General Papers

Real-time Rendering of Translucent Material by Contrast-Reversing Procedure

Ryota DOMON[(1)*1] d.0402.r@gmail.com

Shoji YAMAMOTO[(2)] Yamasho@acp.metro-cit.ac.jp

Kentaro HIKOSAKA[(3)] Kentaro.Hikosaka@nikon.com

Norimichi TSUMURA[(1)] tsumura@faculty.chiba-u.jp

(1) Graduate School of Advanced Integration Science, Chiba University, CHIBA, JAPAN
1-33 Yayoi-cho, Inage-ku, Chiba-city, Chiba

(2) Tokyo Metropolitan College of Industrial Technology, TOKYO, JAPAN
17-1, Minamisenju 8-chome, Arakawa City, Tokyo,

(3) Nikon Corporation, TOKYO, JAPAN
Shinagawa Intercity Tower C, 2-15-3, Konan, Minato-ku, Tokyo

Abstracts

We present a rapid rendering procedure to reproduce the appearance of an object that includes translucent material. The conventional method of rendering the translucence of an object is difficult to implement in real time, since the translucency is accompanied by complicated light behavior such as scattering and absorption. To simplify this rendering process, we focus on the contrast-reversing stimulant property in vision science. This property is based on the perception that we can recognize a luminance histogram compatible between scattering and absorption. According to this property, we propose a simple rendering method to reverse the light path between reflection and transmission. Our method adopts an additional function for selecting a front or back scattering process in the calculation of each pixel value. Because this improvement makes only slight alterations in the conventional reflection model, it can reproduce a translucent appearance in real time while inheriting the advantages of various reflection models.

1. Introduction

Computer-aided reproduction such as digital mock-ups is a remarkable tool for design and development. This tool has the advantage of reproducing various features by changing the shape, color, and material properties of a trial product. When designers consider configurations of a product, the transformation of the vertex position in computer graphics (CG) can realize the change of shape. The control of the pixel color of a polygon can realize the change of appearance in a digital mock-up. This process is accompanied by intuitive judgment, and so a rendering engine is necessary to represent the real appearance of products in real time for a digital mock-up. To express the real appearance, many researchers have made an effort to develop a reflection model in computer graphics. The Phong reflection model is a well-known equation that has parameters of diffuse and specular reflections.[1)] This model can reproduce various appearances having a gloss or matte surface. More detailed formulations and many parameters in the reflection model have been proposed to express accurate appearance. However, as the setting parameters of the reflection model become more complex, rendering the appearance in real time becomes more difficult. A fast and realistic rendering engine for the reflection model is consequently desired for computer-aided reproduction. Furthermore, a rendering engine must have the ability to reproduce a wide variety of appearances of materials such as glass and plastic. Such materials have characteristic appearances of transparency and translucency. The reproduction of transparency is relatively easy to realize by adding Snell's Law and an absorption coefficient into conventional ray tracing. In contrast, the reproduction of translucency requires calculating the light scattering process. Since light scattering generates the deflection of a ray from a straight path by irregularities of the material medium, the rendering process becomes more complex in multi-pass ray tracing. Jensen et al. proposed the dipole approximation model to simplify the calculation of scattering effects [2]. This model can generate a realistic appearance of a translucent material in a short time. However, a simpler model for translucency is desired to reproduce a digital mock-up in real time. Especially, mobile devices such as smartphone and wearable devices have some mechanical or size of constraint because these devices are preferred to be smaller. Even CPU or GPU get higher performance and minimized, the rendering cost should be low. Moreover, by considering the reality of reproduction, three-dimensional reproduction would be better for appearance reproduction.

In this paper, we propose a rapid rendering procedure to reproduce the appearance of an object with translucent material. Based on the contrast-reversing stimulant property in vision science, our proposed method can change the translucency of an object by using the reversal operation of diffuse reflectance. Our proposed method is a simple way to control the translucent appearance while retaining specular reflection. and surface roughness in computer-aided reproduction.

2. Related Work

A very useful reproduction technique in CG is evaluating the appearance of the final product by the process of digital mock-ups. These reproductions are created by a rendering algorithm based on dichromatic reflection models, such as the Phong, Torrance-Sparrow, Ward, and Lafortune models [1)3)4)5)]. For example, the appearance of gold material can be reproduced by setting the appropriate diffuse and specular reflectance. Nevertheless, this rendering system also needs to represent a wide variety of material properties, such as transparency and translucency.

Xiao et al. indicated that translucency depends on the lighting direction and phase function, as shown in Fig. 1 [6]. This figure (Fig. 10 in their paper) shows the comparison between forward lighting of a translucent object and backward lighting of the same object. It is apparent that the luminance of the reproduced object in Fig. 1(a) and Fig. 1(b) are in reversed conditions. To reproduce a realistic appearance, Ishimaru used a volumetric Monte Carlo path tracing method based on the radiation transfer equation [7]. Though this rendering method is sophisticated, the calculation cost of reproducing the translucent object can be very high. In contrast, the skin image reproduction method is enthusiastically studied because it can be applied for many reproduction systems such as video games and movie. Jensen et al. proposed the dipole diffusion model, which is an approximation of scattering effects [2]. This model is widely used because it can reproduce a translucent object in a short time compared with reproduction by Monte Carlo path tracing. The dipole approximation model can generate realistic skin images. Although this method achieved fast reproduction of skin image, it has difficulty reproducing a translucent appearance with backward lighting because it is difficult for this method to take account for medium's thickness. d'Eon et al. proposed real time rendering method based on the dipole approximation model and modified translucent shadow map method (TSM)[8)9)]. TSM is one of the methods which can generates the translucent appearance with taking account for the thickness of the medium. Those methods are very useful and practical, however, they mainly aim for the reproduction of the skin image. Because the skin has a relatively complexed organization, the photon propagation got more complexed. The object with translucent appearance is not only but skin but also wax, soap and so on.

Making a paradigm shift to rendering for translucency, we focus on the image processing method proposed by Motoyoshi [10)]. He implied that simple image statistics or texture metrics are cues for translucency. He found that reversing the luminance histogram for reducing the RMS contrast of reproducing an image can represent translucency. This property, based on visual perception, is very simple image processing for reproducing a translucent object. Though this method does not consider a rendering algorithm and pipeline, his idea provides us with useful knowledge. Our proposed method can represent translucency in real time based on contrast reversing. Moreover, by adding the function that can select a front- or back-scattering process in the calculation of pixel values, we can control the appearance by changing parameters flexibly. We also embed our idea in the rendering pipeline to verify our proposed method.

3. Method

3.1 Simplified Light Transport

We employ some parameters to describe the light transport phenomenon. In our proposed simplified light transport, the state of scattering follows Kubelka-Munk single time scattering. Scattering parameter s indicates the amount of scattered light and back-scattering weight w indicates the ratio of back-scattered light. Another parameter, absorption parameter a, describes the amount of absorbed light in the medium. Next, we explain simplified light transport. Fig. 2 shows the concept of simplified light transport. In this method, we assume that the object is sufficiently thin to transmit through. First, incident light hits the object and enters the medium. As the incident light passes through the medium, it is scattered and absorbed. The effect of each light transport phenomenon is described by the following light transport parameters.

$$I_{backscatter} = wsLi\ , \tag{1}$$

$$I_{frontscatter} = (1-w)sLi\ , \tag{2}$$

$$I_{absorption} = aLi\ , \tag{3}$$

where Li is the intensity of incident light. Because back-scattered light and absorbed light will not pass through the medium, the intensity of transmitted light is determined from these components.

$$I_{transmit} = Li - aLi - wsLi, \quad (4)$$
$$= (1 - a)Li - wsLi$$

In our simplification, we assume that the amount of back-scattered light and front-scattered light is the same. Therefore, back-scattering weight w is assumed to be 1/2. Each component is rewritten by using the value of *w*.

$$I_{backscatter} = 1/2sLi\ , \quad (5)$$
$$I_{frontscatter} = 1/2sLi\ , \quad (6)$$
$$I_{transmit} = (1-a)Li - 1/2sLi\ , \quad (7)$$

3.2 Approximation if the effect of backlighting

Because translucency is effectively represented in the backward lighting condition, the reproduction system requires consideration of the backward lighting effects. In this condition, the observed light is transmitted light. Thus, the intensity of observed light in the backward lighting condition, $I_{backlit}$, can be regarded as the transmitted light component.

$$I_{backlit} = I_{transmit} \quad (8)$$
$$= (1-a)Li - 1/2sLi$$

On the other hand, in the direct or front lighting condition, the observed light is back-scattered light. Thus, the intensity of observed light in the direct lighting condition, $I_{directlit}$, is regarded as the back-scattered light component.

$$I_{directlit} = I_{backscatter} \quad (9)$$
$$= 1/2sLi$$

Let us summarize the approximation of the backward lighting effect. We find the same terms in Eq. 8 and Eq. 9, and so Eq. 8 is rewritten as Eq. 10.

$$I_{backlit} = (1-a)Li - I_{directlit} \quad (10)$$

Eq. 10 indicates that the intensity of light in the backward lighting condition is denoted by the intensity of light in the direct or front lighting condition. We found that Eq. 10 can also explain contrast reversing. The contrast-reversing method is similar to a simple negative-positive inversion, as is denoted in Eq. 11.

$$Output\ \ Value = 1 - Input\ value, \quad (11)$$

where "*Input value*" is the pixel value of the original image and "*Output value*" is the pixel value of the processed image. Eq. 11 is the simplest representation of contrast reversing. Eq. 10 and Eq. 11 also have similar terms. If it is supposed that the absorption in the medium is negligibly small and the intensity of incident light is normalized (*Li* = 1), Eq. 10 can be rewritten as

$$I_{backlit} = 1 - I_{directlit}\ . \tag{12}$$

Eq. 12 indicates that the contrast-reversing method is a kind of approximation of the backward lighting effect.

4. Implementation

Next, we apply our idea to a reflection model. Generally, the dichromatic reflection model has two terms to describe the light transport: diffuse reflectance and specular reflectance. Because this model can represent various material appearances, it is difficult to apply the effects of backward lighting to a practical CG reflection model. However, the effects of backward lighting can be approximated by using the effects of forward lighting, as derived in Eq. 4. Therefore, we embed the idea of contrast-reversing image processing to our reproduction system. Here, the rendering engine of our system employs Ward's reflection model. Ward's reflection model is defined by Eq. 13.

$$f(\theta_i, \phi_i, \phi_o, \phi_o) = \frac{\rho_d}{\pi} + \frac{\rho_s}{4\pi\alpha\sqrt{\cos\theta_i \cos\theta_o}} \exp\left(-\frac{\tan^2\delta}{\alpha^2}\right) \tag{13}$$

where θ and ϕ denote the polar and azimuthal angles of the incident and reflected light directions, respectively, α denotes spread of the specular lobe (hereinafter referred to as roughness), and δ denotes the halfway vector between the incident and reflected directions. In Eq. 13, diffuse reflectance ρ_d, specular reflectance ρ_s, and roughness α are controllable CG parameters in this research. Our system employs OpenGL Shader Language (GLSL) to control the rendering pipeline. As shown in Fig. 3, the output of rendering with Ward's reflection model is calculated by a pixel shader. This pixel shader can calculate the sum of the three variable parameters of CG, such as ambient light, diffuse reflectance, and specular reflectance in order to determine each pixel value.

Eq. 14 explains the general processes calculated in the pixel shader.

$$\text{output} = \text{ambient} + \text{diffuse} + \text{specular}.\ . \tag{14}$$

The diffuse term calculated by OpenGL can be regarded as the case of forward lighting. Therefore, the diffuse term can be assumed to be the intensity of light, $I_{directlit}$. As a result of embedding, contrast-reversing image processing can be applied to the reflection model, as shown in Eq. 15.

$$\text{output'} = \text{ambient} + (1 - \text{diffuse}) + \text{specular}. \tag{15}$$

Hereafter, we refer to the term (1 – diffuse) as “reversed diffuse reflectance”. Eq. 15 is used to reproduce the translucent material instead of Eq. 14. We examine this reproduction in the next section.

4. Verification of our system

As mentioned in the above section, we propose a simple method for reproducing translucent material. Based on the reflection model, our method can represent various translucent appearances rapidly, as well as the changes of gloss appearance. We used an Intel Core i7 processor with 8 GB memory, NVIDIA Quadro FX3700 and WXGA 3D video projector DepthQ HD 3D for displaying the three-dimensional reproduction. The geometry model is standard bunny with 35947 vertices. We render the reproduction at 120 frames per second in accordance with the performance of projector. We assume that speed of framerate is fast enough because it achieves the sped of framerate of the video games and CG movies recently. Therefore, our system achieves real-time rendering. Here, we evaluate our method against the conventional method by comparing the capability for reproducing the translucent appearance of an object. Fig. 3(a) shows the result of reproduction by using our system. Fig. 3(b) shows the result of reproduction by using the "SSS2" algorithm in LightWave 3D (NewTek, Inc). This rendering algorithm and software are used by Motoyoshi and Nagai et al. to study translucency cues [10)11)].

Though our system uses many approximations, appearances with translucent features, such as low contrast of the body and reverse of the bright and dark area, are obtained in Fig. 3(a) and Fig. 3(b). The "SSS2" algorithm in LightWave3D has many parameters for changing the appearance of the reproduced object. The rendering takes about 10 seconds. In contrast, our system easily controls the translucent appearance because we can change the appearance by replacing the reversed diffuse reflectance, specular reflectance, and surface roughness by performing keyboard operations. Moreover, the material appearance, including the opaque appearance, can be reproduced in real time. Therefore, our system is obviously beneficial to existing design tools.

A characteristic relationship is noticed between our method and Fresnel equations. The edge of the transparent object looks brighter due to the effects of Fresnel reflection. In contrast, the edge of the opaque object looks darker due to the effects of shading. Since our system employs the reversal operation of diffuse reflectance, this directly opposite phenomenon of the edge could be expressed as an intermediate link between shading and Fresnel equations. We assume that this expression leads us to translucent perception.

Let us next discuss the parameters of reproduction. Fig. 4(a) is a different case of reversed diffuse reflectance from Fig. 4(a), even though the specular reflectance and the surface roughness are considered to be the same. In the comparison of Fig. 4(a) to Fig. 3(a), the part of the body in Fig. 4(a) is darker and the part of the edge is brighter, since reversed diffuse reflectance is increased. Nagai et al. and Fleming and Bulthoff indicated that the edges or detail structure of objects with high contrast patterns contribute more to translucency than do other regions [11)12)]. Because our proposed system can change specular reflectance, which is one of its advantages, we can consider the effects of specular highlights on translucent material. Fig. 4(b) shows a different surface roughness from Fig. 3(a), even though the reversed diffuse reflectance and the specular reflectance have the same surface roughness. As the result of the comparison between Fig. 3(a) and Fig. 4(b), these reproductions give us a different perception of the material. The rendered object in Fig. 3(a) looks like jade and the rendered object in Fig. 4(b) looks like wax. The difference between these images is only the surface roughness.

6. Discussion

Our proposed method can reproduce a translucent appearance rapidly. Though this method uses many approximations, the difference between our reproduction system and LightWave3D is slight. In addition, in comparison with dipole model approximation, our system reproduces translucency very rapidly. Therefore, our system is very useful for digital mock-ups and other design tools. However, our system has some limitations. In the construction of our method, we assume that the thickness of the object is constant. Thus, it is difficult for our system to reproduce material by accounting for the thickness of an object. Moreover, though the phase function is a very important factor for translucent material appearance, our method regards this as isotropic scattering. The lighting direction is also limited in our system. Oblique lighting causes unnatural reproduction because our method is constructed by limiting the point of view of the observer and the light source position. Background color of reproduction is also important. In our proposed method, we reproduce the translucent material in black background. If we change the background color, relationships between bright area and dark area get reversed and it means the collapse of contrast reversing method. To adopt with this problem, we must take account for the background color like other previous methods. We evaluate an image statistic to describe the translucency. Fig. 5(a) and Fig. 5(b) show the translucent object and the opaque object, respectively, reproduced by our system. These reproduced objects have the same values except for the non-specular component. Luminance histograms of these images are shown in Fig. 6. The red bin is the histogram of Fig. 5(a) and the blue bin is the histogram of Fig. 5(b). It is apparent that the distribution of the histograms is narrower when the reproduced image has translucency. In other words, the image of a translucent object has less RMS contrast, as indicated by Motoyoshi[10)]. Therefore, our proposed system can represent the characteristics of the translucent image. Other “simple” statistical characteristics, such as skewness and variance, also fail to describe translucency.

We realize that specular reflection contributes to translucent material perception. Some previous works indicate that specular highlights are important for natural translucency[10)]. The shape of specular highlights, such as strong and sharp or weak and dull, is not fully examined. Since our proposed method retains the highlights, the effects of specular highlights on translucency can be investigated by referring to the numerical formulation proposed by Pellacini et al.[11)].

7. Conclusion and future work

In this paper, we present a fast rendering method available for digital mock-ups. By applying the contrast-reversing idea to the dichromatic reflection model, our system can produce a realistic translucent appearance rapidly compared to previous works and commercial software. Though our method has some limitations, fast reproduction and maneuverable keyboard operations are very useful for material designing tools such as digital mock-ups. In this work, we defined some parameters to approximate the complicated light behavior of a translucent object. To obtain more suitable results of reproduction for practical use, these parameters should be verified experimentally.

We also realize the effects of various changes of specular highlights on translucent material perception. The effects of specular highlights could be a controversial issue for translucent material perception. From a practical point of view, we need to investigate the relationships between the appearance of objects and the reproduction parameters, including specular reflectance and surface roughness. This investigation would be useful in material design applications in order to reproduce existing materials efficiently.

Acknowledgments

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Footnotes

*1 The author move to Nikon Corporation.

Caption of figures

Figure 1

(a) Forward lighting

(b) Backward lighting

Comparison between forward lighting and backward lighting.

Figure 2

Concept of simplified light transport

Figure 3

(a) Rendered image by our proposed method

(b) Rendered image by LightWave3D

Comparison of two ways of rendering

Figure 4

(a) Rendered image by changing reversed diffuse reflectance

(b) Rendered image by changing surface roughness

Result of our proposed method with different parameters

Figure 5

(a) Rendered image by contrast reversing rendering

(b) Rendered image by using Ward model.

Comparison of translucent rendering and opaque rendering

Figure 6

Histogram of Fig.5

Figures

Figure 1

(a) (b)

Figure 2

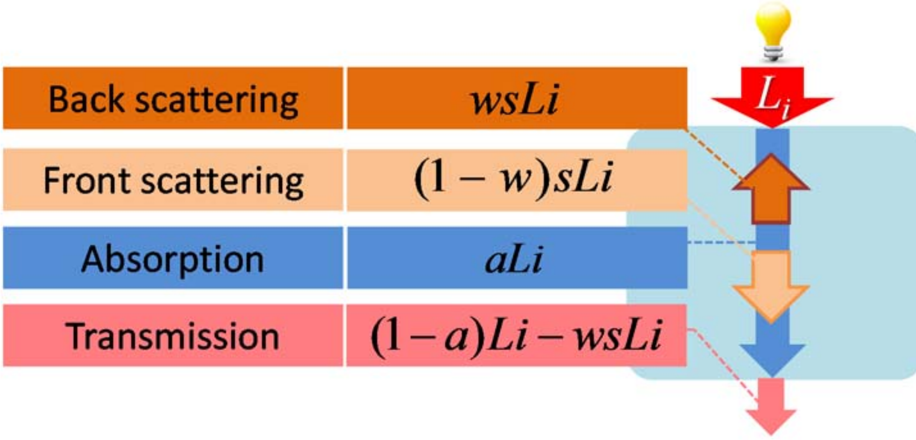
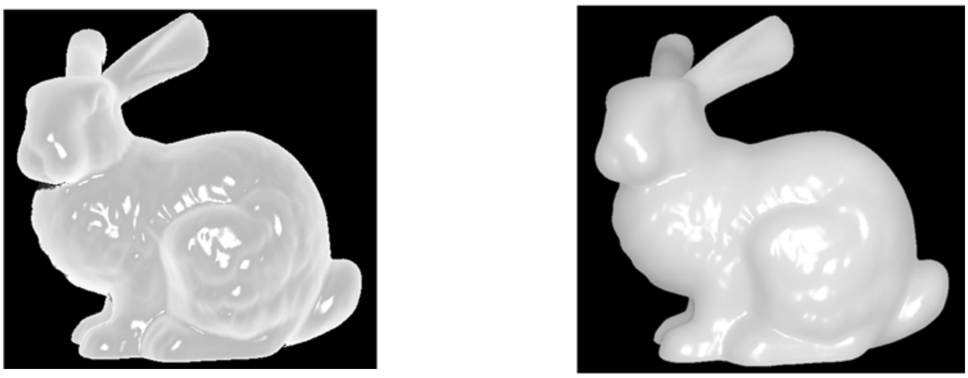
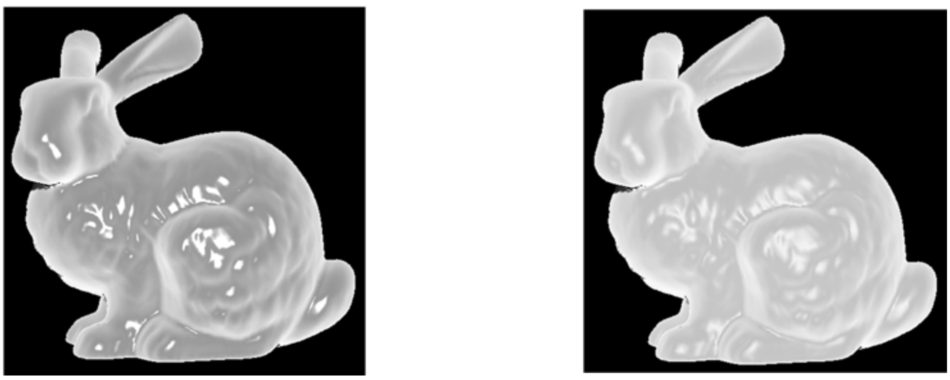


Figure 3



(a) (b)

Figure 4



(a) (b)

Figure 5

(a)

(b)

Figure 6