Design Studies and Intelligence Engineering
L.C. Jain et al. (Eds.)

doi:10.3233/FAIA220709

Dynamic Texture Design Method Based on Fresnel Optical Principle

Fangwei Xu,[a] and Xiaojian Liu[b1]
[a] *Zhejiang Zhaoyi Technology Co., LTD*
[b] *Zhejiang University of Technology, China*

Abstract. To make 3D visual texture effect of surface with bare eye in the plane thickness of micron-level, based on Fresnel optics principle, for conventional free-form surfaces, the continuous surface "collapse" method of reducing the thickness of the Fresnel lens is prone to large areas of visible segmentation planes and the problems that the visual effects of the designed micro-textures are difficult to predict. In this paper, a unit texture construction method is proposed, which differentiates the free-form surface into square mesh cells whose size is smaller than the smallest size that can be recognized by human eyes. The micro-surface in each element is approximately treated as a square column with inclined plane at the top, and the normal vector of the inclined plane is close to the synthetic normal vector of the micro-surface. Then, according to the limit of the design thickness, the inclined plane column is "collapsed" to ensure that one end of the inclined plane touches the bottom, and the height difference of the inclined plane in the unit is less than the designed thickness. Finally, the light source is set for the completed gray image file. The brightness of each point in the image file is inversely proportional to the angle between the point normal vector and the light source, and the visual dynamic rendering effect of the overall scheme simulation is obtained by rotating the light source. The validity of the proposed method and the effectiveness of the simulation results are verified.

Keywords. 3D vision, Fresnel optical principle, free form surface, normal vector

1. Introduction

Micro-texture design is a very important part of CMF design. The reasonable design of surface texture structure can make the product present a vivid and spatial visual effect, which can effectively improve the texture of the product. In the current series of surface micro-texture processing technology, gray scale lithography has become an effective method to manufacture and process 3D micro-structures because of its high processing precision (the minimum can reach nano-meter level), which can cover the whole process of transmission, processing, and formation of micro-patterns. However, grayscale lithography is relatively limited in the depth of processing textures, generally tens of microns. The problem caused by this is that the surface texture designed by the conventional undulating method at the micron-level height is extremely limited in the final light effect. In addition, the cost of grayscale lithography proofing in the adjustment of the texture design scheme is relatively high.

[1] Corresponding Author, Industrial Design Institute, Zhejiang University of Technology, No.288, Liuhe Road, Hangzhou, Zhejiang, China. E-mail: crazylxj@126.com

In this paper, the texture "collapse" based on Fresnel optical principle is carried out in the design of a free-form surface, and the visual simulation of the actual effect of the design scheme is carried out before proofing to solve the two problems of the texture design of free-form surface in grayscale lithography.

In the design of an optical lens, the thickness of the Fresnel lens is thinner than that of a conventional lens. The way to reduce the thickness of Fresnel lens is to "collapse" the whole surface. So that the normal vector of each point in the plane is the same as that of the corresponding conventional lens. But in the same way, when dealing with the free-form surface directly, it is easy to produce irregular and continuous grooves, which will affect the final visual effect. Therefore, this paper adopts the processing method of unitized segmentation, differentiating the surface into a grid of square area cells invisible to human eyes, and "collapsing" each cell separately, the results show that the height difference of the inner points of the unit is within the design height, and the normal vector of each point is close to the normal vector of the original surface, to avoid the generation of separation lines which affect the visual aesthetic feeling, and obtain the light effect similar to the original surface; In addition, the preliminary effect simulation preview is carried out for the completed design drawing file, and the brightness of each point under the given light source is calculated. The overall simulated dynamic lighting effect is output by rotating the light source, which reduces the number of proofing, reduces the cost of the design cycle, and widens the possibility of CMF texture design.

2. Related Research

Grayscale lithography is an important way of micro-texture processing. Compared with the ordinary lithography mask, the transmittance of the mask is only 0 or 1. The light transmittance of different positions of the mask used in grayscale mask lithography is different. After exposure and development, the three-dimensional micro-structure can be obtained[1-3]. In this way, Kick developed a new photoresist for grayscale lithography and used the photoresist to quickly and easily fabricate 3D structures with high complexity[4]. Hamid improves the hydrophobicity of PDMS material surface by micro-patterning of 3D soft materials by gray level lithography[5]. Chevalier, P developed a lithography model based on python and verified the ability of grayscale lithography mask to fabricate 1-3 um micro-structures[6].

For material thinning, because the refraction of light only occurs on the optical surface of Fresnel lens, the intermediate material is removed based on retaining the curvature of convex lens optical surface, and the transformation from spherical lens to planar lens is realized[7].

In terms of micro-texture, it has become an important part of product CMF design in recent years. Kooroshnia, M developed a hybrid strategy to further discover how to promote the relationship between texture and color in complex textured surface design[8]. Zhang, L demonstrated the feasibility of using the surface texture to imitate the tactile friction between wood and skin[9]. Brodsky,A introduced A simple general-purpose optical element design for laser surface texture, which can be used in some custom patterned designs[10].On the other hand, Chan JYE proposed a two-photon aggregation lithography method to achieve high-resolution optical field printing, which is a step forward to ultra-realistic 3D images[11]. Chen LY proposed a large-scale micro graphic printing process based on PS plate and UV transfer printing, which matched with MLA prepared by micro nanoimprinting process, and achieved the effect of three-dimensional naked eye display[12].

It can be seen that micro-structure has its unique features in presenting the special 3D visual effect and touch in the product CMF design, and the grayscale lithography can effectively help the designer to realize the texture structure of the micro nano scale designed by the designer.

3. Modeling Principle of Unit Fresnel Mirror

The core design idea of this paper is to use the optical principle of Fresnel lens. Differential surface first, then the normal vector of each micro surface after differential unchanged, eliminate the thickness of the material, keep the surface of ups and downs height difference within the limit height, when observed under light and the eye as much as possible to keep the surface of 3 d visual features. Finally, the light effect of the output design scheme is simulated, as far as possible to save the cost of the actual proofing test.

Due to the actual processing of surface texture in a series of methods, it is a common design format to provide a plane gray image to express the design texture structure. The gray level is expressed by 8-bit binary number, 0 corresponds to the lowest point, 255 corresponds to the highest point, and the actual size of the pixel is determined by the actual processing accuracy, as shown in Figure 1.

Figure 1. Gray level corresponding height.

Therefore, the expression of each texture model in this paper also follows the expression of plane gray image. The main steps of texture design are as follows :

3.1. Design of Micro-cell Morphology

Before the micro-unit form design, the Fresnel lens type of surface treatment can have two ways, one is the unit of curved surface differential, another is the whole direct to the Fresnel type "surface subsidence process", that is to say, gray "collapse" processing is carried out on the positions whose height exceeds the design height in the gray matrix representing the height. The simplest way to do this is to divide the excess height by the maximum height of the design and then take the mod. After processing a grayscale design drawing representing a lens in this way, a grayscale design drawing similar to Fresnel lens can be obtained, as shown in Figure 2.

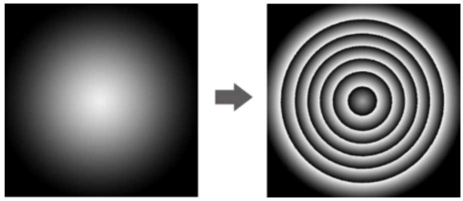

Figure 2. Convex lens to Fresnel lens.

However, if it is a free surface form, the collapse of the curved surface is directly processed, and the collapse edge is prone to appear continuous planes with different areas. As shown in Figure 3, when the divided surface area is larger than the human eye's distinguishable size, the macro characteristics of texture segmentation edge will appear, which will produce processing defects similar to texture defects, which will affect the aesthetics of the surface effect.

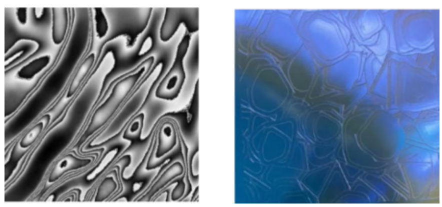

Figure 3. Texture segmentation aliasing.

Therefore, in the treatment of free-form surface, this paper first uses the micro-element method to divide the surface, in which the organization structure of the micro-unit adopts the simplest orthogonal checkerboard. In order to avoid the human eye observing the segmented unit in the actual production, the size of the unit should be smaller than the minimum resolution size of 73um under the naked eye. However, the micro-surface obtained by element partition is approximately treated as an inclined plane, and the normal vector of the inclined plane is approximately equal to the normal vector of the original micro-surface. From a three-dimensional perspective, the three-dimensional shape obtained by the element is approximate to that obtained after the square body is oblique cut. In the top view, there is only one inclined plane and no other plane, as shown in Fig. 4. Then the brightness of the unit under illumination only needs to consider the oblique section of the top surface, which simplifies the design and evaluation of the overall lighting efficiency of the unit.

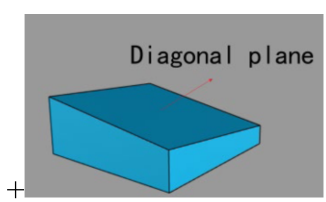

Figure 4. Diagonal cut back square column.

3.2. Grayscale Representation of Micro-unit

After determining the basic morphology of the micro-unit, the unit with only one oblique section is expressed in the form of plane gray. The core work is to fill the square cell with the pixel with linear gray gradient. Before the design, it is necessary to define some basic settings, including the size of the micro-unit and the processing accuracy (that is, the actual size of a single pixel). The square edge length selected in this paper is 50um, the actual processing accuracy is 0.5um/pixel, then the number of pixels in each cell is 100 * 100 pixels, and the maximum height of texture processing is set as [Z].

Firstly, it is necessary to determine the gradient direction of linear gray level change and establish the plane rectangular coordinate axis with the center of the micro-unit as the coordinate origin. The direction of linear change is obtained by the plane projection of the normal vector direction of the divided micro-surface on the bottom surface, as shown in Figure 5.

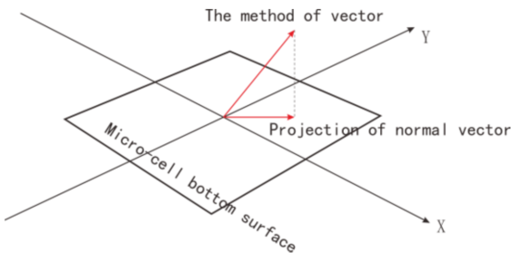

Figure 5. Spatial coordinate model.

The normal vector direction of the micro-surface can be approximately obtained by the normal direction of the plane composed of three points on the surface if the differential element is small enough. The formula for finding normal vector of three points is obtained by cross product of vector：

$$\vec{n} = \overrightarrow{P1P2} \times \overrightarrow{P1P3} \tag{1}$$

Where P1, P2 and P3 are three points on the micro-surface, $\vec{n}$ is the normal vector of the micro-surface and the direction satisfies the right-hand spiral rule. Then calculate the length L of the gradient path, as shown in Figure 6.

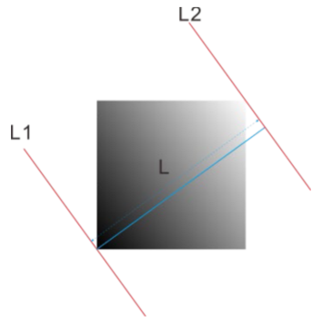

Figure 6. Gray gradient path.

In order to ensure the full application of 255 level gray level and not produce pure black or white horizontal plane, leading to the wrong estimation of optical characteristics of the whole micro-unit, the beveled edge, that is, the two parallel red lines shown in the figure, need to include the square without intersecting. The highest and lowest points of the inclined plane will appear at the corner of the unit. The selection of the lowest point corner point is in the same quadrant as the projection of the normal vector of the inclined plane. The linear equation of the red line L1 passing through the point can be obtained by two points on the straight line. The other point of the line can be obtained by translating a certain distance along the projection direction of the normal vector of the inclined plane and rotating 90 degrees around the corner point, The corner of the highest point is selected in the diagonal direction of the lowest point, and the linear equation can be obtained in the same way. The calculation method of the gradient path L between two red lines can be obtained by the general equation of the two lines：

$$L = |C1 - C2| / \sqrt{A^2 + B^2} \quad (2)$$

For the gray level of a certain position in the micro-unit, the conversion of the gray level can not be directly calculated in proportion, but the height should be calculated first and then converted to the corresponding gray level. The reason is that the change of height is continuous, and its accuracy is higher than that of grayscale transformation. In addition, the dimension of height is the length dimension, which is consistent with the dimension of element bottom surface, so as to ensure that the normal vector does not deform. Before obtaining the height of this point, it is necessary to know the height of the highest and lowest point of the micro-unit, which is located at the corner where two red lines pass through. The height of the lowest point is 0, and the height of the highest point is:

$$Z = \frac{L}{\tan(\gamma)} \quad (3)$$

γ is the angle between the normal vector of the surface and the XY plane. When γ is very small, the calculated Z value exceeds the maximum depth [Z] set by machining, L needs to be segmented so that the height of the inner point of each segment is not beyond the maximum limit depth of machining [Z], as shown in Fig. 7, the left position of two Fresnel lenses, in which the lower lens subdivides an inclined plane into two small inclined planes, which reduces the overall thickness but does not change the normal vector of the surface.

Figure 7. Schematic representation of Fresnel lens.

Finally, the height of a point P in the micro-unit is calculated as follows:

$$H = \frac{L_P}{\tan(\gamma)} - \left[\left(\frac{L_P}{\tan(\gamma)} \Big/ [z] \right) \right] * [z] \tag{4}$$

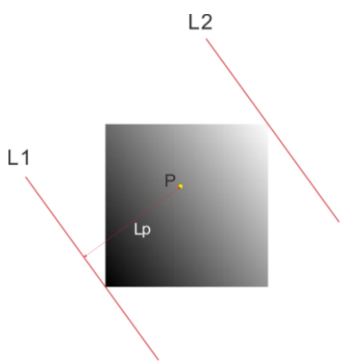

Figure 8. P point gray calculation.

As shown in Figure 8 above, L_P is the distance between this point and the red line at the lowest corner point. The final calculation of H is to take the remainder after dividing [Z] by H to ensure that the calculated height always does not exceed [Z]. After this calculation, the saw-tooth effect is similar to that after the Fresnel lens segment collapse is formed. According to the calculated H, the maximum height corresponding to the processing is converted into a gray value of 0-255. In addition, since the denominator cannot be 0, there can be no horizontal normal vector on the surface.

3.3. Surface Gray Output

After determining the basic form of micro-cell partition and the expression method of cell gray level, the following is the output of the gray level scheme for the overall segmentation of the designed free-form surface. Taking the gray output of 3D ripple surface, which is a typical surface model in texture design, as an example, the maximum height of surface undulation is 100um. Firstly, the coordinates of the ripple center should be given in the plane space, and the period P of the ripple should be set, Then, the height information Z of the point is calculated according to the distance D of each point from the ripple center, and then the height information is converted into the gray value in the output. The calculation method of Z is as follows:

$$Z = \frac{(1 + \sin(\frac{D}{P} * 2 * \pi))}{2} \tag{5}$$

For the interference ripple of two waves, only two centers need to be set, and the height value Z can be simply added. In order to ensure that the Z value after superposition is between 0-1 in the calculation of gray value, it is necessary to divide the superposed value by the number of ripple centers to ensure that the gray value conversion does not exceed the boundary. The gray output after setting two ripple centers and periods is shown in Figure 9.

Figure 9. Ripples in gray.

When the maximum processing depth is set to 20um, the gray output after micro-unit division processing is as follows:

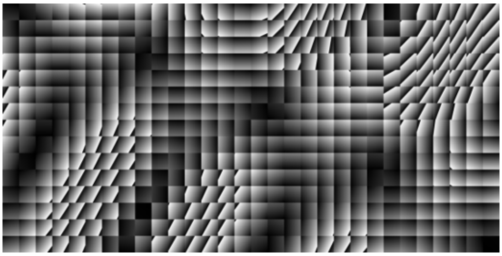

Figure 10. Ripple gray level (after unit processing).

4. Visual Simulation

After the surface is divided into micro-elements, the optical effect of the designed surface can be achieved in theory within the limit of machining depth. However, in the actual texture design, the high time cost and economic cost of processing require the texture designer to take full account of the design scheme. Therefore, it is necessary and practical economic value to carry out some optical simulation on the output texture model gray level before processing. However, some existing conventional 3D model renderers are not targeted at micro-texture structure, and their time and computational cost are unacceptable when faced with such a large number of units and tiles. Based on this, on the basis of the design of micro-texture gray scale scheme, this paper carries out a preliminary imitation of the truth before processing.

4.1. Optical Model of Simulation

First of all, the paper shown in the optical simulation before the object is the designed plane gray scale file before micro-texture processing, for the interpretation of the model of gray level corresponds to the actual machining in practice, the gray level of grade 256 for the position of the height, based on this, the light and shade of the point are calculated, so as to produce visual reality without 3D modeling of micro-texture to test the design effect.

For the completed grayscale image file, the following settings are given. Firstly, the light reflected by each micro-unit is uniform diffuse reflection, that is, the brightness of a point is independent of the observation angle; Secondly, when the dynamic light effect is output, the viewing angle remains unchanged, and the visual effect moving diagram is given by moving the set light source; Finally, in order to get closer to the texture effect observed by the human eye, the light and shade of a pixel output in the simulation map actually corresponds to the brightness fusion of each point on the smallest discernable dimension unit of the human eye on the texture. For example, in FIG. 11, under the setting of laser spot with processing accuracy of 500nm, the 50 * 50um square cell corresponds to 100 * 100 pixels in the gray image file. As the final simulation output, the points in the 100 * 100 area are fused into a bright point, and the fusion method is to calculate the average of the 100 * 100 pixels.

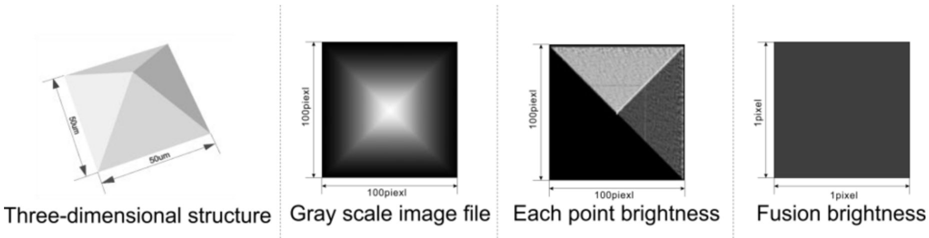

Figure 11. Brightness fusion.

After the basic assumption is completed, it is necessary to give the position of a light source. The light source can be a point light source or a parallel light source. In this case, the light source is set as a parallel light source, and the light direction is a three-dimensional vector $\vec{v}$ to express. The brightness of each point on the textured surface is inversely proportional to the angle between the normal vector and the illumination vector. When the angle is 0, it indicates that the point is in the state of direct light, and the brightest point is pure white. When the included angle is more than 90 degrees, it means that the point is in the shaded state, which is pure black. Therefore, for the illumination simulation of texture surface gray output, we only need to calculate the angle between each point surface vector and light vector, then calculate the gray level of each point according to the angle, and output the light effect information of each point in each unit after fusion.

In this method, the solution of the point vector on the surface is the same as the above method.Finally, the dynamic effect of texture observation under parallel light can be obtained by setting the illumination vector to dynamic change.

In addition, color information is added on the basis of the gray level of the rendering effect, that is, a color point is added to the line with only light and dark gray changes in RGB space, and the head and tail are still black and white points, but the mapping object is no longer a straight line directly connected with the head and tail, but the head and tail points are connected with the color point to form a broken line.

4.2. Simulation Results of Fresnel Mirror

The following figure shows the lighting preview effect of light sources with different angles after the ripple surface unit is differentiated:

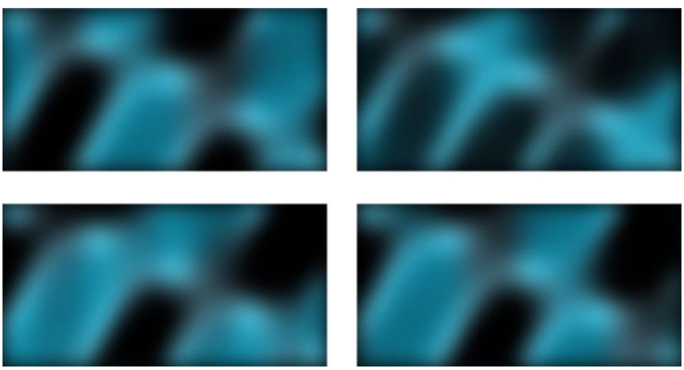

Figure 12. Rendering of light sources from different angles.

5. Application Cases

This paper shows that the ripple surface effect in the case has been verified by gray-scale lithography. The following figure shows the measurement results of micro-structure after lithography under different multiples of laser confocal micro-scope.

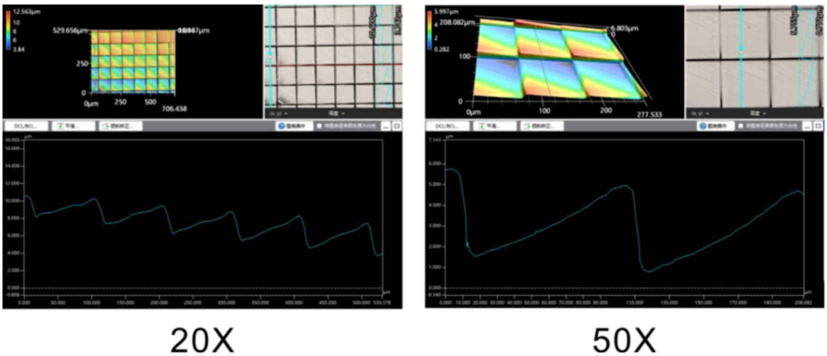

Figure 13. Microscopic survey chart.

From the three-dimensional results of micro measurement, it can be seen that the topography of lithography basically conforms to the designed unit model, and the simulation light effect of visual effect simulation in this paper is also close to the actual texture light effect.

6. Conclusion

The method of surface segmentation based on Fresnel optics proposed in this paper can be well applied to the texture dynamic effect design of micron-level highly free-form surfaces.In addition, the optical simulation of gray scale scheme before machining is also close to the actual visual effect after machining, which can effectively help reduce the design cycle and cost.

The disadvantage of this method is that there are some limitations in using Fresnel mirror to express the surface shape. The normal vector of a point on a free-form surface may face any direction, but the downward normal vector is difficult to express by this method. When the normal vector is parallel to the bottom surface, the z-direction length of the slope will be nearly infinite, which is obviously not allowed either. In addition, due to the limitation of height in the same cell, there may be multiple segments of a serrated slope. The more segments are divided in the cell, the fewer pixels can be used for each segment, and the corresponding accuracy is also lower. This is also a problem that needs to be further considered and solved in the future.

For visual effect simulation, too many factors need to be considered in the simulation, including material characteristics, reflection, refraction, environment, and a series of factors, which need to be gradually added and improved in the next step.

Funding: This research was funded by The National Social Science Fund of Art, China, grant number 20ZD09.

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