8K Digital Content Creation of Cultural Properties having Structural Colors

Takafumi Koike[1], Yuki Asahina[1], Hiroaki Okumoto[2]
Keiko Nakamoto[1], and Tadashi Motoyama[2]

takafumi@hosei.ac.jp
[1]Hosei University, 3-7-2 Kajino-cho, Koganei-shi, Tokyo 184-8584, Japan
[2]Sharp Marketing Japan Corporation, 1-9-2 Nakase, Mihama-ku, Chiba 261-8520, Japan
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ABSTRACT

We are working to realize a high-quality, interactive experience with cultural properties as digital content. We have developed a method to reproduce the texture of cultural properties with structural colors by using several computer graphics techniques.

1 Introduction

In recent years, with the development of computer graphics (CG) technology, more and more cultural properties have been reproduced in realistic CG format for posterity. There are many cases of CG of cultural properties [1-3]. Advances in photogrammetric technology have made it possible to obtain shapes, surface colors, and textures from multiple photographs with sufficient accuracy to create computer graphics of cultural properties.

On the other hand, cultural properties often have complex surface structures and features such as anisotropic reflections and structural colors. Therefore, physically based shading is often used to accurately reproduce reflective characteristics.

When we think the application of physics-based shading for realistic computer graphics of cultural properties, it is necessary to measure the reflectance of light and the surface material and structure necessary to determine the reflectance based on physical laws. However, it is very difficult to obtain the information necessary for physics-based shading for cultural properties because it is often difficult to use special measuring equipment or to take measurements over a long period of time.

On the other hand, let us consider the case where the CG artist adjusts the colors entirely by hand, without any need for physical correctness, to make the CG appearance of an art object as close to the real object as possible. In this case, when the material is widely known and it is easy to define the object's color, adjustment may be easy. However, since most art objects have complex structures, no two of which are alike, and there are many local variations in materials, it is difficult to uniquely define the color on the surface. In addition, when a work of art has complex coloring, such as structural coloring, the position of the light source and local variations in the surface structure have a significant impact on its appearance. Therefore, it is unrealistic for CG artists to manually adjust colors from scratch in content creation.

We propose a shading method for structural color to create interactive content of art objects with thin-film interference and display them on an 8K display. While calculating the reflectance of the thin-film interference on a physical basis, the method uses the structural information of the artwork, such as film thickness and material, which are difficult to measure, as well as the color space and intensity of the structural color when displayed on display, as changeable parameters. This allows the CG artist to make final color adjustments by comparing the actual image with the CG after obtaining a minimum structural color of the thin-film interference.

The contributions of our paper are as follows:

1. We Introduce adjustable parameters for the local variation of film thickness and the material of the underlying thin film layer, which are necessary for calculating the reflectance of thin film interferometry.
2. We introduce the color temperature of the light source and the color space of the conversion destination when converting the reflectance to the display color as adjustable parameters.
3. We can adjust the parameters introduced in the above two points and build a processing flow to make the CG of the artwork used as interactive content look closer to the real thing.

2 Related Works

Structural color is a coloring phenomenon resulting from the wave-like behavior of light, such as diffraction and interference. It is caused by principles such as thin-film interference, multilayer interference, interference due to microscopic irregularities, and the color play effect. Structural color can be observed in various materials such as soap bubbles, tamales, morpho butterflies, the inside of shells, pigeon wings, DVDs, and jewelry.

Many studies have been proposed to compute these structural colors using computer graphics. Arakawa et al [2] and Huang et al [3] proposed the Rendering of dove wings, which are structural colors by thin-film interference.

Belcour et al. extended the microfacet theory for iridescence [4], and Iwasaki et al. proposed a real-time rendering method for soap bubbles considering the structural color of thin-film interference [5]. The structural color is pre-calculated from the reflectance of the thin-film interference. Next, the structural colors are stored in a look-up table (LUT) that takes the film thickness, and angle of incidence as inputs, and the soap bubbles are rendered in real-time. In addition to soap bubbles, studies have reproduced the structural colors of the wings of morpho butterflies and opals [6, 7]. These methods can be applied only to the specific structure of each object; Imura et al. have proposed a general-purpose method for real-time rendering of structure-color objects caused by thin-film interference, multilayer interference, and diffraction gratings [8]. The method utilizes thin-film interference, multilayer interference, and diffraction gratings all change color by changing the optical path difference, and real-time rendering can be performed using a standard method by changing only the optical path difference in addition to the film thickness and angle of incidence, which is also supported by Iwasaki et al.

In addition to the three parameters of Imura et al.'s method, Asahina et al. use five parameters that can be changed in real-time: local variation of film thickness, the material of the underlying thin film layer, color temperature of the light source, color space when converting reflectance to color, and intensity of the structural color [9]. By changing the five parameters in real-time while checking the actual object to be rendered, it is possible to render structural colors that more closely resemble the real object.

3 Our Method

In this research, while calculating the reflectance of thin-film interference on a physical basis using the Asahina et al. method, the color temperature of the light source and the color space used to convert the wavelength of reflected light into color, as well as the film thickness and material of the thin-film structure, which cannot be measured, are parameters that can be changed. The CG artist can adjust these parameters while viewing the real object and create a CG of cultural properties that is close in appearance to the real object.

The shading procedure for a cultural property having structural colors is as follows.

- Modeling the thin-film structure of the cultural property
- Calculation of the reflectance of the thin film interference
- Calculation of structural color considering the source of incident light and the color space to be displayed
- Creation of 3D LUT of structural color for interactive content creation
- Determination of shading color parameters by considering local changes in intensity and thickness of the structural color
- Implementation of real-time shader on a standard game engine

3.1 Calculation of Reflectance of Thin-film Interference

Figure 1 shows the principle of thin-film interference. In the figure, the parameters are that medium b of thickness d exists between medium a and c, and that the refractive indices of each medium are n_a, n_b, and n_c. In this method, based on modeling the thin-film structure of an oil drop bowl, medium a is air, medium b is glass, and medium c is either ferric trioxide or ferric tetroxide.

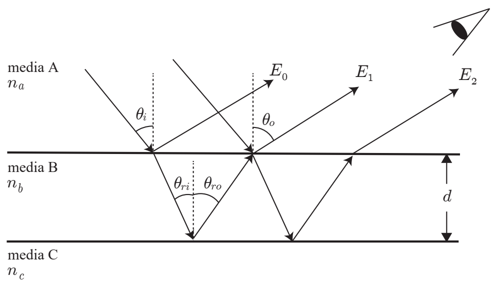

Fig. 1 The Principle of thin-film interference.

The reflectance of thin-film interference, R_{film}, is the square of the amplitude reflectance. Using Snell's law and the laws of electromagnetism, the reflectance is expressed by the following equation.

$$R_{\mathrm{film}} = \left|\frac{E}{E_{\mathrm{inc}}}\right|^2 = \left|r_{ab} + t_{ab}t_{ba}r_{bc}e^{i\phi}\frac{1}{1 - r_{bc}r_{ba}e^{i\phi}}\right|^2, \quad (1)$$

where r_{ab} is the amplitude reflectance between medium *a* and *b*, t_{ab} the amplitude transmission, and ϕ the phase difference. The relation between the phase difference and wavelength λ and optical path difference Δ is the following equation.

$$\phi = \frac{2\pi\Delta}{\lambda}. \quad (2)$$

3.2 Calculation of Structural Colors

We obtain the reflected light spectrum $I_{\mathrm{out}}(\lambda)$ from R_{film} obtained in the previous section.

$$I_{\mathrm{out}}(\lambda) = R_{\mathrm{film}}(\lambda)I_{\mathrm{in}}(\lambda). \quad (3)$$

This is converted to the XYZ color space and then further converted to match the display's color space to determine the structural color. Figure 2 shows example spectrums by thin film interference. As Figure 3 shows, a slight difference in the refractive index causes a significant change in the wavelength distribution, even if the film thickness is the same. The manual color change is difficult because of the multiple wavelength components that are often present.

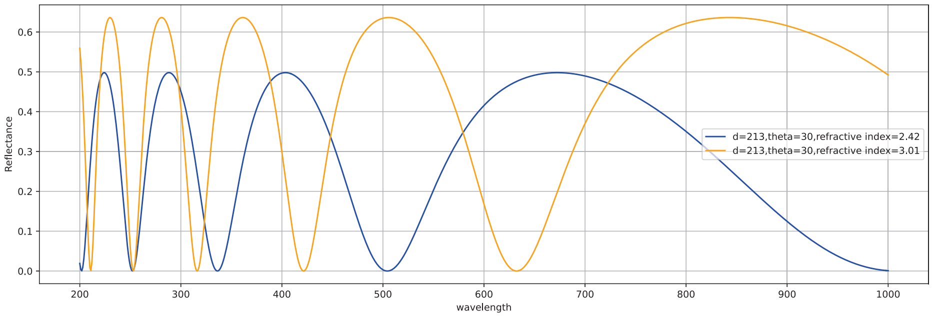

Fig. 2 Example spectrum by thin-film interference.

3.3 3D LUT for Structural Colors

We introduce a three-dimensional look-up table (LUT) as a texture for real-time rendering. This allows the game engine to change structural color parameters in real time. A 3D LUT has an incident angle from 0 to 90 degrees, a reflection angle from 0 to 90, and a film thickness from 0 nm to 400 nm. The size of the 3D LUT is 64 x 64 x 64.

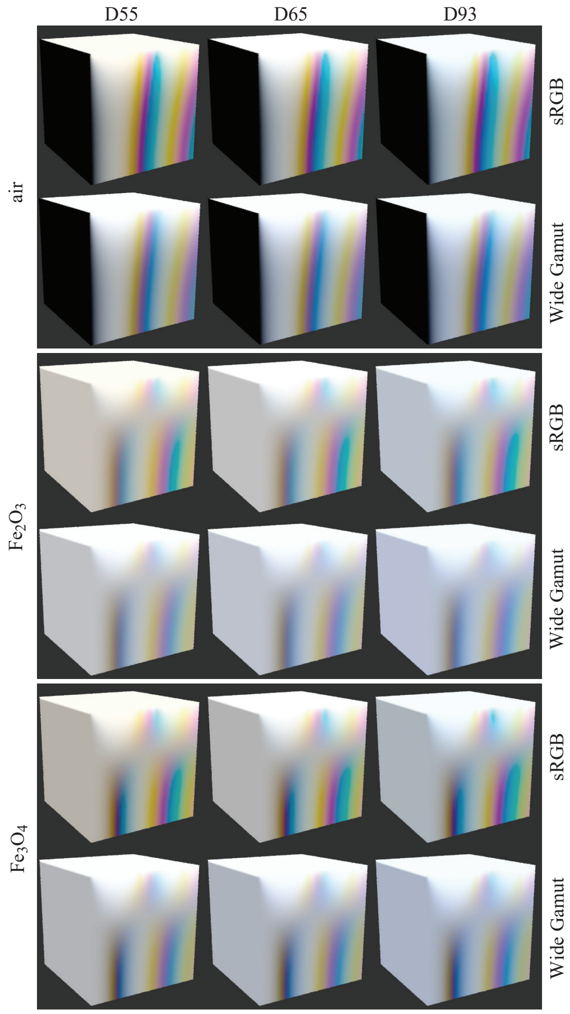

Fig. 3 3D LUT of our method

When creating a single 3D LUT, three parameters must be fixed: the material of the thin film underlayer, the color temperature of the light source, and the color space, which are defined as the parameters that can be changed. To achieve this, we created 18 3D LUTs, as shown in figure 3, by combining the three-parameter candidates in a round-robin fashion. It can be seen that the apparent color varies greatly depending on the combination of the material of the underlying thin film, the color temperature of the light source, and the color space.

I_{out} in equation (3) is the spectrum of the reflected light. The appearance of structural color is often very different when the light source's color temperature is changed, even if the incident angle is the same. Therefore, three color temperatures of Standard Illuminant Series D, 5500K (D55), 6500K (D65), and 9300K (D93), are applied to I_{out}.

4 Results

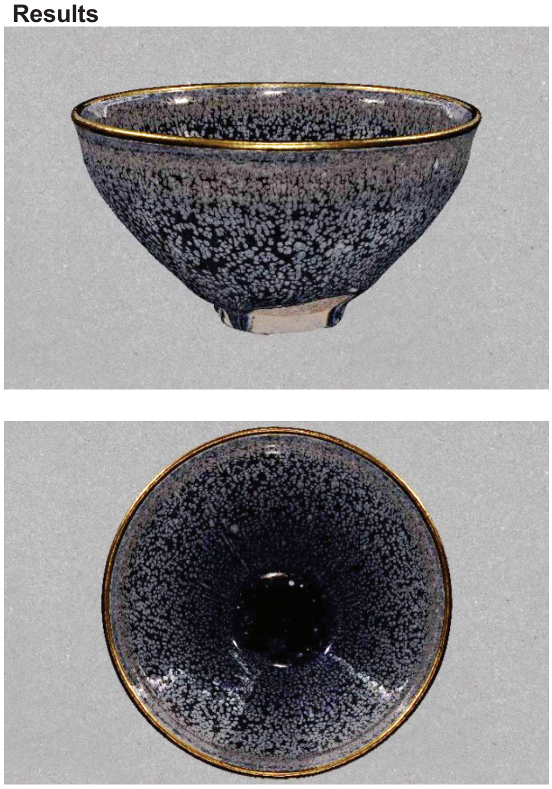

Fig. 4 Rendering results by our system.

Figure 4 shows the result of a teacup rendered with our method. The light source settings and the glazed areas are not colored in the texture; only the structural colors are used. As already mentioned, many parameters determine the color of the structural color, and adjusting them is not easy. For example, as shown in Figure 2, the color varies greatly, even with changes in the refractive index. Therefore, it is necessary to estimate the parameters to some extent by estimating the glaze composition from past literature and the camera image.

In addition, the structural color of thin-film interference also undergoes significant color change due to changes in film thickness. Still, the thickness of the film is not constant in glazed pottery. Therefore, slight differences in film thickness can be accommodated by introducing a texture that represents the film thickness.

The interactive content of computer graphics of work created using our technique is on display at the museum [11, 12].

5 Conclusions

We have developed a real-time shading method for interactive content and displaying them on an 8K display. We can shade the structural colors of thin-film interferences in cultural properties, which are difficult to measure physical parameters in the real world.

Our method is based on a physics-based calculation of the reflectance of the thin-film interference. The technique uses parameters such as thin-film thickness, base layer material, light source color temperature, color space for color conversion of reflected light, and structural color intensity.

In addition, by maintaining the structural color in three-dimensional (3D) LUTs, the shading results can be displayed in real-time by holding the structural colors. Applying the shading method to an oil-drop teacup showed that the CG image was closer to that of the real object than the conventional method.

Our method is based on physics-based calculations but features manual adjustments for parameters that are difficult to measure or calculate. This allows engineers and artists to interactively and manually adjust parameters and reproduce even the most finely textured materials in CG, such as cultural properties.

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