Shape and Light Directions from Shading and Polarization

Trung Thanh Ngo, Hajime Nagahara, and Rin-ichiro Taniguchi
Faculty of Information Science and Electrical Engineering, Kyushu University.

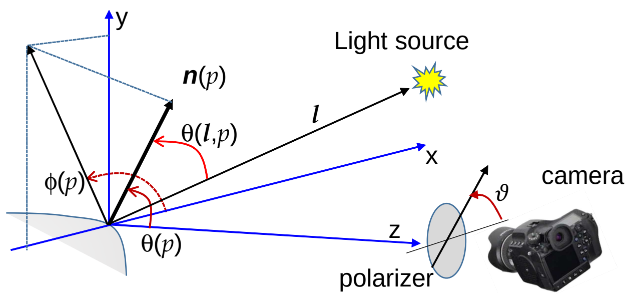

Figure 1: Geometrical configuration of the proposed algorithm.

Photometric stereo and polarization-based methods have complementary abilities. The polarization-based method can give strong cues for the surface orientation and refractive index, which are independent of the light direction. However, it has ambiguities in selecting between two ambiguous choices of the surface orientation, in the relationship between refractive index and zenith angle (observing angle), and limited performance for surface points with small zenith angles, where the polarization effect is weak. In contrast, photometric stereo method with multiple light sources can disambiguate the surface orientation and give a strong relationship between the surface normals and light directions. However, it has limited performance for large zenith angles, refractive index estimation, and faces a heavy ambiguity problem, such as the generalized bas-belief ambiguity, in case the light direction is unknown.

In this research, we present a fusion method that takes the advantages of both approaches and overcome their disadvantages to recover the shape of a smooth dielectric object (non-Lambertian). We present two albedo-free constraints on shading and polarization and use both in a single optimization scheme.

Shading-stereoscopic constraint is presented for two light directions, l_1 and l_2, at the same polarizer angle υ for a pixel p:

$$\frac{I(l_1,\upsilon,p)}{I(l_2,\upsilon,p)} = \frac{\left[1-F(\theta(l_1,p),\eta(p))\right]\cos\theta(l_1,p)}{\left[1-F(\theta(l_2,p),\eta(p))\right]\cos\theta(l_2,p)} \tag{1}$$

or

$$\begin{aligned} &I(l_1,\upsilon,p)\left[1-F(\theta(l_2,p),\eta(p))\right]\cos\theta(l_2,p)- \\ &I(l_2,\upsilon,p)\left[1-F(\theta(l_1,p),\eta(p))\right]\cos\theta(l_1,p)=0, \end{aligned} \tag{2}$$

where $I(l,\upsilon,p)$ is the image intensity of pixel p for light direction l and polarizer angle υ and $F(\theta(l_1,p),\eta(p))$ is the Fresnel reflection coefficient, which depends on the light's incident angle $\theta(l,p)$ and refractive index $eta(p)$ of pixel p. The error function for this constraint is defined:

$$\begin{aligned} &E_s(l_1,l_2,\upsilon,p) = \\ &\Big(I(l_1,\upsilon,p)\left[1-F(\theta(l_2,p),\eta(p))\right]\cos\theta(l_2,p)- \\ &I(l_2,\upsilon,p)\left[1-F(\theta(l_1,p),\eta(p))\right]\cos\theta(l_1,p)\Big)^2. \end{aligned} \tag{3}$$

Polarization-stereoscopic constraint is presented for two polarizer angles, υ_1 and υ_2, of the same light direction:

$$\frac{I(l,\upsilon_1,p)}{I(l,\upsilon_2,p)} = \frac{1+d(\theta(p),\eta(p))\cos(2\upsilon_1-2\phi(p))}{1+d(\theta(p),\eta(p))\cos(2\upsilon_2-2\phi(p))}, \tag{4}$$

or

$$\begin{aligned} &I(l,\upsilon_1,p)\left[1+d(\theta(p),\eta(p))\cos(2\upsilon_2-2\phi(p))\right]- \\ &I(l,\upsilon_2,p)\left[1+d(\theta(p),\eta(p))\cos(2\upsilon_1-2\phi(p))\right]=0 \end{aligned} \tag{5}$$

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

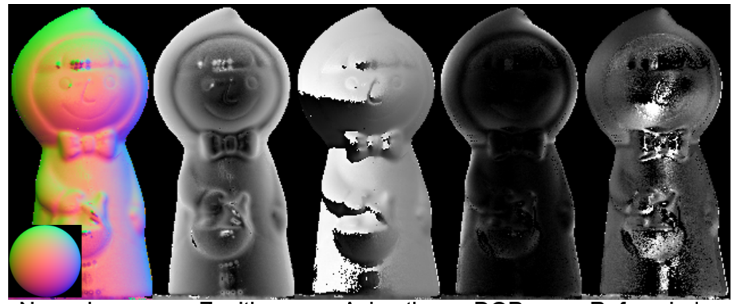

Figure 2: Performance of *Algorithm* 1 for the doll.

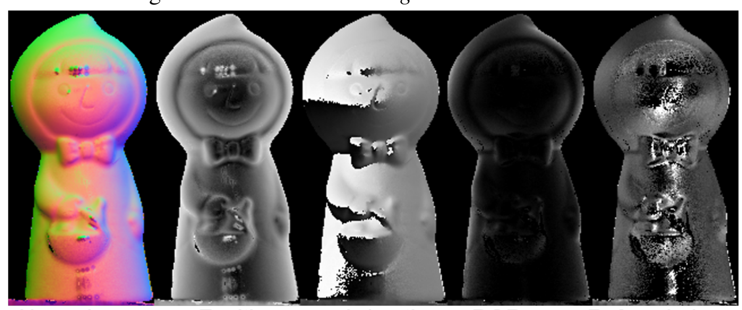

Figure 3: Performance of *Algorithm* 2 for the doll.

where $d(\theta(p),\eta(p))$ is the degree of polarization (DOP) for pixel p, which depends on the associated zenith angle $\theta(p)$ and refractive index $\eta(p)$. $\phi(p)$ is the surface orientation (azimuth angle). The error function for this constraint is defined:

$$\begin{aligned} &E_p(l,\upsilon_1,\upsilon_2,p) = \\ &\Big(I(l,\upsilon_1,p)\left[1+d(\theta(p),\eta(p))\cos(2\upsilon_2-2\phi(p))\right]- \\ &I(l,\upsilon_2,p)\left[1+d(\theta(p),\eta(p))\cos(2\upsilon_1-2\phi(p))\right]\Big)^2. \end{aligned} \tag{6}$$

Using the two constraints for N surface points, we can obtain a total error function for estimating the surface normals, refractive indexes, and light directions:

$$\begin{aligned} &\mathbb{E}(\{l\},\{p\},\{\upsilon\}) = \\ &w_s \sum_{\forall l_i\neq l_j,\upsilon,p} \alpha(l_i,p)\alpha(l_j,p)E_s(l_i,l_j,\upsilon,p)+ \\ &w_p \sum_{\forall l,\upsilon_i\neq\upsilon_j,p} \alpha(l,p)E_p(l,\upsilon_i,\upsilon_j,p)+ \\ &\lambda g(\{l\},\{p\}) \end{aligned} \tag{7}$$

where $\alpha(l,p)$ is the visibility coefficient for the light source at direction l of point p. w_s and w_p are the weights on the shading-stereoscopic and polarization-stereoscopic terms, respectively, such that $w_s+w_p=1$. g is a prior term that stands for the prior constraints on the surface normal and light directions, and λ is the weight used to control this term.

In the real experiments, we could estimate the shape, refractive indexes when knowing the light directions, Figure 2, or without knowing the light directions, Figure 3.