# Development of the Measurement System for Facial Physical Properties with the Short-distance Lighting

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## Abstract.

In this research, we have developed a compact and fast measurement system for 3D shape, normal vector and bidirectional reflectance distribution function (BRDF) of a 3D object. Since the proposed system uses linear light sources and a luminous intensity distribution of these light sources, the BRDF can be measured for a short time and without large measurement space. The proposed system is evaluated by two methods, by measuring sample known objects and by comparing actual and reproduced images, and then we confirmed its accuracy.

**Keywords:**

Face measurement system; 3D shape; normal vector; BRDF; Linear light source; Intensity distribution

## I. INTRODUCTION

It is very important to create a realistic human face with computer graphics since such a face can be used for various applications; e.g. filmmaking, video game or virtual cosmetics. To create the realistic facial image, it is necessary to measure facial physical parameters, i.e. the 3D shape, normal vectors and the bidirectional reflectance distribution function(BRDF) of the face. These parameters can be used for modeling the facial shape and reproducing the face under a various lighting conditions. Especially, the lighting reproduction on the face is important since the appearance of the face is changed drastically by the lighting condition. Therefore an accurate measurement system for obtaining facial physical parameters is required for reproducing realistic human face.

Numerous measurement systems have been proposed for obtaining accurate facial physical parameters. Most of conventional systems require very large measurement apparatus since parallel light is simply assumed for the measurement and the light is kept distant from the face to uphold this assumption. Therefore these systems do not have portability and can not be used in a small space such as the virtual cosmetic system at the store.

In this paper, we propose a compact measurement apparatus for obtaining facial physical parameters. By taking into account the luminous intensity distribution of the light sources, the various physical parameters of face can be measured from short distance. This system has two advantages: it is highly portable and it can be used in a small space. In addition, we use the measured facial physical parameters for reproducing photographs of real human faces. We confirmed that the reproduced facial images have approximately same appearance of the real faces.

## II. RELATED WORK

Numerous approaches have been proposed for reproducing the facial appearance with measured facial physical parameters. These approaches are based on capturing the geometry of the object and calculating the BRDF at each point on the geometry. In this section, we briefly review representative works which are necessary to present our contribution.

Some conventional works use a range scanner to capture the geometry, i.e. 3D shape and normal vectors of the face. Marschner et al.[1] captured the geometry with the range scanner, and captured the spatially varying albedo texture by using polarized filters in front of the camera and lights to avoid the specular reflection from the object. Such a polarizing technique is useful for separating the specular and diffuse components, and we also used a similar technique to capture only the diffuse reflectance images. Weyrich et al.[9] also used a commercial 3D face scanner for obtaining 3D geometry of the face, and the obtained 3D geometry was used to estimate other facial properties. However, these methods have a problem that the range scanner is very expensive. The expensive measurement system is unfavorable for the various applications.

Another frequently-used approach for capturing the geometry is the method using a multi-camera system. Such a approach has an advantage that the system is inexpensive. Guenter et al.[2] used six camera views and reconstructed the geometry based on the dot correspondence on the face, and created texture maps for every frame of the animation. Pighin et al.[3] reconstructed the 3D model with several facial images from different view points. They also proposed to re-synthesized facial animation through 3D model-based tracking and performed facial reproduction. These measurement methods with the multi-camera system can obtain 3D facial model inexpensively, but they also need an operation to find corresponding points between captured images by the multi-camera. This operation is typically difficult to solve and takes a long time to calculate the result.

We therefore use a structured light method[11] for obtaining the 3D facial shape. The structured light method[11] is known as a 3D measurement method without the corresponding points. This is a triangulation method with a pair of a camera and a projector. We can obtain the facial 3D shape easily and inexpensively by using this method, but the obtained 3D shape doesn't have high spatial frequency components. Zhang et al.[4] captured high spatial frequency components of the 3D shape by using both of the multi-camera system and projectors. However, if we use many projectors and cameras, the measurement system will get complex. In our method, we use only one pair of the camera and the projector for obtaining low spatial frequency components of the 3D facial shape. High spatial frequently components are obtained by using photometric stereo method[15].

Photometric stereo method[15] is known as the method for estimating normal vectors of the subject by using images illuminated from various directions. In our method, obtained normal vectors are used as high spatial frequency information of the 3D shape. Normally, photometric stereo method needs long-distance light sources for illuminating the subject. Such a long-distance light source makes the measurement system larger. We solve this problem by considering luminous intensity distribution of light sources. Luminous intensity distribution is also used in measuring the facial BRDFs.

Next, we'll review a measurement method of the facial BRDFs. For measuring the BRDF of the face, many conventional approaches need many images taken under various directional lights. Debevec et al.[5] proposed a lighting system for various directional lights (Light Stage) and saved the images as relightable 3D face models. This system is a very large lighting apparatus and the subject is illuminated from various directions with this system. BRDF of the subject is obtained from captured images. Hawkins et al.[6] extended the technique for variations in lighting for facial expressions, Wenger et al.[7] achieved relightable 3D face video by using very high speed cameras to capture a lot of images under various directional lights in 1/30 second. Einarsson et al.[8] extended this to record human locomotion. These techniques are used in the film industry for post-production to create realistic compositions between the human face and environmental illuminants. Recently, appearance capturing that is highly accurate[9] has been achieved for realistic facial synthesis. However, these methods made measurement apparatuses more large, complex or expensive. Such apparatuses are difficult to be used in practical application.

On the other hand, a BRDF reflectance model is used for obtaining the BRDF of the subject. BRDF is approximated by the BRDF reflectance model, e.g. Phong model or Torrance-Sparrow model. The model can be used as an approximated BRDF by estimating unknown parameters of the model from images taken under various directional lights. This method can reduce the number of captured images than the methods reviewed in the previous paragraph. However, this method still needs the large measurement apparatus for capturing images. Takase et al.[13] proposed a compact measurement system by considering luminous intensity distribution of light sources. In this paper, we improve their method and apply it to the facial BRDF measurement.

## III. COMPACT MEASUREMENT APPARATUS

In this section, we describe the compact face measurement system, the advanced light box. Figure. 1 shows the flow of the process in obtaining the facial physical parameters. These parameters are obtained with three sets of images captured from the proposed apparatus, such as images projected structured light pattern by a projector, images illuminated by 9 LEDs and images captured with two shutter speeds under illumination by linear light sources. This processing flow shares large parts with the processing flow by Weyrich et al.[9]. Unlike their processing, we use the projector instead of a face scanning system and take into account the luminous intensity distribution. Our advanced light box is described first in Subsection A, the facial shape and normals estimation are described in Subsection B and the facial BRDF estimation is described in Subsection C.

### A. Advanced light box

The advanced light box used to capture the set of images is shown in Fig. 2(a). The subject sits down on the chair with a headrest. One video camera takes the face from a distance of approximately 0.8 meter. We are using a color digital camera(SONY DFW-X710) with 1024x768 CCD sensor. The advanced light box has three types of light sources: the projector(TOSHIBA TDP-FF1 Ultra Portable LED Projector), nine LEDs(LUMILEDS LXHL-LW6C White 5W Star LEDs) and two linear light sources(National FHL10EX-W fluorescents). The projector and LEDs are used for obtaining the 3D shape and normals, and the linear light sources are used for obtaining the BRDF. Figure. 2 (b) and (c) show the geometry of the advanced light box which is shown from the side view and top view, respectively. It takes 90 seconds to capture all the required images.

We calibrate the white balance of the camera by taking a diffuse white board illuminated by the linear light sources. The calibration of intrinsic and extrinsic camera parameters is performed with the method using a calibration object whose 3D geometry is known[10]. The calibration between the camera and the projector is also performed with the same method used by Valkenburg and McIvor[11].

All light sources are within 1 meter from the subject. The width, height and depth of the advanced light box are approximately 0.9, 1.5 and 1.2 meters, respectively. These sizes are very small and we can construct this geometry with a small number of building materials compared to conventional systems[5,7,9]. For example, these systems needed a more than 2 meters diameter once-subdivided icosahedron and more than 150 light sources[7,9]. In addition, they needed a special equipment, e.g. a commercial face scanning system[9] or a high-speed digital camera[7]. However, our advanced light box has less than about half the volume of them, and consists of only 11 light sources and 1 projector with 2 linear stages(ORIENTAL MOTOR EZS6E085-K Motorized Linear Slides) for moving linear light sources under the consideration of luminous intensity distribution[12,13] of the light sources as described in the following sub-section.

The luminous intensity distribution of the linear light source[13] was used to measure the BRDF. The luminous intensity distribution indicates the radiance rays from the light sources. Generally, in the BRDF measurement, distant light sources are used as directional light sources as shown in Fig. 3 (a). However, use of the information on the luminous intensity distribution makes possible to measure BRDF with short-distance light sources, as shown in Fig. 3 (b). We use the luminous intensity distribution of the linear light sources as shown in Fig. 3 (c). Since the linear light sources can illuminate the subject by only the linear motion as shown in Fig. 3(e), then the BRDF can be obtained efficiently[14]. The conventional measurement system[13] can’t measure the side of the subject because it has only one linear light source. So our measurement system has two linear light sources to illuminate the large area of the subject as shown in Fig. 2(c). In addition, we can measure the normal vectors with LEDs placed at short distance from the face by considering the luminous intensity distribution of the LEDs.

### B. Measuring facial 3D shape and normal vectors

Facial 3D shape and normal vectors can be estimated from images illuminated by the projector and LEDs. The projector casts a coded pattern onto the face from a distance of approximately 1 meter while the video camera is capturing the images. The captured images are used in the coded structured light technique[11] for reconstructing the facial 3D shape. The LEDs with the polarized filter illuminate the face from various directions, and the polarized filter is also set in front of the video camera for removing specular reflection. From the diffuse reflection images, the normal vectors are obtained by the photometric stereo method[15]. Conventional photometric stereo method needs to keep the light distant from the subject for assuming parallel light. Luminous intensity and directions can be equalized in all measurement points of the subject by this assumption. However, we have to perform photometric stereo method with short-distance LEDs from the subject. So, we consider luminous intensity distribution of LEDs and measured facial 3D shape to set the viewing and illumination angles accurately.

Figure. 4 shows the schematic illustration of our photometric stereo method with short-distance LEDs from the subject. First, we assume that LED's luminous intensity distribution is the same as point light source's one. In this case, the pixel value I at the Lambertian measurement point p is defined as follows:

$$I = \rho_d \frac{s}{r^2}\left(\mathbf{l}^T \cdot \mathbf{n}_p\right) \tag{1}$$

where $\rho_d$ is the diffuse reflectance at the measurement point, $s$ is the luminous intensity, $r$ is the distance between LED and the measurement point, $\mathbf{l}$ is the lighting direction and $\mathbf{n}_p$ is the normal vector of the measurement point. $1/r^2$ shows the attenuation of luminous intensity by the distance between LED and the measurement point. $T$ means transposition of vectors of matrices. For obtaining these unknown parameters, we use the light position vector $\bar{\mathbf{l}}$ and the vertex vector $\mathbf{v}$. $\bar{\mathbf{l}}$ is obviously known, and $\mathbf{v}$ can be obtained since we have already measured the facial 3D shape by using the projector. We can obtain $r$ and $\mathbf{l}$ by using $\bar{\mathbf{l}}$ and $\mathbf{v}$ as follows:

$$\begin{aligned} r &= \left|\bar{\mathbf{l}} - \mathbf{v}\right| \\ \mathbf{l} &= \frac{\bar{\mathbf{l}} - \mathbf{v}}{r}. \end{aligned} \tag{2}$$

If we capture three pixel values $I_i\ (i = 1,2,3)$ under different three light position $\mathbf{l}_i$ , $I_i$ are defined by using $r_i$ and $\mathbf{l}_i$ as follows:

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} = \rho_d s \begin{pmatrix} 1/r_1^2 & 0 & 0 \\ 0 & 1/r_2^2 & 0 \\ 0 & 0 & 1/r_3^2 \end{pmatrix} \begin{pmatrix} \mathbf{l}_1^T \\ \mathbf{l}_2^T \\ \mathbf{l}_3^T \end{pmatrix} \mathbf{n}_p \qquad (3)$$

$$\mathbf{I} = \rho_d s \mathbf{R} \mathbf{L} \mathbf{n}_p .$$

Since $\mathbf{n}_p$ has a unit length, $\mathbf{n}_p$ can be obtained as follows:

$$\mathbf{n}_p = \frac{\mathbf{R}^{-1}\mathbf{L}^{-1}\mathbf{I}}{\left|\mathbf{R}^{-1}\mathbf{L}^{-1}\mathbf{I}\right|}. \qquad (4)$$

By using these equations, we can calculate facial normal vectors with short-distance LEDs from the subject.

The facial 3D shape and normals are shown in Fig. 5. Absolute value of x, y and z coordinates of facial normals are read as R, G and B component of the color. The facial 3D shape and normals are used in a hybrid algorithm[16] for obtaining a more accurate facial 3D shape and normals.

### C. Measuring facial BRDF parameters

We estimate facial BRDF parameters with images illuminated by the linear light sources. The BRDF measurement of the light box means the estimation of diffuse, specular and surface roughness parameters of Torrance-Sparrow model[17]. This model can deal with a off-specular reflection which happens on human skin. Then the Torrance-Sparrow model is found to be useful for measuring facial BRDF. However, this model is not enough for obtaining the correct facial BRDF. We have to consider sub-surface scattering[9] and skin layers which have different reflection properties[5]. In this paper, we used only Torrance-Sparrow model because the consideration of sub-surface scattering and skin layers makes the measurement system more complex. This consideration is one of our future work.

Torrance-Sparrow model is described as follows:

$$\rho_d = \frac{r_d}{\pi}, \qquad (5)$$

$$\rho_s(p, \omega_o \omega_i) = r_s \frac{D(\omega_h, \sigma) G(\omega_o, \omega_i) F(\omega_o)}{4 \cos\theta_o \cos\theta_i}, \qquad (6)$$

where $\rho_d$ and $\rho_s$ are the diffuse and the specular reflectance, $r_d$ and $r_s$ represent the diffuse and the specular parameters, respectively, and $(\omega_o;\omega_i)$ denotes a pair of directions from a surface point $p$ to a light source and a viewer, respectively, and $(\theta_o;\theta_i)$ shows a pair of angles between a surface normal and $\omega_o$ , a surface normal and $\omega_i$ , respectively. In the Torrance-Sparrow reflectance model, $D$, $G$ and $F$ denote a microfacet distribution, a geometric attenuation term and Fresnel reflection, respectively, and $\omega_h$ is a half vector between $\omega_o$ and $\omega_i$ , and $\sigma$ represents a surface roughness. The parameters $(r_d;r_s;\sigma)$ were estimated at each pixel on the acquired image by a least square fitting operation.

For the fitting operation, we use images illuminated by the linear light sources. The linear light sources, whose luminous intensity distribution is measured, are moved linearly by using the linear stage while these linear light sources illuminate the face. The video camera captures the face image at each position of the linear light sources at two different shutter speeds to produce a high dynamic range image.

Three steps are necessary for obtaining the BRDF. Following processing is same to Takase's method[13]. First, high dynamic range images are produced with two images captured at different shutter speeds[18]. Second, the high dynamic range images are separated into diffuse and specular reflection images by using the dichromatic reflection model[19]. We have already obtained diffuse reflection images illuminated by LEDs with the polarized filter. However, we need diffuse and specular reflection images illuminated by linear light sources, and the polarized filter method can't obtain diffuse and specular reflection images at the same time. We solve these problems by using the method of dichromatic reflection model method. Separated images are separated again into unit color vector and its intensity at each pixel[20]. We don't have to estimate BRDF parameter of each color spectrum because color information is separated by this processing. Intensities are used for obtaining BRDF parameters in the next processing.

Finally, the BRDFs are calculated by fitting the BRDF model (Torrance-Sparrow model[17]) to with the consideration of the luminous intensity distribution. Takase et al.[13] proposed the method that can estimate BRDF parameters from images illuminated by a linear light source with the known luminance intensity distribution. In general, the linear light source cannot be used in a measurement because it illuminates the subject redundantly from various incidence angle along the longitudinal direction. In Takase's method, the linear light source is assumed that it is composed of many point light sources. The contribution of each point light sources to the reflection is calculated independently. This enables the BRDF parameter measurement with the linear light source. We can obtain facial BRDF parameters, diffuse parameter, specular parameter and surface roughness by applying their method to the human face. Figure. 6 shows obtained specular parameter and surface roughness at each pixel. Note that Fig. 6(a) shows the value of specular reflectance parameter at each pixel, not the specular reflection component.

## IV. EXPERIMENTAL EVALUATION FOR THE PROPOSED MEASUREMENT SYSTEM

In this section, the effect of the light box is evaluated by experiments. First, we evaluate the accuracy of measured parameters, 3D shape, normal vectors and BRDF. We then evaluate the reproduced human faces with the measured facial physical parameters by comparing them to real human faces.

### A. Experimental evaluation for 3D shape and normals

First of all, we measure the 3D shape of two subjects and compare them to ground truth shape. Subjects of this experiment are board and spherical objects as shown in Fig. 7. We wanted to use a real human face as the subject, but it is difficult to obtain ground truth shape of human faces. We used these simple objects since their ground truth shape can be obtained easily and accurately. Figure. 8(a)(b) show the measured 3D shape of two subjects, and (c)(d) show errors between measured 3D shape and ground truth shape. Table. I shows root mean square error(RMSE) and maximum error calculated from Fig. 8(c)(d). The RMSE of the board is 0.24mm and the RMSE of the spherical object is 0.91mm, respectively. These results show that the light box can obtain the 3D shape of the board and the spherical object with reasonably high accuracy. However, there are large errors up to 5.78 mm at the left side of the sphere. We think these errors have been observed because points on the side of the sphere weren’t illuminated by sufficient rays from LEDs and the projector. From these results, we can say that our system can measure the 3D shape of the measured object at the frontal region.

Then we compare measured normal vectors to ground truth normals. We use a cup showed in Fig. 9(a) as a subject of this comparison. This subject has both high and low spatial frequency components. By using this subject, we can confirm the accuracy of our measurement for both high and low spatial frequency normals. First, we obtain ground truth vectors of the subject. We measure normal vectors by the conventional photometric stereo method instead of our short-distance photometric stereo method, and measured normals are used as ground truth normals in this experiment. Next, we obtain normal vectors by using proposed short-distance photometric stereo method. Finally, these two measurement results are compared. Figure. 9(b) and (c) show normals measured by our method and ground truth, respectively. Absolute value of x, y and z coordinates of facial normals are read as R, G and B component of the color. Figure. 9(d) shows the error between Fig. 9(b) and (c), and Table. II shows RMSE and maximum error calculated from Fig. 9(d). These results show that our short-distance photometric stereo method can measure normals with same level of accuracy as conventional photometric stereo method. The maximum error is 9.86˚ and this is very large difference. However, we think this maximum error is not serious problem because this error only occurs at the boundary with the background.

### B. Experimental evaluation for BRDF

In this experiment, we measure BRDF parameters of two subjects and compare them to ground truth BRDF parameters. Subjects of this experiment are two skin replicas with different colors shown in Fig. 10. These replicas are made of skin-like material, and their BRDF parameters are known. So we can use their BRDF parameters as ground truth.

The light box measures BRDF parameters from only one viewing direction. If the angle between normal vectors and viewing direction vectors is changed, the light box may not measure BRDF parameters correctly. Then, we compare BRDF parameters measured from various viewing directions. Figure. 11 shows the schematic illustration of this measurement. The motorized turntable rotates the subject 0 to 60 degree by 5 degree and BRDF parameters are measured at each angle.

Table III shows average and maximum error between ground truth and measured BRDF parameters, and Fig. 12 shows results of comparing the measured BRDF parameters to ground truth. Note that Fig. 12 shows values of BRDF parameters, not actual reflectance of the subject. These results show that the light box can obtain diffuse parameter and surface roughness of the skin replica with an accuracy of less than 10%. Table. III and Fig. 12 also show that specular parameter has the higher error than other parameters. It is considered that specular parameter is sensitive to changes of the view angle. We think these measurement errors are not large, but these errors may make serious difference on the facial image reproduction. Then, we evaluate measured BRDF parameters by using reproduced facial images in the next subsection. In addition, we think the color of the replica has little effect on the accuracy of BRDF measurement.

### C. Reproduced image evaluation

In this experiment, we compare reproduced facial images to real facial photographs and evaluate the accuracy of reproduced images. First, we measure the facial physical parameters of a subject with the light box. Then, we reproduce the facial image of the subject with measured facial physical parameters. Figure 13(a),(c) show real facial photographs of two subjects and (b) and (d) show reproduced facial images. They have strong resemblance each other in shape and color. As an another example, Fig 14 show real facial photographs and reproduced facial images under different lighting directions and a viewing direction. While these reproduced images have a few differences from real photographs, the appearance of these images is very similar to the appearance of real photographs. From these results, we consider that the measured facial physical parameters have accurate information to reproduce the facial image.

## V. CONCLUSION AND DISCUSSION

In this paper, we have proposed the advanced light box, which is the compact measurement apparatus for obtaining facial physical parameters. By using the advanced light box, we could obtain the 3D shape, normal vectors and BRDFs of the face without a large space. Experiments showed that the facial physical parameters can be measured by using the developed system with small errors. These facial physical parameters were used for reproducing photographs of real human faces. We compared real facial images to resultant images, and the results showed both images have strong resemblance each other.

As a future work, the advanced light box would be improved for more accurate and comfortable measurement. Especially, the improvement of 3D shape measurement error is one of the most important problems to be solved. Our advanced light box has two linear light sources which are moving along the linear stages. If we can move the linear light sources along the face with the trajectory of circle, we will obtain more accurate BRDFs in entire face and can make the advanced light box smaller and simpler. We have evaluated the measured BRDF parameters, but this evaluation is empirically. We have to research how small BRDF error is enough to reproduce the appearance of the object. Therefore it will be necessary to confirm accurate measure of BRDF to reproduce the appearance of the 3D object. In addition, we need to evaluate our system and reproduction with various types of subjects, e.g. elderly people or many racial people.

As an another future work, we have to consider more detail of human skin, e.g. skin layers, sub-surface scattering and anisotropic reflection characteristics. These components are important to obtain accurate reflectance properties of the human skin. We have to improve our measurement apparatus for considering these components.

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## Figure captions

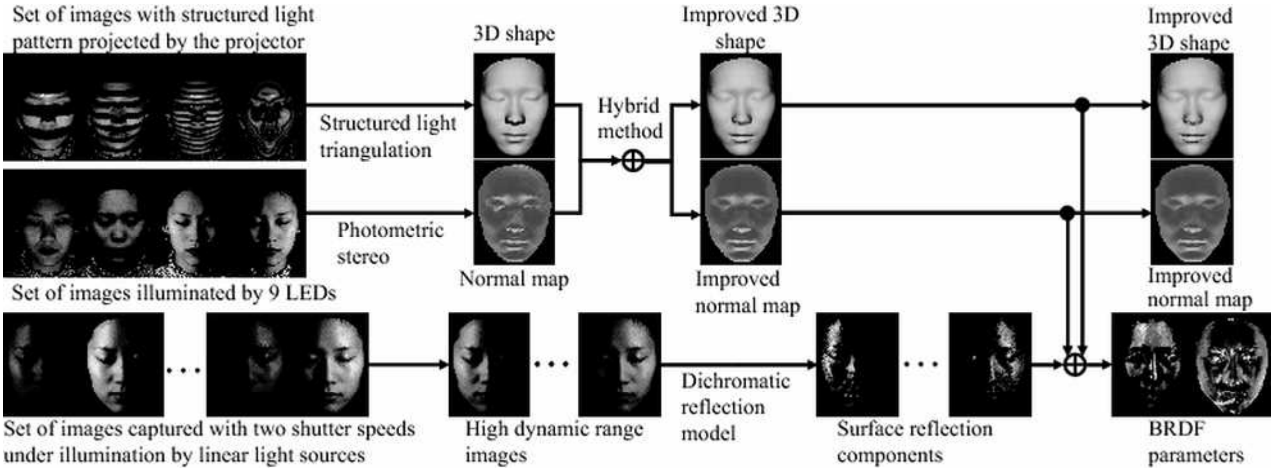


Figure. 1: Flow of the measurement with the advanced light box.

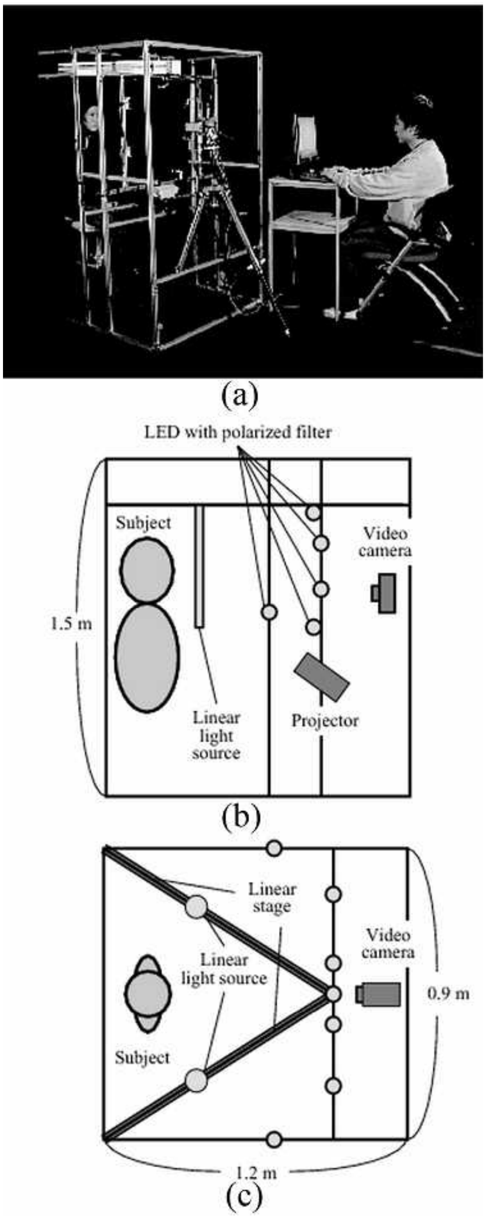


Figure. 2: (a) Geometry of our advanced light box. (b) Illustrations of the side view and (c) topview of the advanced light box. The projector and LEDs are used for obtaining the 3D shape and normals, and the linear light sources are used for obtaining the BRDF.

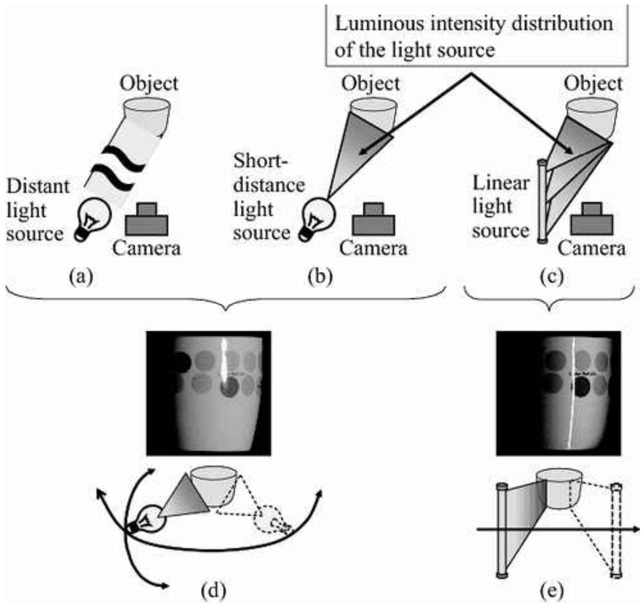


Figure. 3: A point light must be set at the distant point from the subject to make the incident light parallel. A point light (b) or a linear light (c) can be used in the short distance by taking into account the luminous intensity distribution. In case (d) which uses the point light source, it needs to move various angles to measure the subject's whole surface. In case (e) which uses the linear light source, it needs to move by only the linear motion.

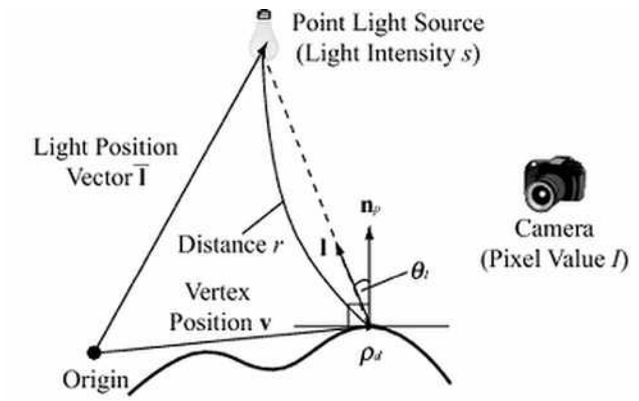


Figure. 4: Schematic illustration of our photometric stereo method with short-distance LEDs from the subject.

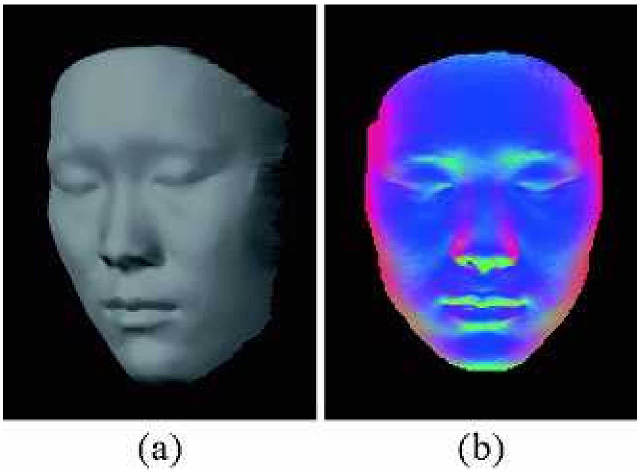

Figure. 5: (a) Obtained facial 3D shape, and (b) obtained facial normals with the hybrid algorithm.

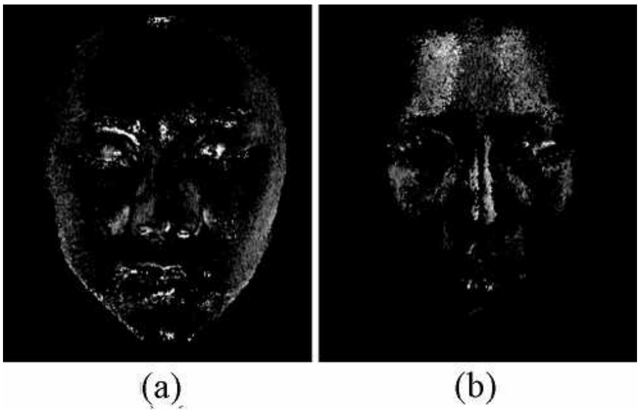

Figure. 6: Obtained BRDF parameters. (a) Specular parameter and (b) surface roughness.

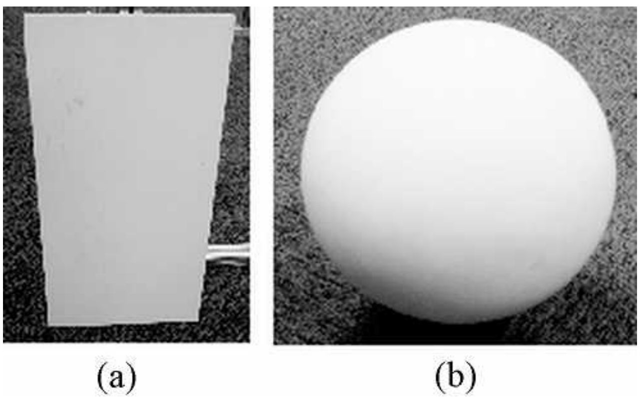

Figure. 7: Subjects used in the experimental 3D shape evaluation. (a) Board and (b) spherical object.

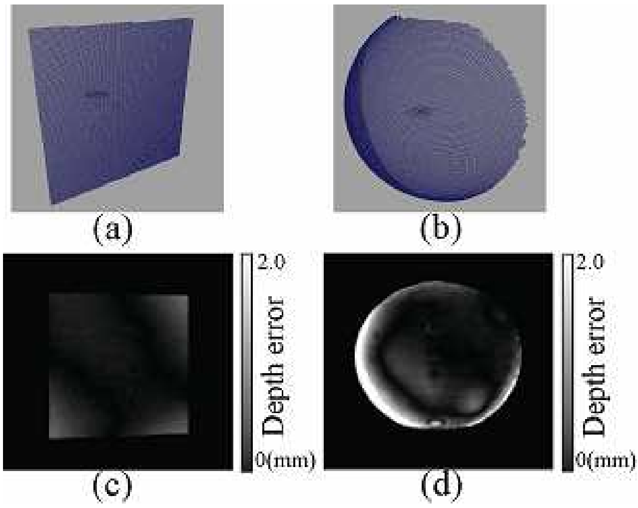


Figure. 8: (a)(b) Measured 3D shape of the board and spherical object, (c)(d) errors between measured 3D shape and ground truth shape.

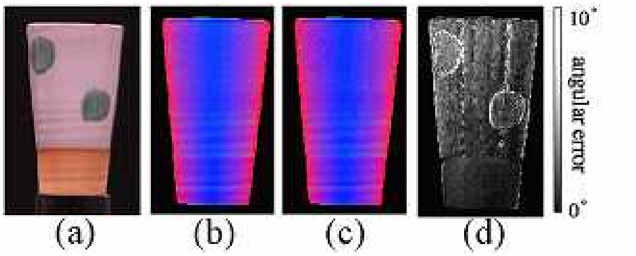


Figure. 9: (a)Subject (b)measured normals by the proposed method (c)measured normals by the conventional method (d)error map image.

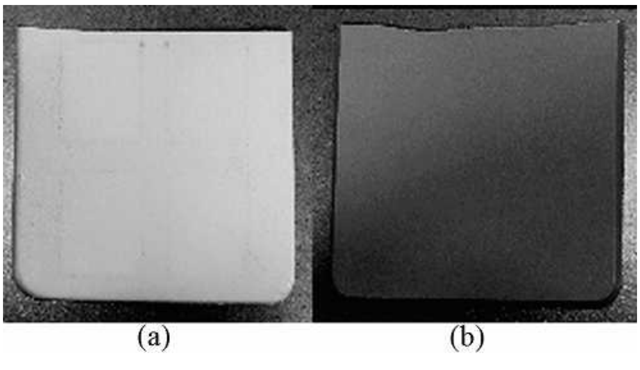


Figure. 10: Two skin replicas used in the experimental BRDF evaluation. (a)Skin replica 1 and (b) 2.

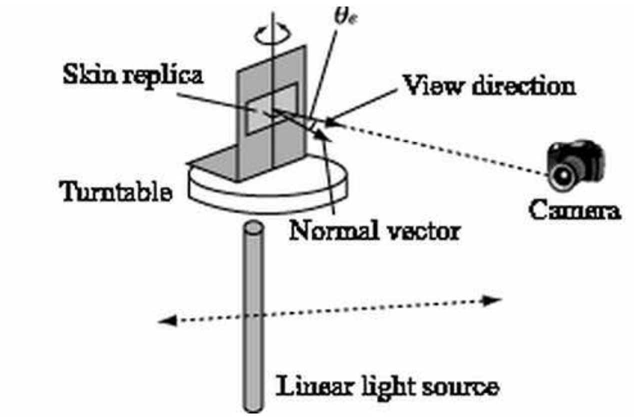


Figure. 11: Schematic illustration of BRDF measurement from various viewing directions.

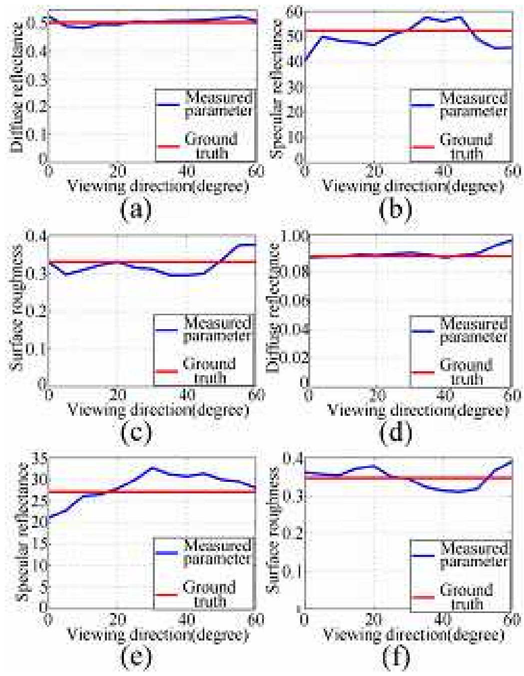


Figure. 12: Comparison of measured BRDFs with ground truth BRDFs(diffuse and specular parameter mean parameters of Torrance-Sparrow model, not actual reflectance). (a)(b)(c) Skin replica 1 and (d)(e)(f) skin replica 2.

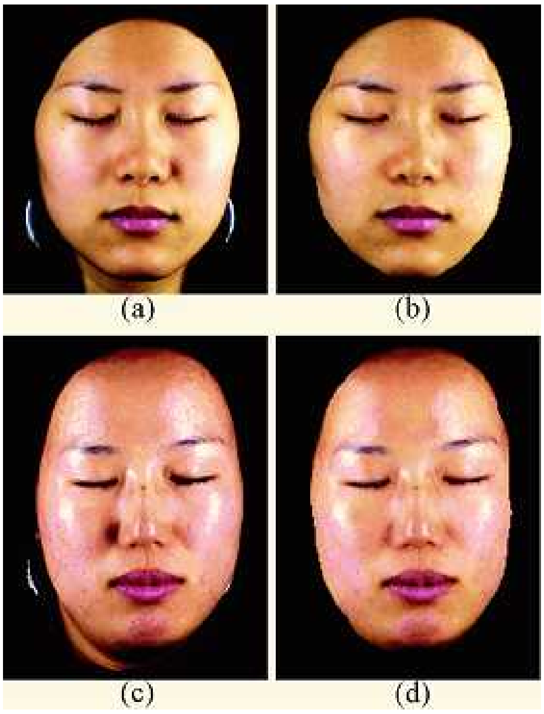


Figure. 13: (a)(c) Real facial photographs and (b)(d) reproduced facial images with measured facial physical properties.

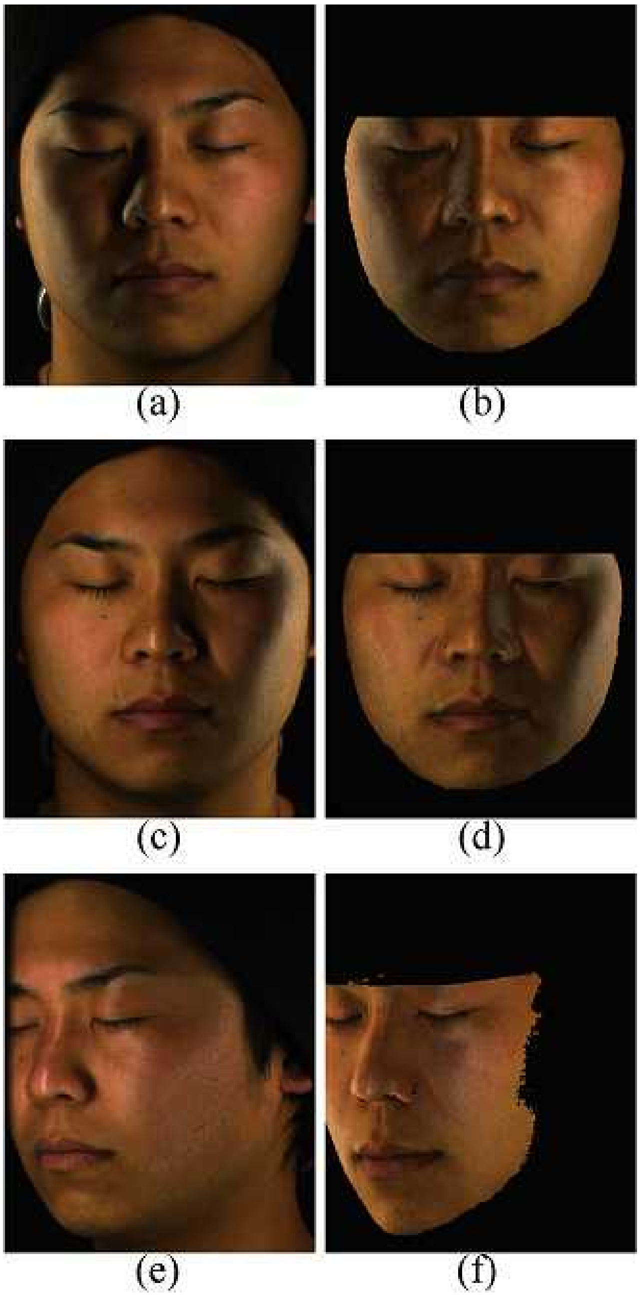


Figure. 14: (a)(c)(e) Real facial photographs and (b)(d)(f) reproduced facial images from different lighting and viewing direction

Table I: RMSE and maximum error of measured 3D shape of two subjects.

| | Board | Sphere |
|---|---|---|
| RMSE(mm) | 0.24 | 1.09 |
| Maximum error(mm) | 0.91 | 5.78 |

Table II: RMSE and maximum error of measured normal vectors by two methods.

| | Error between proposed and conventional methods |
|---|---|
| RMSE( ˚ ) | 1.81 |
| Maximum error( ˚ ) | 9.86 |

Table III: Average and maximum error of measured BRDF parameters(%)

| | Surface replica 1 | | | Surface replica 2 | | |
|---|---|---|---|---|---|---|
| | Diffuse parameter | Specular parameter | Surface roughness | Diffuse parameter | Specular parameter | Surface roughness |
| Average error | 2.31 | 9.92 | 7.51 | 2.52 | 11.09 | 6.14 |
| Maximum error | 5.29 | 23.33 | 12.61 | 12.24 | 22.53 | 12.38 |