A Simulation of Multilayer Thin-film Interference for Pearl Material Preproduction

Kensuke Tobitani
School of Science and Technology
Kwansei Gakuin University
Hyogo, Japan
Email:tobitani@kwansei.ac.jp

Akihiro Okada
Naris Cosmetics Co.,Ltd.
Research & Development Department
Osaka, Japan
Email: a_okada@naris.co.jp

Kumiko Nishiyama
Naris Cosmetics Co.,Ltd.
Research & Development Department
Osaka, Japan
Email: kumiko_nishiyama@naris.co.jp

Atsushi Ishida
School of Science and Technology
Kwansei Gakuin University
Hyogo, Japan
Email: atsushi.ishida@kwansei.ac.jp

Lisa Park
School of Science and Technology
Kwansei Gakuin University
Hyogo, Japan
Email: lpark@kwansei.ac.jp

Noriko Nagata
School of Science and Technology
Kwansei Gakuin University
Hyogo, Japan
Email:nagata@kwansei.ac.jp

***Abstract*—Visual simulation using computer graphics and virtual reality has come to be used recently in the production process to enhance the quality of materials and products. In this paper, we propose a simulation of multilayer thin-film interference for pearl material preproduction such as cosmetic development. Pearls manifest a very specific optical phenomenon caused by the multilayer thin-film structure, and most people have a common sense that pearls have a own beauty. Therefore, the expected merits of the simulation are not negligible. The author of this paper have reported a method of modeling and visualizing perfect sphere pearls. For a construction of the simulation system for a preproduction, it is necessary to apply the visualizing method to free-form surface, and consider the changes of blurring and interference color due to view angle which was not mentioned in the earlier research. As the results, we implemented the pearl visual simulation method as a plug-ins material shader of 3D computer graphics software MAYA and generated high-quality pearl and free-form surface 3D images with optical properties similar to pearl.**

I. Introduction

In the area of materials development, preproduction using visual simulation has come to be considered essential[1]. In this paper, we propose a simulation of multilayer thin-film interference for pearl material preproduction such as cosmetic development. The author of this paper began research using machine vision technology in 1992[2][3] for the evaluation of pearl quality requiring intuitive expertise, even during inspection in the production process. Pearls, widely known as jewelry items, have a multilayer thin-film structure and display a unique rainbow color and a lustrous iridescence due to the diverse behavior of light, such as refraction, interference, diffraction, multiple reflection, etc.[4]. Therefore, the modeling and visualization of a pearl with specific optical and structural features is an interesting theme. The study of a visualization of optical phenomenon in multi-layered structure has previously been reported[5][6], however, no research has yet been performed on a visualization of multilayer thin-film interference as typified by pearls. Nagata and coworkers succeeded in [7] in achieving a realistic representation of a pearl ("pearl-like quality") by means of three principal factors, namely, the interference component, mirroring component, and texture component using physics-based modeling. Dobashi and coworkers indicated the importance of the blurring of light, as a fourth factor, to improve the representation of a delicate appearance, and proposed its computational model and calculation algorithm[8]. Further, a new model named "partial coherent model"was also proposed, including coherent light, in addition to the incoherent light so far considered in the visualization of the interference phenomenon in [7]. In these researches[7][8], they succeeded in generating high-quality perfect sphere pearl CG image. It is, however, necessary for the simulation to apply the visualizing method to free-form surface from the view point of preproduction of material development.

This paper proposes a simulation of multilayer thin-film interference for pearl material preproduction such as cosmetic development. Pearls manifest a very specific optical phenomenon, and most people have a common sense which pearls have a own beauty. Therefore, the expected merits of the simulation are not negligible. The author of this paper have reported a method of modeling and visualizing perfect sphere pearls. For a construction of the simulation system for a preproduction, we apply the visualizing method to free-form surface, and consider the changes of blurring and interference color due to view angle which was not mentioned in the earlier research.

II. COMPUTATIONAL MODEL OF A PEARL BASED ON PHYSICS

This section deals with the previously announced model[7][8] of multilayer thin-film interference of a pearl, blurring of light and the pearl image synthesis algorithm required to explain the simulation method in this paper.

978-1-4673-5621-3/13/$31.00 ©2013 IEEE

A. Computational Model of Multilayer Thin-Films Interference Based on Physics

Pearls show a very specific optical phenomenon that is not seen in the normal thin-film interference. The color fringe changes concentrically from the center of the sphere and, also, can be observed even on the part where light does not hit directly. In other words, the interference color of a pearl depends solely on the viewing direction and not on the direction of the light source.

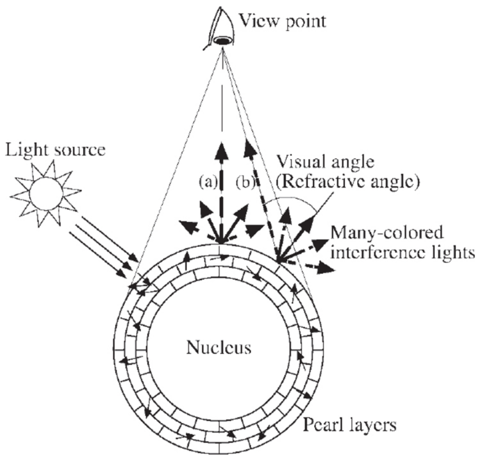


Fig. 1. A physical model of multilayer thin films of a pearl.

The optical model of multilayer thin films of a pearl shown in Fig. 1 can be used to explain this phenomenon. The incident light is distributed to the whole pearl layer through repeated reflection and refraction. As a result, it appears as if each point in the layer had a point light source transmitting rays in all directions (called an "illuminant model"). Each ray causes local interference, and interference lights are propagated in all directions outside the pearl. Taking account of only the interference light waves propagated in the viewing direction and in Fig. 1, the light from each point on the concentric circle is the interference light propagated with the same angle of refraction, so that the phase difference, i.e., the spectrum distribution, must be equivalent. This accounts for the fact that the hue of the interference light does not depend on the direction of the light source and shows concentric circular change.

B. Calculation Algorithm of Interference Light Spectrum

The power spectrum of interference light is calculated in the following manner. First, rays are cast from the viewpoint, and, for all rays intersecting rays with the pearl surface, the incident angle, reflectance, and transmittance are calculated. Next, interference calculations are made from the outer layer to the inner layer of the nacreous layer for all visible wavelength bands, in order to obtain the spectral power. By converting the spectrum obtained into an RGB image, an interference light component described in the next subsection, is generated.

C. Synthesis of a Pearl Image based on illuminant Model

The synthesis algorithm is based on three psychological factors, namely, the sense of depth, brightness, and grain, used previously by Nagata and coworkers in their psychological experiments to evaluate the pearl[3]. In other words, the interference component, mirroring component, and texture component, corresponding to the psychological factors, are synthesized on the diffuse reflection component image. The components and a synthesized image are shown in Fig. 2. Using these methods, a pearl has been successfully represented. However, some experts pointed out the lack of the sense of brightness in the synthesized images. The sense of brightness of a pearl is a material feeling deeply related with not only the intensity of specular light, but the senses of transparency and of gloss. In the next subsection, the representation of the sense of brightness is explained.

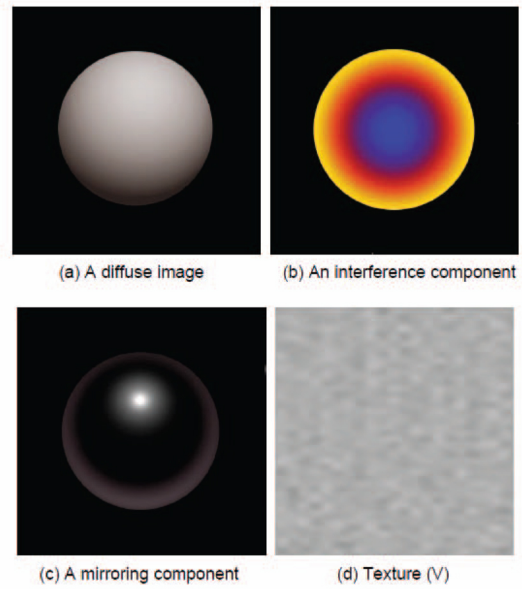


Fig. 2. Components of a synthesized image.

D. Blurring Model of Pearl Due to Subsurface Reflection

The blurring in a pearl can be explained as follows. The quite high transmittance of the nacreous layer causes the light to be repeatedly reflected and transmitted inside the layer. As a result, the spread of light inside the layer tends to have the property of reflection and transmission rather than scattering. The blurring of light in the nacreous layer is attributed to the spread of light due to the deviation of light from the direction of the regular reflection. In order to represent the blurring caused by the subsurface reflection, two models, based on the Monte Carlo method and on the reflection distribution, were proposed and compared in [8]. An example of the blurring component image synthesized based on the reflection distribution is given in Fig. 3, showing clearly the light source image at the center and the blurring around it.

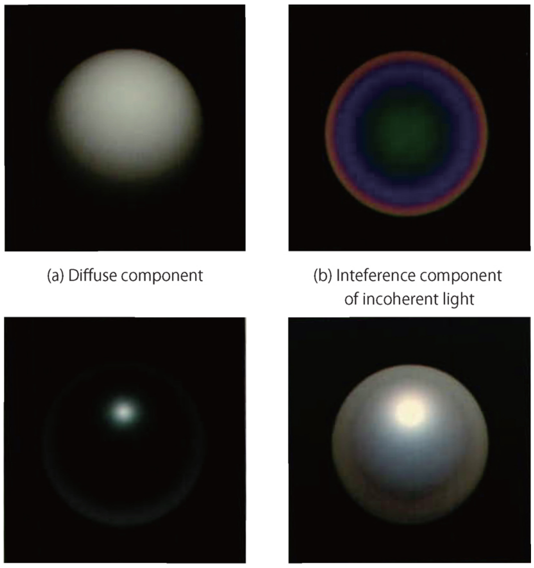
Fig. 3. An image showing blurring.

E. Partial Coherent Interference Model

In Subsection A, the interference phenomenon independent of the direction of light source was taken into consideration to visualize the characteristic of the pearl interference phenomenon. However, even this model failed to describe fully the pearl interference phenomenon. Interference light, the hue of which changes as the light source is moved, is found inside the shell of a pearl oyster, the mother shell of pearl, with a flat nacreous layer like that of a pearl. This indicates that the general thin-film interference also occurs in the nacreous layer, and a careful observation of the pearl shows that the highlight does get slightly colored, which contributes to the improvement in pearl-like quality, especially in the sense of brightness. In other words, the interference phenomenon observed in a pearl is the mixture of the interference of highlight (spatial coherent light), dependent on the direction of the light source, and the interference of multiple reflection of light (spatial incoherent light), so that it is necessary to take account of both elements in order to carry out modeling of the interference seen in a pearl and to synthesize the pearl images. This model was called as the "partial coherent model"in [8] since both coherent and incoherent light are taken into account.

F. Synthesis of a Pearl Image based on Partial Coherent Model

Examples of synthesized images obtained through the partial coherent model and the blurring model mentioned in the above subsection are given in Fig. 4, with Fig. 4(a) showing an image of diffuse component, Fig. 4(b) showing the interference component of incoherent light obtained through the illuminant model, Fig. 4(c) showing mirroring component and blurring component with the interference component of coherent light obtained through the partial coherent interference model and Fig.4(d) showing synthesized pearl image containing all four components. Both the concentric hue distribution of interference light and the coloring of highlight are visualized with no sense of incompatibility, providing an additional feel of pearl-like quality, and slightly contributing to the improvement in the sense of brightness. Further, the contrast between highlight and blurring gives a synergistic effect to further improve the sense of brightness, proving that blurring is an important factor in the visualization of a pearl.



(a) Diffuse component
(b) Inteference component of incoherent light
(c) Mirroring, blurring and inteference of coherent light components
(d) Synthesized image of pearl

Fig. 4. Images of each components and synthesized pearl.

G. Implementation to the Simulator

A visual pearl-quality evaluation simulator was built using the visualization technique[5], in order to synthesize the virtual pearl images. Virtual sample images of various qualities can be synthesized by manipulating the following parameters:

1) sense of depth (intensity of interference component and diffuse reflection component);
2) sense of brightness (directivity of the specular reflection and distribution of blurring);
3) sense of grain (texture strength);
4) object color (hue of diffuse reflection component);
5) interference color (hue of interference component);
6) direction of light source.

High-quality pearl CG images can be generated with the simulator. The generable images are, however, limited to having a spherical shape. Further, the light source is limited to a parallel light. In the next section, we propose a generalization of the pearl visual simulator for a pearl material preproduction by expansion of the blurring model and applying the method of visualizing pearls to general-purpose 3D computer graphics software MAYA as plug-in material shader for free-form surface modeling.

III. GENERALIZATION OF THE PEARL VISUAL SIMULATOR

In this section, we describe a method to generalize the pearl visual simulator mentioned above.

A. Expansion of Blurring Model

The pearl visual simulator described in Section II can generate only perfect sphere. Consequently, the generated image depends on only light angle regardless of view angle. For the generalization, It is necessary to expand the blurring model by considering view angle. Therefore, we review the simulation using Monte Carlo method to represent the blurring of light considering view angle.

1) Simulation Using Monte Carlo Method: The Monte Carlo method, which is also applied to the calculation of light scattering. The stochastic process of tracing the reflection and transmission is repeated for the light entering the nacreous layer with a certain incident angle, and the intensity of the light finally leaving the surface is integrated for each outgoing direction to obtain the whole reflection distribution for a certain incident angle. The same process is carried out for each incident direction to calculate the bidirectional reflectance distribution function(BRDF), i.e., the reflectance distribution function with the incident direction and reflection direction as variables. We describe the BRDF in the form of a lookup table(LUT). The calculation procedure is illustrated in Fig. 5.

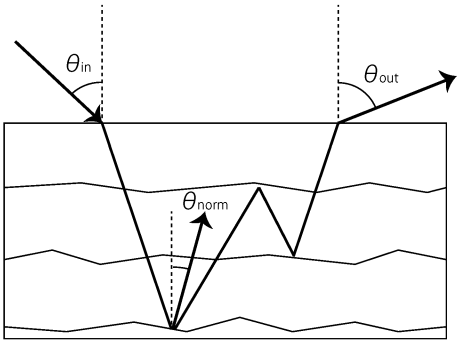


Fig. 5. Simulation using Monte Carlo algorithm.

First, it is supposed that a light ray enters the layer with the incident angle θ_{in}, and is reflected or transmitted by a microfacet with normal vector and with a slope θ_{norm} against the normal vector of the layer. The slope of the microfacet is stochastically determined in the following manner by using the microfacet distribution function.

$$\theta_{norm} = f(R) \tag{1}$$

Here, R are uniform random numbers, and function f is the probability density function of the normal distribution. Whether to trace the reflection or the transmission of light is determined stochastically. The incident angle is obtained from the normal direction of the microfacet, and the reflection/transmission direction is calculated by using Snell's law. The light energy after the reflection/transmission is obtained by multiplying the current energy with the reflectance/ transmittance calculated by using Fresnel's formula. The process of tracing the light is repeated until the ray exits the nacreous layer or the intensity of the light falls below the threshold value.

Through repetition of the process of adding the intensity of the light to the solid angle containing the exit direction θ_{out}, we can obtain the reflection distribution for a certain incident angle. By carrying out the same process for all incident angles, we can obtain the BRDF. We simulated the method under conditions which the number of aragonite crystal layer and conchiolin layer is 500, the refraction index of aragonite crystal layer is 1.53, the refraction index of conchiolin layer is 1.43 and the slope of the microfacet is distributed normally.

Fig. 6 shows the BRDF for an incident angle of 30 degrees using the aforesaid method. The BRDF shows asymmetricity distribution of light with the direction of regular reflection as the center, indicating that the blurring phenomenon is properly simulated.

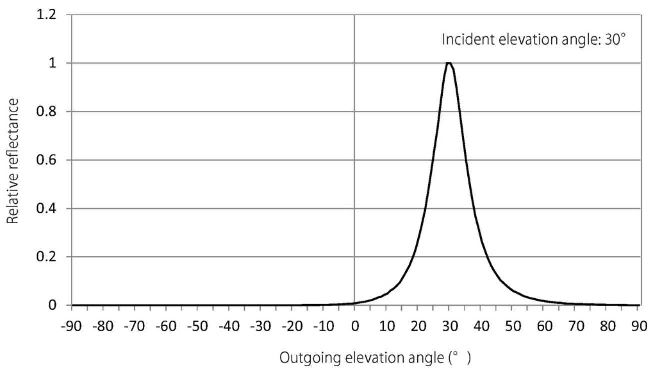


Fig. 6. An example of BRDF by Monte Carlo algorithm.

Fig.7 shows a transition of the BRDF by changing the incident angle from 0 degree to 90 degrees at intervals of 10 degrees. As shown in Fig. 7, the asymmetricity shifts left side to right side of the distribution with increase the incident angle, and the BRDF finally has a large peak value by influence of Fresnel reflection. Actually, we measured BRDF of the under side of pearl oyster shell as shown in Fig. 8. Although the pearl shell was not perfect flat surface, measured BRDF indicates a similar tendency of the BRDF simulation. Therefore, it is reasonable to support that the blurring phenomenon is properly simulated by the method.

2) Designing of Look-up Table: The BRDF with Monte Carlo method described in foregoing section is determined by incident and outgoing elevation angle. For the application to free-form surface, it is necessary to consider the alteration on the BRDF due to outgoing azimuth angle. We postulate that the BRDF decay with increasing the difference between incident azimuth angle and outgoing azimuth angle ϕ as shown in Fig. 9. Fig.10 shows the BRDF for an incident angle of 30 degrees considering the decay due to difference of the azimuth angle. We implement the BRDF considering azimuth angle as LUT in plug-in material shader of 3DCG software MAYA for application the blurring model to free-form surface.

3) Implementation of Partial Coherent Model: We implement the partial coherent model described in Section II in plug-

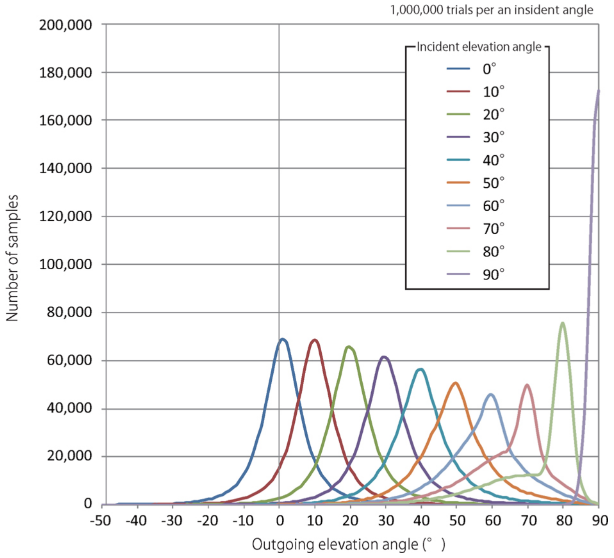


Fig. 7. Transition of BRDF.

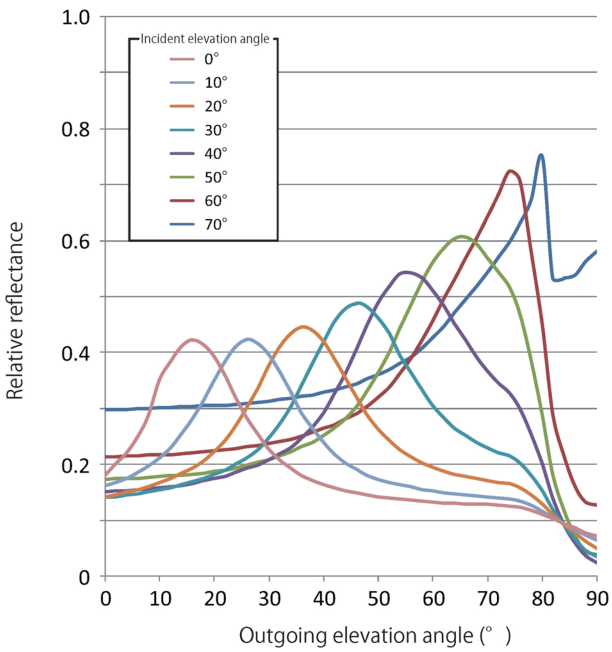


Fig. 8. BRDF of pearl oyster shell.

in material shader of 3DCG software MAYA without major modification.

B. Generation of Pearl and Free-form Surface CG Image

We generate 3D images of pearl and free-form surface applied the pearl optical model on MAYA. Fig.11 shows 3D pearl image and Fig. 12 shows free-form surface with diffuse component, interference component, blurring and mirroring

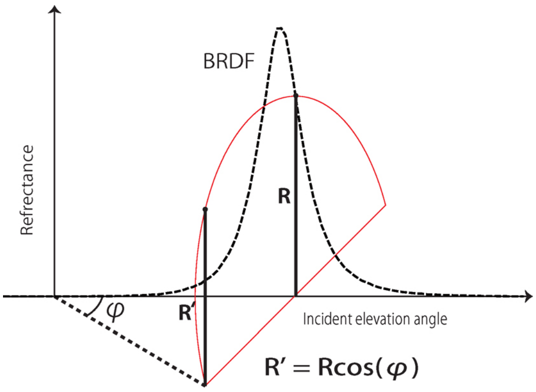


Fig. 9. BRDF decaying model.

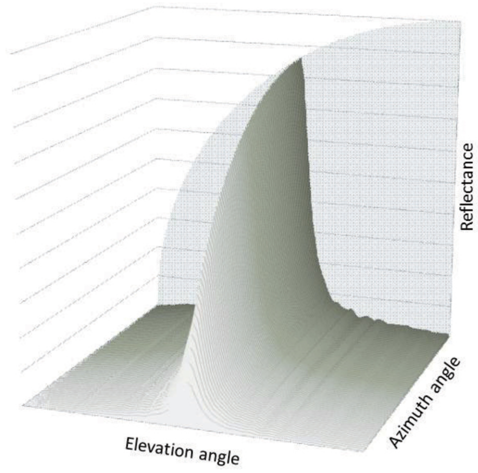


Fig. 10. BRDF considering azimuth angle

component and coherent light interference component. These images represent texture component with bump mapping.

As shown in Fig.11 and Fig.12, we succeed to generalize the pearl visual simulator by application to free-form surface.

IV. Conclusion

We have proposed a simulation method for pearl material preproduction by generalization of image synthesis algorithm and optical models of interference and blurring for pearl visualization based on physics-based modeling. In order to represent the blurring model considering view angle, a model, based on the Monte Carlo method, were reviewed. As for the representation of pearl interference, we adopted the interference model for both coherent light and incoherent light to visualize the physical phenomena more exactly. We implemented these functions on 3DCG software MAYA as plug-in material shader for application to free-form surface, and confirmed that this implementation was succeeded.

In the future, we plan to introduce natural fluctuations and irregularities to build a model much closer to the actual phenomena of a pearl. Further, we are determined to study information compression and speeding up the calculation.

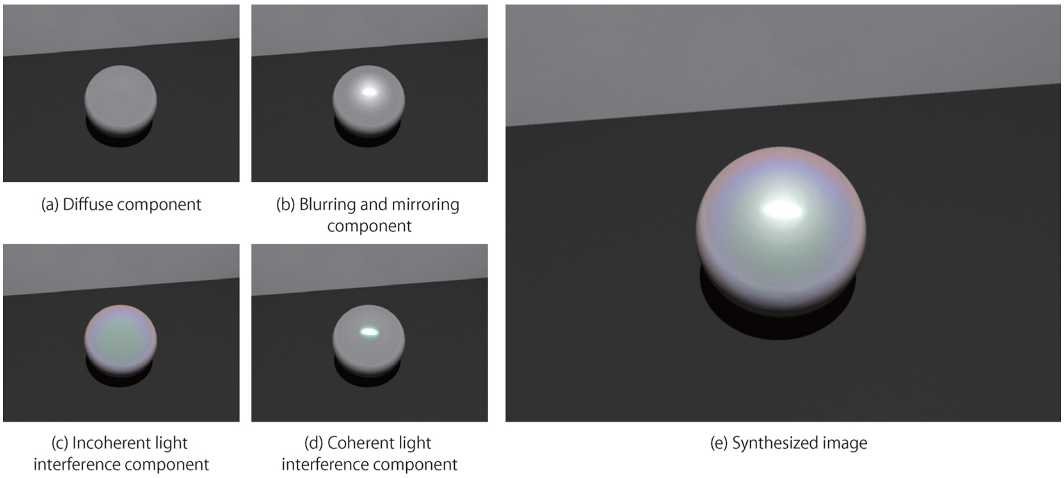


Fig. 11. Synthesized peal image with four components

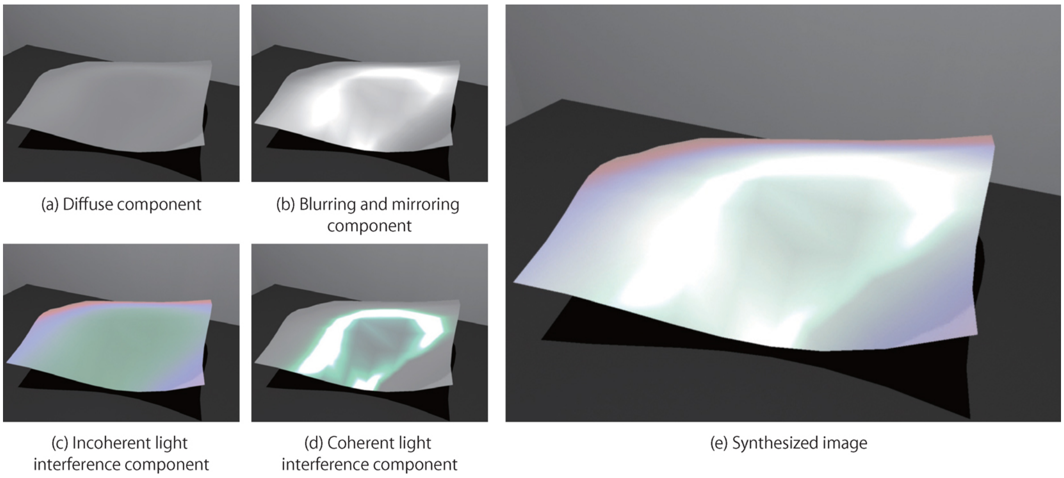


Fig. 12. Synthesized free-form surface with four components

References

[1] Maxfield, J., Dew, P. M., Zhao, J., Juster, N. P., Taylor, S., Fitchie, M., Ion, W. J., and Thompson, M.,"Predicting Product Cosmetic Quality using Virtual Environment,". in *Proceedings of 2000 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* Baltimore, Maryland, USA, 2000.

[2] N. Nagata, M. Kamei, M. Akane, and H. Nakajima, "Development of a pearl quality evaluation system based on an instrumentation of eKanseif,". in *Trans. Inst. Elect. Eng. Jpn. C,* vol. 112-C, no. 2, pp. 111-116, 1992.

[3] N. Nagata, M. Kamei, and T. Usami, "Factors identification using sensitivity of layered neural networks and its application to pearl color evaluation,". *Trans. Inst. Elect. Eng. Jpn. C,* vol. 116-C, no. 5, pp. 556-562, 1996.

[4] K. Wada, "*Pearl* ". Tokyo, Japan: National Jewelry Association, 1982.

[5] J. S. Gondek, G. W. Meyer, and J. G. Newman, "Wavelength dependent reflectance functions,". in *Proc. Computer Graphics Annu. Conf. Series,* 1994, pp. 213-220.

[6] Craig Donner, and Henrik Wann Jensen, "Light diffusion in multi-layered translucent materials,". in *ACM Transactions on Graphics,* vol. 24, no. 3, pp. 1032-1039, July. 2005.

[7] N. Nagata, T. Dobashi, Y. Manabe, T. Usami, and S. Inokuchi, "Modeling and visualization for a pearl-quality evaluation simulator,". *IEEE Trans. Visual. Comput. Graphics,* vol. 3, pp. 307-315, Oct./Dec. 1997.

[8] T. Dobashi, N. Nagata, Y. Manabe, and S. Inokuchi, "Implementation of a Pearl Visual Simulator Based on Blurring and Interference,". *IEEE/ASME Transactions on Mechatronics,* vol. 3, no. 2, pp. 106-112, June. 1998.