

Shape from shading and polarization constrained by approximate shape

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Abstract

We propose a method which estimates the surface normal from shading information and polarization information. Unlike photometric stereo techniques which use three lights, shape-from-shading uses a single light and is an ill-posed problem. Therefore, to uniquely determine the surface normal using a shape-from-shading method, additional assumptions or additional inputs are required. We use polarization for additional input, because polarization can constrain the surface normal. One example of common assumption is to limit the target object to be a single color, but such assumption restricts the application field. Therefore, we use an approximate shape of the object to solve this problem. Thanks to this approximate shape, we can estimate the surface normal of multi-colored object.

1 Introduction

Shape-from-shading, which uses a single image, is an ill-posed problem, and thus, existing methods [1, 2, 3] used additional assumptions, additional inputs, or training data to solve the problem. Polarization is also useful for estimating surface normal. A small number of method obtains the surface normal from shading and polarization under a single light. Most of them assume a single-colored object for target objects, while we overcome this problem using an approximate shape of the object as a cue. Thanks to this additional information, our method (Fig. 1) can be applied to multi-colored objects.

Shape-from-shading [1, 2, 3, 4, 5, 6], which use a single image, is an ill-posed problem. Polarization [7] is also useful for estimating the surface normal of objects, and polarization is used for photometric stereo [8, 9, 10, 11, 12, 13] and shape-from-shading [15, 16, 17, 14]. These methods [15, 16, 17] used the degree of polarization; however, the degree of polarization depends on the index of refraction and surface roughness. Previous work [14] did not use the degree of polarization but used the phase angle of polarization, because it is independent to the index of refraction nor surface roughness. Because the phase angle of polarization solely cannot determine the surface normal, shading information is also used where the light source is set almost next to the camera. The previous method

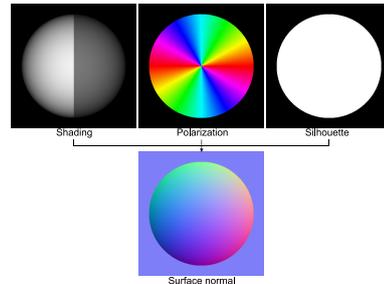


Figure 1. Proposed method: Shape from shading, polarization, and silhouette.

determined the albedo as the maximum brightness of the object because the surface normal heading to the light source has the same brightness as the albedo if the object is single colored. In order to overcome this problem, we use an approximate shape, which is calculated from the silhouette of the object. We prove that our method can estimate the surface normal of the object which has multiple colors.

2 Shape from shading, silhouette, or polarization

Under the condition that the object obeys the Lambertian reflection model and the light source is an infinite-far single light, the observed brightness i can be represented as follows.

$$i = \rho \mathbf{n} \cdot \mathbf{l}. \quad (1)$$

The unit vector $\mathbf{l} = (l_x, l_y, l_z)^\top$ represents the light source direction. The surface normal is represented as the unit vector $\mathbf{n} = (n_x, n_y, n_z)^\top$. The reflectance of diffuse reflection (hereafter, albedo) is denoted ρ .

Assuming that the light source direction is given, we have three unknowns, ρ , n_x , and n_y . Note that n_z is automatically obtained from $n_z = \sqrt{1 - n_x^2 - n_y^2}$. Since shape-from-shading has one constraint (Eq. (1)), we need additional two information to determine all three parameters. Two information are silhouette and polarization. The detailed process of using these three information is described in Section 3.

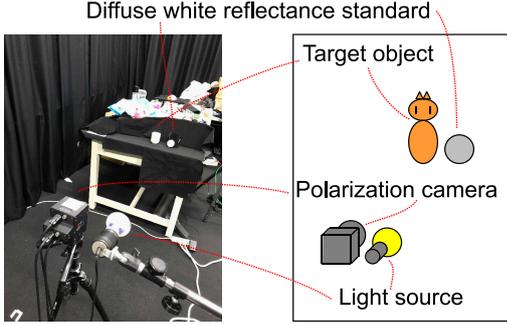


Figure 4. Experimental environment.

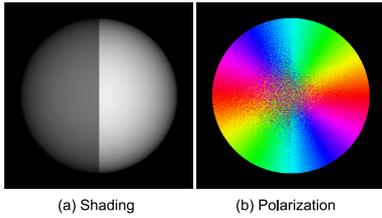


Figure 5. Simulationaly generated input data: (a) Target object and (b) azimuth angle with ambiguity.

Two possible candidates of the surface normal are calculated from Eqs. (7)–(8), i.e., either ϕ or $\phi + 180^\circ$ is the correct azimuth angle (Section 2). We use the guide normal \tilde{n}_x and \tilde{n}_y (Section 2) to uniquely determine the azimuth angle ϕ or $\phi + 180^\circ$ in the range between 0 to 360° . Eq. (9) shows the dot product between the (x, y) component of the surface normal of guide normal and the orientation which represents the azimuth angle ϕ , while Eq. (10) shows the dot product between the guide normal and the azimuth angle $\phi + 180^\circ$.

$$A_\phi = \tilde{n}_x \cos \phi + \tilde{n}_y \sin \phi, \quad (9)$$

$$A_{\phi+\pi} = \tilde{n}_x \cos(\phi + \pi) + \tilde{n}_y \sin(\phi + \pi). \quad (10)$$

Note that, the angle between two vectors are smaller than 90° if the dot product is positive, and that are greater than 90° if it is negative. If $A_\phi \geq A_{\phi+\pi}$, we determine the surface normal as Eq. (7). If $A_{\phi+\pi} \geq A_\phi$, we determine the surface normal as Eq. (8).

4 Experiments

The experiments are performed in a dark room (Fig. 4). The light source is placed close to the camera. The polarization camera captures the linear polarization parameters in a single shot.

4.1 Performance evaluation

First of all, we analyzed our algorithm using simulationaly-generated sphere (Fig. 5 (a)), which is

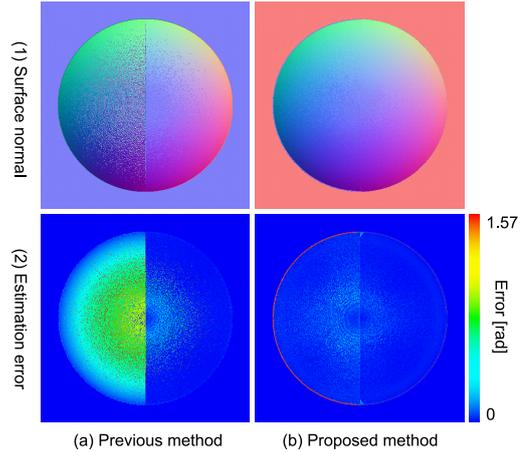


Figure 6. Comparison between (a) previous method and (b) proposed method: (1) Computed surface normal and (2) angular error between estimated surface normal and true surface normal.

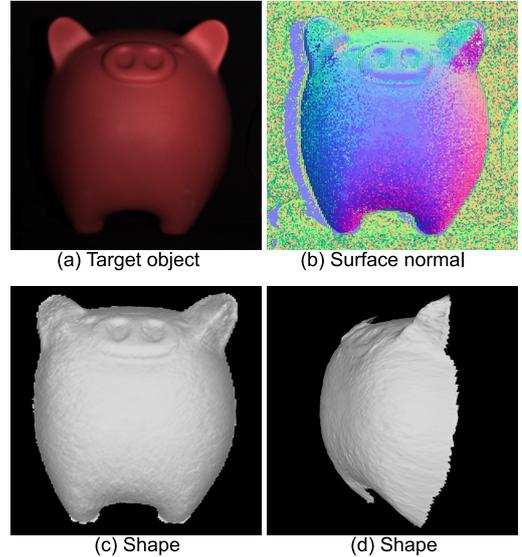


Figure 7. Experimental result [pig]: (a) Target object, (b) estimated surface normal, and (c) (d) reconstructed shape.

multi-colored. The input polarization data with noise added is shown in Fig. 5 (b) in pseudo color whose hue represents the orientation. The estimated surface normal of the previous method [14] and the proposed method is shown in Fig. 6 (1a) and Fig. 6 (1b), respectively. Surface normal is represented by pseudo color, where x , y , and z represents R, G, and B, respectively. The error between the estimated normal and the true normal is shown in Fig. 6 (2a) and Fig. 6 (2b), respectively. The average error of previous method is 0.309 [rad] and that of our method is 0.078 [rad]. The result

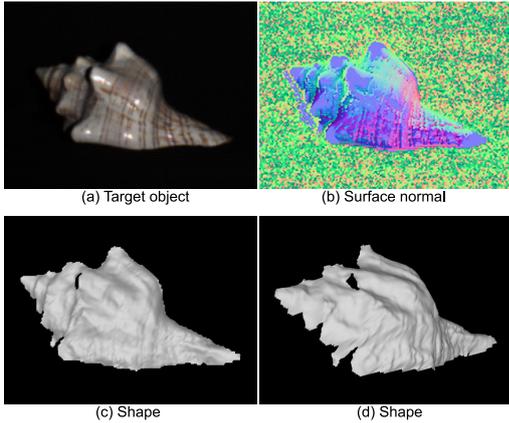


Figure 8. Experimental result [shell]: (a) Target object, (b) estimated surface normal, and (c) (d) reconstructed shape.

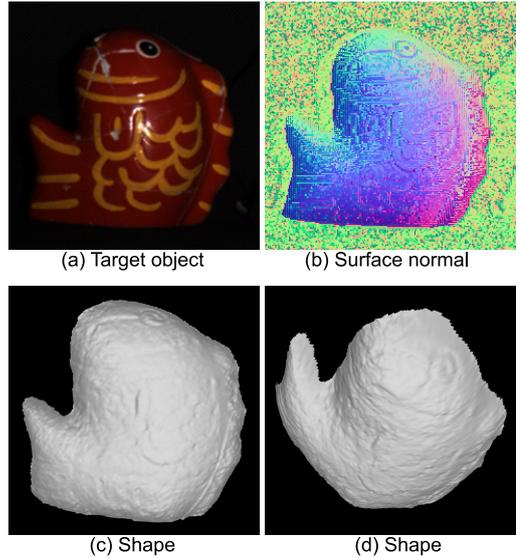


Figure 10. Experimental result [fish]: (a) Target object, (b) estimated surface normal, and (c) (d) reconstructed shape.

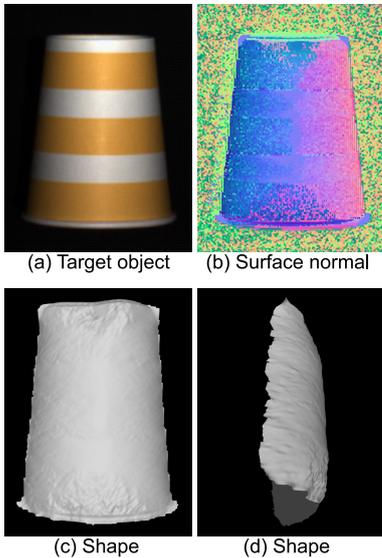


Figure 9. Experimental result [cup]: (a) Target object, (b) estimated surface normal, and (c) (d) reconstructed shape.

shows that the performance of our method is higher than that of previous method. Our method can be applied to multi-colored object.

4.2 Experimental results

We applied our method to objects shown in Figs. 7 (a), 8 (a), 9 (a), and 10 (a), whose shapes look like a pig, a shell, a cup, and a fish, respectively. The objects shown in Figs. 7 (a) and 8 (a) are single-colored, while those shown in Figs. 9 (a) and 10 (a) are multi-colored. The estimated surface normals are shown in Figs. 7 (b), 8 (b), 9 (b), and 10 (b), respectively. The reconstructed

shapes are shown in Figs. 7 (c) (d), 8 (c) (d), 9 (c) (d), and 10 (c) (d), respectively. These figures show that our method successfully estimated the shape of the object.

Although the guide normal cannot represent the detail of the shape, our method can recover the details of the shape, as is shown in the nose of Fig. 7, and the thorn of Fig. 8. However, as is shown in the top rim and the bottom rim of the cup shown in Fig. 9, the shape which is different from the guide normal is difficult to solve. Such dilemma is difficult to solve fundamentally, and it is our challenging future work.

5 Conclusion

We have proposed a method which estimates the surface normal from shading, polarization, and silhouette. Approximate shape calculated from silhouette is used as a cue. Shading information constrain the z-axis of surface normal. Polarization information constrain the x- and y-axes of surface normal. The experimental results show that our method can estimate the shape of multi-colored object from a single image.

Our future work is to use additional input, additional constraint, or additional training data so that we can estimate the shapes which are quite different from the guide normal.

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