Shape Reconstruction of Skin Surface from Shading Images Using Simulated Annealing

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abstract

This paper describes about a new method for reconstructing a shape of a skin surface replica from three shading images taken with three different lightings. Since the shading images include shadows caused by surface height fluctuation, the conventional photometric stereo method is not suitable for reconstructing its surface shape. In the proposed method, the evaluation function of the surface shape is defined in consideration of the effects of shadow, then the shape is reconstructed by optimizing the evaluation using simulated annealing. The experiments to reconstruct the shape from synthesized images and real images demonstrate that the proposed method is effective for shape reconstruction from shading images which include shadows.

1 Introduction

For investigating the effect of cosmetics, various characteristics of skin surface, such as shape, color, and moisture, are inspected. The shape of the skin surface provides much information such as the age of the skin, so it is very significant to extract characteristics on the shape of the skin surface [1, 2]. In general, skin surface replicas are used for inspection of the skin surface shape. The skin surface replicas are made of rubber which is formed on the skin surface, and then the rubber surface becomes the reverse shape of the skin surface. Since the required resolution of the skin surface shape measurement is almost the order of μm, it is difficult to obtain 3D shape by applying general 3D shape measuring techniques. Therefore, the shape characteristics are implicitly inspected by analyzing 2-D microscope images in the conventional method.

This paper describes an new approach to reconstruct 3D shape of skin surface from the microscope images of the skin surface by applying the principle of *shape from shading* technique. We use a microscope with three lightings on different angles as shown in figure 1. The microscope provides three images taken with three different lightings. Therefore, the shading of these images can provide 3D shape of the object by using the conventional photometric stereo method [3, 4]. However, since there are many mountains and valleys on the skin surface, many shadow region are included in the images. Therefore, the 3D surface of the skin replica cannot be reconstructed by only applying the conventional photometric stereo method.

In this paper, we propose a new method for reconstructing 3D shape from shading images including some shadows. This method uses simulated annealing (SA) method for finding the shape which provides the closest shading images to taken shading images. The experiments to reconstruct the shape from synthetic images and real images demonstrate that the proposed method is effective for shape reconstruction from shading images which include shadows.

2 Shape Reconstruction

The flow of the proposed method is presented in figure 2. In this method, the shape of the surface is estimated by the iterating process. In each iteration, the estimated shape $z(x, y)$ is evaluated by comparing the estimated shading images $R_k(x, y)$, which are synthesized from the estimated shape $z(x, y)$ in the consideration of the effect of the shadow, with the input shading images $I_k(x, y)$, where k={1, 2, 3}. The evaluation value is optimized by using SA for obtaining the global optimum, then the shape of the surface is reconstructed. The detail of each step of the flow is described in the follows.

2.1 Validity check of shading values

As there are three shading images, each pixel has three different shading values. For each pixel, validity of the shading values which represents the existence of shadow is checked by thresholding. Let $I_k(x, y)$ represent a shading image taken with a lighting of $k = \{1, 2, 3\}$. If a pixel value in the shading image is lower than the threshold value I_{th}, the shading value is regarded as shadow, that is invalid value. The coefficient $a_k(x, y)$ is defined as the following equation for representing the validity of the shading value $I_k(x, y)$.

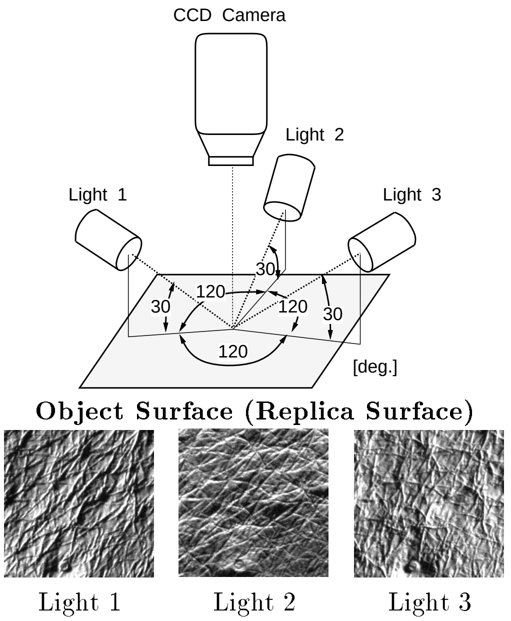


Figure 1: Scheme of the microscope with three different lightings and example of the shading images of skin surface replica.

$$a_k(x,y) = \begin{cases} 1 & I_k(x,y) > I_{th} \\ 0 & \text{otherwise (shadow)} \end{cases} \quad (1)$$

The number of valid pixel number (non shadow pixel), which is represented as $v(x,y) = \{3,2,1,0\}$, is defined as the number of $a_k(x,y) = 1$ at the pixel (x,y).

2.2 Evaluation of estimated shape

This section describes about the evaluation function used for iterative optimization of the estimated shape. The estimated shape is evaluated at every local position by the following three terms.

(1) Evaluation of Shading $e_i(x,y)$

(2) Evaluation of Gradient $e_g(x,y)$

(3) Evaluation of Smoothness $e_s(x,y)$

Then, total evaluation value for each point can be represented as

$$e_t(x,y) = w_i e_i(x,y) + w_g e_g(x,y) + w_s e_s(x,y), \quad (2)$$

where, w_i, w_g, and w_s are weighting coefficient for each term. The average evaluation values in an image are also represented as E_i, E_g, and E_s, and then the total average evaluation E_t can be expressed as

$$E_t = w_i E_i + w_g E_g + w_s E_s. \quad (3)$$

The details of the definition of each term is described in the following.

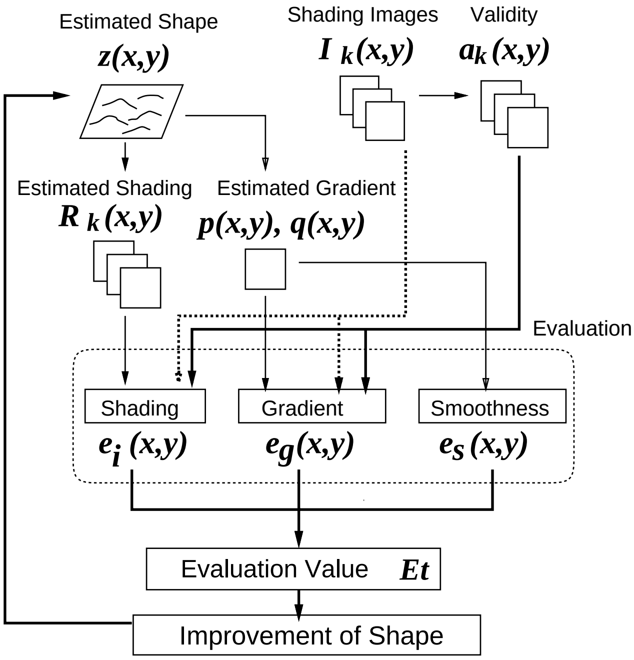


Figure 2: Flow of the proposed method.

2.2.1 Evaluation of shading

By assuming that the surface is Lambertian, the shading image can be uniquely synthesized from the estimated shape as the following equation [3].

$$R_k(x,y) = r_0(\boldsymbol{n}_k \cdot \boldsymbol{n}), \quad (4)$$

where $\boldsymbol{n}_k$ represents the normalized direction vector of the kth illumination, and $\boldsymbol{n}$ shows the surface normal vector. However, the shading value can not be obtained by this equation when the illumination is occluded by the shape itself. In such case,

$$R_k(x,y) = 0. \quad (5)$$

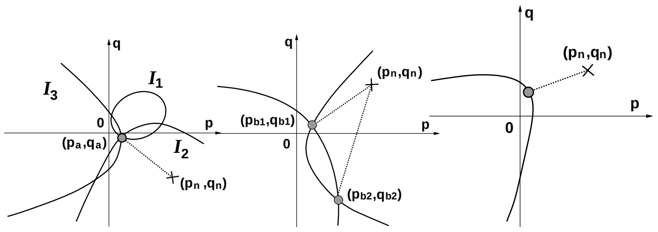
The shading value of taken image, $I_k(x,y)$, must be close to the reflectance value, $R_k(x,y)$, which is calculated from the estimated shape $z(x,y)$ as described above. Therefore, the evaluation of shading $e_i(x,y)$ is defined by the difference between $I_k(x,y)$ and $R_k(x,y)$ as the following equation.

$$e_i(x,y) = \frac{\sum_{k=1}^{3} a_k(x,y)|I_k(x,y) - R_k(x,y)|}{v(x,y)}, \quad (6)$$

where $v(x,y)$ represents the number of valid pixel at (x,y).

2.2.2 Evaluation of gradient

The gradient of the surface can be estimated by using the photometric stereo [3]. The evaluation of gradient is



(a) $v(x, y) = 3$. (b) $v(x, y) = 2$. (c) $v(x, y) = 1$.

Figure 3: Gradient vector space used in evaluating surface gradient.

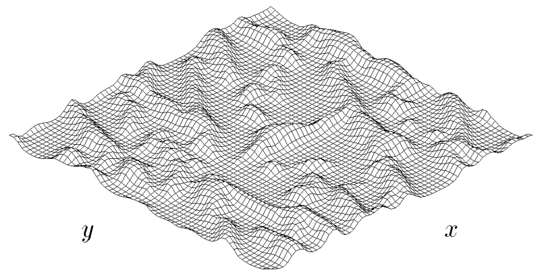


Figure 4: Assumed original shape.

defined by the difference between the estimated gradient and the gradient calculated from the shading of taken images. Because the shadow region is included in the shading images, the gradient is calculated according to the number of valid pixel $v(x, y)$.

- $v(x, y) = 3$ (Figure 3 (a))
  If the all pixel value are valid, the gradient of the surface can be uniquely determined by the photometric stereo analysis, which is represented as $(p_a, q_a, -1)$. In this case, the evaluation of gradient $e_g(x, y)$ is defined as the flowing equation.

$$e_g(x, y) = \sqrt{(p_n - p_a)^2 + (q_n - q_a)^2} \quad (7)$$

  where $(p_n, q_n, -1)$ is the gradient of the estimated surface.

- $v(x, y) = 2$ (Figure 3 (b))
  If two values are valid (one value is regarded as shadow), the gradient can have two solution as shown in figure 3(b) which are represented as $(p_{b1}, q_{b1}, -1)$! "$(p_{b2}, q_{b2}, -1)$. The evaluation of gradient $e_g(x, y)$ is defined as

$$\begin{aligned} e_g(x, y) &= \sqrt{(p_n - p_{b1})^2 + (q_n - q_{b1})^2} \\ &\quad \sqrt{(p_n - p_{b2})^2 + (q_n - q_{b2})^2} \end{aligned} \quad (8)$$

  where $(p_n, q_n, -1)$ is the gradient of the estimated surface. This definition means that the e_g becomes smaller when $(p_n, q_n, -1)$ get closer to either $(p_{b1}, q_{b1}, -1)$ or $(p_{b2}, q_{b2}, -1)$.

- $v(x, y) = 1$ (Figure 3 (c))
  This evaluation is defined as the shortest distance between the the gradient of the estimated surface $(p_n, q_n, -1)$ and the equal reflectance curve which is determined by one valid shading value.

- $v(x, y) = 0$
  In every shading value in the taken images are regarded as shadow, the evaluation of gradient e_g is set to zero so that this evaluation does not affect to total evaluation.

2.2.3 Evaluation of smoothness

For the purpose of interpolating the pixels with $v(x, y)$ = 0, smooth constraint is used. This evaluation e_s is defined as

$$e_s(x, y) = \sqrt{(\Delta p)^2 + (\Delta q)^2}, \quad (9)$$

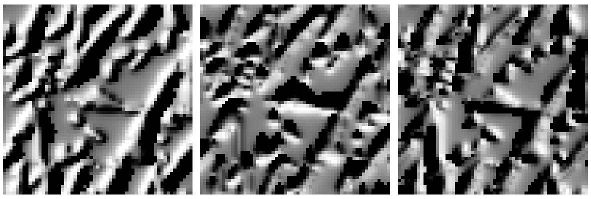
where

$$\begin{cases} \Delta p &= \sqrt{(p_n(x, y) - p_n(x-1, y))^2} \\ \Delta q &= \sqrt{(q_n(x, y) - q_n(x-1, y))^2}. \end{cases}$$

2.3 Optimization of the estimated shape

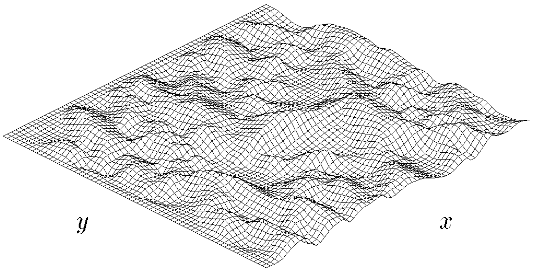
In the proposed method, SA is applied to iterative optimization of estimated shape $z(x, y)$. For an estimated shape, a position (x, y) is randomly selected and then the height at the position $z(x, y)$ is changed to $z \pm \Delta z$. The evaluation values of the changed shape are represented by E_t^+ and E_t^- for the cases of Δz and $-\Delta z$, respectively. These evaluation values are calculated according to the definition described in the previous section. The shape providing the smaller evaluation value in these two changes (Δz or $-\Delta z$) is selected as the new shape of which the evaluation value is represented by E_t^{new}. The evaluation value of the shape before the change is represented by E_t^{old}. Then the difference between the old and the new shape is $\Delta E_t = E_t^{new} - E_t^{old}$. If $\Delta E_t < 0$, then the new shape is accepted as the improved shape. If $\Delta E_t \geq 0$, the new shape is accepted under the probability of $\exp(-\Delta E_t/T)$, where T represents the temperature parameter. By repeating this improvement process with decreasing T, the shape which satisfies a convergence condition is regarded as the reconstructed shape.

In the following experiment, the initial temperature T is 20, and every 20,000 iteration, the T is reduced by the factor 0.95. After the reduction of T is repeated 100 times (2,000,000 iteration), the estimated shape is regarded as the reconstructed shape. The step height Δz is first set to 1.0, and it is reduced by the factor 0.95 in the same time with the temperature T. An unit of the height is equal to the pixel size, 20 μm.

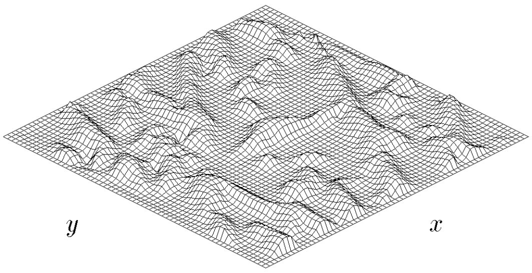


(a) Light 1. (b) Light 2. (c) Light 3.

Figure 5: Synthesized input shading images.



(a) Conventional method.



(b) Proposed method.

Figure 6: Reconstructed shapes.

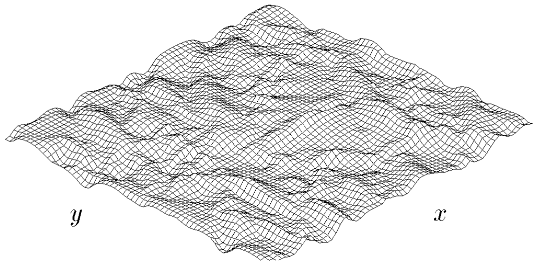
3 Experimental Results

We performed reconstructing experiment for demonstrating the efficacy of the proposed method. The shading images used for shape reconstruction have 64×64 pixels (1 pixel = 20×20 μm).

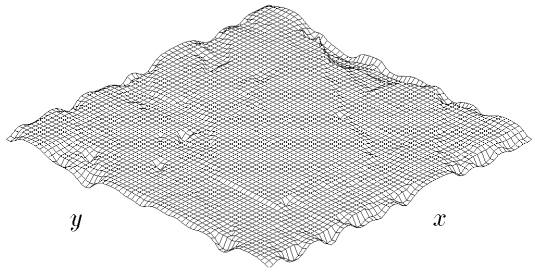
The arrangement of the surface replica and the lightings are shown in figure 1. We regarded the imaging system as the orthographic projection, because the distance between the replica and the CCD camera is much longer than the replica size. We also assumed that the surface is Lambertian.

The shading images shown in figure 5 are synthesized from the assumed shape shown in figure 4. Because of the surface shape fluctuation, some shadow regions are included in these shading images.

The shape is reconstructed from the synthesized shading images by using the proposed method. Because there is no noise in the shading image, the smooth constraint is not necessary for reconstruction, the weight w_i, w_g, and w_s are set to 1.5, 25.0, and 0.0, respectively. In figure 6, the reconstructed shape obtained by the proposed method and the reconstructed shape obtained by the conventional photometric stereo method [3] are shown. Figure 7 show the height error of the reconstructed shapes. These results shows that the proposed method is effective to reconstruct the shape from the shading image including some shadow regions, while the conventional method does not provide accurate shape because of the existence of shadow in the shading images.



(a) Conventional method.



(b) Proposed method.

Figure 7: Error of reconstructed shapes.

Figure 8 shows the variation of the evaluation value in iteration of improvement by SA. These graphs show that SA can effectively optimize the evaluation function.

The real shading images of V-shaped model surface replica and skin surface replica are shown in figure 9 and figure 10, respectively. In the reconstruction of the

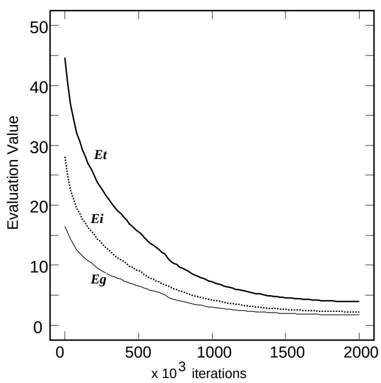
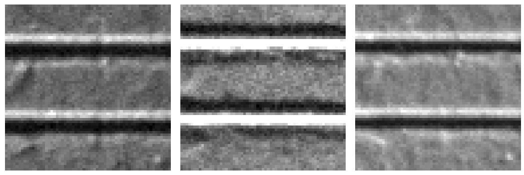


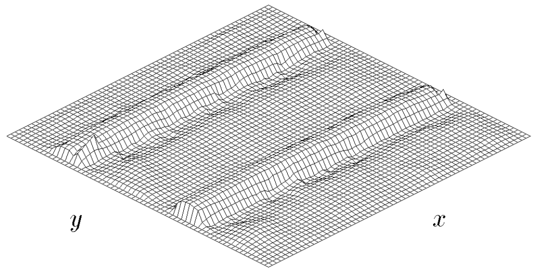
Figure 8: Variation of evaluations in case of synthesized shading images.

shape from these real shading images, the weight w_i, w_g, and w_s are set to 1.5, 25.0, and 4.0, respectively.

In figure 9 and figure 10, the reconstructed shapes from the real shading images are also shown. The mountain like regions in the reconstructed shapes are corresponding to the streak in the shading images. This means that qualitatively correct shape can be reconstructed, although the quantitative accuracy can not be investigated for the reconstructed shape from the real images.



(a) Light 1. (b) Light 2. (c) Light 3.



(d) Reconstructed shape.

Figure 9: Shading images and its reconstructed shape of V-shaped replica.

4 Conclusion

The new method to reconstruct the shape of the skin surface from shading images including shadows is proposed. In this method, SA is employed to optimize the evaluation function which considers the existence of shadows. The proposed method provides the closer reconstructed shape to the original object shape than the conventional method. Consequently, the efficacy of the proposed method can be demonstrated.

Acknowledgments

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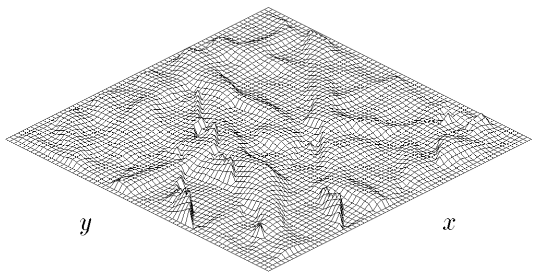
(a) Light 1. (b) Light 2. (c) Light 3.



(d) Reconstructed shape.

Figure 10: Shading images and its reconstructed shape of skin surface replica.

References

[1] A. Awajan, D. Rondot, J. Migiot, "Quick method of measuring the furrows distribution on skin surface replicas", Medical & Biological Engineering & Computing, Vol.27, pp.379-389, 1989.

[2] K. Shinmoto, T. Honda, and S. Kaneko, "Reconstruction of 3D orientation of skin surface replicas by expanding photometric stereo", Trans. IEICE, Vol.J77-D-II, pp.1797-1805, 1994 (in Japanese).

[3] R. J. woodham, "Photometric method for determinating surface orientation from multiple images", Optical Engineering, Vol. 19, pp.139-144, 1980.

[4] K. Ikeuchi and B. K. P. Horn, "Numerical shape from Shading and Occluding Boundaries", Artificial Intelligence, Vol. 17, pp.141-184, 1981.

[5] S. Kirkpatrick, C. D. Gelatt, Jr., and M. P. Vecchi, "Optimization by Simulated Annealing", Science, Vol.220, pp.671-680, 1983.