Reflectance Estimation from Motion under Complex Illumination

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Abstract

In this paper, we propose a method for recovering the reflectance properties of a moving Lambertian object from an image sequence of the object taken by a fixed camera under unknown, complex illumination. Our proposed method is based on the spherical-harmonic representation of Lambertian reflectance under arbitrary illumination. Then, by combining the geometry reconstructed by Shape-From-Motion (SFM), we recover the albedo of the object and the illumination distribution only from the image sequence of the moving object. The proposed method enables us to synthesize realistic images of the object in arbitrary poses under arbitrary lighting conditions by using reconstructed shape and albedo. We conducted a number of experiments by using both synthetic and real images to confirm the effectiveness of our proposed method.

1. Introduction

To render a realistic image of an object, we require a detailed model of the object, including both geometric and photometric properties. Because the traditional manual method of constructing models is too labor-intensive to realize, the algorithms which work backward from photographs to model of the scene has increase great interest in recent years.

In this work, we focus on the estimation of photometric properties from real object's images. The problem of recovering photometric properties from real images has been discussed mainly under three different assumptions: variable illuminations [1, 11, 12], different viewing directions [6] or variable poses[8, 5, 13]. Among them, the methods which use the images of the object with variable poses to recover photometric properties is applicable to a moving object, and in this work we focus on this branch.

For a moving object, the algorithm of Shape-From-Motion (SFM) [10] can be used for recovering the 3D shape of an object from the input images of the object taken with varying poses. However, SFM in its original formulation does not take into account intensity variation due to pose change, and thus it cannot be used for recovering photometric properties of the object. So a texture-mapping technique is usually used to render new images. However, there are some apparent weaknesses in these synthetic images, such as inconsistency with respect to illumination and seams between mapped textures.

Different from traditional texture-mapping, Debevec *et al.* [4] presented view-dependent texture-mapping which interpolated between the given photographs of the scene depending on the user's point of view. This algorithm resulted in more lifelike animations, but still did not recover the reflectance properties of the objects and could not synthesize images under new lighting conditions.

To cope with the limitations of texture-mapping, some methods recover reflectance properties of a moving object, however, the applicability of the method is limited because the methods assume some specific illumination conditions: Maki *et al.* [5] proposed a method for recovering the shape and albedo of a moving, Lambertian object under a small number of point light sources. Zhang *et al.* [13] proposed a method for recovering the shape and albedo of a moving, Lambertian object, which is illuminated by a single point light source and an ambient light.

In contrast to these methods, we present a new method for recovering the reflectance properties of a convex object in motion under *unknown, complex* illumination conditions. The object is assumed to be Lambertian, so the reflectance properties here are albedo. The illumination distribution, which is relatively distant, can include an arbitrary combination of point source, extended source and diffuse light. The convex shape of the object ensures that there are no cast shadows and interreflection.

Our work is based on the analysis of the Lambertian re-

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flectance in the frequency domain by Ramamoorthi – Hanrahan [7] and Basri – Jacobs [2]. They showed that a set of images of a convex Lambertian object in a fixed pose under arbitrary illumination is represented approximately by using low-order spherical harmonics. Combining this theoretical analysis with the geometry reconstructed by SFM, we obtain a set of equations with respect to the harmonic coefficients of illumination distribution and the albedo of the object's surface. Therefore, we can recover the albedo of an object even from an image sequence of the object in motion under complex illumination conditions.

To demonstrate the effectiveness of our proposed method, we conducted some experiments by using both synthetic and real images. We also explain why there are errors in the solution of harmonic coefficients of the illumination distribution and find that, by using recovered harmonic coefficients, we can obtain a very similar illumination distribution over the hemisphere centered at the camera viewing direction.

Finally, we mention a recent paper which is related to ours. Simakov *et al.* [9] proposed a method for reconstructing the shape of an object from motion under complex illumination condition. The method is also based on the theoretical analysis by using spherical harmonics [2, 7]. However, the method focuses on dense shape reconstruction and does not ensure the consistency of the illumination distribution, while our work focuses on recovering the *photometric properties* of an object from motion under complex illumination conditions.

2. Proposed Method

In this part, we begin to explain how to recover the albedo from multiple images of a moving object with known geometry. These images can be obtained by tracking a number of feature points on the object according to SFM. We used this technique to perform an experiment with real images.

2.1. Spherical Harmonic Representation of Lambertian Reflectance

Ramamoorthi – Hanrahan [7] and Basri – Jacobs [2] represented the convolution form of reflection in terms of spherical harmonic function as follows

$$\begin{aligned} I(x,y,z) &= \rho(x,y,z)\int_{\Omega} L(\theta_i,\phi_i)A(\theta_i')\sin\theta_i \mathrm{d}\theta_i \mathrm{d}\phi_i \\ &= \rho(x,y,z)\sum_{l=0}^{\infty}\sum_{m=-l}^{+l}\sqrt{\frac{4\pi}{2l+1}}A_l L_{l,m} Y_{l,m}(x,y,z). \end{aligned}$$

Here, $I(x,y,z)$ is brightness of the point on the object whose normal direction is (x,y,z). Function $L(\theta_i,\phi_i)$ represents illumination distribution, which depends on global incident angle (θ_i,ϕ_i). $A(\theta_i')$, which is equal to $\max(\cos\theta_i',0)$, represents the reflectance properties of Lambertian surface with respect to local incident angle θ_i'. $\rho(x,y,z)$ between 0 and 1 is the albedo. The coefficients $L_{l,m}$ and A_l can be computed in the standard way by integrating $L(\theta_i,\phi_i)$ and $A(\theta_i')$ against the spherical harmonics $Y_{l,m}$

$$L_{l,m} = \int_{\theta_i=0}^{\pi}\int_{\phi_i=0}^{2\pi} L(\theta_i,\phi_i)Y_{l,m}(\theta_i,\phi_i)\sin\theta_i \mathrm{d}\theta_i \mathrm{d}\phi_i, \tag{1}$$

$$A_l = 2\pi\int_{\theta_i=0}^{\pi} A(\theta_i')Y_{l0}(\theta_i')\sin\theta_i' \mathrm{d}\theta_i'.$$

Asymptotic behavior of A_l for large even l is $A_l \sim l^{-2}$ while $A_l = 0$ for odd $l > 1$. Accordingly more than 99% of the energy is captured by $l \leq 2$. Thus we can omit $A_l(l > 2)$ and approximate reflectance of the Lambertian surface by using only the first nine terms [7, 2].

$$\begin{aligned} &I(x,y,z) \\ &\approx \rho(x,y,z)\sum_{l=0}^{2}\sum_{m=-l}^{+l}\sqrt{\frac{4\pi}{2l+1}}A_l L_{l,m} Y_{l,m}(x,y,z). \end{aligned} \tag{2}$$

2.2. Recovering Illumination Distribution

The equation (2) forms the basis of our proposed method. We chose a total of N visible points and P variable poses of the object. We substituted the specific expression of $Y_{l,m}(x,y,z)$ in terms of normal direction (x,y,z) and suppose that $\bar{\rho}(x,y,z) = \rho(x,y,z)L_{0,0}$, $\bar{L}_{l,m} = L_{l,m}/L_{0,0}$; then equation (2) will change to

$$\begin{aligned} &I_n^{(p)} \approx \bar{\rho}_n(\frac{\sqrt{\pi}}{2} + \sqrt{\frac{\pi}{3}}\bar{L}_{1,0}z_n^{(p)} + \sqrt{\frac{\pi}{3}}\bar{L}_{1,1}y_n^{(p)} + \cdots) \\ &(n = 1,2,...,N; p = 1,2,...,P). \end{aligned} \tag{3}$$

Here n means different points and p means different poses of the object.

We have recovered the geometry of the object according to SFM, and the values of $I(x,y,z)$ of all the visible points can be obtained from one image of the object. So in these equations, only $\bar{\rho}(x,y,z)$ and $L_{l,m}(l = 0,1,2; -l \leq m \leq l)$ are unknowns. Because the unknowns $\bar{\rho}$ and $L_{l,m}$ are in multiplication form, we should first remove the unknowns $\bar{\rho}$ to obtain equations only according to $L_{l,m}$.

Now we need to obtain the ratios of brightness between the same point observed with different poses. Supposing

	1	2	3	4	5	6	7	8	9	10
Recovered ρ	0.100	0.910	0.102	0.988	0.976	0.980	1.027	0.102	0.974	0.102
Ground truths	——	1.000	0.100	1.000	1.000	1.000	1.000	0.100	1.000	0.100

Table 1. Recovered albedo of football

	$L_{0,0}$	$L_{1,0}$	$L_{1,1}$	$L_{1,-1}$	$L_{2,0}$	$L_{2,-1}$	$L_{2,1}$	$L_{2,-2}$	$L_{2,2}$
Recovered	1.000	-0.117	-0.295	-0.372	-0.344	0.110	-0.180	-0.166	-0.191
Ground truths	1.000	-0.253	0.463	-0.660	-0.047	0.238	-0.124	-0.0003	-0.0001

Table 2. Recovered $L_{l,m}$

that $I_n^{(p+1)}/I_n^{(p)} = k_n^{(p)}$, we can obtain $N(P-1)$ equations about $\bar{L}_{l,m}$:

$$-\frac{\sqrt{\pi}}{2}(k_n^{(p)}-1) \approx \sqrt{\frac{\pi}{3}}\bar{L}_{1,0}(k_n^{(p)}z_n^{(p)} - z_n^{(p+1)}) + \sqrt{\frac{\pi}{3}}\bar{L}_{1,1}(k_n^{(p)}y_n^{(p)} - y_n^{(p+1)}) + \cdots$$

$$(n = 1, 2, ..., N; p = 1, 2, ..., P-1). \quad (4)$$

By now we have removed the unknown $\bar{\rho}_n (n = 1, ..., N)$.

As all the equations are approximate equations, we obtain the optimal solutions of $\bar{L}_{l,m}$ in the sense of the least square error.

2.3. Recovering Albedo of Visible Points

Then we want to substitute the solution of $\bar{L}_{l,m}$ into the following equation to recover the $\bar{\rho}_n$ of every visible point.

$$\bar{\rho}_n = \frac{I_n}{\frac{\sqrt{\pi}}{2} + \sqrt{\frac{\pi}{3}}\bar{L}_{1,0}z_n + \sqrt{\frac{\pi}{3}}\bar{L}_{1,1}y_n + ...} \quad (n = 1...N). \quad (5)$$

Because the albedo is a relative value, we should set a standard albedo and obtain the relative value of albedo $\tilde{\rho}_n$. Supposing that $\tilde{\rho}_1 = 1$, we can obtain the relative albedo of other points by

$$\tilde{\rho}_n = \bar{\rho}_n/\bar{\rho}_1 = \rho_n/\rho_1 \quad (2 \le n \le N). \quad (6)$$

3. Experimental Results

We now present experimental results obtained with our algorithm by using synthetic and real images. We compare our recovered albedo/texture with the ground truths to verify the effectiveness of our method.

3.1. Experiment with Synthetic Images

We used two objects, a football and a textured cube, to verify the validation of our proposed method[1]. Fig.1 shows (a) the incident illumination distributions and (b) the rendered images of football and cube.

We obtained the brightness of arbitrary visible point on the football from the images. After substituting $k_n^{(p)}$ and normals' directions $x_n^{(p)}, y_n^{(p)}, z_n^{(p)}$ into the simultaneous equations (4), we solved the optimal solutions of $\bar{L}_{l,m}$ in the sense of the least square error. Then we substituted the solutions of $\bar{L}_{l,m}$ into the equations (5) to solve the $\bar{\rho}_n$ and further recovered the relative albedo $\tilde{\rho}_n$ according to equations (6), supposing a standard value of the first point $\tilde{\rho}_1 = 0.100$. The first row of Table 1 illustrates the recovered relative albedo of nine arbitrary points on the football compared with point 1. The second row shows the ground truths. We see that the real and recovered albedo match closely.

For the textured cube, we computed the albedo of one representative point on one face. Since all the points of one face have the same normal direction, only albedo affects their brightness. Thus we recovered the texture of one face based on ratios of brightness between the representative point and other points on the face. Fig.2 (a) is the original texture of the cube and (b) shows the recovered texture of two faces of the cube.

Table 2 shows the recovered $L_{l,m}$ from images of the football and their ground truths. We see that each $L_{l,m}$ is not accurately recovered. The reason is that, in our method, we used a image sequence taken from a fixed viewpoint to obtain $L_{l,m}$'s approximate solutions. This means that the illumination distribution over the hemisphere centered at the viewing direction has a great effect on the brightness of observed parts of the object, while that over the hemisphere on the other side only has slight contribution to the observed brightness. So, by using the recovered $L_{l,m}$, we can approximate the illumination distribution over the hemisphere centered at the viewing direction, which affects observed brightness greatly, and thereby the errors of recovered $L_{l,m}$ do not affect the accuracy of recovered albedo as seen above. Fig.3 verifies the above discussion. Fig.3 (a)

1 We used software Radiance and Probe Image [3] to render the synthetic images under general illumination.

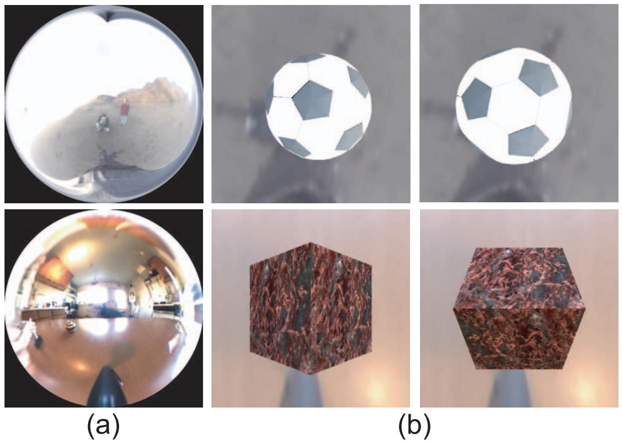

Figure 1. Synthetic images under general illumination: (a) Light probe images. (b) Synthetic images under general illumination conditions.

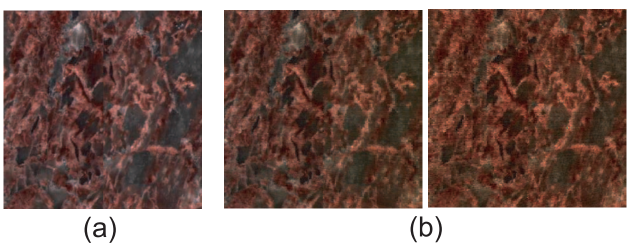

Figure 2. Recovered texture of the cube: (a) Original texture. (b) Recovered textures of two faces of the cube.

is the original probe image of the beach, from which we obtained the lighting distribution $L(\theta_i, \phi_i)$; then, according to the equation (1), we computed the real values of $L_{l,m}$ as ground truths. Fig.3 (b) shows the low-order approximation of illumination distribution represented with real $L_{l,m}$. Fig.3 (c) shows the illumination distribution estimated by using our proposed method. Comparing (b) and (c) allows us to observe that the illumination of the upper hemispheres indicated with blue boundaries, which is centered at the viewing direction, are similar to each other. We applied these two low-order approximations of illumination to synthesizing images of a football observed from the viewing direction. Their results are shown in Fig.3 (d) and (e). We see that (d) and (e) are very similar to each other.

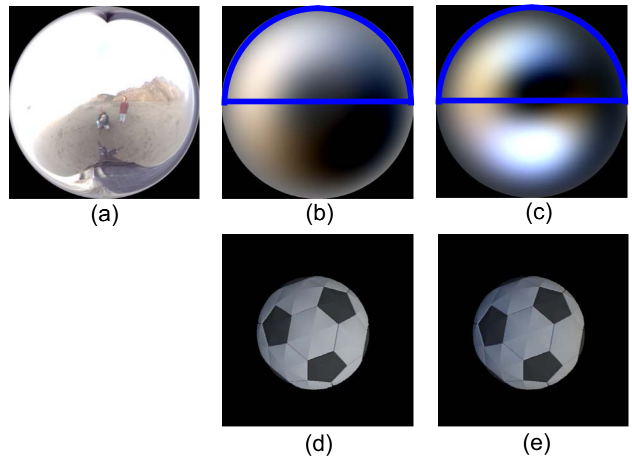

Figure 3. Recovered illumination distribution: (a) Original probe image. (b) Low-order simulation of illumination represented with real $L_{l,m}$. (c) Estimation of illumination obtained from our proposed method. (d) Synthetic images by using illumination in (b). (e) Synthetic images by using illumination in (c).

3.2. Experiment with Real Images

In an experiment with real images, a cube was rotated and photographed using a Sony DFW-VL500 video camera. We posted a piece of matte paper on the surface of the cube. The images were taken under orthographic projection. By tracking several feature points, the geometry of the cube was obtained using SFM [10]. Note that, since geometry estimation is not the motivation of our research, we tracked the feature points manually. Fig.4 (a) and (b) show two examples of the cube whose features have been tracked. Fig.4 (c) shows the recovered geometry of the cube indicated with red lines. We can know that by tracking several feature points, we recovered the object's geometry precisely.

We computed the texture of the cube (matte paper) by running our algorithm with the estimated geometry. Fig.4 (d) is the input image of the cube and (e) is the recovered texture. We see that our algorithm can recover the albedo/texture of a Lambertian surface to high accuracy under complex, unknown illumination.

4. Conclusions

In this paper, we have presented a new method for recovering the albedo of a convex, Lambertian object under a general and distant illumination condition. From multiple

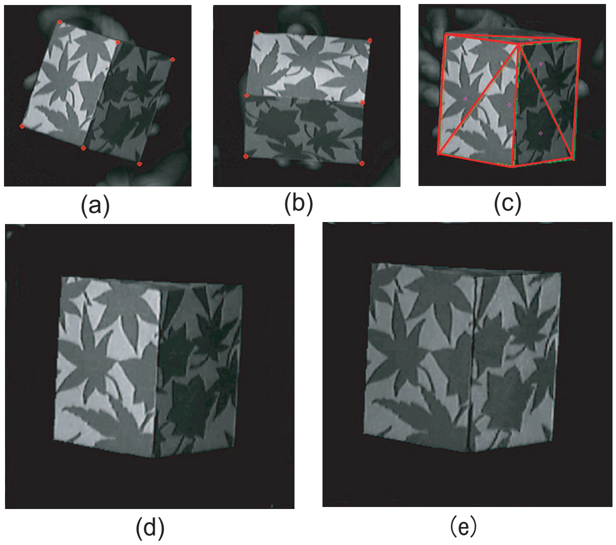

Figure 4. Recovered illumination distribution: (a) and (b) Images of tracking features. (c) Recovered geometry. (d) Original images. (e) Recovered texture.

images of a moving object,we first estimated the geometry of the object according to SFM, and then recovered albedo based on the low-order spherical harmonics representation of Lambertian reflectance. We have performed some experiments with synthetic and real images and confirmed the effectiveness of our proposed method.

In the future, we plan to extend our proposed method to more complex reflectance properties beyond the Lambertian model and try to recover the illumination distribution more robustly.

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