JOINT ESTIMATION OF MULTIPLE LIGHT SOURCES AND REFLECTANCE FROM IMAGES

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Abstract In this paper, we propose a new method for estimating jointly light sources and reflectance properties of an object seen through images. A classification process firstly identifies regions of the object having the same appearance. An identification method is then applied for jointly (i) deciding what light sources are actually significant and (ii) estimating diffuse and specular coefficients for the surface.

Keywords: Light sources detection, reflectance properties estimation, identification method.

1. Introduction

Light sources estimation is a key issue for many applications related to computer vision, image processing or computer graphics. For example segmentation algorithms, shape from shading methods or augmented reality approaches can be improved when the incoming light direction is known.

>From images, several works propose to estimate directional or point light sources: with stereo images [1], using convex objects contours [2], shadows [3] or reflectance maps [4]. Recent methods favor the use of lambertian or specular spheres for acquiring radiance maps [5] or detecting point light sources [6, 7].

Our approach can be applied to a set of images for a single object and does not need any additional test pattern or specific object such as a sphere. In this paper our contributions include: (i) a new method for estimating several directional and point light sources from images of an object; (ii) an algorithm capable of estimating light sources jointly with the surface reflectance of the object; (iii) results for a series of experiments.

2. Overview

Our method applies to a set of images representing an object without cavity. For each image, we make the assumption that the camera position and orientation are known. In practice, we use as well synthesized images and photographs of real objects (see figure 1).

a. *b.* *c.*

Figure 1. *a. Images of some virtual objects we used; b. Image of a real plastic object (clown model courtesy of Rodolphe, 3 years old); c. Voxel-based reconstructed clown.*

A preprocessing step recovers a voxel-based geometry of the object, using the *shape from silhouette* approach proposed by Szeliski [8] (figure 1.c). For each voxel, a polygonal surface is produced according to the *marching cubes* algorithm and a normal is estimated (for more details, see [9]).

Each pixel of an image corresponds to the radiance emitted by the object in the direction of the camera (from one voxel to the camera). Each voxel is seen from several viewpoints; thus, for each voxel it is possible to store the set of radiances associated with pixels. We distinguish two types of light source (point and directional) and two types of surface (diffuse and specular-like). The broad lines of our light sources estimation algorithm are:

- classify voxels into regions according to hue and orientation;
- for each region, estimate the type of surface (diffuse or specular-like) ;
- for each region, search for a point light source ;
- for each region, search for a directional light source ;
- for each region, identify sources parameters and surface properties;
- validate light sources positions/directions and surface properties.

3. Light Sources Detection

In this work, as a BRDF model, we choose the *modified Phong-model* proposed in [10] since it is physically plausible and represents diffuse and/or specular surfaces with only 3 coefficients. According to this model, the radiance reflected L_r at a point P to a direction $\overrightarrow{R}$ is expressed as:

$$L_r = \frac{L_s K_d}{\pi r^2} \cos\theta + \frac{(n+2) L_s K_s}{2\pi r^2} \cos\theta \cos^n \phi$$

where L_s is the radiance emitted by a light source S; r is the distance between S and P; K_d and K_s are respectively diffuse and specular coefficients for reflection; n defines the specular lobe size; θ is the light incident angle; ϕ is the angle between $\overrightarrow{R^m}$ (mirror reflection direction) and $\overrightarrow{R}$.

3.1 Voxels Classification

In this paper we make the assumption that the surface can be made up with different types of materials and lit by several light sources. To simplify the problem, voxels are firstly classified according to hue (using HSV color-space). For each class defined, voxels are then grouped again according to orientation so that all the voxels in a group be likely lit by the same (single) light source.

3.2 Type of Surface Estimation

Fir each voxel class, the type of surface (diffuse or specular-like) is estimated with the help of a variation coefficient $\mathcal{V}$ computed from radiance samples (pixels):

$$\mathcal{V} = \sqrt{\sum_{i=1}^{NbV} \sum_{j=1}^{NbL_i} \left(\frac{L_{i,j} - L_i^{moy}}{L_i^{moy}} \right)^2 / \sum_{i=1}^{NbV} NbL_i}$$

where NbV represents the number of voxels in the class, $L_{i,j}$ is the j^{th} radiance sample of V_i (V_i is the i^{th} voxel), and L_i^{moy} is the average radiance of V_i. NbL_i corresponds to the number of radiance samples in the class. $\mathcal{V}$ varies according to the surface specular aspect.

3.3 Point Source Detection

For each voxel of a given class, we firstly estimate a directional light source; the point source position is then deduced from this set of directions. If the point source is far enough to the surface, the algorithm concludes it is a directional light source.

For Diffuse Surfaces. The radiance emitted by a diffuse surface element is constant whichever reflection direction. This radiance corresponds to the product $L_s K_d \cos\theta$. For all the voxels of a given class we consider that $L_s K_d$ is constant. For each class, the voxel V^{ref} having the highest radiance L_V^{ref} is chosen as a reference for initializing our iterative process: its normal is used as the incident direction of light $\overrightarrow{I_V^{ref}}$, with $\theta_V^{ref} = 0$ and $L_V^{ref} = L_s K_d$. Consequently, for each voxel V in the class, $\theta_V = \arccos(L_V / L_V^{ref})$. This estimation of θ_V does not directly provide the incident direction but a cone of directions (figure 2.a).

For V, the incident direction belongs to the plane defined by the centers of V, V^{ref} and the incidence direction $\overrightarrow{I_V^{ref}}$ (figure 2.a). The intersection between the cone of directions and this plane gives 0, 1 or 2 incident directions.

Momentarily the algorithm ignores the voxels having two possible incident directions. All the *single-incident* directions are stored in the matrix form $\mathcal{M}\mathcal{X} = \mathcal{D}$, where $\mathcal{X}$ corresponds to the searched point light source coordinates. $\mathcal{X}$ is obtained with the help of a pseudo-inverse matrix $\mathcal{M}^{pi}$. From

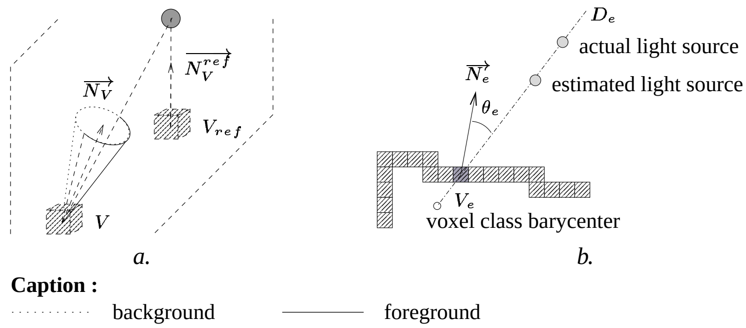

Figure 2. a. Intersection between the cone and the plane containing the point source; b. Choice of a new voxel V_e for estimating point light source, where θ_e is known.

this first estimation, for each voxel ignored (having two correct incident directions), one of the two directions (the most consistent with the estimation of $\mathcal{X}$) is added to the matrix system. A new estimation of $\mathcal{M}^{pi}$ and $\mathcal{X}$ is computed.

However, the quality of this estimation is very dependent on choice of V^{ref}: the normal of V^{ref} is rarely perfectly aligned with the light source direction. For refining the solution, the algorithm selects various V^{ref} (see figure 2.b) so as to reduce the following error criterion: $E_d = \sum_{i=1}^{2m}(\mathcal{M}_i\mathcal{X} - \mathcal{D}_i)^2$, where $\mathcal{M}_i$ is the i^{th} row of the matrix $\mathcal{M}$ and m corresponds to the number of incident directions. E_d provides the final result significance. This process is repeated as long as the estimated error E_d decreases.

For Specular-like Surfaces. For non-lambertian surfaces, the specular lobe can be used to estimate the light source position; the incident radiance L_s is mostly reflected by the surface in the mirror direction $\overrightarrow{R^m}$. We propose to represent the specular lobe as a curved surface and identify the coefficients from voxels radiance samples (figure 3.a). For estimating $\overrightarrow{R^m}$, we use a parabolic surface $L_{\alpha,\beta} = a(\alpha - \delta_\alpha)^2 + b(\beta - \delta_\beta)^2 + c$. >From this equation, the mirror direction $\overrightarrow{R^m}$ is defined by $(\delta_\alpha, \delta_\beta)$ (see figure 3.b).

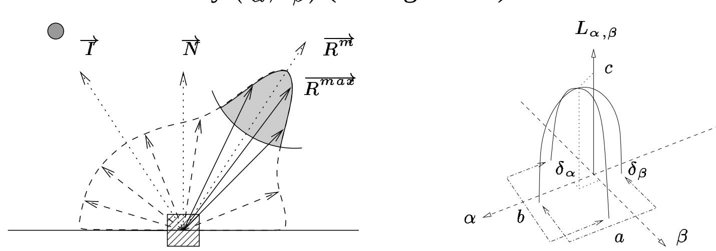

Figure 3. a. Radiance samples for a voxel, the grey tint contains radiance samples of the specular lobe; b. Radiance emitted by a surface point according to the angles α and β (polar coordinates of the reflected direction).

For estimating these coefficients we identify a, b, c, δ_α and δ_β from radiance samples with a *gradient descent* method. As for diffuse surfaces, the direction estimated for each voxel is stored in a linear system solved with a pseudo-inverse matrix to recover the point source position.

3.4 Directional Source Detection

For Diffuse Surfaces. The radiance emitted by a voxel V is : $L_V = L_s K_d \cos(\theta_V) = L_s K_d(\overrightarrow{I}.\overrightarrow{N_V})$ where $\overrightarrow{N_V}$ is the surface normal inside V and $\overrightarrow{I}$ is the searched incident direction. In this equation, L_s, K_d, and $\overrightarrow{I}$ are the same for all the voxels of a class. Again, this system can be described and solved using a matrix form $\mathcal{M}\mathcal{X} = \mathcal{D}$, where $\mathcal{X}$ represents the product $L_s K_d \overrightarrow{I}$, $\mathcal{D}$ is a vector containing L_V values and $\mathcal{M}$ corresponds to the set of vectors $\overrightarrow{N_V}$.

For Specular-like Surfaces. As for point light sources, specular lobes can be used. Once a direction has been estimated for each voxel (for a given class), the light source direction corresponds to the average of all estimated directions.

3.5 Joint Identification

Each light source estimation algorithm is independently applied for each voxel subclass, providing one point light source and one directional light source. For each analysis, we estimate an error:

$$E_a = \sum_{i=1}^{NbV} \sum_{j=1}^{NbL_i} [(\frac{L_s K_d}{\pi r^2} \cos\theta_i + \frac{(n+2) L_s K_s}{2\pi r^2} \cos\theta_i \cos^n \phi_{i,j}) - L_{i,j}]^2$$

where $L_{i,j}$ corresponds to the radiance sample j of the voxel V_i; the parameters $L_s K_d$, $L_s K_s$ and n are unknown. We apply an identification algorithm with the help of a gradient descent method in order to obtain the final parameters $L_s K_d$, $L_s K_s$ and n (keeping E_a as small as possible).

A final step groups the detected light sources according to their types and position/orientation.

4. Results and Conclusion

For validating our method, we used a set of voxels lit by only one (known) light source. Voxels positions, radiance samples directions and normals have been randomly generated. As shown in table 4, our point light source detection method provides a directional light source when the distance is too high.

With images of virtual objects, the estimated direction of incoming flux is precise about 15 degrees in the worst case; the average precision is about 6 degrees.

Though validation is difficult to achieve through real objects, we applied our method to the clown shown in figure 1.b. It has been lit by 2 spots, actually

Surface type	Object-source distance	Estimated final source	inaccuracy on		
			source pos/dir	$L_s K_d$ $L_s K_s$	n
diffuse	$0 - 9m$	point	$< 1cm$	1%	$\times$
	$> 9m$	directional	$< 1°$		
specular-like	$0 - 2m$	point	$< 15cm$	1%	5%
	$6m$	none	$1m$		
	$> 6m$	directional	$< 1°$		

Figure 4. Point light source detection with a 1-meter diameter object.

estimated as directional light sources with an error ranging from $30°$ to $40°$. This error is mainly due to two factors. Firstly, the used object contains many unreconstructed small cavities. Secondly, our calibration method is still not precise enough.

Our method could probably be improved with the help of *specular spots* seen on images. Moreover, since the method has proven efficient for virtual objects, we aim at validating it with photographs of real objects.

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