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

doi:10.3233/FAIA250253

Research on Simulation Technology of CMF Design of Transmissive Materials Based on Gray Scale Lithography

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Abstract. It is a common method of product appearance design that transmission materials form specific visual effects through photolithography process. Designers face two major challenges in the design process:first, it is difficult to accurately grasp the relationship between microstructure and macro dynamic visual effects; second, the proofing process is time-consuming, high cost and low design efficiency. Therefore, based on the gray-scale lithography process and the computer-aided industrial design technology, the optical simulation model of transmission grating is established, and the dynamic visual effect simulation technology of transmission material CMF design is developed. The visual effect of transmission grating texture is simulated, and the dynamic image is output to help the designer quickly evaluate the design scheme before the actual proofing and reduce invalid proofing. In addition, the paper puts forward the method of unit texture design, summarizes the creative process of constructing texture from unit, and provides a creative path for designers. Through the practical application verification, the simulation system is true and reliable, improves the designer's work efficiency, and provides a new creative boundary for CMF design.

Keywords. CMF design, transmissive material, grayscale lithography, simulation, Computer Aided Design

1. Introduction

Applying grayscale lithography to transmission materials with uneven thickness, the microstructures of the outer patterns cause refraction of light, thereby producing new composite effects on the printed patterns at different angles. However, the preparation cost of microtextures based on grayscale lithography is relatively high, and the optical effects produced by the microstructures are quite complex. Designers find it difficult to predict the final combination effects of the textures and printed patterns, which affects design efficiency and outcomes. Therefore, addressing how to use intelligent design techniques to simulate the final effects of textures and underlying graphics on transmission materials is a topic worthy of research and of practical significance. This

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Funding: The National Social Science Fund of Art, China, Grant/Award Number: 20ZD09

paper aims to develop a dynamic visualization simulation system for CMF design of transmission materials to enhance the feasibility of design schemes.

2. Current Research Status

The research contents related to the technology to be developed in this paper are the display mode of gray mask lithography technology in CMF micro texture design scheme and the implementation mode of computer-aided industrial design in the field of CMF design simulation.

As a micromachining technology, gray-scale lithography can produce three-dimensional microstructure in photoresist. Gray scale lithography requires coating and exposure equipment, as well as at least one mask far below the tool resolution limit [1], [2],[3].Gray mask lithography corresponds to different light transmittance through different gray levels. At the same exposure time, due to the different gray levels, the corresponding exposure distribution is generated on the photoresist surface. After development, the corresponding three-dimensional micro nano structure can be obtained [4].At present, gray-scale lithography technology is mainly used in the production of optical components, chips and other components that need a three-dimensional micro nano structure on the surface.Ran he and other scholars proposed a method to produce micro structures with customized micro wavy patterns, which improved the efficiency of preparing chips with complex patterns [5].Tang Jiaxuan used gray-scale lithography to fabricate spherical microlens array. The gray-scale lithography technology and nanoimprint technology were studied through simulation and experiment [6].Xufangwei has developed an intelligent aided design system to assist designers in the design of gray-scale masks, which helps designers reduce some work pressure, improve the efficiency of texture design and reduce the proofing cost of enterprises [7].Through the gray-scale lithography technology, the surface micro texture can be prepared, and the light can be reflected, refracted or diffracted through the surface micro texture to achieve a certain function or produce a specific optical effect, which can be applied in the field of CMF design.

The texture design of CMF can be used for visual effect presentation. Simulation technology is an intuitive way of visual effect presentation. Fangwei Xu proposed a segmentation method of free-form surface using Fresnel unit, which can segment the free-form surface into micro textures with micron height and present dynamic optical effects on the material surface [7].Zhang Mi used genetic algorithm to study the CMF design of fabric woven materials and provided the rendering simulation method of woven texture materials, so that the rendering presented a 3D effect [8].Some scholars also proposed a real-time image space technology to simulate the refraction of the remote environment, and verified the effectiveness of the method by real-time simulation of refraction [9].The research on the simulation visual presentation of lithography micro texture design scheme is still very rare. The software of the lithography machine only has very simple functions, and does not support the preview of dynamic light effect. It is difficult for designers to predict the final combination effect of texture and printed pattern. Therefore, the research and development of special technology is very necessary.

3. Analysis of technical requirements for visual effect simulation of transmission materials

3.1. Technical requirements analysis

Gray scale mask lithography is a process technology that can produce different exposure on the surface of photoresist substrate by adjusting the transmittance of ultraviolet light at different positions [10].It is different from the ordinary mask method. It can accurately carve a three-dimensional microstructure [11].Based on the principle of gray-scale mask lithography, when using transmission materials to design CMF, designers can not be limited to the transmission materials of ordinary uniform gratings such as microlenses and cylindrical lenses, but also realize more special texture transmission materials by making gray-scale mask images of arbitrary shape textures such as uneven distribution of special textures.

This process technology enables designers to have a higher degree of freedom in texture design, but it also brings a problem. It is difficult to quickly confirm the effect. The complete texture proofing is completed, and the exposure and development processes need to be completed, which takes a period of time to complete, and then confirm the final effect, which leads to a long time for designers to confirm the effect. If the proofing or modification times are too many, it will waste a lot of time and cost of consumables. Therefore, before the gray-scale mask lithography technology, there needs to be an evaluation gateway to intercept the invalid scheme that deviates from the expectation, so that the designer can further optimize the scheme before the machine proofing, that is, preview the effect of any transmission material texture design, and predict the result. At present, the dynamic simulation technology for non-uniform transmission grating is not mature, and this paper studies it.

3.2. Dynamic visual simulation of transmission materials

Based on the above demand analysis, this paper will build an optical simulation system to assist designers to produce designs more efficiently, divergent design thinking, and produce more CMF design related ideas in the design stage. In the stage before design proofing, it will provide designers with preview of texture effects, evaluate design schemes, and save proofing costs. Therefore, the construction of CMF design simulation system for transmission materials based on gray-scale lithography will be studied in two directions: refraction optical model and dynamic visual simulation preview dynamic effect.

3.2.1. Optical simulation model of transmission grating

In optical analysis, the texture characteristics of transmission grating have an important impact on its optical modeling and image processing methods. For uniform transmission gratings, due to the consistency of their optical properties, a unified microlens model can be used to simplify the processing, which can be directly applied to image processing tasks. On the contrary, the optical properties of non-uniform transmission gratings show significant differences in space, and each point is equivalent to a microlens with unique optical properties. This difference requires a comprehensive traversal analysis of the lithographic gray image of the grating to ensure the accuracy of the optical characteristics and image processing. Therefore, in order to realize the special texture gray mask image designed based on gray-scale lithography process, different refraction effects produced by different textures on its surface make the base image superimposed with it have different deformation and produce rich texture effects. It is necessary to analyze the basic principle of light refraction, summarize the refraction model in optics, and make the system feedback the final superposition effect through the refraction model. By inputting an incident ray and a normal vector, the optical model can obtain the refracted ray. At this point, the designer can calculate the different appearance of the base print pattern through different textures on the surface through this simulation system, and these changeable results can stimulate more creativity of the designer again.

Because the simulation system needs fast calculation and fast output of design results, this study uses two assumptions for dynamic visual simulation. First, when constructing the refractive optical model, the line between the human eye and a point on the texture is regarded as the incident light, so as to calculate the new pixel points pointed by the refractive light. Secondly, the simulation system does not consider the influence of ambient light on the texture of transmission material when building the optical system, but only simulates the refraction of light generated by the texture of transmission material.

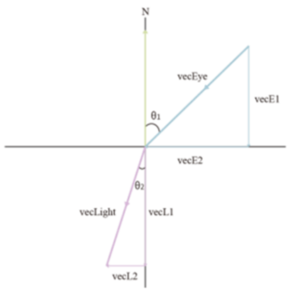


Figure 1. Refractive optical model.

The unit vector formula of refracted light can be derived from Figure 1:

$$\overrightarrow{vecLight} = \overrightarrow{vecEye} * \frac{1}{e} + \overrightarrow{N} * (\frac{cos\theta_1}{e} - cos\theta_2) \quad (1)$$

In Eq.(1), $\overrightarrow{\mathrm{vecEye}}$ is the incident light, $\overrightarrow{\mathrm{vecLight}}$ is the refracted light, $\overrightarrow{\mathrm{N}}$ is the normal vector, $\theta_1$and θ_2 represent the incident angle and exit angle of the light refracted at the junction of the two media, and e is the refractive index.

The human eye is in a real three-dimensional space when actually previewing the effect, and it needs to convert the two-dimensional picture information into coordinates in three-dimensional space [12].Therefore, to establish a solid space, as shown in Figure 2, all elements including material position, material shape, human eye position, projection plane position, etc., have coordinate positioning.

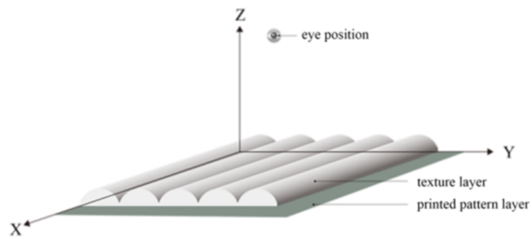


Figure 2. Establishment of entity space.

After the solid space and optical model are established according to the above, it is necessary to process the texture and base image to be simulated, so that they can get the desired simulation result image after passing the optical model. Firstly, the gray image is processed according to the input information, and the gray image information is transformed into the entity space coordinates. Then calculate the size of each gray level in the solid space. In order to reduce the calculation error, the mean filtering method is used to smooth the image.That is, the average value of the pixel grayscale of 3 × 3 around the grayscale pixel is taken as the new grayscale value of the pixel. The gray value of pixels in row i and column j is shown in Figure 3:

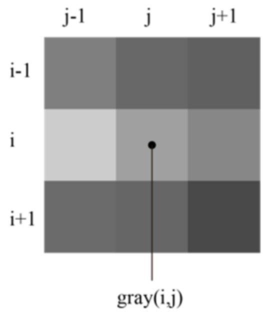


Figure 3. Schematic diagram of gray level fusion algorithm.

By traversing each pixel of the texture gray image, the coordinates of each pixel in the entity space can be obtained:

$$p = (i, j, gray(i,j) * h/255) \tag{2}$$

Calculate the normal vector $\vec{N}$ of each pixel of texture gray image.Similarly, in order to reduce the calculation error, all triangle normal vectors $\overrightarrow{N_1}$,$\overrightarrow{N_2}$,$\overrightarrow{N_3}$,$\overrightarrow{N_4}$ that can form a plane can be calculated from the four adjacent points of the pixel, as shown in Figure 4:

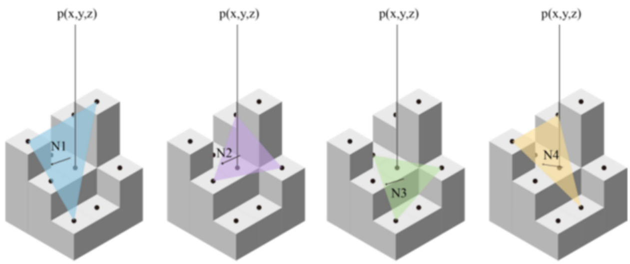


Figure 4. Schematic diagram of normal vector calculation.

Calculate the average value to get the normal vector of the required pixels:

$$\vec{N} = \vec{N_1} + \vec{N_2} + \vec{N_3} + \vec{N_4} \tag{3}$$

Calculate the incident ray and incident angle. The line between each pixel $p(x, y, z)$ and the eye $p_{eye}(x_e, y_e, z_e)$ is regarded as incident light, as shown in Figure 5:

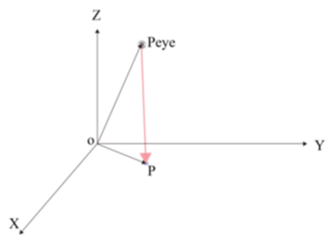


Figure 5. Schematic diagram of incident light calculation.

The incident ray vector $\overrightarrow{vecEye}$ and the angle θ_1 between the pixel normal vector $\vec{v}$ and the incident ray vector are derived from Figure 5.

$$\begin{cases} \overrightarrow{vecEye} = \overrightarrow{op_{eye}} - \overrightarrow{op} \\ \theta_1 = acos\left(\frac{\vec{N} \cdot \overrightarrow{vecEye}}{|\vec{N}||\overrightarrow{vecEye}|}\right) \end{cases} \tag{4}$$

In Eq.(4),$\overrightarrow{vecEye}$ is the incident ray vector, $\overrightarrow{op_{eye}}$ is the vector from the origin O to the human eye coordinates in solid space, $\overrightarrow{op}$ is the vector from the origin o to each pixel P, θ_1 is the incident angle, and $\vec{N}$ is the normal vector of pixel P.

The user inputs the refractive index n_2 of the texture material, that is, the refractive index of the medium where the light is refracted. The default medium for incident light is air, that is, $n_1 = 1$. Input the incident ray vector $\overrightarrow{vecEye}$, normal vector $\vec{N}$ and refractive index e calculated in the above steps into the above refractive optical model to obtain the unit vector $\overrightarrow{vecLight}$ of the refracted ray.

Find the corresponding pixels of the base map pattern by refracting the light. The light is refracted through the texture medium and will point to the pixels of the base image, as shown in Figure 6:

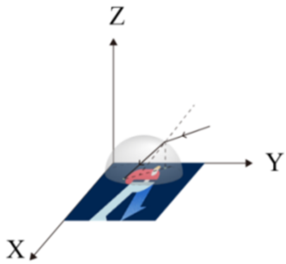


Figure 6. Light refracts on the texture surface.

After Eq (2) , you can know the specific size of $gray(i,j) * h/255$ in the Z direction of each pixel. The offset Δx and Δy of refracted rays in the X-axis and Y-axis can be calculated through the unit vector $\overrightarrow{vecLight} = (L_x, L_y, L_z)$:

$$\begin{cases} \Delta x = \frac{gray(i,j)*h/255}{L_z} * L_x \\ \Delta y = \frac{gray(i,j)*h/255}{L_z} * L_y \end{cases} \quad (5)$$

It can be seen from Figure 7 that before refraction, the pixel point of the base image corresponding to this pixel point is point A; After refraction, the base image pixel corresponding to this pixel point is point B, and point B has Δx and Δy offsets in X and Y directions respectively with respect to point A. At this point, we can find the corresponding pixels after refraction, recombine the new pixels corresponding to all texture map pixels into a picture, and write the pixel information into a new BMP file, which is the final simulation picture.

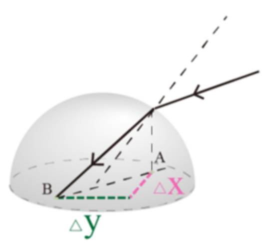


Figure 7. X and Y offsets of refracted rays.

3.2.2. Dynamic visual simulation and preview of transmission materials

The system can get a final texture refraction image by setting the position of an eye. In reality, with the movement of the observation position of the human eye, the information of the base map is also changing. Therefore, through the movement of eye position, the frame that can make GIF dynamic effect map is automatically generated.

The user can input the initial position and final position of the eye, and the number of frames is m frames (m>=2). Connect E1 and E2, and divide the line segment E1,E2 into M-1 evenly according to the number of frames. At this time, m viewpoints required by the motion picture can be obtained. The coordinates of these viewpoints $e_1 \ldots \ldots e_{m-2}$ can be expressed as:

$$e_n = (x_1 + n * \frac{x_1+x_2}{m-1}, y_1 + n * \frac{y_1+y_2}{m-1}, z_1 + n * \frac{z_1+z_2}{m-1}) \tag{6}$$

Through the simulation of these viewpoints by the simulation system, the frames required by the user are simulated one by one.

4. Texture design method of nonuniform transmission grating

Due to the nature of gray-scale mask, the gray-scale image recognized by the lithography machine is usually in the form of BMP file. It is a bitmap image, which is composed of pixels. Therefore, the rows and columns of pixels can be regarded as orthogonal grids, and the gray level of each pixel represents the height of grid points. The transmission gratings in the market are mainly uniform gratings, while non-uniform gratings are rare. This paper introduces the gray mask design method of non-uniform transmission gratings by introducing orthogonal grids.

4.1. Unit construction

In this study, the orthogonal grid method is used to construct 3D shape based on 2D graphics of the plane. Each pixel is understood as grid point coordinates. Only the height of each pixel covered in the required plane is calculated and converted into gray value, and the 3D shape can be obtained. In this way, three-point interpolation, a common method in computer image processing, will be used, as shown in Figure 8.

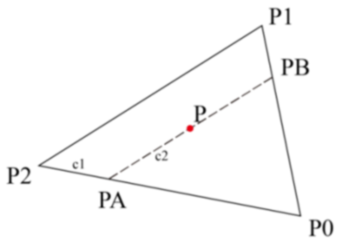


Figure 8. Schematic diagram of three point interpolation method.

The coordinates of the three points constructed into a triangle are $P_0(x_0, y_0, z_0)$,$P_1(x_1, y_1, z_1)$,$P_2(x_2, y_2, z_2)$and the Z coordinate is directly related to the gray level. The coordinate of any point P in the triangle is $P(x, y)$, and the parallel line of p1p2 can be made through point P to obtain point PA and point Pb. Point P is interpolated by point PA and point Pb, while point PA is interpolated by point P2 and point P0, and point Pb is interpolated by point P1 and point P0. Based on this relationship, it can be obtained that the coordinates of point P are functions of parameters C1 and C2, and C1 and C2 are values between 0 and 1. The coordinates of point P are as follows:

$$\begin{cases} x = c_2 * (x_{pB} - x_{pA}) + x_{pA} \\ y = c_2 * (y_{pB} - y_{pA}) + y_{pA} \\ z = c_2 * (z_{pB} - z_{pA}) + z_{pA} \end{cases} \tag{7}$$

Traversing the parameter space is to calculate each pixel covered by the required graph. In order to traverse each pixel efficiently, Newton dichotomy is used for traversal search. By Eq (5) ,It can be seen that the function for calculating any point P is related to C1 and C2. By double cycling C1 and C2, we can traverse the entire internal space of the triangle and calculate the number of rows and columns(iRow, iCol)of the point in the pixel matrix:

$$\begin{cases} i_{row} = int\left(int\left(\frac{d_{P0_{P1P2}}}{0.5*d}\right) * \frac{y-y_{bottom}}{H}\right) \\ i_{col} = int\left(int\left(\frac{d_{PAPB}}{0.5*d}\right) * \frac{x-x_{left}}{W}\right) \end{cases} \tag{8}$$

In Eq. (8), H and W are the height and width of the grayscale image, and are the X and Y coordinates of the left and bottom edges of the image, d is the pixel spacing, and int is rounding.The pixel gray of irow and icol column is:

$$Gray_{(iRow,iCol)} = Int\left(255 * \frac{z}{h_{max}}\right) \tag{9}$$

Hmax is the maximum height of the global cell, that is, the thickness of the maximum texture of the material surface set by the user. This value is preset.

The above is the basic steps of the three-point interpolation method. The three-point interpolation method is the most commonly used calculation method in texture design. Using the basic calculation logic, the method can be extended to the calculation of constructing 3D form from 2D form of polygon or other forms.

4.2. Parametric unit design

The previous section describes the basic construction method of a single unit. Texture is an attribute of the object surface, which is composed of multiple units. Therefore, some unit morphological features can be extracted from it for parametric design. Its features can be summarized into three types, namely top feature, edge line feature and height feature [13],[14],[15].Taking the top feature as the measurement feature, a variety of textures can be designed through the following parametric methods:

Top feature: the top feature of the texture unit is generally point, line or face, as shown in Figure 9. Lines and faces can also be divided into two types: parallel to the bottom and not parallel to the bottom.

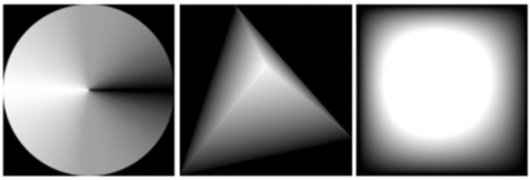


Figure 9. The top features are point, line and face texture units.

Edge line feature: the edge line connecting the bottom and the vertex in the texture unit can be a straight line or a curve feature, as shown in Figure 10.

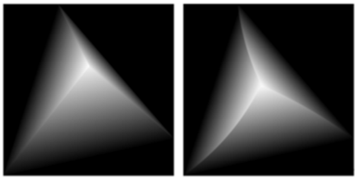


Figure 10. Edge line features are texture units of lines and curves respectively.

Height feature: height feature refers to the height of the texture in the Z direction. The height of each cell does not necessarily reach the maximum value. Taking Figure 11 as an example, the height of each unit Z of the texture varies upward, and gradually increases to the highest.

Figure 11. Each unit has different height characteristics.

The above content is the three texture unit features extracted from the texture, and the controllable parameters of the unit are further extracted from the three unit features to make the design texture parametric and controllable. Taking the top feature as the measurement feature, a variety of textures can be designed through the following parametric methods:

Characterized by points: the number of vertices and the z-direction height of vertices can be used as parameters for design, as shown in Figure 12.

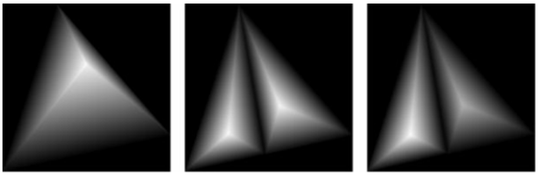


Figure 12. Changes in the number and height of vertices.

Characterized by lines: the shape, number, starting point and ending point of lines can be designed as parameters, as shown in Figure 13.

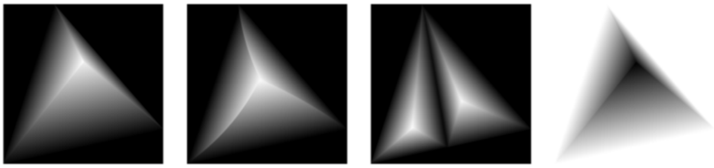


Figure 13. Changes in shape, quantity and height of edge lines.

Characterized by faces: the shape, number and Z-direction height of faces can be designed as parameters, as shown in Figure 14.

Figure 14. Changes in surface shape and height.

In general, when designing texture units, parameters can be designed with a single feature, such as selecting one or more parameters of point features for adjustment; It can also be designed with multiple parameters of multiple features, such as selecting multiple parameters in point and face features for adjustment.

4.3. General texture design process

Integrating the above processes and methods, the texture design process is obtained, which provides a standardized step for designers as a reference for texture design. Finally, the lithography gray-scale image is output, as shown in Figure 15.

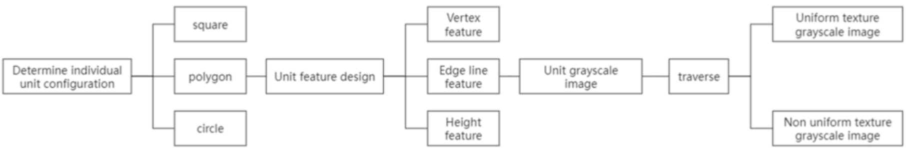


Figure 15. General flow chart of texture design.

First, determine the shape of a single cell, that is, the whole image is segmented through the same cell. The cell shape is diverse, usually based on square, polygon or circle. As shown in Figure 16 below, the whole image is segmented by the same unit.

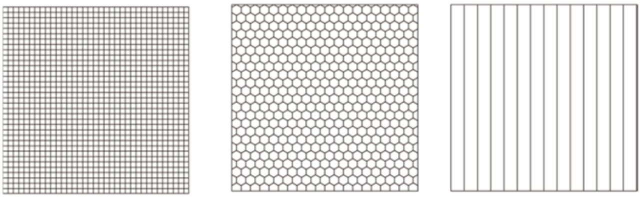


Figure 16. Cell division method.

Secondly, a single cell is designed, and the texture features are designed according to the cell shape. It is assumed that the design is based on the edge line as the unit feature, and the interior of the unit is divided by the edge line. Three point interpolation method is used to calculate the gray level of a single unit. The cells are constructed into three-dimensional shape and converted into gray image form, and the complete texture is constructed by traversing each cell. After handling the form of a unit, you can traverse each unit and perform the same processing on each unit. At this point, a set of uniform textures is obtained, as shown in Figure 17.

Finally, the texture changes between some cells are given. The above is the practice of uniform texture. If we want to build a non-uniform texture, we need to give some changes between cells. If the z-direction height of the vertex is taken as a parameter change, the unit can be gradually reduced towards the x-direction height, as shown in Figure 18.

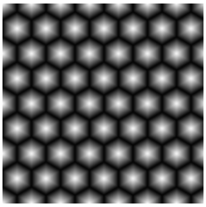


Figure 17. Uniform hexagonal pyramid texture grayscale image.

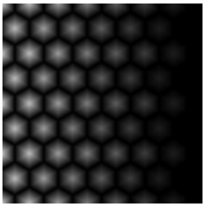


Figure 18. Non uniform hexagonal pyramid texture gray image.

Uniform texture is generally composed of the same and repeated elements regularly. As shown in Figure 19:

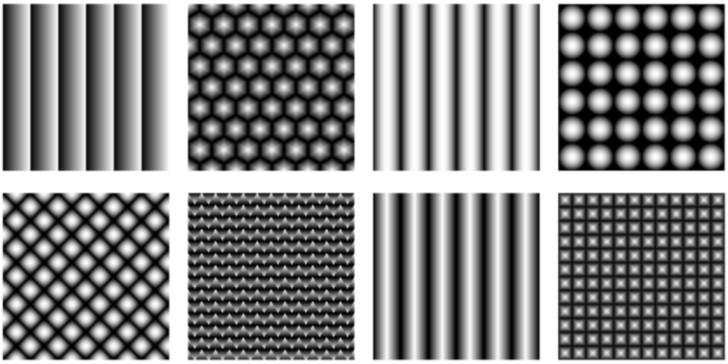


Figure 19. Uniform texture.

Non uniform texture is generally composed of elements of the same kind that change regularly. As shown in Figure 20:

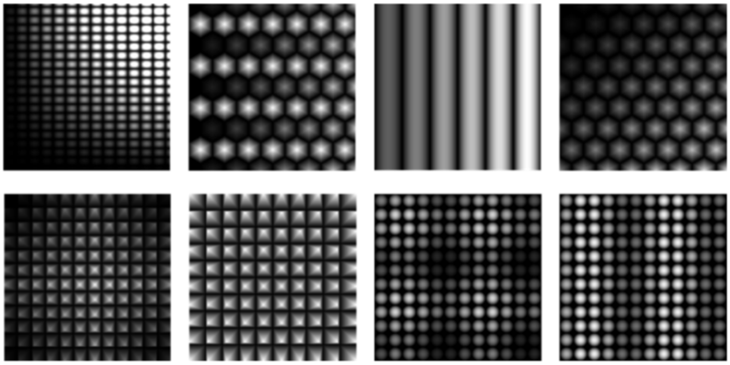


Figure 20. Non uniform texture.

To sum up, by changing the unit features and parameters in the texture, we can build a variety of texture designs. By parameterizing the texture design, a uniform texture can be upgraded again, and a gray image scheme with multiple non-uniform textures can be generated. This design method improves the efficiency of texture design for designers, reduces the working pressure of designers, and provides many creative sources. By designing transparent gratings that are different from the existing textures in the market, designers can make the sparks generated by transparent gratings matching with the base map more diverse and intense.

5. Technology implementation and Application

5.1. Technical method and route

In this paper, the macro command of the graphic design software CorelDRAW vector drawing software is used for secondary development, and the two-dimensional gray image is directly output. Based on the refraction optical model, the effect of the texture and base image on the transmission material is simulated, and the texture transmission simulation system platform based on CorelDRAW platform is built. The specific technical route of the simulation system is shown in Figure 21:

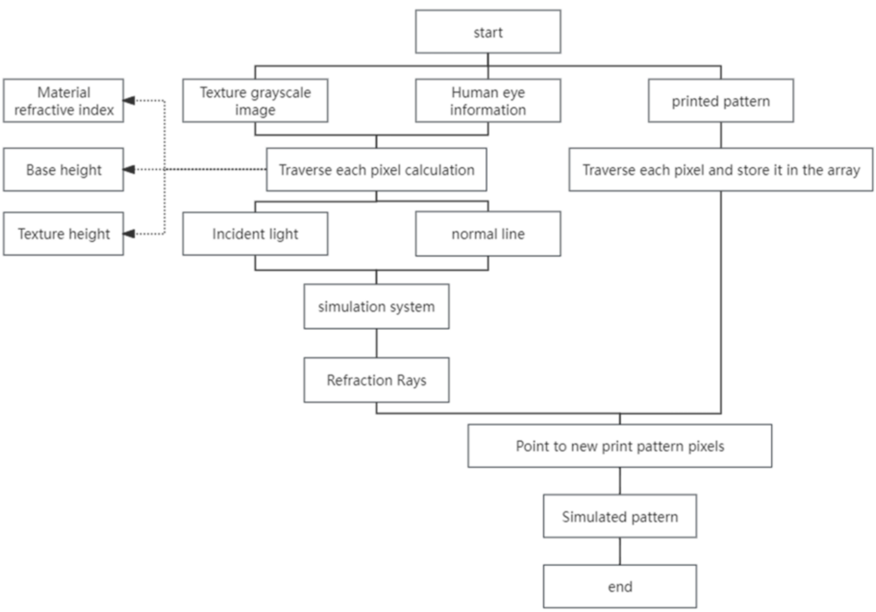
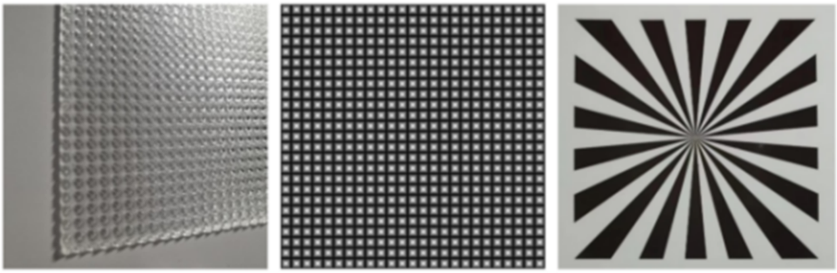


Figure 21. Technology Roadmap.

5.2. Case presentation

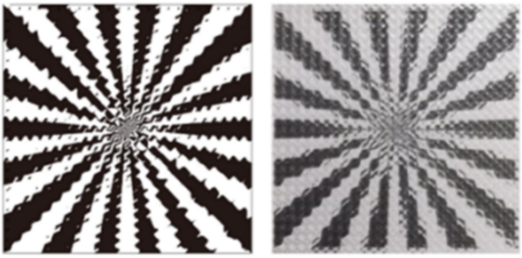
First, the case of uniform texture grayscale image and regular base image is shown. The real object is made of acrylic transmission material with a refractive index of 1.49. The texture area of 5cm*5cm points and the base image of 5cm*5cm irregular graphics are selected to overlay as shown in Figure 22.



(a) (b) (c)

Figure 22. Uniform grating and its base map.(a)Raster real object(b)raster gray image(c)base image.

The superposition effect of simulation results and real objects is shown in Figure 23:



(a) (b)

Figure 23. Comparison of simulated objects.(a) Simulation results (b) physical results.

The output animation frame is shown in Figure 24:

Figure 24. Animation frame(https://www.kdocs.cn/l/cg0UWt5Q03zy).

Secondly, the case of non-uniform texture gray-scale image and regular base image is shown. The material used in the real object is the transmission material made of photosensitive resin, whose refractive index is 1.49. The texture area of 5cm*5cm points and the regular base image of 5cm*5cm are selected to overlay as shown in Figure 25.

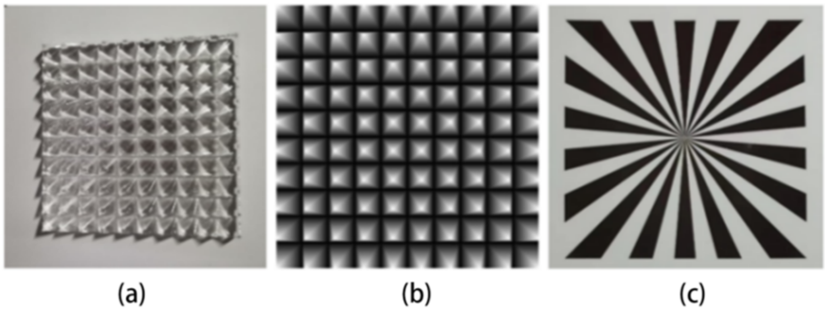


Figure 25. Non uniform grating and its base map.(a)Raster real object(b)raster gray image(c)base image.

The superposition effect of simulation results and real objects is shown in Figure 26:

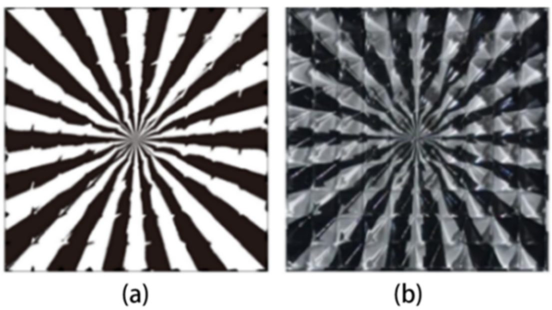


Figure 26. Comparison of simulated objects.(a) Simulation results (b) physical results.

The output animation frame is shown in Figure 27:

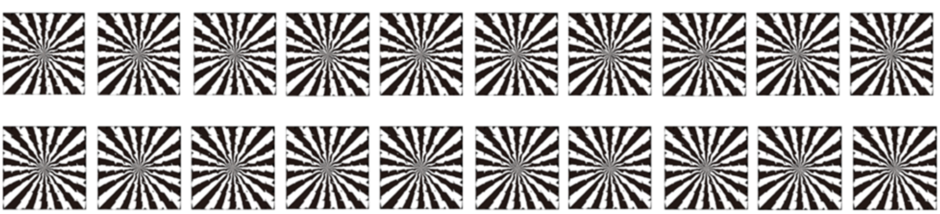


Figure 27. Animation frame.(https://www.kdocs.cn/l/cn0d4b8hJWvr)

After comparing and analyzing the simulation results with the real object, this study found that the correctness of the simulation was high, and the results were consistent with the final effect observed by the naked eye. It can help designers play a role in texture grayscale mask, base image design and effect evaluation, but they cannot directly participate in the actual proofing process of texture production and base image production, so they cannot ensure that the final material object of texture is completely consistent with the grayscale image. In addition, the final presentation of the texture also depends on the cooperation of the technologist, and many factors in reality, such as the abrasion at the sharp corners of the edges, may lead to differences between the actual object and the ideal effect. However, the simulation results provided by this system are enough to provide effective judgment basis for designers and help them eliminate a large number of schemes that do not meet the expectations.

6. Conclusion

The theory of related optics and computer graphics are deeply studied, and the refractive optical model is constructed. With the help of computer-aided industrial design technology, based on the graphic design software CorelDRAW platform, the CMF design simulation system of transmission grating is developed, which realizes the visual dynamic effect simulation, assists the designer in the scheme evaluation before proofing, improves the designer's design efficiency and reduces the cost of proofing. Compared with the existing technology, the technology in this paper gives a variety of changes different from the conventional square unit in the unit parametric design, and proposes a general texture unit design method, which standardizes and parameterizes the texture design process. It provides a large number of texture design cases, providing designers with more creative entrance. The effectiveness and correctness of the system are verified by a complete design process from texture design to visual simulation to scheme evaluation and then to the actual proofing test.

Acknowledgement

The National Social Science Fund of Art, China, Grant/Award Number: 20ZD09

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