Estimating Specular Anisotropy Angle with Polarized Photometric Stereo Setup

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Anisotropic characteristics of a material are generally modeled by three parameters: the principal direction where an incident light yields the largest response, the width of the lobe along the principal direction, and the width of the lobe perpendicular to the principal direction[3]. Acquiring these parameters usually requires gonioreflectometer setups [3] capturing large amounts of data. Improvements have been made to utilize spherical harmonic illumination patterns to estimate the reflectance [2], however, such approaches still require complicated setups in order to acquire sufficient data.

This paper presents a method to estimate the specular anisotropy angle ψ which characterizes the principal direction with a polarized photometric stereo setup. We show how the angle of anisotropy can be estimated with various shifted sinusoidal lighting patterns when a pure specular response can be separated from the diffuse response. A polarized photometric stereo setup, along with the algorithm that simulates the sinusoidal specular response is presented. The proposed method has been shown to yield high-quality estimation.

Given a shifted sinusoidal lighting pattern $I(\phi) = \sin(f\phi + \psi) + 1$, Lamond at el. [1] showed that the observed radiance E is:

$$E = \rho_d + \rho_s + \int D(\vec{\phi}) \sin(f\phi + \psi) d\phi + \int S(\vec{\phi}) \sin(f\phi + \psi) d\phi \quad (1)$$

ρ_d and ρ_s describe the diffuse and specular radiance, while $D(\vec{\phi})$ and $S(\vec{\phi})$ are the diffuse and specular reflectance functions. Equation (1) was used by Lamond et al. for diffuse and specular response separation. However, assuming the pure specular response is available, this equation can be used for the estimation of the specular anisotropy angle. By singling out the specular response one can arrive at the following formula:

$$E_{spec} = \rho_s + \int S(\vec{\phi}) \sin(f\phi + \psi) d\phi \quad (2)$$

$$= \rho_s + (C\cos(\psi) + S\sin(\psi)) \quad (3)$$

where parameters C, S, and ρ characterizes the specular reflectance function. The formula can be rewritten as:

$$E_{spec} = \rho_s + \sqrt{S^2 + C^2}\left(\frac{C}{\sqrt{S^2 + C^2}} \cos\psi + \frac{S}{\sqrt{S^2 + C^2}} \sin\psi\right) \quad (4)$$

$$= \rho_s + \sqrt{S^2 + C^2} \cos(\psi - \theta), \quad (5)$$

$$\theta = \arccos \frac{C}{\sqrt{S^2 + C^2}} = \arctan \frac{S}{C} \quad (6)$$

As one can see, the specular response achieves its maximum when the sinusoidal lighting pattern has a phase shift θ. It is then straight forward to show that θ is the specular anisotropy angle.

The sinusoidal specular response can be simulated with data acquired from photometric stereo setups, we propose a setup consisting of six light sources surrounding the camera, the light sources are spread 60° apart on a circle with a radius of fifteen centimeters. Linear polarizers are placed on the camera lens and on all light sources to separate the specular response from the diffuse response. Each light source consists of two white Nichia LED lights, one polarized vertically, the other horizontally. The camera we use is the FLIR Blackfly S machine vision camera, with Kowa LM16SC lens. The camera lens is polarized horizontally.

Denoting the six light sources as $L_\phi, \phi \in [0, \pi/3, 2\pi/3, \pi, 4\pi/3, 5\pi/3]$, for each light source one can obtain the pure specular response E_ϕ, giving six specular responses corresponding to each light source. The response for the sinusoidal lighting pattern $I(\phi) = \sin(\phi + \psi) + 1$ can then be post-simulated with the following formula:

$$E_\psi = \frac{1}{n} \sum_{i=1}^{n} \sin(\phi_i + \psi) I(\phi_i) \quad (7)$$

(a) hardware setup for data acquisition (b) illustration of implementing equation (7)

Figure 1: System setup for obtaining sinusoidal illumination responses

We simulate the sinusoidal specular response shifted with six different offset angles. Figure 1(a) shows the hardware setup and figure 1(b) illustrates the process of simulating the sinusoidal response, the columns correspond to images taken under individual point lights and the rows correspond to the six offset angles. One can solve for C, S, and ρ with a least square approach, the estimated results can then be used to calculate the specular anisotropy angle using equation (6).

The results of the estimated angle are presented in figure 2. Figure 3 shows the rendered results with the anisotropy angle and specular reflectance map. With the anisotropy angle estimated, one can employ non-linear optimization methods to estimate other parameters required to model the anisotropic properties.

(a) anisotropic fabric (b) estimated surface normal (c) est. anisotropy angle

Figure 2: Anisotropy angle estimation

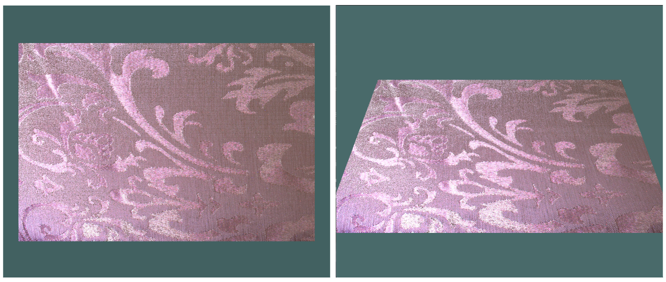

Figure 3: Rendered results with the anisotropy angle

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