two fundamental parameters Feed and Kill reduces the computational load to an enormous degree but at the same time gives very complex possibilities of morphological change.

2.2.1. Chemical Reaction Mimicry of the Model

The Gray-Scott model simulates the following chemical reaction process (as shown in Figure 3):

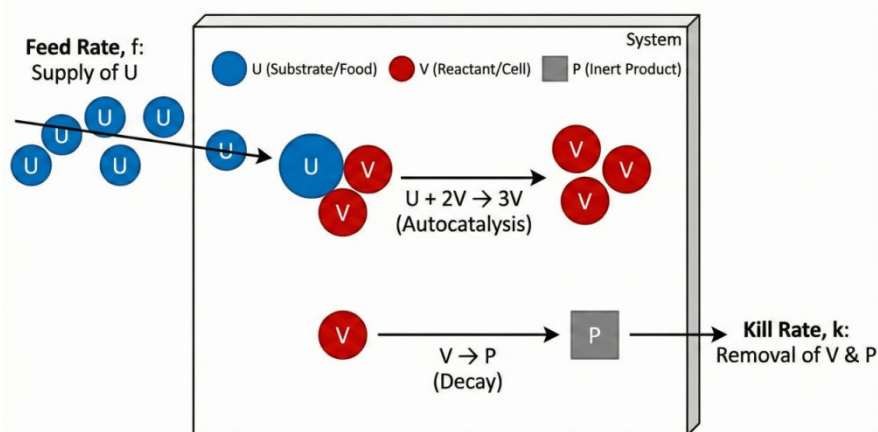


Figure 3. Gray-Scott Model (Drawn by the author)

$u+2v\rightarrow 3v$ (Substance v consumes 2 units of substance u to generate 3 units of substance v , i.e., the autocatalytic proliferation of v)

$v\rightarrow p$ (Substance v decays over time or converts into inert substance p)

Here u can be considered as food and v as cells. The system needs to constantly feed u back into the environment and eliminate surplus v in order to maintain the reaction. These two processes are equivalent to the two most significant parameters of the model design:

(1)**Feed rate (f):** This is the amount of u that is fed into the system. The higher f , the more food

available and the easier it is for the texture to fill space.

(2) Decay rate (k): The rate at which substance v decays or is removed. The larger the value of k , the faster v disappears and the harder it is to keep the texture and the formation of sparse structures.

2.2.2. Pearson Classification and Parameter Phase Transitions

The interesting feature of the Gray-Scott model is that even a small change in the combination of f and k values can result in drastic changes in the morphology. This relation between the parameter range and the pattern morphology is often expressed by using Pearson classification (parameter phase space) as shown in Figure 4.

Spotted state: If f is moderate and k is large, then the inhibitory effect will be dominant. The activators are only activated at some local regions and form circular spots on the surface. This kind of pattern is similar to the spotted animals.

Striped and Labyrinthine States: The effective range of action increases with the increase in f or decrease in k . Separated points start to link up together, creating uninterrupted labyrinth-like structures that look like fingerprints or brain folds. Such patterns have a particular aesthetic appeal in product texture design since they are visually continuous and structurally coherent, which is especially evident in the Pearson / 0 model.

Chaos and Solitons: When the parameters are taken to some value, then it can be seen that as we increase the parameters the lines will start to disappear. The texture is now characterized by splitting and merging of the lines which makes the texture more fluid in nature.

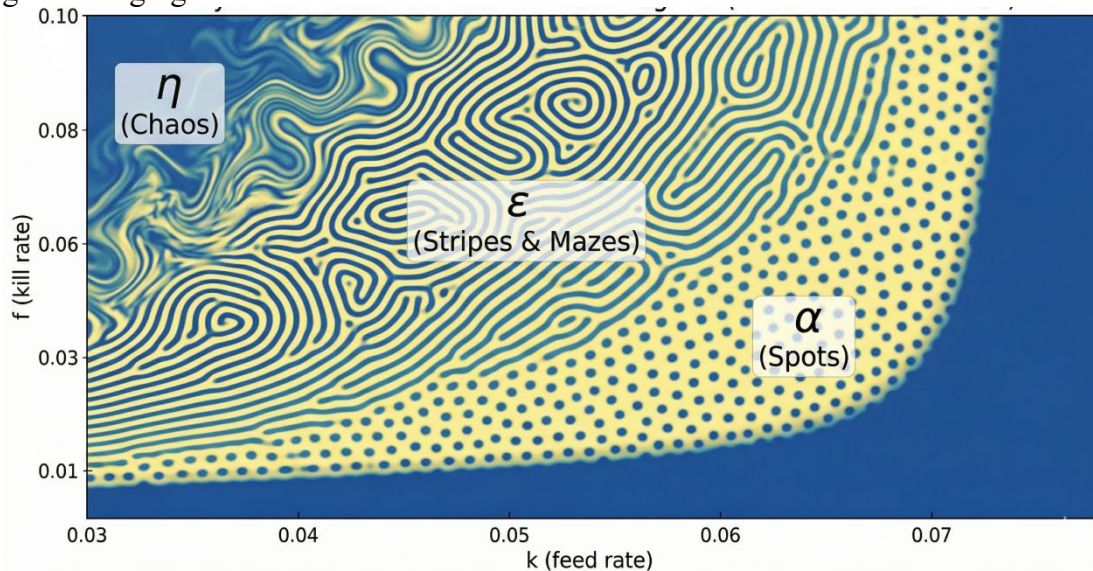


Figure 4. Pearson Classification of the Gray-Scott Model (Drawn by the author)

(The value [0.03-0.07] is shown on the x-axis and the value [0.01-0.1] is shown on the y-axis. This demonstrates the distribution of the region [spots], region [stripes], and region [chaos]. This diagram is an intuitive illustration of the fact that with just sliding two numbers one can travel a huge design space between order and disorder.)

2.2.3. Digital Solution and Discretization

In the case of using this model in the parametric software (Rhino Grasshopper or Houdini), the partial differential equations need to be converted and solved with the help of Laplace operator. The product surface is divided into a number of small mesh faces, i.e. cells, which are subdivided into tens of thousands of cells that store the present concentration values of u and v . The algorithm will update the concentration of every mesh by iterative computations and finally map the concentration levels (0. 01. 0) to geometric characteristics.

To sum up, the Gray-Scott model is not a simulator but rather a parametric design program. The two genetic parameters f and k can be adjusted to any value and the designer will be able to generate any complex texture that is in line with the natural laws of evolution and also meets the

industrial needs of production.

3. Parametric Generation and Control Strategies for Product Surface Textures

Texture design in the real product development process is not just an image mapping anymore, but it is a systematic engineering process that involves complicated surface calculation, parametric logic control and digital manufacturing. This chapter will create a full workflow between mesh growth to gradient control and lastly to entity construction.

3.1. Manifold Mesh-Based 3D Growth Algorithms

In order to implement RD textures in the design of products, the main issue that should be solved is the problem of mapping. Conventional texture processing tends to use UV mapping technology where a 3D surface is unwrapped into a 2D plane to paint it with texture and then rewrapped on the 3D model. But in case of products having complex topological structures (handles with undercuts or double-curved headphone shells), UV mapping inevitably leads to stretching and discontinuity of texture at poles or seams which destroy the continuous aesthetic of natural textures.

3.1.1. Mesh Simulation

To overcome the topological restrictions of conventional UV mapping techniques for creating textures on complicated surfaces, we employ the Reaction-Diffusion on Surfaces technique suggested by Turk (1991) in an original way, carrying out repetitive computation straight on the 3D manifold mesh [2], free from the limitations of 2D parameter space. The product surface is discretized into a dense triangular mesh in the pre-processing phase, and texture generation on 3D surfaces is realized. Different from ordinary operations based on the X YXY coordinate system, this algorithm makes full use of the mesh topology structure to efficiently compute substance concentration via vertex connection. Specifically, diffusion computation in the triangular mesh is accomplished through the weighted average between a vertex and its adjacent vertices based on the Laplacian Operator (as illustrated in Fig. 5).

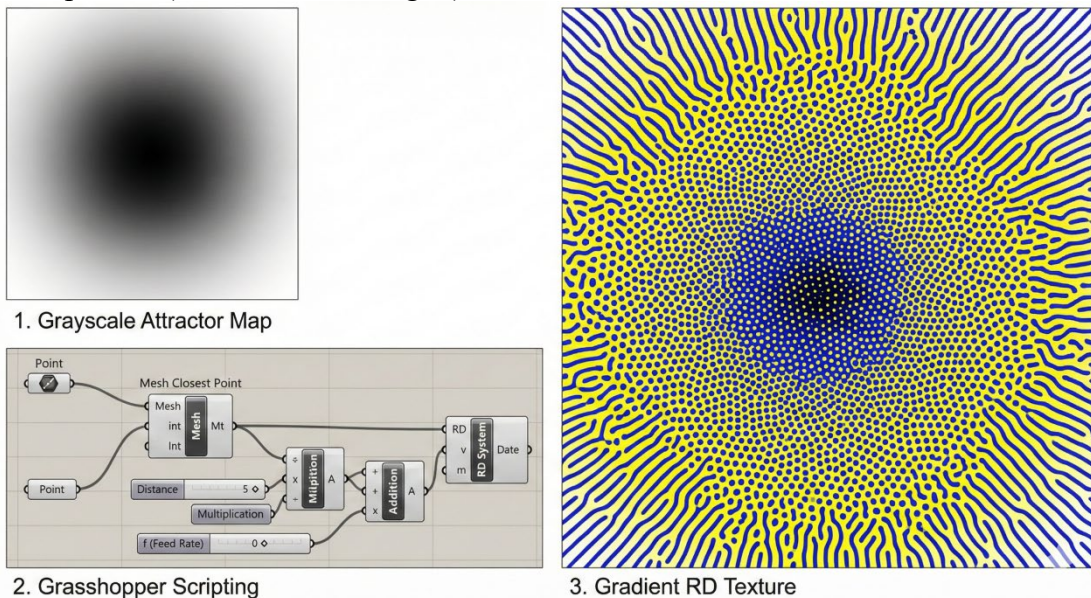


Figure 5. Mesh simulation process and effect presentation(Drawn by the author)

This is an effective way of calculating the surface in 3D. On the one hand, because this process of calculation is strictly according to the geometric characteristics of the surface, the growth direction of texture can be extended on the tangent plane of the curved surface; on the other hand, no matter how complex and changeable the product form is, the texture of the surface can be made locally isotropic and globally continuous, which solves the problem of seams that are hard to avoid. The experimental results show that it is possible to achieve perfect adaptation to any kind of complex product surface with a certain degree of uniformity of the details of the textures.

3.1.2. Mesh Subdivision and Calculation Accuracy

The simulation accuracy is based on the mesh resolution. In order to achieve a delicate grain effect, the original CAD model has to be re-meshed so that all the edges of the mesh have equal length. Usually, one mesh unit should be smaller than the size of expected texture detail (e.g., when the minimum texture feature is 1mm, it is suggested to regulate the mesh edge length in the range of 0.2mm-0.3mm). Although this makes the computation more expensive, it guarantees fidelity of details in the morphogenesis process.

3.2. Gradient Control Based on Interference Fields

In the industrial design, evenly distributed textures are usually non-functional and visually tense. To satisfy ergonomic and aesthetic demands, one should implement non-linear control measures, namely, using Interference Fields to intervene in the parameters of the RD system locally and thus obtain gradient changes in texture morphology.

3.2.1. Construction of Spatial Interference Sources

According to the research conducted by Witkin and Kass, it is possible to direct the texture generation through anisotropic terms or spatially varying parameters in reaction-diffusion equations[3]. This paper develops two primary sources of interference:

(1) Geometric Attractors: Points, curves, or surfaces are designated as interference sources in 3D space. The Euclidean distance d from the mesh vertex to the interference source is computed.

(2) Image Samplers: A gray scale image (0-255) is used as data source and mapped on the UV space of the product surface to retrieve the brightness value L at each position.

3.2.2. Spatial Heterogeneity Mapping of Parameters

The central parameters of the Gray-Scott model feed rate (f) and kill rate (k) are dynamically remapped using the distance d or brightness L obtained earlier as weighting factors.

For instance, to generate dense spots in the grip area of a handle and sparse stripes in the peripheral area, the following mapping function can be established:

$$f(x) = f_{base} + \alpha \cdot L(x).$$

where, x is the mesh vertex position, $L(x)$ is the control image grayscale value at that point and α is the adjustment coefficient. Thus, as a result of the smooth transition of the grayscale, the α value will change continuously on the mesh and the texture will smoothly transition between the spot state and the stripe state or even the blank state, achieving intelligent design in the real sense of form follows function, as illustrated in Figure 6.



Figure 6. Game Controller (Drawn by the author)

3.3. Materialization of Textures and Manufacturing Constraints

After calculation by the RD algorithm, the remaining color information at the mesh vertices (Concentration Value, generally a floating-point number between 000 and 111) needs to be translated into solid geometry with real thickness for mold making or 3D printing. In order to close the loop between digital simulation and physical realization, such a translation from fields of data to solid geometry still needs to be completed in the design procedure. It is not a format conversion, but a necessary step of geometric reconstruction and validation under engineering constraints: firstly, abstract concentration values should be converted into accurate 3D topology; then the geometry should be physically corrected according to different processing techniques to guarantee the manufacturability of the generated complex textures instead of just being visible.

3.3.1. Geometric Reconstruction: From Scalar Fields to Watertight Solids

The path from data to geometry generally moves from direct mapping toward volumetric computation.

The most basic method is displacement mapping in which the vertices of the mesh are displaced along the surface normal to a concentration value. It is computationally simple, but with RD textures having high degree of curvature and porous connections it can easily lead to self-intersections or non-manifold geometry, as well as loss of model integrity.

In order to eliminate these topological issues, this paper employs voxelization and Marching Cubes algorithm^[4]. The triangular mesh that contains concentration data is first transformed into a 3D voxel field and the geometric shell is then extracted by establishing an isosurface threshold. This procedure assists in smoothing out sharp noise created during computation as well as creating closed watertight solids^[5]. It can especially be applied to RD textures with connected pore structures and gives a more accurate model of further fabrication.

3.3.2. Engineering Verification: Design for Manufacturing (DfAM)

The physical manufacturability is not the same as geometric perfection of a digital model. Oxman has put forward the multi-scale manufacturing theory which states that the design of digital materials should be strictly consistent with the physical resolution and material properties of the manufacturing equipment^[6]. Thus, process constraint logic needs to be added at the stage of materialization:

(1) In the case of Injection Molding: The use of laser texturing process on the mold is a potential risk of undercutting texture. RD textures are by their very nature, they are not easy to demold because of their natural organic shapes. There is need to have algorithms that can identify and constrain the depth of growth of normal in the form of texture or make it into a bas-relief shape with draft angle analysis.

(2) In the case of Additive Manufacturing: When stereolithography (SLA/DLP) 3D printing is used, the key issue is the minimum feature size. When the pore diameter of the micro-pore structure generated by RD is less than the surface tension limit of the resin (e.g., less than 0.5mm), there is a high possibility that it will clog or lose details during printing. At the same time, overhang angles will be too excessive to allow the slicing software to place support structures, which will destroy the quality of the inner surface of the texture. Thus, parametric program should have an operator known as a thickness analysis which automatically removes or fixes tiny features beyond process limits.

The Reaction-Diffusion mechanism is ultimately able to translate the abstract mathematical model into a manufacturable industrial product with the help of the dual processing of geometric reconstruction and engineering verification mentioned above.

4. Application Practices of Reaction-Diffusion Textures in Different Product Categories

To validate the generality and efficacy of the RD mechanism in industrial design, we choose two typical product categories in this chapter for empirical study: one is a smart home product (Smart Speaker) related to visual semantics and acoustic performance; the other is a handheld tool (Power

Tool) concerning ergonomics and physical performance. These two cases show different strategies of the RD algorithm in handling aesthetic expression and functional optimization, respectively.

4.1. Visual Aesthetics: Smart Speaker Skin Design Based on Acoustic Visualization

4.1.1. Design Background and Semantic Construction

The smart speaker is not the device to play audio but a feeling center of the human-machine interaction in the ecosystem of the smart home. The conventional speakers are usually made of homogeneous fabric or metal grid and are rather plain in shape. The present case will attempt to materialize the sound, i.e., to explain how one can represent the meaning of the sound flow by the natural texture of the product shape. RD textures have a natural cross media synesthesia with the characteristics of dynamic nature of sound waves because they possess the sensation of biological growth and constant flow.

4.1.2. Parametric Implementation Strategy

The design process adopts a "data-driven generation" logic, mapping intangible sound wave data into tangible geometric interference fields:

(1) Data Acquisition and Processing: A representative sample of audio (e.g., the climax of a symphony) is chosen, and its frequency and amplitude data are extracted through Fast Fourier Transform (FFT).

(2) Interference field mapping: The amplitude intensity of the sound wave is mapped as a grayscale gradient map onto the cylindrical skin. High amplitude areas map to high grayscales, acting as strong interference sources to the RD system.

(3) Algorithm generation: In the interference source regions the ff parameter of the Gray-Scott model is adjusted on-the-fly to generate maze-like textures with high porosity and large openings; in calm regions of low amplitude dense and fine bone-like textures are generated.

4.1.3. Comprehensive Effect Evaluation

Acoustic Performance Optimization: This non-uniform random maze structure is a complex diffraction grating acoustically. The irregular edges of the RD texture compared to regular meshes allow for the diffuse reflection of high-frequency sound waves, which in turn effectively eliminates standing wave interference within the cavity and enhances sound purity.

Visual Aesthetic Expression: Along with internal LED breathing light effects, light is cast through the organic pores of the RD texture- like coral skeletons- producing a dappled and layered effect of light and shadow. Such dynamic visual experience, which is life-like, increases significantly the technological aesthetics and liveliness of the product. (As shown in Figure 7).



Figure 7. LED Lamp (Drawn by the author)

4.2. Human-Computer Interaction: Functional Gradient Textures for Power Tools Based on Pressure Distribution

4.2.1. Design Background and Human-Machine Contradiction

Power tools (e.g., impact drill, electric screwdriver) require very stable grip under heavy-load operation. Conventional designs commonly use homogeneous knurling or graining. However, this design often compromises between anti-slip performance and comfort: deep texture avoids slip but causes pain and imprint on hand; shallow texture fails to combat reaction force and hand sweat during operation. Thus, the design goal is to build an intelligent gradient texture that matches the physiological features of human hand accurately.

4.2.2. Parametric Implementation Strategy

In this instance, ergonomic data are incorporated into the RD system as boundary conditions in order to make texture formation more consistent with functional demand as demonstrated in Figure 8.

(1) Pressure Heat Map: The heat map of pressure is based on the measurements of the grip sensors that are under normal working conditions and then converted to a color-coded heat map. Red spots in this case are used to denote the places where there is more pressure, including the thumb web and the pad of the thumb, and blue spots are used to mark the less pressurized parts, including the side of the handle.

(2) Morphological Parameter Regulation:

High-Friction Zone: The higher values in the pressure map are attributed to certain f and k combinations (such as $f = 0.03$, $k = 0.06$) which cause the system to be driven into more intense and compact spot-like states. This raised texture increases the area of contact with the skin thus assisting in increasing the coefficient of static friction.

Comfort Zone: In the low pressure regions of the hand, the raised ridges are not so high as in the case of high-pressure areas. This is because this will allow it to increase the surface area and spread out the force on the palm and decrease the chances of developing a mark on the palm with an extended period of holding on to something.

4.2.3. Comprehensive Performance Evaluation

Tribological Properties: The simulation analysis of the non-uniform RD textures can increase the grip stability in the most stressed areas by about 15% as compared to the uniform knurling.

Moisture Wicking and Thermal Control: The channels that are created by the RD texture of a labyrinth-like structure will allow it to absorb some sweat. Sweat is wicked along the grooves of the texture during its use, and not on the surface of contact. This feature makes the wicking process less slippery, which in turn improves the safety of operations and comfort of grip.

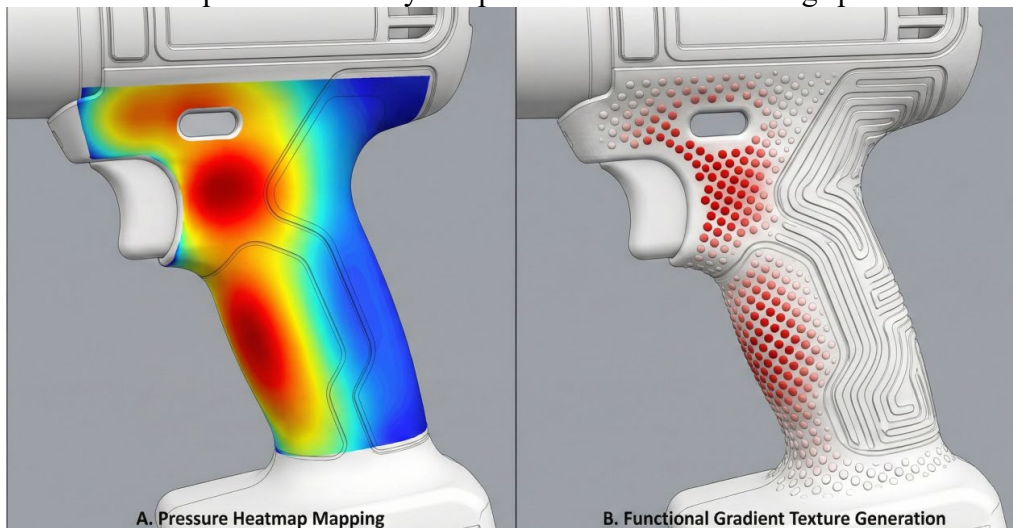


Figure 8. Analysis of Handle Pressure Mapping and Texture Generation (Drawn by the author)

Image Description: The left image is a digital thumb model with a pressure heatmap. Red areas represent the main pressure points which are localized at the base of the thumb and the pad of the thumb. On the right side, the generated physical texture model can be seen, whose surface morphology is slowly changing according to the distribution of pressure, between a raised, spotted structure and a smoother, striped structure. This change is an indication of functional differentiation of the hand in the process of gripping.

5. Conclusion

5.1. Research Overview

This paper is a research on the design of product surface texture, which was based on the reaction-diffusion (RD) mechanism and included a complete workflow of designing the surface textures, mathematical modeling, parametric generation and physical fabrication. The analysis of Gray-Scott model enabled the chemical self organization to be converted into a digital form that can be controlled in the design process. It has been found that the interference fields have an ability to modify the local parameters in the RD system so that two-dimensional image data can be turned into three-dimensional manifold meshes. This procedure also helps to convert the outputs of algorithms into manufacturable surfaces with the help of manufacturing constraints.

5.2. Value Reconstruction

One of the important contributions of this study is the fact that RD mechanisms are not treated as a decorative tool but as an organization of complex surface topologies with a balance between functional and aesthetic needs. The texture generation based on RD seems to be more appropriate in dealing with complex surfaces than the traditional geometric modeling and texture mapping since such problems as stretching and visible discontinuities are common in these cases. Another feature that can allow a surface system to react to various performance needs, such as acoustic diffusion, heat dissipation, and friction associated with grip, is parametric gradient control. In this respect, the current paper proves that there exists a stronger relationship between product functionality and surface formation.

5.3. Limitations and Outlook

There are still some limitations for applying RD algorithms in product design. Firstly, high resolution 3 D3D3D simulation needs a lot of computing resources, thus real-time feedback is not possible during the design phase. Secondly, concerning industrial production, although additive manufacturing can provide a large design freedom, mass production is still dominated by injection molding. Five axis laser texturing with micrometer precision is still quite expensive and this might limit its use in low-cost consumer products.

In the future, the two technologies will be combined with artificial intelligence and computer graphics to create a new generation of computing that will replace the computational bottleneck in the form of neural networks by using deep learning technology. Moreover, as biometric system is introduced into the design system, the users will be able to load their own customized data on the system and the system will automatically produce the personalized RD texture which will fit them perfectly. This will lead to the change in product design of industrial aesthetics to more human centric intelligent digital organisms.

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