MVA '98 IAPR Workshop on Machine Vision Applications, Nov. 17-19, 1998, Makuhari, Chiba, Japan

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3D Reconstruction of Skin Surface from Image Sequence

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Abstract

This paper proposes a new method for reconstruction a shape of skin surface replica from shading image sequence taken with different light source directions. Since the shading images include shadows caused by surface height fluctuation, and specular and inter reflections, the conventional photometric stereo method is not suitable for reconstructing its surface accurately. In the proposed method, we choose intensity data which do not include specular and inter reflections and self-shadows so that we can calculate accurate normal vector from the selected intensity data using SVD (Singular Value Decomposition) method. The experimental results from real images demonstrate that proposed method is effective for shape reconstruction from shading images which include specular and inter reflections and self-shadows.

1 Introduction

Since the 3D shape of skin surface depends on the biological condition of skin, precise 3D measurement of skin surface is important for diagnostic of skin quality and condition. For inspecting 3D shape of human skin, the replicas are often used for copying the surface shape precisely. The use of the replicas is good for making the surface reflectance property same for every skin. Even though the reflectance property can be homogeneous for every object, the reflectance is not completely Lambertian but including specularity. In addition to the specularity, inter reflection and self-shadows are also occur in the shading images of the replicas[1, 2, 3]. Consequently, it is difficult to recover the 3D shape of the replica surface with conventional Shape-from-Shading techniques[6, 7].

For overcome those problem, we think that multiple images under different light source directions can provide sufficient information on the reflectance information, which is similar as previous researches[4, 5]. In those researches, parameters on reflectance property are tried to recover from multiple images. In such method, the problem of specularity can be solved, however, the inter reflection and self-shadows can not be easily solved because those effects completely depends on the object shape itself. The effects of inter reflection and shadows can not be analyzed without having the shape itself. In our previous studies [1, 2] we proposed the method to recover the shape by the framework of "Analysis by Synthesis", in which the assumed shape synthesizes the shading images by regarding those effects, and then the synthesized images are compared with the input images for actual shape analysis. Although this method can handle the inter reflection and shadows for reconstruction of the shape, accurate reconstruction is difficult if there are some ambiguity in obtained shading images.

In this paper, we propose a new method for reconstructing 3D shape of the skin surface from shading image sequence taken with moving light source. Since the multiple shading images of the sequence contain sufficient information on the way of inter reflection, self-shadows, and other complex effects, we can recover accurate 3D shape by analyzing the images. In our method, we define a matrix equation under the simple model in which the Lambertian property with no inter reflections and shadows. We regard the complex effects as an error of the simple model, then employ the SVD (Singular Value Decomposition) for solving the matrix equation. Because the amount of error gives difference between the simple model and the actual situation, we can select out erroneous samples according to the error value. Repeating this selection, we can select only the samples which obey the simple model. In this way, we can remove the effect of inter reflection and shadows, then reconstruct accurate 3D shape of the skin.

For demonstrating the effectiveness of the proposed method, we also show 3D shape of skin replica, which is reconstructed from real image sequences.

2 Arrangement for Replica Image Correction

For taking multiple images under different light source direction, we use the arrangement as shown in figure 1, which has three lights at an interval of 120°, and each lights can rotate 120°.

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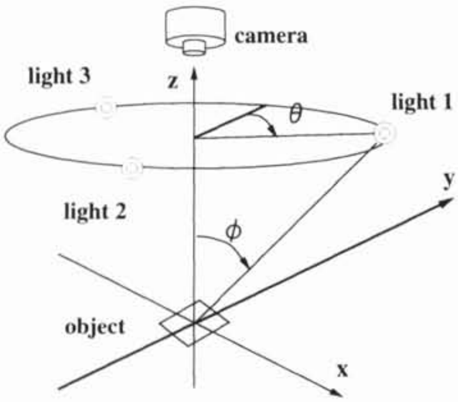


Figure 1: Arrangement for taking replica images under various direction light source.

3 Model of Image Intensity

Under the assumption of orthographic projection, Lambertian surface, and a distant single-point light source, the intensity at arbitrary point(x, y) can be represented as the following equation:

$$I = \eta \mathbf{L} \cdot \mathbf{n} \tag{1}$$

where η is the albedo of the surface, $\mathbf{n}$ is the surface normal, $\mathbf{L}$ is the vector of the light source direction. If we have values of I at three different light source direction $\mathbf{L}$, we can recover the surface normal at (x, y) with the albedo η [6]. If we take three images under three different light source, and the equation can be satisfied at every pixel, then we can recover the surface normal at every pixel. However, because of specularity, inter reflection, and self-shadows, the equation can not satisfied at many pixel.

To overcome such problems, we take multiple images at different light directions $\mathbf{L}(\theta)$, which are under different angle θ and constant ϕ. Then the equation (1) can be rewrite as the following form.

$$\begin{aligned} I(\theta) &= \eta \mathbf{L}(\theta) \cdot \mathbf{n} && (2) \\ &= \eta \left[\sin\phi \sin\theta, \sin\phi\cos\theta, \cos\phi\right] \cdot \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} && (3) \end{aligned}$$

If every value at every light source direction satisfy the equation (1), the value must fit sinusoidal function as

$$I(\theta) = A \sin(\theta + B) + C, \tag{4}$$

where

$$A = \eta \sin\phi \sqrt{n_x^2 + n_y^2}$$

$$B = \tan^{-1} \frac{n_y}{n_x}$$

$$C = \eta \cos\phi \; n_z$$

Consequently, we can estimate the surface normal by fitting sine curve to $I(\theta)$ at each pixel. For the fitting, we employ SVD method for solving the simultaneous equation.

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \eta \begin{bmatrix} \sin\phi\sin\theta_1, & \sin\phi\cos\theta_1, & \cos\phi \\ \sin\phi\sin\theta_2, & \sin\phi\cos\theta_2, & \cos\phi \\ \vdots & \vdots & \vdots \\ \sin\phi\sin\theta_n, & \sin\phi\cos\theta_n, & \cos\phi \end{bmatrix} \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \tag{5}$$

where the light source directions are under n different angles $[\theta_1, \theta_2, ...\theta_n]$ and constant ϕ.

In the actual case, some of $I(\theta)$ will satisfy the model equation (1), but some will not. This is caused by some effects, that is inter reflection, specular reflection, and shadow caused by the occlusion of the light source. We need to extract only the intensity data which can be fitted on the model of the sine curve for accurate estimation of surface normal (n_x, n_y, n_z). For extracting "on-model" intensity data, we employ the following process.

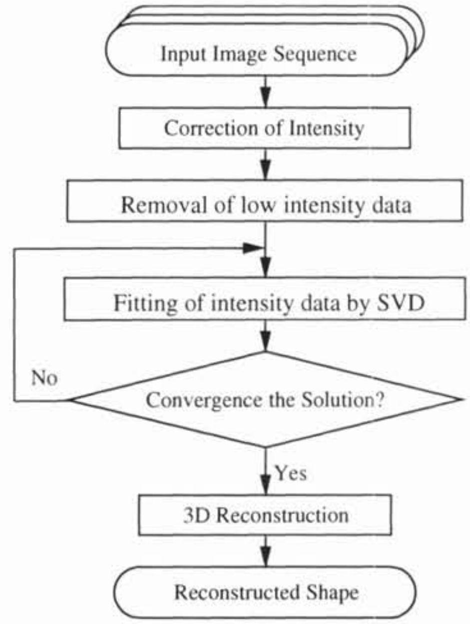


Figure 2: Flow of the proposed method

4 Shape Reconstruction

4.1 Flow of the proposed method

Flow of the proposed method is shown in figure 2. First we correct intensity because three lights power aren't the same. Next we choose intensity data which do not include specular and inter reflections and/or self-shadows as describe in the following section. We then calculate normal vector from intensity data by solving equation (5) using SVD method. Finally, the normal vectors are integrated to get the 3D shape of skin surface.

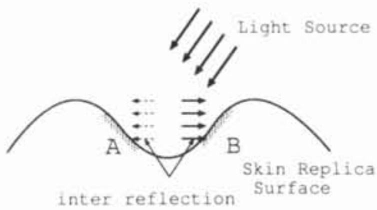
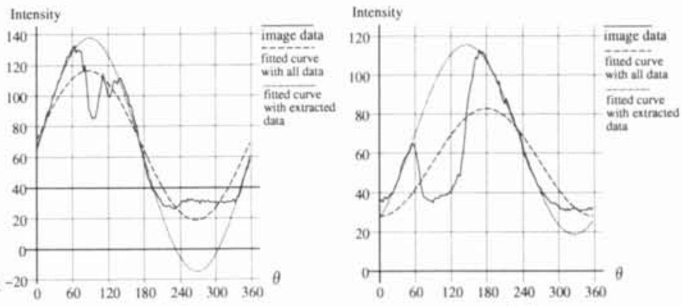


Figure 3: Mechanism of the inter reflection on skin replica surface.



(a) (b)

Figure 4: Examples of intensity data along with fitted sinusoidal curves.

4.2 Removal of low intensity data

In figure 4, the solid lines show examples of $I(\theta)$, which is the intensity curve at the same pixel under 120 different light source angles. In the intensity curve of figure 4 (a), the intensity is almost the same value around the minimum ($200° \sim 340°$). As shown in this curve, the intensity data can not be lower than some level, which can not be reasonably fitted to any sine curve.

For removing those low intensity data from the process of fitting to sine curve, we take simple thresholding method, in which the intensity data lower than threshold are removed. The threshold is determined with initial experiment. By the initial experiment, we decide the threshold is 40, that is shown by the thick horizontal line in figure 4 (a).

The reason that the intensity data do not have lower value is mostly caused by the inter reflection. The inter reflection gives some intensity in addition to the direct reflection of the light source. Figure 3 shows mechanism of the inter reflection effect. On the surface region of A, most inter reflected light comes from the surface region B. However, the intensity of the inter reflection is not large, because the normal direction of the surface B is approximately vertical to the light source direction. Contrary to this, the intensity of the inter reflection on the surface region B is significantly large, because most of inter reflection come from the surface region A, of which normal is almost parallel to the light source direction. According to such brief modeling of the effect of the inter reflection, we can assume that the inter reflection mostly affects to low intensity data, which mean the direct reflection intensity is small as the case of surface B.

4.3 Repetitive fitting of intensity data

Even after removing the low intensities, the intensity curve can not be completely fitted to the sine curve. This is mostly caused by the specular reflection and self-shadow.

If the difference between the intensity data of the image ($I_o(\theta)$) and the intensity calculated by equation (5) ($I_{svd}(\theta)$) is larger than the threshold level, then the data ($I_o(\theta)$) is excluded from the equation (5) because they can include specular reflection and/or self-shadow. After removing such data, the equation (5) is solved with SVD again. Repeating this process, only the data which can be regarded as Lambertian model of equation (1) provide accurate surface normal.

The effectiveness of those removal is demonstrated in figure 4. By extracting the on-model data, the sine curves are accurately fitted to the extracted data. Instead of this, the fitted sine curves by all intensities do not match well with the intensity data.

4.4 Integral

After extracting the on-model data and calculating the surface normal (n_x, n_y, n_z) by using equation (5), the surface gradients $(p(x,y), q(x,y))$ are derived according to the following equation.

$$p(x,y) = -\frac{n_x}{n_z} \tag{6}$$

$$q(x,y) = -\frac{n_y}{n_z} \tag{7}$$

The gradients are integrated to get the shape of skin surface($z(x,y)$).

$$z(x,y) = \frac{1}{2}\int(p(x,y)dx + q(x,y)dy) \tag{8}$$

5 Experiments

Our method has been applied to real images taken from the real skin negative replicas. The image size are 256×256 pixel. Real size are about 4.5×4.5 mm. Input images are taken under 120 different θ at interval $3°$.

Figure 5 shows example images of 120 input images taken for skin replica. The reconstructed shape from the image sequence is shown as the bird view in figure 6. Range image of the reconstructed shape is compared with the averaged image of all input images in figure 7. We can observe that the reconstructed shape is qualitatively reasonable because the 2D structure of the reconstructed range image is almost the same as the averaged image, which indicates 2D structure of the skin grooves and hair

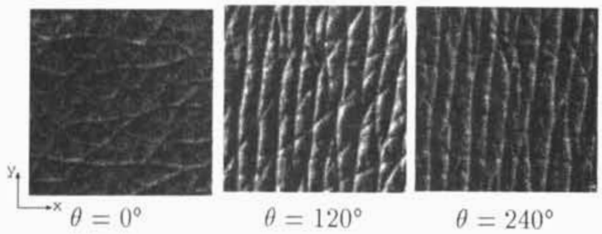


Figure 5: Examples of input image sequence

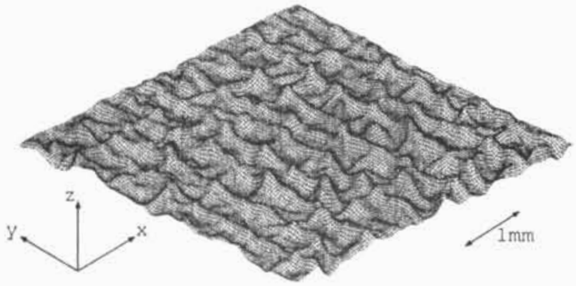


Figure 6: Reconstructed shape

holes, although the averaged image does not have any shape information quantitatively.

Figure 8 shows the reconstructed shape for the case of replica that has the wave shape profile. The cross section image of the replica, which is obtained by actually cutting of the replica, is compared with the profile of the reconstructed shape in figure 9. Since the actual cross section of the replica is close to the reconstruction by our method, our method can be effective for accurate reconstruction of shape of the replicas.

6 Conclusion

We propose a new method for reconstruction a shape of skin surface replica from shading image sequence taken with different light source directions. In this method, the "on-model" intensity data are extracted so that the accurate normal vector can be estimated by fitting of the extracted intensity to sine curve. The experimental results from real images demonstrate that proposed method is effective for shape reconstruction of skin replicas from shading images which include specular and inter reflections and self-shadows.

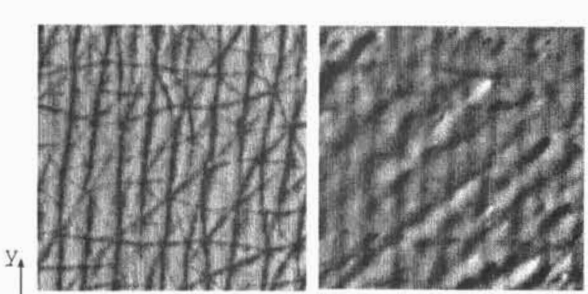


Figure 7: Comparison of range image (right) with averaged input image (left).

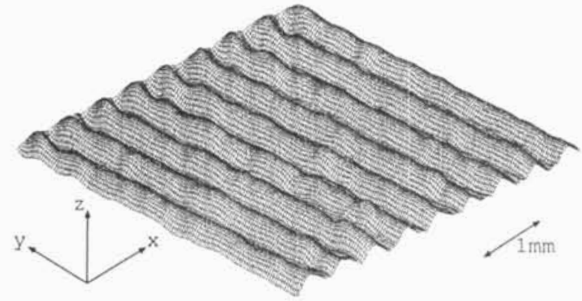


Figure 8: Reconstructed shape

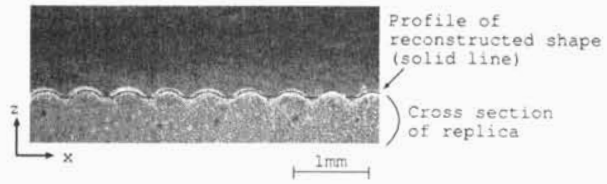


Figure 9: Comparison of reconstructed profile with actual cross section

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