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SPECIAL ISSUE PAPER

Physically based cosmetic rendering[†]

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ABSTRACT

Simulating realistic makeup effects is one of the important research issues in the 3D facial animation and cosmetic industry. Existing approaches based on image processing techniques, such as warping and blending, have been mostly applied to transfer one's makeup to another's. Although these approaches are intuitive and need only makeup images, they have some drawbacks, for example, distorted shapes and fixed viewing and lighting conditions. In this paper, we propose an integrated approach, which combines the Kubelka–Munk model and a screen-space skin rendering approach, to simulate 3D makeup effects. The Kubelka–Munk model is used to compute total transmittance when light passes through cosmetic layers, whereas the screen-space translucent rendering approach simulates the subsurface scattering effects inside human skin. The parameters of Kubelka–Munk model are obtained by measuring the optical properties of different cosmetic materials, such as foundations, blushes, and lipsticks. Our results demonstrate that the proposed approach is able to render realistic cosmetic effects on human facial models, and different cosmetic materials and styles can be flexibly applied and simulated in real time. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS
skin rendering; translucent rendering; cosmetic rendering

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1. INTRODUCTION

Realistic rendering of human faces with makeup is critical for many applications in 3D facial animation and cosmetic industry because facial makeup is one of the most common routines for many females or even for some males. Makeup is a multi-layered process: skin care products are usually applied first and some cosmetics, such as foundation, blush, lipstick, and eye-shadow, are then smeared on one's face. By smearing the cosmetics on one's face, facial appearance changes obviously.

Several methods have been proposed to render makeup effects. These methods can be divided into two categories as follows: cosmetic transfer and makeup simulation. Cosmetic transfer requires examples of makeup images to transfer makeup effects. The transfer process can be performed very efficiently because it is computationally inexpensive. Nevertheless, cosmetic transfer has some limitations. For instance, each example image needs to be taken under a similar viewing and lighting direction, and the style of makeup effects is restricted by the examples. Furthermore, cosmetic transfer can only generate the makeup effects under a fixed viewing and lighting direction. In contrast to cosmetic transfer, makeup simulation needs to know the optical properties of cosmetics and skins, such as scattering coefficients and absorption coefficients, to simulate makeup appearance. The optical properties are usually captured using special devices. Once the optical properties are captured, the style of makeup simulation can be freely set.

In this paper, we aim to simulate the realistic rendering effect of human skin with cosmetics applied. A screen-space skin rendering technique [1] and a physically based Kubelka–Munk model [2] are employed to rendering cosmetic effects. Some cosmetic effects such as pearl and glitter effects are not handled in the proposed method because their optical properties are difficult to be measured. Our work makes the following two contributions: (i) proposing a framework that combines a screen-space skin rendering method and the Kubelka–Munk model for cosmetic rendering; (ii) developing a makeup simulation system that allows users to modify cosmetic styles and materials in real time.

2. RELATED WORK

Cosmetic transfer. Cosmetic transfer aims to transfer one's makeup information to another's. Such methods

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[†] Supporting information may be found in the online version of this paper.

usually require one or more makeup examples as the source cosmetic information. Tong *et al*. used two example images of the source face representing the facial appearances before and after makeup to derive a cosmetic map [3]. The cosmetic map was then applied to an image of the target face to transfer the makeup effect. Guo and Sim proposed another approach to transfer cosmetic effects based on one source image and one target image [4]. They applied image processing techniques to analyze the source image and utilized the obtained information to generate the final result. These two methods both utilized 2D image warping, which might cause the shape of makeup to be distorted. They also needed to capture the example images at the same or similar viewing condition.

Scherbaum *et al*. built a database of facial geometry captured by structural lights and used the database to synthesize the makeup effect [5]. Their database stored pairs of images of human faces without and with makeup. The information from a pair of images, such as position, surface normal, diffuse map, scattering profile, specular, and the cosmetic map were extracted. In the run-time, the user inputs a 2D facial image to retrieve a similar 3D face. The 3D face was then deformed to fit the input 2D image. After fetching the suitable face, the best matched facial appearance and cosmetic map in the principal component analysis (PCA) space were selected from the database. They then synthesized the cosmetic map and applied it to the diffuse map. This approach provided a good way to transfer makeup effect, but it still has some problems. First, the style of makeup is fixed; second, the system needs more hints to synthesize a plausible cosmetic map. Finally, the system needs many examples to produce the appearance correctly.

Cosmetic simulation. Moriuchi *et al*. used a physical model and a statistical approach to simulate foundation [6]. They measured the foundation from different viewing angles and captured its reflectance between 400 and 700 nm. They then fitted the data with the Cook–Torrance model to find the appropriate parameters. Using Cook–Torrance model to describe the translucent material, however, is not sufficient, because it is originally used to describe the bidirectional reflectance distribution function, not translucent materials. Therefore, they employed a statistical approach to analyze the reflectance data using PCA. Doi *et al*. used the Kubelka–Munk model to render the foundation on human skin [7]. They measured the reflectance of female skin and liquid foundations and showed the estimated skin color and foundation makeup using a color palette. Although they measured the skin reflectance, they did not apply it to 3D rendering. The translucent appearance of skin was also not handled. In this paper, we render cosmetic effects on 3D facial models using the diffusion approximation and thus can simulate the translucent effect.

Translucent and skin rendering. Human skin appearances can be simulated by translucent rendering. Among different translucent rendering approaches, the diffuse approximation has been used widely in recent years. Jensen *et al*. introduced the dipole diffuse approximation to solve the radiant transfer equation [8]. By assuming that the thickness of the material is infinite and the scattering coefficient σ_s is much larger than the absorption coefficient σ_a, they transformed the complex computation of interior behavior to a dipole function of distance and thus speeded up the computation process. Donner and Jensen extended the dipole approximation by adopting the multipole function to approximate thin-layered materials, such as skin and leaves [9]. After computing the reflectance of each layer, they used multilayered model to combine each layer. However, they did not deal with the measurement of the parameters of multipole model. The parameters acquired by the dipole model may not be used in the multipole model either.

d'Eon *et al*. further proposed a real-time texture-space algorithm for accelerating skin rendering [10]. They used sum-of-Gaussian to fit the diffuse profile and replaced the costly surface integration by multiple Gaussian blurring. The computation can be performed by graphics processing unit while physically plausible simulation is still retained. Jimenez *et al*. extended the texture-space technique to screen-space by applying screen-space information to blur the result in multiple times [1]. Krishnaswamy and Baranoski proposed a biophysically based spectral model for skin parameter acquisition [11]. Donner *et al*. [12] and Ghosh *et al*. [13] also obtained the skin parameters by fitting the measurement data to the appearances of human faces. All of these methods were designed only for skin rendering, not cosmetics. We focus on handling the combined rendering effects of cosmetics and skin layers in this paper.

3. APPROACH

Facial makeup is a multilayered structure. It usually consists of the skin layer, the foundation layer, the blush layer, and the eye shadow layer. To render this multilayered structure, we propose a framework that consists of a screen-space translucent rendering approach and the Kubelka–Munk model to simulate the makeup appearance. The proposed cosmetic rendering framework deals with two types of layers as follows: cosmetic and skin layers. We assume that the cosmetics do not have the pearl and the sparkle effect.

Figure 1 shows an overview of the proposed framework. To render the human skin with cosmetics, our system first computes the reflectance and transmittance of cosmetics. Next, the irradiance that passes through the cosmetic layers is calculated. After obtaining the irradiance of skin, we apply a screen-space subsurface scattering method to estimate the outgoing radiance. Then, the specular terms of skin and cosmetics are computed. Finally, the radiance of skin passing through cosmetics is combined with the reflectance of cosmetics.

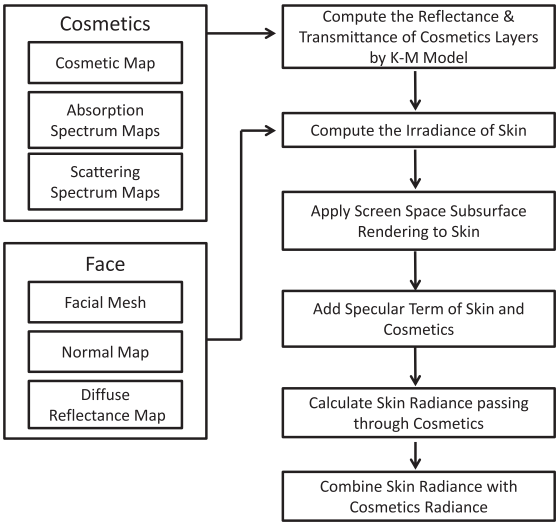


Figure 1. Overview of our cosmetic rendering framework.

3.1. Reflectance and Transmittance of Cosmetics

When the incident light reaches the surface of cosmetic layers, light is reflected to the air or transmitted to skin. To model this lighting behavior, we adopt the Kubelka–Munk model [2] to compute the reflectance and the transmittance of each cosmetic layer and then use the multilayered theory to compute final reflectance and transmittance. The Kubelka–Munk model computes reflectance R_0 and transmittance T using the following equations:

$$R_0 = \frac{\sinh bSX}{a \sinh bSX + b \cosh bSX} \tag{1}$$

$$T = \frac{b}{a \sinh bSX + b \cosh bSX} \tag{2}$$

where S and K are scattering and absorption coefficients per unit length, respectively. X is the thickness of a layer. $a = 1 + \left(\frac{K}{S}\right)$. $b = \sqrt{a^2 - 1}$. Note that R_0 means the reflectance that is not affected by the beneath background. The scattering coefficient S and the absorption coefficient K can be obtained by applying an inversion procedure to the measured reflectance. The detailed measurement procedures will be discussed in Section 4. R_0 and T computed by the Kubelka–Munk models are wavelength dependent and cannot be directly used for rendering. Hence, we first convert the spectra of the total reflectance and transmittance to CIE XYZ color space, which are then converted to the CIE RGB color space for rendering.

In order to represent different cosmetic styles for rendering, we use a cosmetic map to mark the region and thickness of each makeup layer. Therefore, we can fetch the corresponding texel to check whether it is covered by a cosmetic or not. Figures 2(a) and 3(a) illustrate two cosmetic maps. For multiple cosmetic layers, we need to combine different layers to obtain the final reflectance and transmittance. The combination of reflectance and transmittance of two layers involve multiple reflection. Figure 4 shows the path of the diffusion radiation for two layers. The reflectance and transmittance can be formulated in sum of geometric series, which can be calculated by Equations (3) and (4). This formulation can be extended to solve the cases that involve more than two layers.

$$R_{1,2} = R_1 + \frac{T_1 R_1 T_1}{1 - R_1 R_2} \tag{3}$$

$$T_{1,2} = \frac{T_1 T_2}{1 - R_1 R_2} \tag{4}$$

3.2. Skin Subsurface Scattering

We adopt a screen-space skin rendering technique proposed by Jimenez *et al.* [1] to render the appearance of human skin. In our work, we consider whether the surface is covered by the cosmetics or not. If the surface is covered, the received energy will be affected by the transmittance of

(a) (b) (c) (d) (e) (f)

Figure 2. Makeup rendering of Digital Coco for multilayered cosmetics. (a) Cosmetic map. Red: foundation area. Blue: lipstick. Yellow: blush + foundation. (b) The appearance of skin. (c) Foundation 1 + Lipstick 1 + Blush 1. (d) Foundation 5 + Lipstick 1 + Blush 1. (e) Foundation 5 + Lipstick 3 + Blush 2. (f) Foundation 3 + Lipstick 3.

(a) (b) (c) (d)

Figure 3. Makeup rendering of Digital Orange for multilayered cosmetics. (a) Cosmetic map. (b) The appearance of skin. (c) Foundation 1 + Lipstick 7 + Blush 1. (d) Foundation 3 + Lipstick 6 + Blush 1.

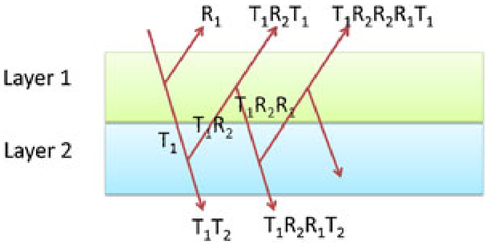


Figure 4. Reflectance and transmittance of two non-homogeneous layers.

the cosmetics. The total energy of light passing through the cosmetics is computed and stored in a screen-space irradiance map. The irradiance map is then blurred several times and combined. In each blurring pass, alpha blending is used to accumulate the blurring result, where the blending weights are set according to the sum-of-Gaussian.

3.3. Specularity of Skin and Cosmetics

The specular term is the most important for describing the highlight effect. In our observations, if we apply cosmetics to human skin, cosmetics usually make the skin surface look smoother. In particular, when foundation is applied, fine wrinkles on the skin surface are filled with the foundation, which changes the microfacet of skin and makes surface smoother. Unfortunately, the Kubelka–Munk model does not consider the specular term. Dorsey and Hanrahan [14] proposed a simple way to solve this problem. For each layer, they used the Kubelka–Munk model to compute the reflectance and transmittance and added specular effect by a simple model $C_s(\vec{N} \cdot \vec{H})^{1/r}$, where C_s is the specular color, r is the roughness, and $\vec{N}$ and $\vec{H}$ are the normalized normal vector and half vector, respectively. We use a similar way to simulate the specularity of each layer. Figure 5 shows the results of specular effects due to different foundations, where the left image only considers the specularity of skin, the middle image only considers the specularity of foundation, and the right image considers the specularity for both foundation and skin layers.

For each layer, we use the bidirectional reflectance distribution function specular model introduced by Kelemen *et al.* [15] to compute the specular term. This model is listed in Equation (5).

$$f_{r,spec}(\vec{L},\vec{V}) = P_{\vec{H}}(\vec{H})\frac{F(\vec{H}\cdot\vec{L})}{2(1+\vec{L}\cdot\vec{V})} \tag{5}$$

Figure 5. The rendering result with specularity. Left: only skin specularity added; middle: only foundation specularity added; right: both skin and foundation specularity added.

where $\overrightarrow{L}$ is the normalized light direction, $\overrightarrow{V}$ is the normalized view direction, $\overrightarrow{H}$ is the normalized half vector, $F(\overrightarrow{H} \cdot \overrightarrow{L})$ is the Fresnel term, and $P_{\overrightarrow{H}}(\overrightarrow{H})$ is the Beckmann distribution function. For the Fresnel term, we use Schlick's approximation to simulate the non-metal materials. The specular computation is performed from the bottom layer to the top layer. The remained specular lighting is reduced by the transmittance of the next layer, then combined with the new specular effect. In our implementation, we cannot measure the roughness and the index of refraction accurately. Therefore, we simply adjust the roughness to control the highlight and set a constant value. We believe that if we can obtain these parameters, more realistic results can be achieved.

4. MEASUREMENT OF COSMETICS

To compute the reflectance and transmittance of cosmetics layers, we need the scattering coefficient S and the absorption coefficient K. We measured these properties of cosmetics according to the Kubelka–Munk model. S and K can be evaluated by Equations (6) and (7), respectively. Both S and K are wavelength dependent.

$$S = \frac{1}{bD}\left[\coth^{-1}\frac{a-R}{b} - \coth^{-1}\frac{a-R_g}{b}\right] \tag{6}$$

$$K = S(a-1), \tag{7}$$

where $a = \frac{1}{2}\left(\frac{1}{R_\infty} + R_\infty\right)$, $b = \sqrt{a^2-1}$, and D is the thickness of sample. R_∞ denotes the reflectance of the layer when it is thick enough to be opaque. R represents the reflectance of the thin layer painted on the background, and R_g is the reflectance of the background. Note that the reflectance R differs from R_0 in Equation (1). R in Equation (6) contains the influence of background beneath the cosmetic layer, whereas the R_0 in Equation (1) is the reflectance of the layer only.

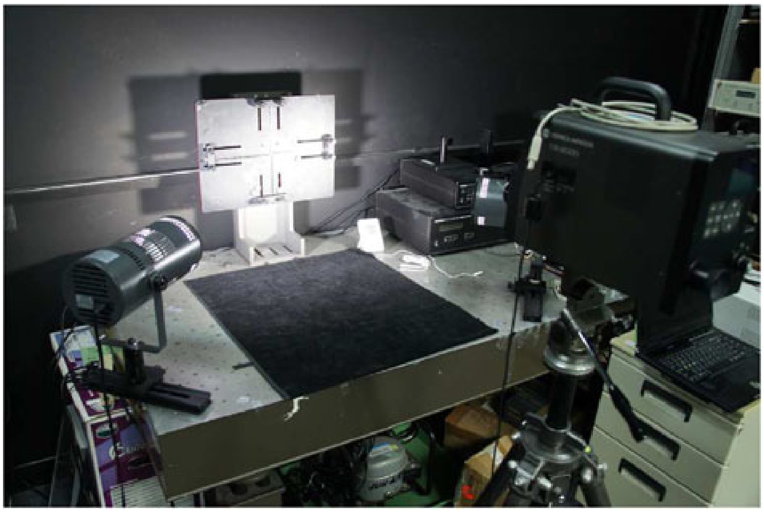
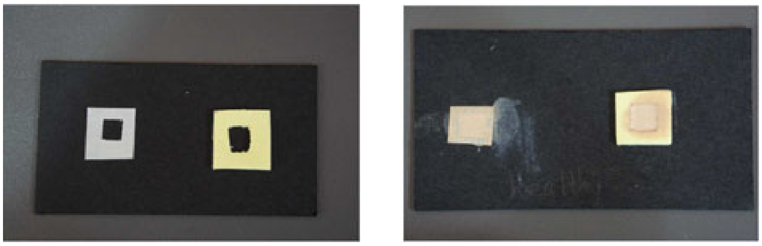


Figure 6. Our capture device and environment.

Figure 7. Liquid foundation samples. Left: the background. Middle: thick layer. Right: thin layer.



(a) (b)

Figure 8. (a) The container. (b) Loaded with liquid foundation. The depth of shallow and deep containers are 0.15 and 2 mm, respectively.

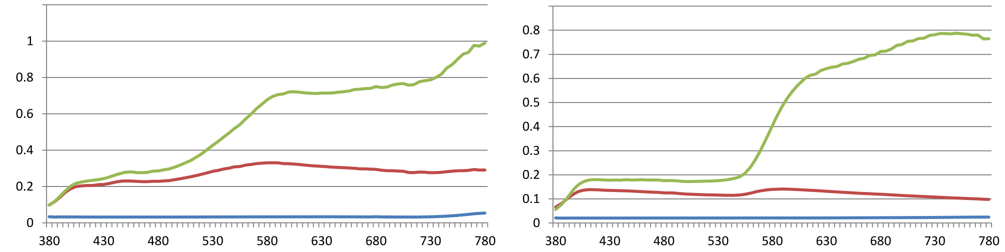
Solving for both the scattering coefficient S and the absorption coefficient K requires corresponding R_∞, R, and R_g. We use a spectroradiometer (MINOLTA CS-2000) to measure liquid foundation, cream blush, cream eye shadow, and lipstick. A D55 light source is used, and measurement is performed for wavelength between 380 and 780 nm with the interval of 5 nm. Figure 6 shows our measurement device and environment.

The spectroradiometer measures the radiant energy coming from the light and being reflected by the material. As the received radiant energy is influenced by the spectrum of light source, we need to convert the radiant energy to the reflectance, which can be expressed as

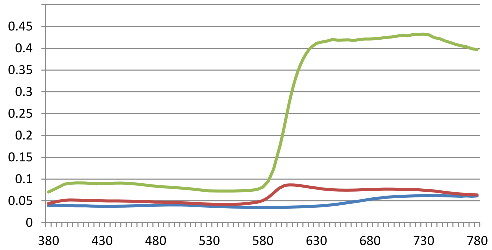
$$R(\lambda) = \frac{E_m(\lambda)}{E_L(\lambda)} \tag{8}$$

$E_m(\lambda)$ is the radiant energy of light that hits the surface and reflects to the spectroradiometer. $R(\lambda)$ is the reflectance of the material, and $E_L(\lambda)$ is the radiant energy of the incident light. We use barium sulfate of purity 99% as the standard white material to measure radiant energy of light source E_L. The reflectance of the measured material can be computed by Equation (8). After this process, we obtain the reflectance of each material $R(\lambda)$.

In our measurement experiments, we paint a cosmetic sample with enough thickness on the black background to make it opaque and measure its reflectance to obtain R_∞. Then, we paint the sample on a black background with certain thickness to measure R. Finally, we measure the reflectance of the background to determine R_g. Figure 7 shows a liquid foundation sample. We also make a simple container to load samples as shown in Figure 8. By

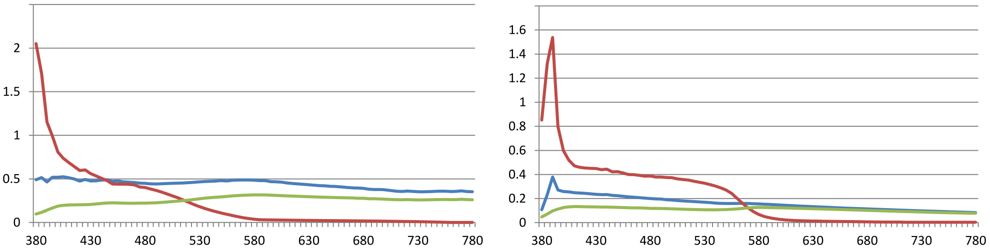


(a) Foundation 1 (b) Blash 1

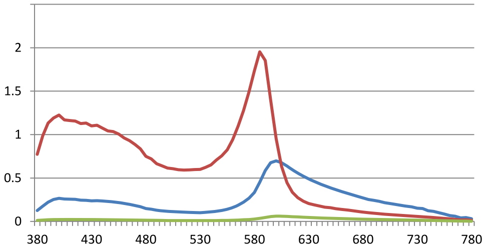


(c) Lipstick 1

Figure 9. The spectrum reflectance of some of the measured cosmetics. X-axis and Y-axis are the wavelength in nm and reflectance value, respectively. Red: reflectance of a 0.15-mm thin layer (with background) R; Green: reflectance of a thick layer R_∞; Blue: reflectance of background R_g.



(a) Foundation 1 (b) Blush 1



(c) Lipstick 1

Figure 10. The obtained parameters of some of the measured cosmetics. Red: absorption coefficient K; Green: reflectance of thin layer (without background) R_0; Blue: scattering coefficient S.

using this container, we can easily make a flat sample and measure the thickness of the sample. Figure 9 shows the reflectance of R_∞, R, and R_g of three different cosmetics.

We apply R_∞, R, and R_g to Equations (6) and (7) to obtain the scattering coefficient S and the absorption coefficient K, respectively. The S and K of each wavelength are then used in Equations (1) and (2) to simulate the reflectance R_0 and transmittance T of a thin layer. We can also use different thickness X to describe cosmetic materials of different thickness.

5. RESULTS

We implemented our cosmetic rendering system in DirectX 10 and HLSL. We rendered the makeup effects on two human facial models, including Digital Coco and Digital Orange. The geometry and appearance of both models were captured using the Light Stage X, including high-resolution meshes, normal maps, and diffuse reflectance maps. All rendering results were generated on a PC equipped with Intel Core i5 750 2.67 GHz CPU, 4 GB RAM, and an NVIDIA GTX 260 graphics card. The resolution of frame buffer is 1280 × 720. The rendering frame rate is about 170–175 frames per second for all cosmetic rendering results.

We measured the optical properties of different cosmetics, including five liquid foundations, two cream blushes, and seven lipsticks. The brands of these cosmetics are listed in Table A of the supplemental material. We first acquired the reflectance spectrum of these cosmetics. Figure 9 shows some of the measured results. Next, we used Equations (6) and (7) to compute the absorption coefficient K and scattering coefficient S. Finally, we reconstructed the reflectance R_0 and transmittance T using Equations (1) and (2). Figure 10 depicts K, S, and reflectance R_0 of these cosmetics in Figure 9. Once the optical parameters of cosmetics are obtained, we can use our system to render human skin with cosmetics. Our system allows the user to change the cosmetic material and simulates its makeup effects in real time. The rendering result of each measured cosmetic can be found in Figures A–C of the supplemental material.

Makeup usually combines layers of different cosmetics. Our method is able to render the skin with multilayered cosmetics. Figures 2 and 3 show our results of multilayered cosmetics. In particular, the cheeks are influenced by both foundation and blush. Our system allows the user to manipulate multiple cosmetics intuitively. Figure 11 shows

Figure 11. Comparison with the reference image of real makeup. Left: reference image; Right: our result.

a comparison of our result with the photo of a real makeup. We apply the hybrid normal map method proposed by Ma *et al*. [16] to generate the reference images. Their method can reproduce the surface shading of the object being captured because it acquires the specular and diffuse normal maps by polarized illumination in Light Stage. As we do not have the exact cosmetic map of the real makeup, our result is slightly different from the real makeup. Nevertheless, one can still observe that our rendering result provides a very similar appearance to the reference image.

Limitations. In the current approach, we do not consider the cosmetics that have pearl or sparkle effects. As these effects are view dependent, it is difficult to simulate them by simply using the Kubelka–Munk model. These effects, however, are also important for makeup simulation. Besides, we do not consider the cosmetics in the sparse powder form. This may not be a big problem though as it is not easy to distinguish the differences among liquid, cream, and sparse powder when the makeup is smeared evenly. Finally, compared with the work by Donner and Jensen [9], our approach ignores the subsurface scattering effects of cosmetics. This works well for some cosmetics, but not all cosmetics, especially for those kind with high translucency.

6. CONCLUSION

Our approach provides a simple way to realistically render cosmetics on human skins by combining a screen-space skin rendering method with Kubelka–Munk model. Different from existing makeup transfer methods that warp an example makeup image to a user's facial image, our makeup simulation system is physically based and provides flexible user control on cosmetics' thickness and styles in real time. Our system can be used in cosmetic industry to provide an interactive preview system that allows customers and designers to quickly simulate makeup effects. We believe that our work would greatly benefit many related applications in the cosmetic industry.

In the future, we would like to simulate more complex makeup effects that are view-dependent and handle cosmetics in powder forms. Also, we currently use some auxiliary 2D tools to help users design the cosmetic map. In the future, we can employ 3D mesh painting tools to allow users to paint makeup directly on a their facial models. Another direction is to combine the cosmetic map with cosmetic transferring method. The makeup styles can be extracted from images and represented as cosmetic maps, which then can be used in the proposed system to simulate the makeup effects in different styles.

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REFERENCES

1. Jimenez J, Sundstedt V, Gutierrez D. Screen-space perceptual rendering of human skin. *ACM Transactions on Applied Perception* 2009; **6**(4): 23:1–23:15.
2. Kortüm G. *Reflectance spectroscopy: principles, methods, applications*. Springer-Verlag New York, Inc., New York, NY, USA, 1969.
3. Tong W-S, Tang C-K, Brown MS, Xu Y-Q. Example-based cosmetic transfer, In *IEEE Conference on Computer Vision and Pattern Recognition 15th Pacific Conference on Computer Graphics and Applications*, PG'07, Maui, Hawaii, USA, 2007; 211–218.
4. Guo D, Sim T. Digital face makeup by example, In *IEEE Conference on Computer Vision and Pattern Recognition (CVPR 2009)*, IEEE, Miami, Florida, USA, 2009; 73–79.
5. Scherbaum K, Ritschel T, Hullin M, Thormählen T, Blanz V, Seidel H-P. Computer-suggested facial makeup, In *Computer Graphics Forum (Proceedings of Eurographics 2011)*, Vol. 30, Wiley Online Library, 2011; 485–492.
6. Moriuchi Y, Tominaga S, Horiuchi T. Precise analysis of spectral reflectance properties of cosmetic foundation. In *Image Analysis*. Springer, New York, NY, USA, 2009; 138–148.
7. Doi M, Ohtsuki R, Tominaga S. Spectral estimation of skin color with foundation makeup. In *14th Scandinavian Conference on Image Analysis, Joensuu, Finland (SCIA 2005)*, In *Image Analysis*. Springer, New York, NY, 2005; 95–104.
8. Jensen HW, Marschner SR, Levoy M, Hanrahan P. A practical model for subsurface light transport, In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '01)*, ACM, New York, NY, USA, 2001; 511–518.
9. Donner C, Jensen HW. Light diffusion in multi-layered translucent materials, In *ACM Transactions on Graphics (TOG) (SIGGRAPH '05)*, Vol. 24, ACM: New York, NY, USA, 2005; 1032–1039.
10. d'Eon E, Luebke D, Enderton E. Efficient rendering of human skin, In *Proceedings of the 18th Eurographics Conference on Rendering Techniques*, Proceedings of the Eurographics Symposium on Rendering, Grenoble, France, 2007; 147–157.

DOI: 10.1002/cav

11. Krishnaswamy A, Baranoski GVG. A biophysically based spectral model of light inteaction with human skin. *Computer Graphics Forum* 2004; **23**(3): 331–340.
12. Donner C, Weyrich T, d'Eon E, Ramamorthi R, Rusinkiewicz S. A layered, heterogeneous reflectance model for acquiring and rendering human skin, In *ACM Transactions on Graphics (TOG), (SIGGRAPH ASIA '08,* Singapore), Vol. 27, ACM: New York, NY, USA, 2008; 140.
13. Ghosh A, Hawins T, Peers P, Frederiksen S, Devebec P. Practical modeling and acquisition of layered facial reflectance, In *ACM Transactions on Graphics (TOG), SIGGRAPH ASIA '08,* Singapore, Vol. 27, ACM: New York, NY, USA, 2008; 139.
14. Dorsey J, Hanrahan P. Modeling and rendering of metallic patinas, In *Proceedings of the 23rd Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '96)*, New Orleans, Louisiana, USA. ACM: New York, NY, USA, 1996; 387–396.
15. Kelemen C, Szirmay-Kalos L. A microfacet based coupled specular-matte BRDF model with importance sampling. *In Eurographics Short Presentations* 2001; **25**: 34.
16. Ma W-C, Hawkins T, Peers P, Chabert C-F, Weiss M, Debevec P. Rapid acquisition of specular and diffuse normal maps from polarized spherical gradient illumination, In *Proceedings of the 18th Eurographics Conference on Rendering Techniques*, Eurographics Association, 2007; 183–194.

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