One-day outdoor photometric stereo via skylight estimation

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Traditional photometric stereo methods require three or more input images under different distant point light sources of which the directions are non-planar on the unit sphere. So far, an outdoor environment has been regarded as full of unknowns and complexities compared to a controllable lab environment. The appearance of an open field changes drastically depending on its weather condition and time of day, but at the same time, it does have a general appearance. While the appearance of a room can easily be influenced by which kind of light we turn on, an outdoor field on a clear day presents a relatively predictable scene.

We present an outdoor photometric stereo method based on the motivation that the outdoor illumination which is mainly contributed by the sun and clear sky can be generally modeled. We process geo-tagged, time-stamped images captured from a static camera in a single day to estimate the surface normal of the scene. We simulate a sky hemisphere for each image according to its GPS and timestamp, and parameterize the obtained sky hemisphere into a quadratic skylight and a Gaussian sunlight distribution. Unlike previous works which usually model outdoor illumination as a sum of constant ambient light and a distant point light, our method models natural illumination according to a popular sky model and thus provides sufficient constraints for shape reconstruction from one day images. We generate pixel profiles of uniformly sampled unit vectors for the corresponding time of captures and evaluate them using correlation with the actual pixel profiles. The estimated surface normal is refined by MRF optimization. We have tested our method to recover objects and scenes of various sizes in real-world outdoor daylight and compared with the previous methods [1, 2].

There are three major contributions of this work. First, we adapt the skylight distribution [4] to work for outdoor photometric stereo without any depth priors of the scene. Second, we overcome the weak rank-3 qualification of sunlight directions during a single day by exploiting natural illumination via skylight estimation. Finally, since we deal with a handful of images, there exist pixels lit by the sun in less than two images. Incomplete surface normal estimation for these pixels are refined using information from their neighboring pixels of similar profiles through MRF optimization.

We simulate the sky hemisphere using Preetham's sky model [4] and separate it into a dominant sunlight and a diffuse skylight to model shadowed and non-shadowed pixels:

$$L_{sky}(\mathbf{s}_k) = \mathbf{s}_k^T \mathbf{A}_q \mathbf{s}_k + \mathbf{b}_q^T \mathbf{s}_k + c_q, \tag{1}$$

$$L_{sun}(\gamma) = a_g \exp(-((\gamma - b_g)/c_g)^2), \tag{2}$$

where $\mathbf{s}_k$ is the direction of a sky element k, which can be defined by the angle γ with respect to the position of the sun. The parameters of the quadratic function are composed of a symmetric matrix $\mathbf{A}_q \in R^{3\times3}$, a vector $\mathbf{b}_q \in R^{3\times1}$ and a constant $c_q \in R$.

The imaged appearance $I(x)$ at a given pixel x depends on the surface orientation $\mathbf{n}_x$. The lighting environment $\mathbf{L}$ and the material Ψ form reflected radiance $\mathbf{R}_\Psi(\mathbf{n}_x, \mathbf{L})$ that gives the appearance for a given surface orientation. The reflected radiance is computed by integrating the incident irradiance $\mathbf{E}$ modulated by the reflectance over the illumination $\mathbf{L}$,

$$\mathbf{R}_\Psi(\mathbf{n}_x, \mathbf{L}) = \int \rho(\omega_i, \omega_o; \Psi)\mathbf{L}(\omega_i) \max(0, \mathbf{n}_x \cdot \omega_i) d\omega_i, \tag{3}$$

$$\mathbf{E}(\mathbf{n}_x, \mathbf{L}) = \int \mathbf{L}(\omega_i) \max(0, \mathbf{n}_x \cdot \omega_i) d\omega_i, \tag{4}$$

where ω_i and ω_o are the incident and outgoing (viewing) angles of the light on the surface [3]. Assuming Lambertian reflectance, albedo ρ is invariant to the viewing direction. Therefore, we model the pixel intensity of each color channel to be proportional to the incident irradiance $\mathbf{E}$ on the surface by the albedo:

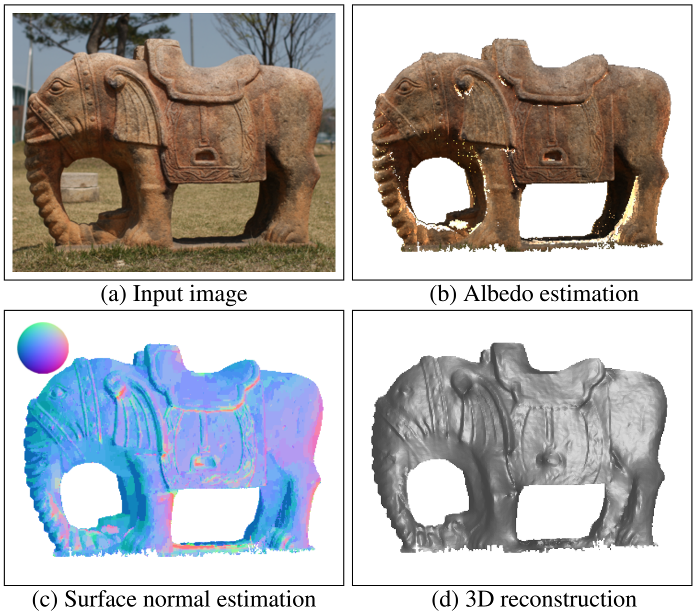
(a) Input image (b) Albedo estimation
(c) Surface normal estimation (d) 3D reconstruction

Figure 1: An example of one-day outdoor photometric stereo. 15 input images are captured at intervals of 30 minutes. The surface is reconstructed using Poisson solver [5].

$$I(x) = I_{sky}(x) + S(x) I_{sun}(x), \tag{5}$$

$$I_c(x) = \rho_c(x)(\mathbf{E}(\mathbf{n}_x, \mathbf{L}_{sky}) + S(x)\mathbf{E}(\mathbf{n}_x, \mathbf{L}_{sun})), \tag{6}$$

where c denotes a color channel and $S(x)$ is a binary value which indicates the pixel x is in shadow. The equations hold independently for each input image t, but we omit the subscript for simplicity.

Using the simulated sky hemisphere as an illumination map, we calculate the incident irradiance for uniformly sampled unit vectors, as Eq. (4). The incident irradiance due to skylight illumination $\mathbf{L}_{sky}$ and sunlight illumination $\mathbf{L}_{sun}$ are computed separately. For each pixel, the estimated shadow mask $S(x)$ is applied to sum those two incident irradiances as Eq. (6). The incident irradiance values for all the input images are stacked to be a profile for each sample unit vector. These sample profiles in the dimension of the number of images are compared with the actual pixel profiles.

We detect the shadowed pixels explicitly and estimate the initial (relative) albedo using the color ratio. The surface normal is estimated using the correlation between the pixel profile and the sample profiles generated according to the image formation model. The (absolute) albedo is updated and then the surface normal is refined by MRF optimization.

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[5] Tal Simchony, Rama Chellappa, and M Shao. Direct analytical methods for solving poisson equations in computer vision problems. *IEEE TPAMI*, 12(5):435–446, 1990.

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