Implementation of a Pearl Visual Simulator Based on Blurring and Interference

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***Abstract*—Visual simulation using computer graphics has attracted wide attention in many fields. In this paper, we propose a method of modeling and visualizing pearls to implement a pearl visual simulator. Pearls manifest a very specific optical phenomenon. To investigate this feature, we propose an optical model of blurring and pearl interference. The experimental results show that the physics-based modeling of internal blurring in the multilayer of a pearl and the partial coherent interference model are effective for high-quality pearl visualization.**

***Index Terms*—Blurring, computer graphics, Monte Carlo, multilayer thin-film interference, pearl, physics-based modeling.**

I. Introduction

THERE have been many studies in various fields to add sensitive values, such as "uniqueness" and "delicacy," to the conventional computer graphics representations [1], [2]. The authors began research using machine vision technology in 1992 [3], [4] for the evaluation of pearl quality requiring intuitive expertise, even during inspection in the production process. Later, the visual simulation technique was introduced, and a visual simulator was experimentally produced to investigate the optimization of inspection conditions and normalization of standards [5]. The purpose was to carry out modeling of the optical behavior, so as to conform as closely as possible to the actual phenomenon, in order to clarify how the physical parameters contribute to the pearl quality. This approach can be ranked as an "analysis-by-synthesis" method in the field of pattern recognition.

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. [6]. The modeling and visualization of a pearl with specific optical and structural features is an interesting theme. The study of the optical phenomenon of pearl mica paint has previously been reported [7], however, no research has yet been performed on the optical phenomenon of actual pearls. The authors succeeded in [5] 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, by using physics-based modeling.

This paper indicates the importance of the blurring of light, as a fourth factor, to improve the representation of a delicate appearance, and proposes its computational model and calculation algorithm.

The blurring of light in a translucent body is caused by the internal spread of light, which is normally explained by the scattering of light. Research into the simulation of the scattering phenomenon has often been reported [8]–[10]. However, the blur observed in a pearl is considered a phenomenon different from the mere scattering of light. In this paper, the authors explain the blur in a pearl as the spread of light caused by repeated specular reflection and transmission, and produce the blurring component image through simulation.

Further, a new model is also proposed, including coherent light, in addition to the incoherent light so far considered in the visualization of the interference phenomenon.

II. Computational Model of a Pearl Based on Physics

This section deals with the previously announced model [5] of multilayer thin-film interference of a pearl and the pearl image synthesis algorithm required to explain the interference and blurring models proposed in this paper.

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.

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 a and b 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

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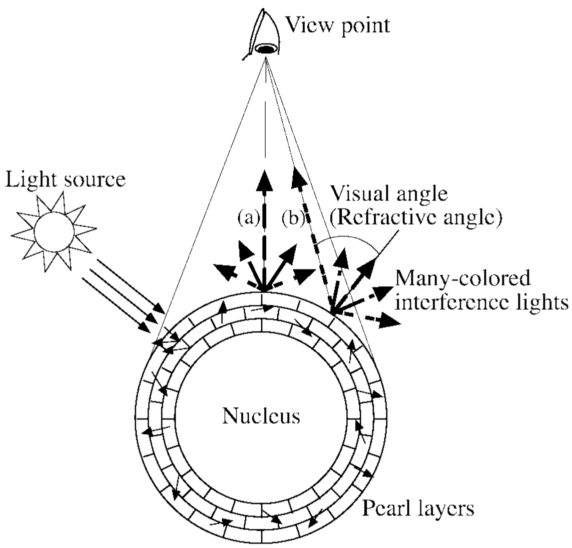

Fig. 1. A physical model of multilayer thin films of a pearl.

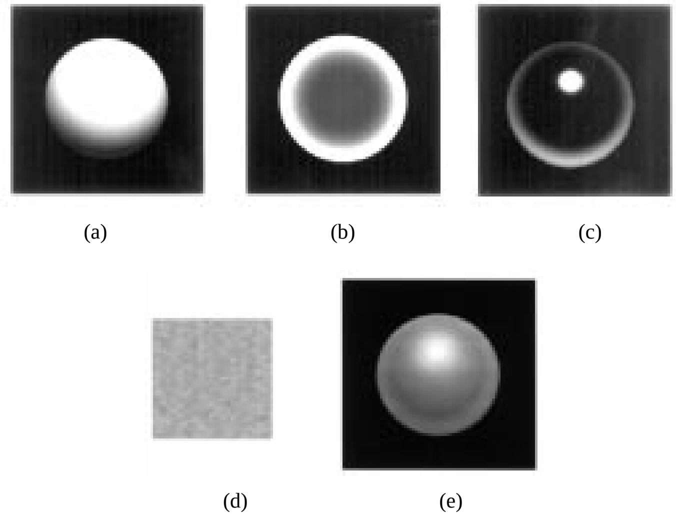

Fig. 2. Components and a synthesized image. (a) Diffuse component. (b) Interference component. (c) Mirroring component. (d) Texture component (value). (e) Synthesized image. (Original images are in color.)

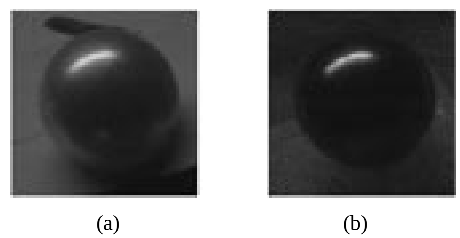

Fig. 3. Blurring of light.

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, which we will describe in the next section, is generated.

C. Synthesis of a Pearl Image

The synthesis algorithm is based on three psychological factors, namely, the sense of depth, brightness, and grain, used previously by the authors in their psychological experiments to evaluate the pearl [4]. 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 section, the representation of the sense of brightness is explained.

III. Simulation of Blurring

Pearl representation has so far been carried out mainly through interference simulation, so the representations of other factors were not fully considered, because of the adoption of conventional shading models.

Most general shading models use only the information of the object surface and cannot represent the uniqueness coming from the subsurface structure.

This section proposes the model of blurring and the synthesis algorithm to represent a sense of brightness.

A. Blurring Model of Pearl Due to Subsurface Reflection

The blurring of light in a translucent body is normally explained by the scattering phenomenon. The various types of scattering include isotropic scattering where the light scatters uniformly in all directions, Rayleigh scattering, and Mie scattering caused by fine particles in atmosphere.

However, the blurring of light in a pearl is quite different from these. Fig. 3 shows an example of the blurring of light seen in a pearl. Fig. 3(a) shows a reflection pattern of a fluorescent light on a pearl, and Fig. 3(b) shows the reflection pattern on a gold-coated pearl. The surface of the pearl is coated with gold 10–30 μm thick to prevent light from entering the subsurface, retaining the surface state.

Because the reflectance of an object varies according to its refractive index, the two images cannot be directly compared, but it is apparent that appearance of the reflections of the light source are different in Fig. 3(a) and (b). In Fig. 3(b), a sharp reflection of the light source, a characteristic of a mirror surface, is seen, while in Fig. 3(a), the sharp reflection of light source seen in Fig. 3(b), together with blurred light around

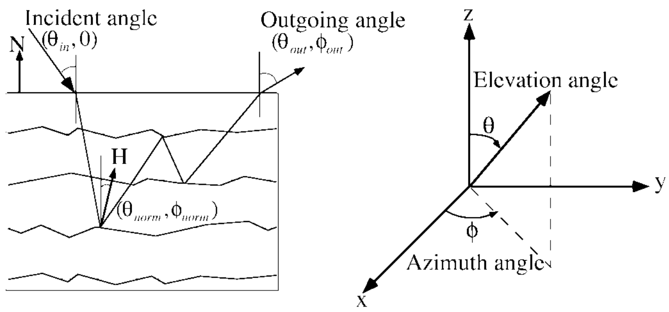

Fig. 4. Simulation using Monte Carlo algorithm.

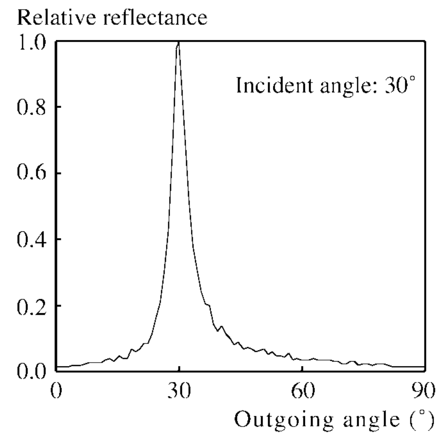

Fig. 5. An example of BRDF by Monte Carlo algorithm.

the light image, is observed. The luminance of this blurring is stronger around the highlight than at the point where the light enters nacreous layers at right angles to the surface, indicating that the behavior of the light entering the nacreous surface has the characteristic of regular reflection instead of scattering. The subsurface of a pearl has a layered structure, so specular reflection with strong directivity must be taking place inside the layers, as well as on the surface. (Since the photographs have been excessively exposed to light, in order to clarify the blurring, the light source image has become saturated, appearing wider than the actual image.)

From these observations of a pearl, 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.

Proposed below are two algorithms to represent the blurring of light caused by subsurface reflection.

B. Simulation Using Monte Carlo Method

The first algorithm uses 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.

The calculation procedure is illustrated in Fig. 4. First, it is supposed that a light ray enters the layer with the incident angle ($\theta_{\rm in}$, 0), and is reflected or transmitted by a microfacet with normal vector $\mathbf{H}$ and with a slope ($\theta_{\rm norm}$, $\phi_{\rm norm}$) against the normal vector $\mathbf{N}$ of the layer. The slope of the microfacet is stochastically determined in the following manner by using the microfacet distribution function

$$\theta_{\rm norm} = f(R_1) \tag{1}$$

$$\phi_{\rm norm} = 2\pi R_2. \tag{2}$$

Here, R_1 and R_2 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 ($\theta_{\rm out}$, $\phi_{\rm out}$), 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.

Fig. 5 shows the BRDF for an incident angle of 30° using the aforesaid method. The BRDF shows nonsymmetrical distribution of light with the direction of regular reflection as the center, indicating that the blurring phenomenon is properly simulated.

This algorithm features high-quality simulation. It has the drawback, however, of calling for the preparation of a lookup table beforehand and fails to satisfy the reliability and continuity unless a large number of experiments are carried out.

C. Fast Simulation Based on Reflection Distribution

The next algorithm we would like to propose is more simplified and faster than the previously mentioned model.

The simulation results of the previous model show that the rate of deviation of a ray from the direction of regular reflection/transmission becomes higher as the ray goes through a layer by repeating reflections and transmissions.

Assuming that the ray inside the nacreous layer keeps its directivity near the surface, and that the reflection distribution in deeper layers has a wider directivity, and by summing up the reflection distributions calculated and weighted for each layer, we can obtain the entire blurring distribution for subsurface reflection.

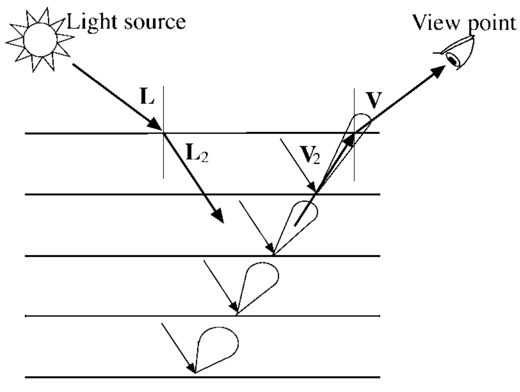

Fig. 6. Fast simulation using specular reflection distribution.

The calculation process illustrated in Fig. 6 shows the tracing of a ray away from the viewpoint and sums up the reflection distributions differing in each layer from the surface to the deeper layer.

The extent of reflection distribution is controlled by the Beckmann function used in the Cook–Torrance reflection model. The Beckmann function is expressed by

$$D = \frac{\exp\left[-(\tan\,\delta/m^2)\right]}{m^2\,\cos^4\,\delta}. \tag{3}$$

Here, m is the parameter indicating the surface roughness, and δ is the angle between the surface normal and the microfacet normal.

In the Cook–Torrance model, variable m has the physical meaning of the normal distribution of microfacets, but, in our model, we handle this variable as a distribution parameter related with both the incident $\mathbf{L}_2$ that reflects light in the $\mathbf{V}_2$ direction and the microfacet normal $\mathbf{H}$.

It is usually taken for granted that the color of specular reflection is equivalent to the color of a light source. The pearl blurring component, however, is caused by the light that has entered the subsurface, and, so, we have allotted an object color according to the depth of the layer.

Compared with the Monte Carlo algorithm mentioned above, this algorithm is more approximate, but has the advantages that it requires the calculation of only those rays that reach the eye and that the amount of calculation can be scalable to the quality or calculation time required, because the cost is proportional to the number of layers for which the reflection distribution is calculated. Fig. 7 shows an example of the BRDF for an incident angle of 30° calculated by using this algorithm, with the graph showing sufficient approximation to the graph in Fig. 5.

This algorithm keeps the characteristic of the first algorithm, namely, the direction becomes more and more deviated from the regular reflection as the ray moves deeper into the nacreous layer, while keeping the calculation cost comparatively low.

D. Image Synthesis of Blurring Component

An example of the blurring component image synthesized by using the fast algorithm is given in Fig. 8, showing clearly the light source image at the center and the blurring around

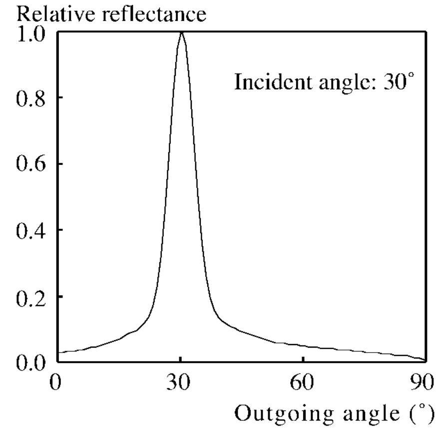

Fig. 7. An example of BRDF by fast simulation.

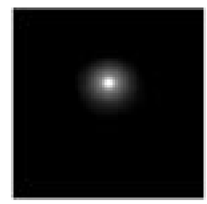

Fig. 8. An image showing blurring.

it. The synthesized pearl image, including this blurring component image, is given in Section IV-C for the convenience of explanation.

IV. Partial Coherent Interference Model

In Section II, 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. In this section, therefore, we intend to take due account of the interference light which is dependent on the direction of the light source to propose a model based on the actual phenomena.

A. Failure in Pearl Representation Using General Thin-Film Interference Model

Originally, we carried out simulation on the assumption that the pearl interference phenomenon depended on the general thin-film interference model. During the process, however, the appearance of a strange image quite different from a real pearl made us abandon the general model and search for the new illuminant model mentioned in Section II.

Here, we would like to confirm again the concept of a general thin-film interference. In a general thin-film interference, the hue distribution of the interference light greatly depends on the direction of the light source, apparently because of the dependency of the phase difference between two interference waves on the incident angle of the light. This phenomenon is seen in the shifting of the transmitted/reflected light spectrum of a narrow bandpass filter or a multilayer thin film coating in the short-wave direction when the incident angle becomes

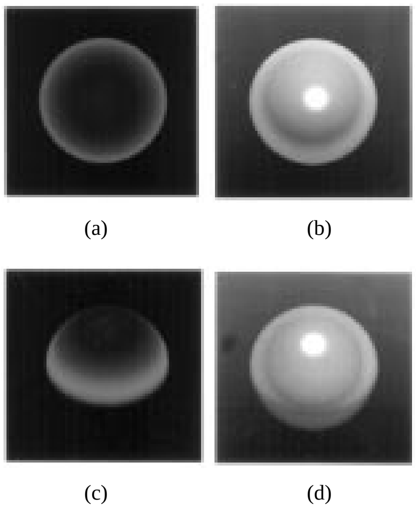

Fig. 9. Incorrect images based on a wrong model. (a) Interference component image when the viewing direction is closer to the light source direction. (b) Synthesized image when the viewing direction is closer to the light source direction. (c) Interference component image when the viewing direction is away from the light source direction. (d) Synthesized image when the viewing direction is away from the light source direction. (Original images are in color.)

larger. It can be easily observed that the light changes its color from green to blue, violet, red, etc., when a narrow bandpass filter facing a light source is gradually inclined.

The synthesized images based on the conception of a general interference are given in Fig. 9(a) and (b). The images looked fine at first. Fig. 9(a) shows the image of the interference component, and Fig. 9(b) shows the synthesized pearl image. However, when the light-source position is changed, the interference component image and the synthesized image were changed, as shown in Fig. 9(c) and (d), and are quite different from the images of a real pearl.

After consideration, it was revealed that no problem arose when the angle between the light-source direction and the viewing direction was narrow and that the incompatibility between the real and synthesized images appeared when the angle between the light source direction and the viewing direction became wider. Further observations and simulations showed that the interference hue was always distributed concentrically from the center of the sphere, which led us to develop a model which was independent of the direction of the light source.

B. Partial Coherent Interference Model

We have succeeded in explaining the concentric distribution of the interference hue from the center of the sphere and in synthesizing pearl-like images by using the illuminant model. It is true that the concentric distribution of the interference hue is the main feature of the pearl interference, as mentioned in the previous section, but it does not necessarily mean that the pearl does not also have general thin-film interference.

Actually, 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

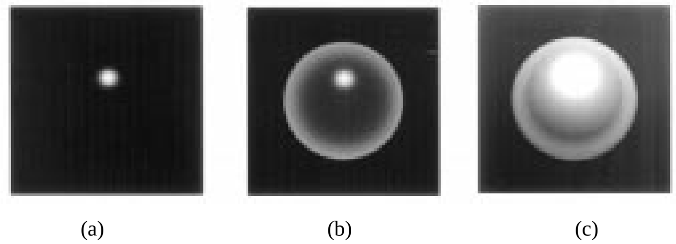

Fig. 10. A synthesized image with interference and blurring. (a) Coherent light interference image. (b) Partial coherent interference image. (c) Synthesized image. (Original images are in color.)

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.

We call this model the “partial coherent model,” since both coherent and incoherent light are taken into account.

C. Image Synthesis

Examples of synthesized images obtained through the partial coherent model and the blurring model mentioned in the above section are given in Fig. 10, with Fig. 10(a) showing an image of interference component of coherent light and Fig. 10(b) the mixed image of Fig. 10(a) and the interference component of incoherent light obtained through the illuminant model.

Fig. 10(c) shows a synthesized pearl image containing both the partial coherent interference image in Fig. 10(b) and the blurring component image in Fig. 8. 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.

V. Implementation to the Simulator

A visual pearl-quality evaluation simulator was built using the visualization technique, in order to synthesize the virtual pearl images. Fig. 11 shows an example of the visual pearl simulator. Using this simulator, 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);

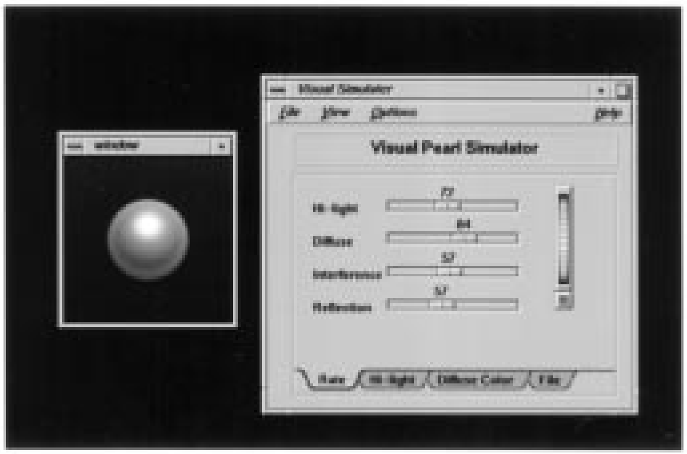

Fig. 11. A pearl visual simulator. (Original image is in color.)

5) interference color (hue of interference component);
6) direction of light source.

We can visualize how the physical parameters contribute to the pearl quality by changing the values of the operating amount of these parameters.

The simulator is implemented on an SGI Power Onyx graphics workstation. It takes a few minutes to prepare a lookup table for the interference component, but, once made, the interference component images can be synthesized only by using the lookup table. The time needed to synthesize the images of components other than the interference component is in the order of a few seconds for a 200×200 resolution image, which we think is within a permissible range of time.

Furthermore, this simulator is equipped with a superimposition function and is capable of placing a synthesized image in a real scene. Examples of synthesized images in real scenes are shown in Fig. 12.

The superimposition of the synthesized pearl images and real scenes is useful not only for quality evaluation, but, also, for wide applications, such as designing jewelry and ordering through the Internet. With the time currently required for calculation and the present level of image quality, before long the simulator will be able to be applied to experience the feeling of a product in a catalog by placing synthesized jewelry on the facial image of customers at jewelry shops, or in a virtual jewelry design system allowing the interactive design of made-to-order jewelry.

VI. Conclusion

We have proposed an image synthesis algorithm and optical models of interference and blurring for pearl visualization based on physics-based modeling. 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. Both models were found to provide sufficient quality for pearl representation, so we adopted the latter model, which had lower calculation costs. 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 synthesized the pearl images to confirm the improvement in the sense of brightness and pearl-like quality.

(a)

(b)

Fig. 12. Superimposition of synthesized images on photos of real pearls. (a) Synthesized image (left) and real image (right). (b) Real image (left half) and synthesized image (right half). (Original images are in color.)

Further, we implemented these functions on a simulator to carry out the real-time synthesis of virtual and real pearl images and confirmed that this system could be put into practical use in jewelry shops.

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 by using the elementary factor of "pearl-like quality."

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