Journal of Imaging Science and Technology® 55(1): 010503–010503-7, 2011.
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Computational Lighting Reproduction for Facial Live Video with Rigid Facial Motion

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Abstract. *In this research, we develop a practical lighting reproduction technique to reproduce the appearance of a face under an arbitrary lighting condition in a facial live video with rigid facial motion. The reproduced facial image has texture detail and novel shading by combining image-based components and model-based components. Our technique is practical because it requires using only polarizing filters with the conventional green screen matting technique. © 2011 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.2011.55.1.010503]

INTRODUCTION

Lighting reproduction is a very important technique used in various areas. For example, in the film industry, lighting reproduction techniques have been used to reproduce an actor's appearance in various lighting conditions. Debevec et al.[1] presented a technique for reproducing a static facial image under varying lighting conditions. Wenger et al.[2] presented a lighting reproduction technique for actors in a performance. The lighting reproduction can be used as a live simulator of a person applying cosmetics in a store by reproducing the facial appearance under a particular lighting condition. If we can apply the lighting reproduction for cosmetic simulators, we can simulate the appearance of the face of the person wearing the cosmetics under various lighting conditions. However, these lighting reproduction techniques require a large apparatus, such as a once-subdivided icosahedron of more than 1.5 m in diameter.[1,2] A large apparatus is inappropriate for the cosmetic simulator because the simulator is usually used in a small space, such as at a store counter.

In this article, we develop a real-time lighting reproduction technique with a small apparatus. The apparatus requires only adding polarizing filters to the conventional chroma-key technique. Our technique reproduces the appearance of a face in a facial live video with rigid facial motion in real time under an arbitrary environmental lighting condition. We use both image-based components (captured live video image) and model-based components [three-dimensional shape, surface normals and the bidirectional reflectance distribution function (BRDF)] instead of a large apparatus. By combining the image-based components and model-based components, we can reproduce the facial appearance realistically in the live video stream. The reproduced facial image has the detail texture from the image-based components and the shading of the novel lighting from the model-based components.

In the next section, we briefly review related work in the area of facial relighting and real-time processing. We then propose a computational lighting reproduction system for facial live video. The geometry of this system, the computational shading and surface reflection, the environmental mapping techniques and the face-tracking technique are described in detail. Then we show how our method can capture the background scene and the sphere map of the video stream, and how we obtain the light sources existing in the background scene. Finally we show the results of our system, and demonstrate its effectiveness.

RELATED WORK

Previous related work exists in two categories: facial relighting and real-time processing systems. Numerous approaches have been proposed for these categories, but an exhaustive survey is beyond the scope of this article. However, we briefly review some representative studies that provide the necessary background for our contribution.

In facial relighting, the parametric approach (model-based approach) is based on capturing the geometry of the human face and calculating the BRDF at each point on the

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Received Jan. 4, 2010; accepted for publication Aug. 16, 2010; published online Dec. 14, 2010.
1062-3701/2011/55(1)/010503/7/$20.00.

geometry. Guenter et al.[3] used six camera views and reconstructed the geometry based on the dot correspondence on the face, and created texture maps for every frame of animation. Pighin et al.[4] resynthesized facial animation through three-dimensional (3D) model-based tracking and performed facial relighting. Marschner et al.[5] used a range scanner to capture the geometry, and captured the spatially varying albedo texture using polarizing filters in front of the camera and lights to avoid surface reflection. We used a similar technique to capture only the diffuse reflectance video. In the work of Marschner and Greenberg,[6] a uniform BRDF of surface reflection was assigned on each vertex of the geometry.

Recently, capturing the appearance with high resolution[7] and high accuracy[8] has been achieved for realistic facial synthesis. Haro et al.[9] proposed a fine-scale human skin structure by synthesizing the normal map of skin using a texture synthesizing technique to reproduce the detail texture. However, this kind of detail geometry is very difficult to handle in video processing. The detail texture is effectively expressed by a ratio image. Marschner and Greenberg[6] proposed using the ratio image for relighting. The ratio image is calculated as the ratio between the reference images with and without detail, and it is applied to another image without detail to add the detail texture. Liu et al.[10] proposed using the ratio image for expression synthesis. Paris et al.[11] used the ratio image to reproduce the detail texture of skin. In this article, we use a similar technique to replace the low spatial frequency component of the current shading image with that of the target shading image by keeping the detail texture of shading. It should be noted that our processes are only applied to the shading component in this article. This is important in order to keep the reality of the skin appearance in image-based processing.

A nonparametric approach (image-based approach) is essentially based on many images taken under various directional lights. Realistic human faces can be obtained by this approach without geometry. Debevec et al.[1] proposed a lighting system for various directional lights (Light Stage) and saved the images as relightable three-dimensional (3D) face models. Hawkins et al.[12] extended the technique for variations in lighting for facial expressions. Wenger et al.[2] achieved a relightable 3D face video by using very high speed cameras to capture many images under various directional lights in 1/30 s. Einarsson et al.[13] extended this to record human locomotion. Borshukov and Lewis[14] combined an image-based model, an analytic surface BRDF, and an image-space approximation for subsurface scattering to create highly realistic face models for the movie industry. Peers et al.[15] transferred reproduced facial appearances to another subject. These techniques are used in the film industry for postproduction to create realistic compositions between the human face and environmental illuminants. However, these techniques cannot be used for live video. Debevec et al.[16] achieved live-action composition between an on-site human and a stream of environmental maps with a special lighting apparatus (Light Stage 3). This technique will be used effectively in the film industry to enable an actor to perform in a previously captured environment while checking the reproduction in real time. However, a special apparatus is required to light the face directly. In this article, we instead use a computational lighting approach.

In the real-time processing system for a live video stream, numerous approaches and applications have been proposed [for example, see Open Source Computer Vision Library (OpenCV library) by the Intel corporation[17]]. We focus here on reviewing some recent work. As described above, Debevec et al.[16] achieved live-action composition between a human on-site and a stream of environmental maps. Matusik and Pfister[18] built a scalable system for real-time acquisition, transmission, and display of 3D scenes. With the recent development of programmable graphics hardware, it is becoming more effective for real-time processing to process a video stream on graphics hardware. Tsumura et al.[19] built the system and process to control the skin melanin texture for a facial live stream as an e-cosmetic function. They processed the pyramid decomposition and composition in programmable graphics hardware. In this article, we also use graphics hardware to accelerate the process of analysis for the facial live stream.

COMPUTATIONAL LIGHTING REPRODUCTION SYSTEM

In this section, we describe the computational lighting reproduction system for the facial live video and how we reproduce the appearance of the face in live video under arbitrary lighting conditions. Figure 1 shows the flow of the process of computational lighting reproduction. It is performed by combining image-based components and model-based components. Image-based components are the original facial shading and color components of the facial live video stream. Model-based components are the shading and surface reflection calculated with the premeasured physical parameters of the face. The face is captured with the video camera, and the camera and light sources are equipped with polarizing filters. Polarizing filters are used to remove the surface reflection. The obtained live video stream expresses the diffuse reflection component of the facial image. This input facial live video is separated into melanin, hemoglobin and shading components by the technique of Tsumura et al.[20] The image-based shading component is combined with the model-based shading component. For position matching between the image-based and model-based components, we track the rigid facial movement and estimate the facial rotation angle and translation distance.[21] The computational lighting reproduction is performed by combining the melanin and hemoglobin, combined shading, and model-based surface reflection.

Geometry of the System

The computational lighting reproduction system is shown in Figure 2. The subject sits in a chair in front of the green screen used for matting. One video camera views the face from a distance of approximately one meter, and the captured facial live video stream is used as input images. This

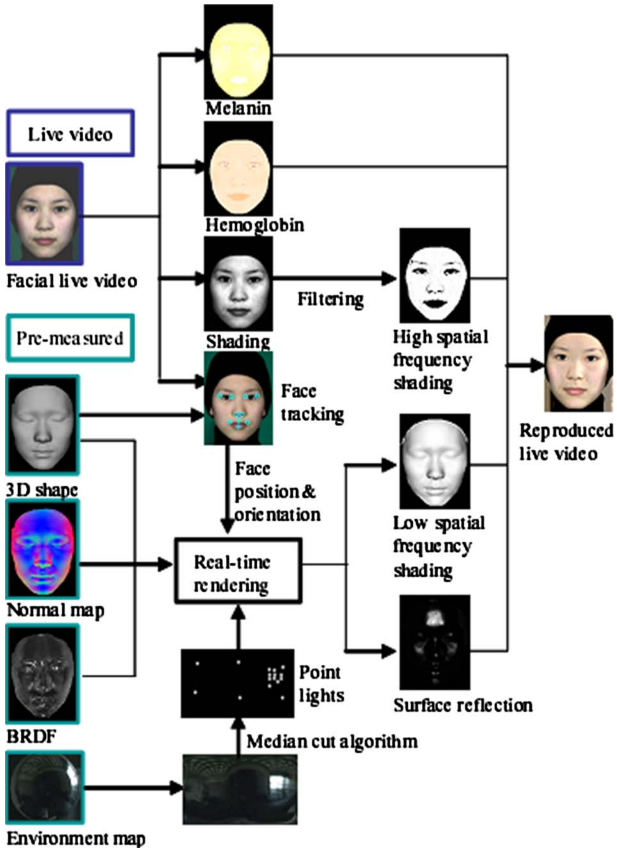


Figure 1. Flow of computational lighting reproduction.

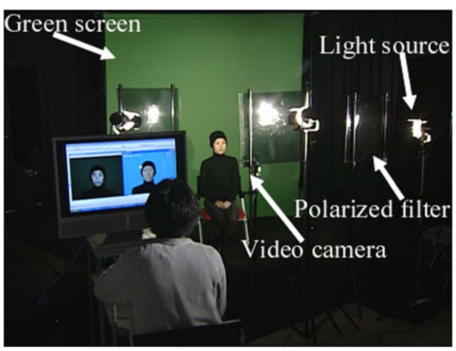


Figure 2. Geometry of our computational lighting reproduction system. The subject is illuminated by three light sources and captured by the video camera. Polarizing filters are attached in front of the light sources and the camera for removing the surface reflection on the face. The green screen is used for matting. The captured facial video stream is used as input images for the computational lighting reproduction process.

system has three light sources for illuminating the face. For removing the surface reflection, polarizing filters are attached in front of the light sources and the camera. This system can render the shading and surface reflection components from the face model and composite them into the diffuse reflection image of the face. This layout is easy to carry and set up. It is thought that this system is practical compared to previous systems.[16,22,23]

Premeasurement

For our facial lighting reproduction, we need to obtain the 3D shape, facial normal, and BRDF of the subject by premeasurement. Especially, BRDF measurement needs a large or special measurement apparatus, such as those used in previous techniques.[1,2] In this article, we use the measurement method of combining 3D positions and normals[24] for obtaining the 3D shape and normals, and the measurement method with linear light sources[25] for obtaining the BRDF. This BRDF measurement method can estimate BRDF parameters with a small apparatus. In our other research, we constructed a small measurement system for all facial physical parameters.[26]

The premeasurement is needed only once per person before using the reproduction system. Therefore, the premeasurement system does not interfere with the practicality of our proposed technique.

Computational Shading Reproduction

The shading component of the reproduced facial appearance is calculated by combining the image-based and model-based shading components. First, we describe the image-based processing for extracting the shading component from the facial live video. We separate the input facial live video stream into the color and shading components by using a human skin color separation technique.[20] This technique extracts the melanin, hemoglobin, and shading components from a single diffuse reflection image. This separation is defined as follows:

$$\boldsymbol{c}^{\log}(x,y) = -\rho_m(x,y)\boldsymbol{\sigma}_m - \rho_h(x,y)\boldsymbol{\sigma}_h + p^{\log}(x,y)\mathbf{1} + e^{\log}, \tag{1}$$

where $\boldsymbol{c}^{\log}(x,y)$ is the logarithm vector of the sensor response from the video camera; $\boldsymbol{\sigma}_m$, $\boldsymbol{\sigma}_h$, ρ_m, ρ_h are the melanin and hemoglobin vectors and their densities, respectively; $\mathbf{1}$ and $p^{\log}(x,y)$ are the shading vector of (1, 1, 1) and the logarithm of the shading intensity, respectively; and $\boldsymbol{e}^{\log}$ is the logarithm vector of the bias color. Equation (1) shows that the captured signals can be represented by the weighted linear combination of the melanin, hemoglobin and shading vectors with the bias vector. Since $p^{\log}(x,y)$ in Eq. (1) is logarithmic, the exponential of $p^{\log}(x,y)$,

$$p_{\text{in}}(x,y) = \exp(p^{\log}(x,y)), \tag{2}$$

is the image-based shading component that is changed to a novel shading component.

Next, we describe the method of combining the image-based and model-based shading components. The model-based shading component $p_{\text{model}}(x,y)$ expresses the shading under novel illuminants, which are explained in the next paragraph. However, $p_{\text{model}}(x,y)$ is lacking in high spatial frequency components compared to image-based shading $p_{\text{in}}(x,y)$, because the fine structure of the skin is lost in the shape model of the face. Therefore, we propose a reproduction technique that combines the high spatial frequency components of $p_{\text{in}}(x,y)$ and the low spatial frequency components of $p_{\text{model}}(x,y)$. This technique has the advantages of both $p_{\text{in}}(x,y)$ and $p_{\text{model}}(x,y)$. Moreover, this technique is similar to other techniques[6,9] that combine the base and detail of the target object for reproducing a realistic image. The combined computational shading $p_{out}(x,y)$ is calculated as follows:

$$p_{out}(x,y) = \frac{p_{in}(x,y)}{p'_{in}(x,y)} p_{model}(x,y), \tag{3}$$

where $p'_{in}(x,y)$ is the blurred shading component produced by applying a Gaussian blur filter to $p_{in}(x,y)$. The blurred shading component $p'_{in}(x,y)$ indicates the image-based shading component without high spatial frequency components. The division of $p_{in}(x,y)$ and $p'_{in}(x,y)$ gives the ratio of high and low spatial frequency components in the image-based shading. By multiplying this ratio by $p_{model}(x,y)$, we can obtain the model-based shading with the high spatial frequency components. The combined computational shading $p_{out}(x,y)$ is used in Eq. (1) based on Eq. (2) to obtain the facial diffuse reflection image $\boldsymbol{c}_{out}(x,y)$ under novel light sources.

Next, we describe the model-based processing for calculating the shading component on the face model. Here, $p_{model}(x,y)$ is calculated with light source vectors $\boldsymbol{l}_k(k=1\ldots N)$, power of each light source g_k and facial normal vector $\boldsymbol{n}(x,y)$. We approximate the lighting environment with N point light sources, since it is a high-cost computation to calculate the shading directly from the entire environmental map. The detail of this approximation is described in the next section. The equation for the calculation is as follows:

$$p_{model}(x,y) = \sum_{k=1}^{N} g_k d_k(x,y), \tag{4}$$

where

$$d_k(x,y) = \begin{cases} \boldsymbol{l}_k \cdot \boldsymbol{n}(x,y) if & \boldsymbol{l}_k \cdot \boldsymbol{n}(x,y) > 0 \\ 0 & \text{else} \end{cases}.$$

The model-based component $p_{model}(x,y)$ can be set according to the variation of $\boldsymbol{l}_i$ and g_k in the environmental map.

Computational Surface Reflection Reproduction

The surface reflection $\boldsymbol{s}(x,y)$ caused by N point light sources is reproduced with the premeasured facial BRDF model. The Torrance-Sparrow model[27] is used as the BRDF model in this article. The equation for the surface reflection is as follows:

$$\boldsymbol{s}(x,y) = \sum_{k=1}^{N} \boldsymbol{h}_k f(\boldsymbol{l}_k, \boldsymbol{n}(x,y), r(x,y), q(x,y)), \tag{5}$$

where $f(\boldsymbol{l}_k, \boldsymbol{n}(x,y), r(x,y), q(x,y))$ and $\boldsymbol{h}_k$ are the reflectance function of the Torrance-Sparrow model and the color vector of the light source power, respectively. The parameters $r(x,y)$ and $q(x,y)$ are the surface reflectance and shininess, respectively, in the Torrance-Sparrow model.

Facial Appearance Reproduction

The facial appearance under an arbitrary lighting condition can be reproduced with $\boldsymbol{c}_{out}(x,y)$ and $\boldsymbol{s}(x,y)$. The reproduced facial appearance $\boldsymbol{v}(x,y)$ is calculated as the weighted sum of these components, as follows:

$$\boldsymbol{v}(x,y) = w_{shade}\boldsymbol{c}_{out}(x,y) + w_{surf}\boldsymbol{s}(x,y), \tag{6}$$

where w_{shade} and w_{surf} are the weights of the shading and surface reflection, respectively. These weights are used for adjusting $\boldsymbol{v}(x,y)$, since $\boldsymbol{v}(x,y)$ is changed by the characteristics of the display device. We also use these weights for enhancing the appearance of the reproduced face.

There are two important processes necessary to achieve the realistic reproduction of the facial appearance. One is the lighting reproduction of the eyes. Since the subject closes his or her eyes during the premeasurement, we cannot obtain the physical parameters of the eyes. The other is smoothing the boundaries between the image-based and model-based components.

We modeled the appearance of the eyes by using two sphere models. The positions of the spheres are arranged based on the information of face tracking, and the surface reflection of the eyes is calculated with the normals of these spheres based on the environmental mapping technique. The intensity of environmental mapping is reproduced with the sphere environmental mapping technique.[28] As described in the next section, the video of this environmental map is captured under the lighting condition, which is required for reproduction. The size and BRDF of the spheres are decided empirically. The reproduced appearance is rendered at the eye region of the face while the subject has his or her eyes open.

The boundaries between the image-based and model-based components are smoothly connected by alpha blending. The face region is defined with the melanin and hemoglobin components.[19,20] We applied the blur filter to the face regions for a smooth connection between the face region and other regions, and we set the value of the blurred face region to the value of the alpha blending.

Facial translation and rotation tracking

Above, we described computational lighting reproduction techniques with the assumption that position matching of the face image and face model had already been performed. In this section, we describe how we match the face image and face model. For matching, we must estimate the facial pose, i.e., the translation and rotation of the face. A 3D face model database is often used for matching the face image and the face model.[29,30] However, these techniques are unsuitable for real-time processing. We use a particle filtering technique[21] for tracking the face and estimating the facial pose. The facial pose vector $\boldsymbol{b}_t$ at frame t is defined as follows:

$$\boldsymbol{b}_t = (T_{xt}, T_{yt}, T_{zt}, \phi_t, \theta_t, \psi_t), \tag{7}$$

where (T_{xt}, T_{yt}, T_{zt}) is the translation distance, and $(\varphi_t, \theta_t, \psi_t)$ is the rotation angles of the roll, pitch and yaw,

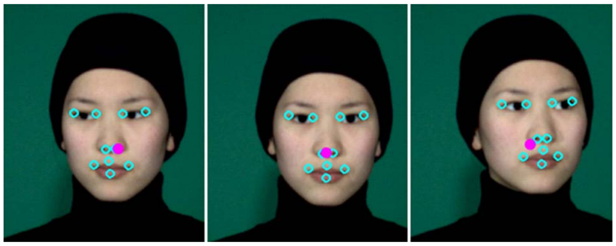


Figure 3. The results of face tracking. The gray circle shows the center of the face, and the ten white circles in each reproduction show the ten feature points tracked.

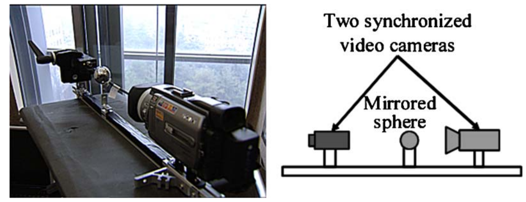
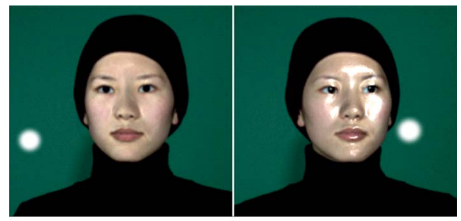


Figure 4. The camera system for capturing the background and sphere mapping video stream. In the left photo, the video camera in the forefront captures the background scene, and the other video camera captures the mirrored sphere.



(a) (b)

Figure 5. Computational lighting reproduction for a facial live video stream. (a) Reproduction under an arbitrary point light source and (b) reproduction with surface reflection enhancement.

respectively. In this particle filtering technique, the probability density function of a facial pose is represented as a set of N discrete samples. This sample set is defined as $\{\boldsymbol{b}_t^{(i)};\pi_t^{(i)}\}(i=1\ldots N)$. Each facial pose sample $\boldsymbol{b}_t^{(i)}$ has a corresponding weight $\pi_t^{(i)}$. Face tracking is performed with the following motion model:

$$\boldsymbol{b}_t^{(i)} = \boldsymbol{b}'_{t-1} + \tau \boldsymbol{v}_{t-1} + \omega, \tag{8}$$

where $\boldsymbol{b}'_{t-1}$ is the chosen sample from $\{\boldsymbol{b}_{t-1}^{(i)};\pi_{t-1}^{(i)}\}$, τ is the time interval, v_{t-1} is the velocity of the facial pose, and ω is system noise. We generate a new set of N samples $\{\boldsymbol{b}_t^{(i)}\}$ with Eq. (8). The weight of each new sample $\{\pi_t^{(i)}\}$ is calculated with template matching between the input facial image and the templates of a few facial features. Finally, facial pose $\boldsymbol{b}_t$ is estimated as follows:

$$\boldsymbol{b}_t = \frac{\sum_{i=1}^{N} \boldsymbol{b}_t^{(i)} \pi_t^{(i)}}{\sum_{i=1}^{N} \pi_t^{(i)}}. \tag{9}$$

Figure 3 shows the results of the face tracking. In our method, ten facial features are used for calculating the weights. The size of the image templates is set to 15×15, and N is set to 900. Using the facial pose, we can set the position and orientation of the face model according to the face in live video.

CAPTURING THE BACKGROUND AND SPHERE MAPPING VIDEO

The background video is used for combining the actor and the background based on the chroma-key technique. The sphere mapping video stream is used for calculating the shading and surface reflection components of the face, described in the previous section.

Figure 4 shows the geometry of our camera system for capturing the background and sphere mapping video. This system has two video cameras and one mirrored ball. The video camera in the forefront of this system is the same one used in the real-time processing system. This camera captures the background video. By using the same camera used in the real-time processing, the background video and the facial live video have the same camera parameters, field of view and lens aberration. Having the same camera parameters is important for natural combining of the background video and subject images. Another video camera captures the mirrored ball placed in front of this camera. The captured video is used as the sphere mapping video stream. The two cameras in the system are synchronized and the two videos are captured together.

The light sources used for calculation in the shading and surface reflection components are obtained from the captured sphere mapping video. In each frame of the sphere mapping video, we approximate the lighting environment with N point light sources that have different positions and powers. These N light sources are used as the light sources existing in the captured sphere mapping video for the calculation of facial shading and surface reflection. For this approximation of lighting, we use the median cut algorithm,[31] which is a technique that can represent the lighting environment with light sources simply and efficiently.

RESULTS

In this section, we show the experimental results of the computational lighting reproduction to demonstrate the effectiveness of our system. It should be noted that the following results are performed in real time for the facial live video stream. We use a Windows-based PC with an Intel Core 2 Duo 2.67 GHz and an NVIDIA GeForce 7950 GX2. The number of extracted light sources N is set at 16 in this experiment. The frame rate is approximately 60 s^{-1} in the single point light source, vs 30 s^{-1} in conventional video. The frame rate depends on the number of point light sources. The video resolution is 640×480.

Facial images reproduced under arbitrary lighting conditions are shown in Figure 5. Figure 5(a) exhibits the reproduction of the shading and the surface reflection of the

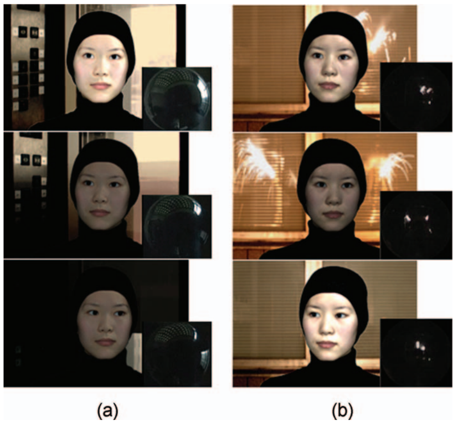


Figure 6. Results of the reproduction under two conditions. (a) Results of the reproduction under the lighting condition of an elevator. (b) Results of the computational lighting reproduction in the environment of fireworks. In these results, the sphere mapping video stream is used as mirrored sphere images.

face under a virtual point light source. In Fig. 5(a), the shading and surface reflection components are reproduced according to the position of the light source. For example, the side of the nose illuminated by the point light source is bright, whereas the far side is dark. In addition, we can also control the appearance of the skin in real time. Fig. 5(b) shows the result of enhancing the surface reflection of the face by increasing the intensity of the surface reflection. The surface reflection component is mostly generated on the side of the face illuminated by the point light source.

Figure 6(a) shows the results of computational lighting reproduction using the sphere mapping video of a scene in an elevator. The side of the face that is closer to the window is brighter than the far side, since the face is illuminated by the incident light from the window. The facial appearance is reproduced brightly at the top of Fig. 6(a). In the middle and the bottom of Fig. 6(a), the reproduced facial appearance is dark when the incident light from the window is obstructed as the elevator moves. We found a defective region that is unnaturally bright on the surrounding area of the nose, which is caused by the process of blurring for the image-based shading component. In Eq. (3), the high spatial frequency component of the image-based shading is calculated by using the division of the blurred and nonblurred shading components. Therefore, the facial region where the shading component greatly changes, such as the shadowed area of the nose, is affected by the calculation and becomes unnatural.

Fig. 6(b) shows the results of the computational lighting reproduction in an environment of fireworks. In the top of Fig. 6(b), the right side of the reproduced face is bright whereas the left side is dark, since both fireworks are on the right side of the face. The surface reflection is also highly generated on the right side of the reproduced face. In the middle of Fig. 6(b), the whole area of the reproduced face is illuminated equally, since both fireworks are on each side of the face. In the bottom of Fig. 6(b), the reproduced face is very bright since both of the fireworks are in front of the face. These images show that we can reproduce the variation of shading and surface reflection according to the movement of the illuminating objects.

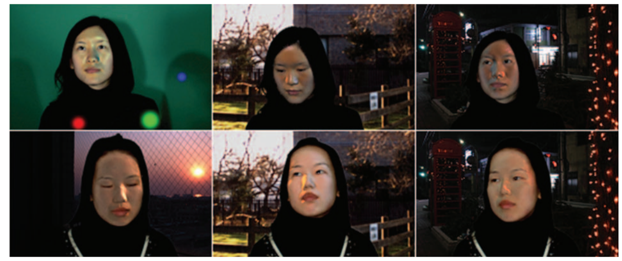


Figure 7. Reproduced live video under various kinds of environmental illuminants.

Figure 7 shows another live video reproduced under various kinds of environmental illuminants. It is shown that our technique can reproduce convincing results for face composition in various scenes.

DISCUSSION AND CONCLUSIONS

The appearance of a face in a facial live video was reproduced in real time under an arbitrary environmental illuminant by using our computational lighting reproduction system. The results of experiments using this system confirmed the effectiveness of the system.

In the reproduction of a human image, the appearance of the hair and the clothes is very important for reproducing a realistic appearance. However, our system can reproduce only the appearance of the face with rigid facial motion. Therefore, at this time we must use a black cloth and a hair band to avoid showing the shade and surface reflection on the hair and clothes. One aspect of our future work is to investigate a real-time lighting reproduction system for a subject's hair and clothes.

The appearance of reproduced facial images also depends on the measured facial physical properties. We can reproduce more realistic surface reflection and shading by using more accurate properties. Thus, we need to improve the measurement system for facial properties.

Another approach of future work is to apply facial expressions to the facial 3D shape. The face-tracking technique used in our system cannot track the facial expression. For this problem, effective techniques already track the facial expression, such as the techniques proposed by Dornaika and Davoine.[32] By adopting these techniques, our system will be able to track the facial expression. The result of facial expression tracking could be used to deform the 3D shape of the face in a live video. We may also be able to apply the morphing technique of ratio images to express the change of facial expression, as was done by Liu et al.[10]

In addition, we need to solve the problem that there is an unnaturally bright region on the area surrounding the nose. We think this problem may be solved by considering the facial geometry in the blurring process in Eq. (3). However, we think that such blurring is difficult to implement and run in real time. Resolving this problem is also part of our future work.

We will reproduce the appearance of the face applying cosmetics under the arbitrary environmental illuminant by using our reproduction technique and the reflectance property of cosmetics. Finally, we will apply our technique in a live simulator of a person applying cosmetics in a store.

ACKNOWLEDGMENT

This research was supported in part by a Grant-in-Aid for Scientific Research (Grant No. 19360026) from the Japan Society for the Promotion of Science.

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