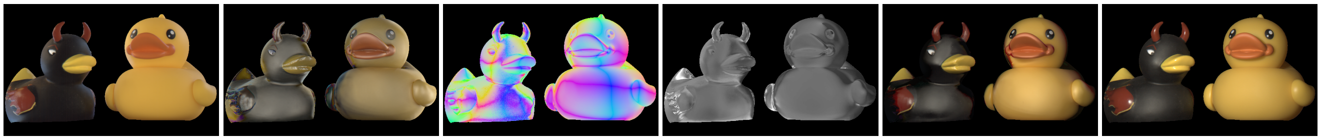
# Free-form Polarized Spherical Illumination Reflectometry

Kaori Kikuchi[1 2] Bruce Lamond [1] Abhijeet Ghosh[1] Pieter Peers[1 3] Paul Debevec[1]

University of Southern California[1]
Institute for Creative Technologies

Ritsumeikan University[2]

The College of William & Mary[3]



(a) diffuse albedo (b) specular albedo (c) surface normals (d) specular roughness (e) rendering (f) validation

**Figure 1:** *Reflectance parameters of two glossy toys estimated using free-form polarized spherical illumination. A rendering with the estimated parameters (e) is a close match to a validation photograph (f) under similar frontal point lighting condition.*

## 1 Introduction

We present a prototype system for in-situ measurement of per-pixel appearance parameters (i.e., surface orientation, diffuse albedo, specular albedo, and specular roughness) of general scenes. The proposed system requires no specialized hardware, is light weight, and requires no on-site calibration. This makes our system particularly well suited for capturing the appearance of real-world scenes under uncontrolled conditions.

The proposed system consists of three steps. First, we acquire a series of photographs of a scene while waving a light source around the subject similar to Masselus et al. [2002] and Winnemöeller et al. [2005], except that we employ a polarized light source. Once all data is acquired, we estimate the illumination direction in each captured photograph. Finally, we generate relit images of the scene under first and second order spherical gradient illumination conditions. From these images, we can then compute surface normals, diffuse and specular albedo, and specular roughness similar to Ghosh et al. [2009] without requiring explicit fitting of the measurements to analytic BRDF models.

## 2 Method

**Capture.** The basic mechanics of the acquisition procedure are similar to those of Masselus et al. [2002] and Winnemöeller et al. [2005]: we manually reposition a light source aimed at the subject while continuously taking photographs of the scene from a fixed viewpoint. A key difference over prior work is that we place a left circular polarizer in front of the camera. Additionally, we capture the first half of the photographs with a left circular polarizer in front of the light source, and a right circular polarizer for the last half. We ensure that we cover the full sphere of lighting directions as uniformly as possible for each polarizer.

**Light Direction Estimation.** To estimate light directions, Masselus et al. [2002] place a diffuse calibration sphere in view near the scene, and infer the light directions from the shading on this sphere. Winnemöeller et al. [2005] estimate light directions (up to a global rotation) using multi-dimensional scaling (MDS) on the appearance distance between the different photographs. Prior works in computer vision, e.g., [Basri et al. 2007], estimate surface normals and light directions simultaneously, but are limited to Lambertian scenes and assume uniformly distributed surface normal directions.

In this work we take an alternative approach to compute light directions. We start by estimating surface normals and subsequently infer the light directions. To estimate surface normals, we start by defining the vector $(X(p),Y(p),Z(p))$:

$$X(p) = \sum_i R_i(p) sign(l_{ix}),$$

$$Y(p) = \sum_i R_i(p) sign(l_{iy}),$$

$$Z(p) = \sum_i R_i(p) sign(l_{iz}),$$

where $l_i = (l_{ix}, l_{iy}, l_{iz})$ is the $i$-th light direction, and $R_i(p)$ is the observed reflectance for a pixel $p$ while lit from direction $l_i$. The function *sign* returns $+1$ if the argument is positive, or $-1$ otherwise. It can now be easily shown that by normalizing the vector $(X(p),Y(p),Z(p))$ an estimate of the surface normal in pixel $p$ is obtained. If the surface point $p$ is unoccluded and purely Lambertian, and the sphere of incident light direction (i.e., the distribution of $l_i$) is uniformly sampled, then this estimate corresponds exactly to the surface normal. Practically, the above equation implies that if we add all images lit from one side (right, top, or front), and subtract all images lit from the other side (left, bottom, or back respectively), then the resulting value is proportional to a component (respectively $X$, $Y$, or $Z$) of the surface normal times some constant. By simply normalizing the three components, an estimate of the surface normal is obtained.

The above equation requires knowledge of the light directions, which is exactly the quantity we are trying to estimate. However, we observe that users can fairly accurately classify from which quadrant of incident light directions an object is lit. This information is sufficient, since we only require knowledge of the *sign* of one of the components of the light direction vector. Since the number of captured images is modest (approximately 200), the overhead of this manual process is manageable.

The surface normal computation is most accurate for diffuse reflectance only. We exploit the properties of circular polarization to divide the captured photographs in two groups: one that contains only diffuse reflections (which we use for the normal computation), and one that contains both specular as well as diffuse reflections. For incident light directions less than the Brewster angle, specular reflections are canceled out when the scene is lit by left circularly polarized illumination. Specular reflections are *not* canceled out in the case of right circularly polarized illumination. For incident light directions beyond the Brewster angle, the roles of left and right circularly polarized illumination swap. One problem is that we do not know the incident light directions yet. To overcome this, we observe that the Brewster angle lies close to 45° (e.g., 53° for an index of refraction of 1.33). Hence, we classify left/right circularly polarized photographs lit from the front/back respectively as diffuse.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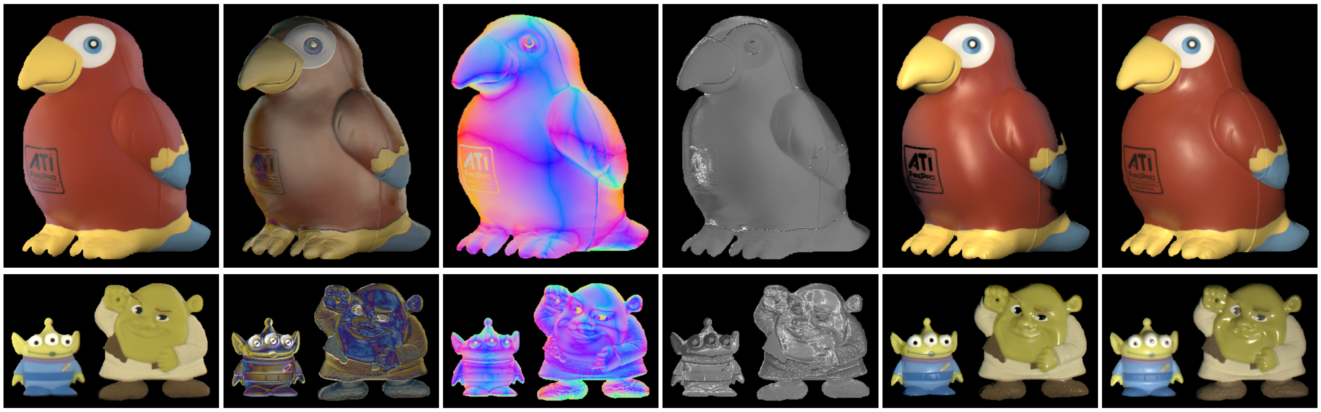
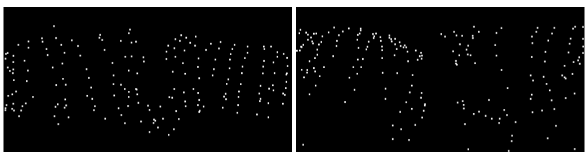


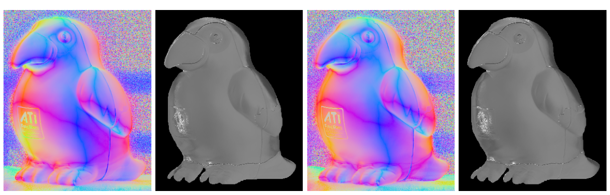
(a) diffuse albedo (b) specular albedo (c) surface normal (d) specular roughness (e) rendering (f) photograph

**Figure 2:** *Reflectance parameters of a few glossy toys estimated using free-form polarized spherical illumination with surface normal estimated without photographing a reference object. Rendering with the estimated parameters (e) is a close match to a validation photograph (f) under similar frontal point lighting condition.*



(a) light directions from diffuse ball (b) light directions directly from scene

**Figure 3:** *Estimated light directions shown in latitude-longitude parameterization. (a) Light directions estimated using a calibration diffuse ball (b) light directions estimated directly from the scene.*



(a) normal from ball's light dir. (b) roughness from ball's light dir. (c) normal from bird's light dir. (d) roughness from bird's light dir.

**Figure 4:** *Comparison of reflectance parameters obtained when estimating lighting directions using the method of Masselus et al. [2002] versus the proposed method which does not require any additional calibration object.*

Finally, light directions are computed by using Lambert's law and the known surface orientations: $R_i = Nl_i$, where $R_i$ are the observed reflectances in the diffuse photographs larger than some threshold $\delta$ for light source $i$ stacked in a single vector. Pixels with a reflectance smaller than $\delta$ are omitted. The matrix $N$ contains in each row the estimated surface normals corresponding to the observed reflectances included in $R_i$. Solving this overconstrained linear system yields an estimate of the light direction $l_i$.

**Appearance Parameter Computation.** To compute the reflectance properties, we employ a method based on [Ghosh et al. 2009]. Unlike Ghosh et al., we do not light the scene with first and second order gradient illumination conditions during acquisition, but generate images of the scene under these illumination conditions by image-based relighting afterwards as detailed in [Masselus et al. 2002]. However, the method of Ghosh et al. strongly relies on polarization differencing of linearly polarized illumination to separate diffuse and specular reflections under the gradient illumination conditions. In our case this separation is achieved by subtracting corresponding relit images under the different gradient illumination conditions from the diffuse and diffuse+specular image sets. This still produces good results, due to the band-pass behavior of diffuse reflectance, even though the sampling patterns for both sets are not exactly the same.

## 3 Results and Discussion

Figures 1 and 2 show two different scenes for which we estimated reflectance parameters using our prototype system. For each scene we captured approximately 200 photographs using a Canon 5D DSLR while using an LED light as light source. For each example we show the computed diffuse albedo, specular albedo, estimated surface orientation, and specular roughness. We illustrate the quality of our estimated properties by comparing a rendering of the scene (using the obtained parameters) with a reference photograph (not used in the estimation of the parameters). As can be seen, the rendering is a close match. The main source of visual differences are that we modeled the light source as a directional light source, which is somewhat different to the actual light source used during acquisition.

To evaluate the quality of the light direction estimation and the impact of specular reflectance (in the diffuse+specular image-set), we compare the estimated light directions with estimates obtained using the method of Masselus et al. [2002]. As can be seen in Figure 3, the estimated directions are similar, but differences are noticeable. However, the impact of these differences on the estimation of the reflectance properties are somewhat mitigated due to the low frequency nature of the first and second order gradients.

**Limitations.** As with many polarization-based methods, the diffuse-specular separation degrades around the Brewster angle. This is further impacted by the approximation made when selecting images lit by left or right circularly polarized illumination for the diffuse and diffuse+specular image sets. This can be seen in the form of diffuse pollution in the specular albedo images. Finally, objects with a dark albedo and very shinny objects also pose problems for the proposed method.

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