Uncalibrated Photometric Stereo Based on Elevation Angle Recovery from BRDF Symmetry of Isotropic Materials

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Photometric stereo is difficult because real-world scenes show a variety of different surface reflectances, resulting in diverse and complex bidirectional reflectance distribution functions (BRDFs). As a result, most of the previous uncalibrated (i.e., when light sources are unknown) methods assume a simple Lambertian reflectance, and solve surface normals up to the Generalized Bas-Relief (GBR) ambiguity [1]. The GBR ambiguity can be further resolved by using various properties observed in real-world BRDFs, such as symmetries [6] and diffuse maxima [2].

Some recent methods [3, 5] were proposed without assuming a Lambertian BRDF. However, they still face a challenge as far as elevation angle recovery goes: they must assume that the light sources cover the whole sphere uniformly or else the surface normals' elevation angle accuracies drop significantly. In this paper, we exploit surface reflectance properties to meet this remaining challenge. In particular, our contributions include: 1) a derivation of constrained half-vector symmetry; 2) an algorithm to determine the elevation angles of surface normals by using this symmetry; 3) light source estimation in the case of general isotopic reflectances.

A BRDF measures the ratio of the reflected radiance from a surface patch. It is a function $f(\omega_{in}, \omega_{out})$ of incoming and outgoing light directions in a local coordinate system. By introducing the half vector [4], which is the bisector of ω_{in} and ω_{out}, a BRDF can be parameterized as $f(\theta_h, \phi_h, \theta_d, \phi_d)$, as illustrated in Fig. 1 (a). It produces pixel values by

$$I = f(\theta_h, \phi_h, \theta_d, \phi_d)(\mathrm{n}^{\mathrm{T}}\mathrm{s}), \tag{1}$$

where n is the surface normal and s is the point light source.

Let us examine a special case of isotropic reflectance wherein a set of surface normals $\{\mathrm{n}\}$ with different elevation angles share the same azimuth angle with a light source s in the view-centered coordinate system, as shown in Fig. 1 (b). This results in a fixed θ_d and also $\phi_d = 0$ or $\pi/2$ in the conventional BRDF parameterization in Fig. 1 (a). Consequently, this simplifies the isotropic BRDF function to either $f_{\theta_d,\phi_d=0}(\theta_h)$ or $f_{\theta_d,\phi_d=\pi/2}(\theta_h)$. If one further assumes reciprocity of ω_{in} and ω_{out}, the two representations can be unified to be $f_{\theta_d,\phi_d=0}(\theta_h)$, which represents a 1D slice from the original BRDF, as shown in Fig. 1 (b). Since $f_{\theta_d,\phi_d=0}(\theta_h)$ is symmetric about the half-vector (i.e., $\theta_h = 0$), it leads to the following observation.

Observation 1 *By assuming isotropy and reciprocity, if the elevation angles of the surface normals and the light source are correctly measured, the BRDF data computed from the observations in Fig. 1 (b) should be distributed symmetrically about the half vector.*

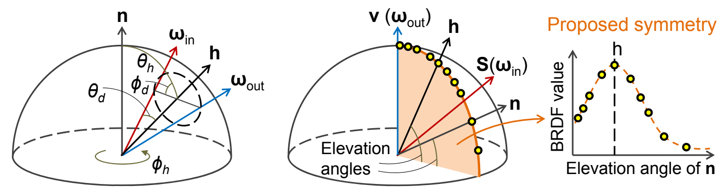
We use this "constrained half-vector symmetry" to refine the elevation angles of the surface normals so that any 1D BRDF slice observed in the scene satisfies the symmetry. We model the refinement as an elevation angle re-mapping process. By assuming correct azimuth angles, which are supported by results from [3, 5], we establish a one-to-one mapping $\varepsilon \mapsto \hat{\varepsilon} : \hat{\varepsilon} = m(\varepsilon)$ with boundary conditions $m(0) = 0$ and $m(\pi/2) = \pi/2$ to refine any elevation angle ε. The problem is formulated by

$$m(\cdot) = \underset{m(\cdot)}{\mathrm{argmin}}(E_{data} + E_{smooth}),$$
$$\text{s.t.} \quad m(0) = 0, m(\pi/2) = \pi/2, m([0, \pi/2]) \subseteq [0, \pi/2], \tag{2}$$

where functions E_{data} and E_{smooth} guarantee the BRDF symmetry and the smoothness of the function $m(\cdot)$. Eq. (2) can be effectively solved in its matrix form as described in the paper.

Our method also contains a light source estimation step. Following the observation in [7], we apply dimensionality reduction to recover unknown light sources. However, our technique differs from [7] in that it supports more general isotropic reflectances and also resolves their remaining rotation/flip ambiguity. Finally, our method achieves average estimation errors of 5.89° for surface normal and 7.43° for light sources on the MERL dataset. Examples of surface normal recovery are shown in Fig. 2.

This is an extended abstract. The full paper is available at the Computer Vision Foundation webpage.



(a) Local coord. sys. (b) View-centered coord. sys.

Figure 1: (a) Standard BRDF parameterization; (b) in a view-centered coordinate system, we examine the surface normals having the same azimuth angle as a light source, and observe the *constrained half-vector symmetry*.

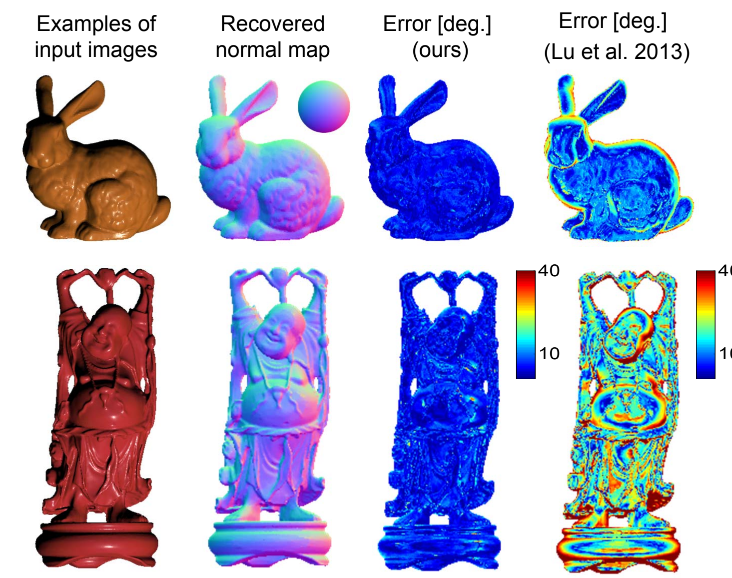


Figure 2: Representative results for synthetic 3D surfaces. Two out of the ten test materials are shown in the first column.

[1] P. N Belhumeur, D. J Kriegman, and A. L Yuille. The bas-relief ambiguity. *Int'l Journal of Computer Vision*, 35(1):33–44, 1999.

[2] P. Favaro and T. Papadhimitri. A closed-form solution to uncalibrated photometric stereo via diffuse maxima. In *CVPR*, pages 821–828, 2012.

[3] Feng Lu, Yasuyuki Matsushita, Imari Sato, Takahiro Okabe, and Yoichi Sato. Uncalibrated photometric stereo for unknown isotropic reflectances. In *CVPR*, 2013.

[4] Szymon M Rusinkiewicz. A new change of variables for efficient brdf representation. In *Rendering techniquesą́ 98*, pages 11–22. Springer, 1998.

[5] I. Sato, T. Okabe, Q. Yu, and Y. Sato. Shape reconstruction based on similarity in radiance changes under varying illumination. In *ICCV*, pages 1–8, 2007.

[6] P. Tan, L. Quan, and T. Zickler. The geometry of reflectance symmetries. *IEEE Trans. PAMI*, 33(12):2506–2520, 2011.

[7] Holger Winnemöller, Ankit Mohan, Jack Tumblin, and Bruce Gooch. Light waving: Estimating light positions from photographs alone. *Computer Graphics Forum*, 24:433–438, 2005.