Semi-calibrated Near-Field Photometric Stereo

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Motivation

The accuracy of photometric stereo is critically dependent on the knowledge of lighting conditions: light source brightness, distribution.

Accurate knowledge of the brightness requires careful measurements with either specialized equipment (LUX meters) or reference objects with known geometry.

LEDs tend to flicker, auto-exposure is desirable, accurate distribution of lighting is hard.

[9] introduced the notion of semi-calibrated PS, proved an exact solution under classical setup and proposed an alternating optimization method.

Contribution

- Known light source positions but not brightness.
- Perspective geometry, specular reflections and non-uniform light attenuation fully modeled.
- Jointly recover geometry, albedo and specularity coefficient.

Irradiance Equation

Irradiance equation from [27]:

$$i_k(\mathbf{x}) = \rho(\mathbf{x})\phi_k a_k(\mathbf{x}, z)(\overline{\mathbf{N}}(\mathbf{x}) \cdot \overline{\mathbf{W}}_k(\mathbf{x}, z))^{\frac{1}{c(\mathbf{x})}} \tag{1}$$

where the direction of light is parametrized as the difference between the surface point $\boldsymbol{\chi} \in \Sigma$ and the position of the point light source $\mathbf{P}_k$ both dependent on the image point $\mathbf{x}$, that is:

$$\mathbf{L}_k(\mathbf{x}, z) = \boldsymbol{\chi}(\mathbf{x}) - \mathbf{P}_k(\mathbf{x}). \tag{2}$$

The perspective normal vector $\mathbf{N}(\mathbf{x})$ is parametrized according to the notation provided in [35], that is:

$$\mathbf{N}(\mathbf{x}) = \frac{1}{f}\big(f\nabla z(\mathbf{x}), -f - z(\mathbf{x}) - \mathbf{x}\cdot\nabla z(\mathbf{x})\big) \tag{3}$$

and finally $\mathbf{W}_k(\mathbf{x}, z) = \overline{\mathbf{L}}_k(\mathbf{x}, z) + \min\left\{1, \frac{|1-c(\mathbf{x})|}{\varepsilon}\right\}\overline{\mathbf{V}}(\mathbf{x})$

We finally consider the following image ratio to calculate z and c:

$$\left(\frac{i_h(\mathbf{x}, z)\phi_k a_k(\mathbf{x}, z)}{i_k(\mathbf{x}, z)\phi_h a_h(\mathbf{x}, z)}\right)^{c(\mathbf{x})} = \frac{\mathbf{N}(\mathbf{x}) \cdot \overline{\mathbf{W}}_h(\mathbf{x}, z)}{\mathbf{N}(\mathbf{x}) \cdot \overline{\mathbf{W}}_k(\mathbf{x}, z)}. \tag{4}$$

that yields the following albedo independent PDE:

$$\mathbf{b}_{hk}(\mathbf{x}, z) \cdot \nabla z(\mathbf{x}) = s_{hk}(\mathbf{x}, z). \tag{5}$$

Following the derivation in [27], we denote the vector components with superscript indexes and by removing the dependencies for readability, the vector function $\mathbf{b}_{hk}$ and the scalar function s_{hk} can be written as follows:

$$\mathbf{b}_{hk} = \Big[(\phi_k a_k i_h)^c\left(f\overline{w}_k^1 - x^1\overline{w}_k^3\right) - (\phi_h a_h i_k)^c\left(f\overline{w}_h^1 - x^1\overline{w}_h^3\right), (\phi_k a_k i_h)^c\left(f\overline{w}_k^2 - x^2\overline{w}_k^3\right) - (\phi_h a_h i_k)^c\left(f\overline{w}_h^2 - x^2\overline{w}_h^3\right)\Big]$$

and

$$s_{hk} = (f + z)\Big((\phi_k a_k i_h)^c\,\overline{w}_k^3 - (\phi_h a_h i_k)^c\,\overline{w}_h^3\Big). \tag{6}$$

Prototype

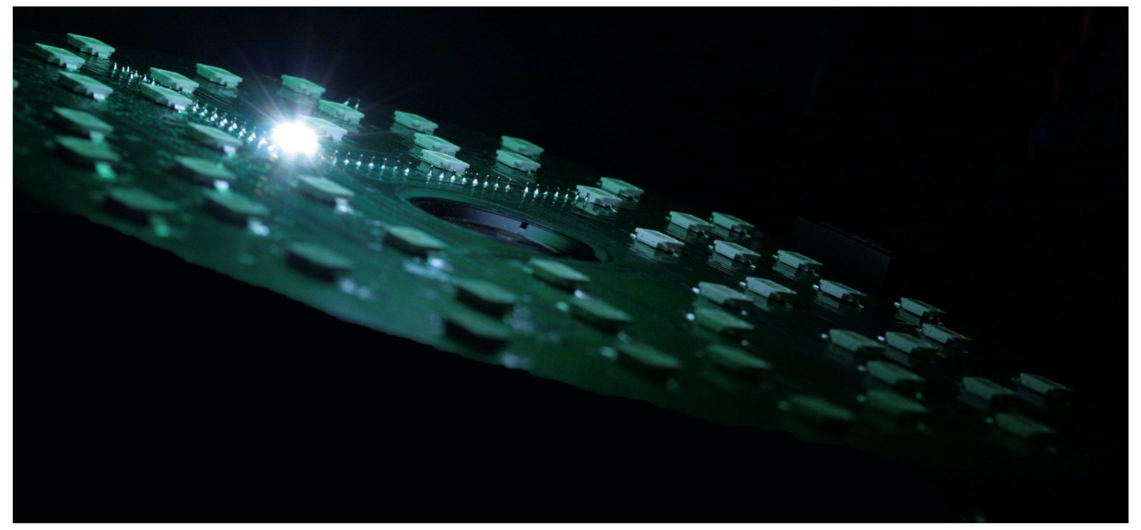

Figure 1: Prototype used for the data acquisition.

Solving the Semi-Calibrated problem

The step-wise procedure for solving the semi-calibrated problem is based on rearranging the irradiance equation (1) so that the albedo, brightness, attenuation map and shininess parameter can be approximated. That is:

$$\rho(\mathbf{x}) = \frac{i_k(\mathbf{x})}{\phi_k a_k(\mathbf{x}, z)D_k(\mathbf{x}, z)} \quad\Rightarrow\quad \begin{bmatrix}\phi_1 a_1(\mathbf{x}, z)D_1(\mathbf{x}, z)\\ \vdots \\ \phi_{N_{img}} a_{N_{img}}(\mathbf{x}, z)D_{N_{img}}(\mathbf{x}, z)\end{bmatrix}\rho(\mathbf{x}) = \begin{bmatrix} i_1(\mathbf{x})\\ \vdots \\ i_{N_{img}}(\mathbf{x})\end{bmatrix} \tag{7}$$

where $D_k(\mathbf{x}, z) = (\overline{\mathbf{N}}(\mathbf{x}) \cdot \overline{\mathbf{W}}_k(\mathbf{x}, z))^{\frac{1}{c(\mathbf{x})}}$.

As for the brightness,

$$\phi_k = \rho(\mathbf{x})\frac{i_k(\mathbf{x})}{a_k(\mathbf{x}, z)D_k(\mathbf{x}, z)} \quad\Rightarrow\quad \begin{bmatrix}\rho(\mathbf{x_1})a_k(\mathbf{x_1}, z)D_k(\mathbf{x_1}, z)\\ \vdots \\ \rho(\mathbf{x_{N_{px}}})a_k(\mathbf{x_{N_{px}}}, z)D_k(\mathbf{x_{N_{px}}}, z)\end{bmatrix}\phi_k = \begin{bmatrix} i_k(\mathbf{x_1})\\ \vdots \\ i_k(\mathbf{x_{N_{px}}})\end{bmatrix}. \tag{8}$$

and:

$$c = \frac{\log(\mathbf{N} \cdot \overline{\mathbf{W}}_h) - \log(\mathbf{N} \cdot \overline{\mathbf{W}}_k)}{\log(i_h) + \log(\phi_k a_k) - \log(i_k) - \log(\phi_h a_h)}. \tag{9}$$

We finally calculate light attenuation per pixel per image to go beyond the uniform light dissipation model. To avoid under-constraint problem, we assume that nearby pixels (in a small patch) have the same attenuation and solve for the attenuation of the patch. The unknowns to be calculated are: N_{patch} albedos $\rho(\mathbf{x})$, N_{patch} depths $z(\mathbf{x})$, N_{patch} shininess coefficients $c(\mathbf{x})$ and N_{img} attenuation $a_k(\mathbf{x}, z)$.

Thus, for the number of equations to exceed the number of unknowns, we require that: $N_{img}N_{patch} > 3N_{patch} + N_{img} \iff N_{patch} > \frac{N_{img}}{N_{img}-3}$. Hence, a 3x3 patch is good enough and so:

$$a_k(\mathbf{x}, z) = \frac{i_k(\mathbf{x})}{\rho(\mathbf{x})\phi_k D_k(\mathbf{x}, z)} \quad\Rightarrow\quad \begin{bmatrix}\rho(\mathbf{x_1})\phi_k D_k(\mathbf{x_1}, z)\\ \vdots \\ \rho(\mathbf{x_{N_{px}}})\phi_k D_k(\mathbf{x_{N_{patch}}}, z)\end{bmatrix}a_k(\mathbf{x}, z) = \begin{bmatrix} i_k(\mathbf{x_1})\\ \vdots \\ i_k(\mathbf{x_{N_{patch}}})\end{bmatrix}. \tag{10}$$

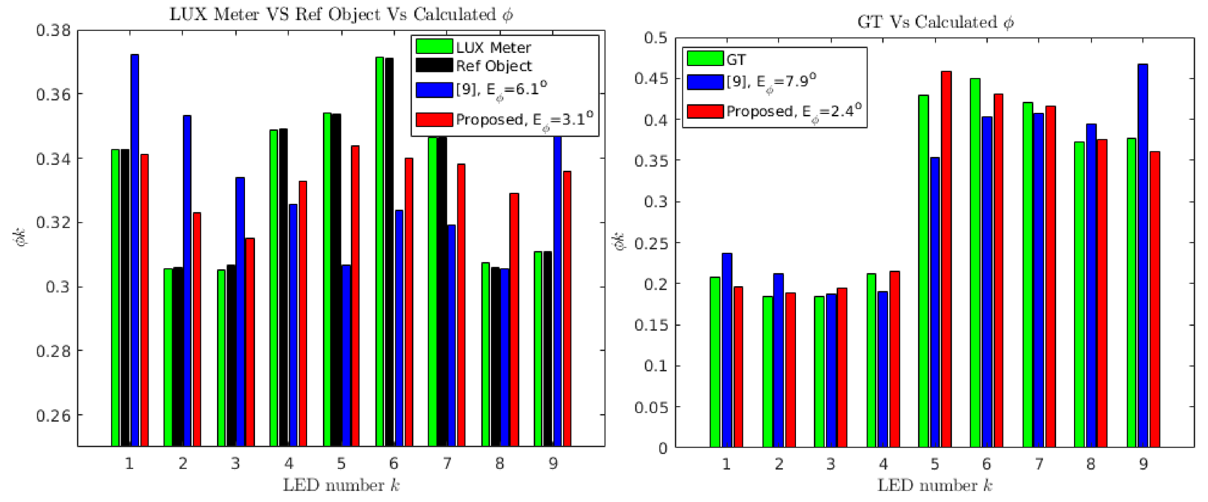

Figure 2: Estimation of light source brightness

Alternating Optimization

Alternate between updating all the unknowns as described above. To converge fast, follow the order:

1. ϕ : 1 scalar per image, very robust to inaccuracies.
2. z : highly dependent on ϕ independent of ρ.
3. ρ a, c: local, sensitive properties.

Synthetic data

We considered three synthetic data cases: classic PS (orthographic projection, directional lighting, diffuse reflection), near field diffuse and near field specular (using Cook & Torrance BRDF which is not consistent with equation 1) .

Figure 3: Synthetic data samples and ground truth.

Comparison over synthetic data

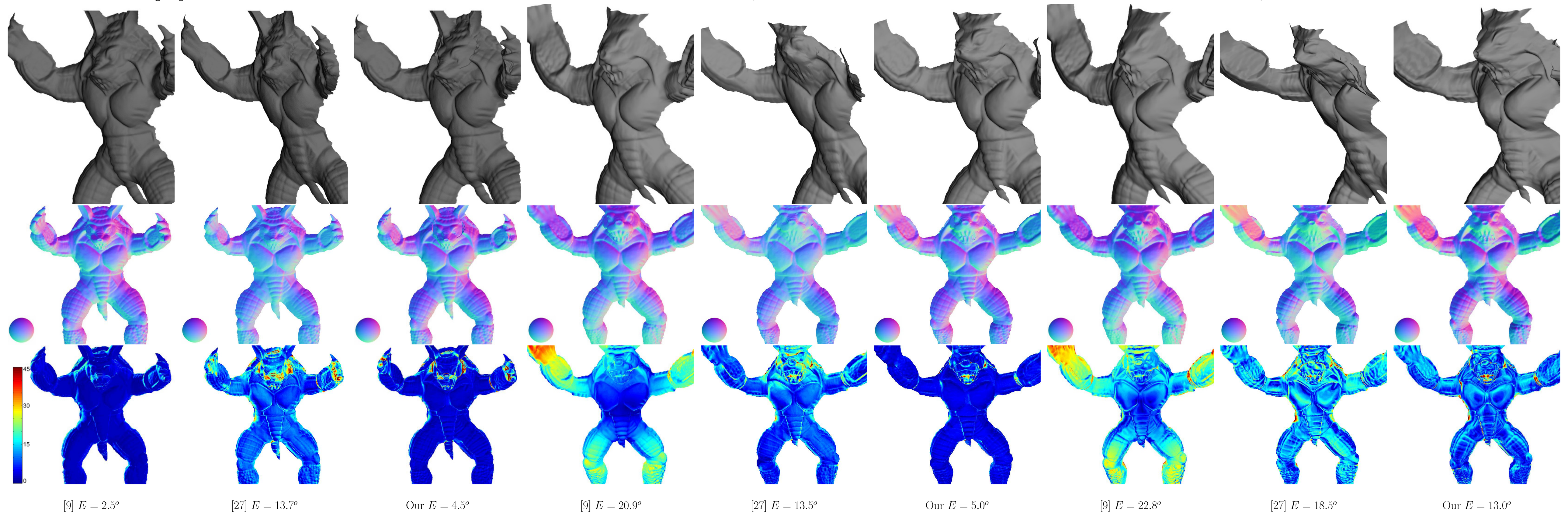

Figure 4: Comparison with [9] (semi-calibrated classic PS) and [27] (near field fully calibrated PS). From top line to bottom: reconstructions, normals (obtained by numerical differentiation of depth maps) and angular error for normals.

Real data experiments

We evaluated the algorithm on various real data sets: a hand holding a sea shell, a marble statue next to a 3D print of the Armadillo (plastic), the marble Buddha from [27] and a plastic baseball player miniature.

Figure 5: Two sample images for each object .

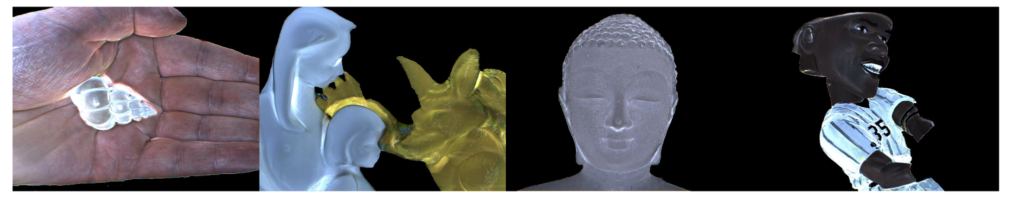

Figure 6: Calculated albedos.

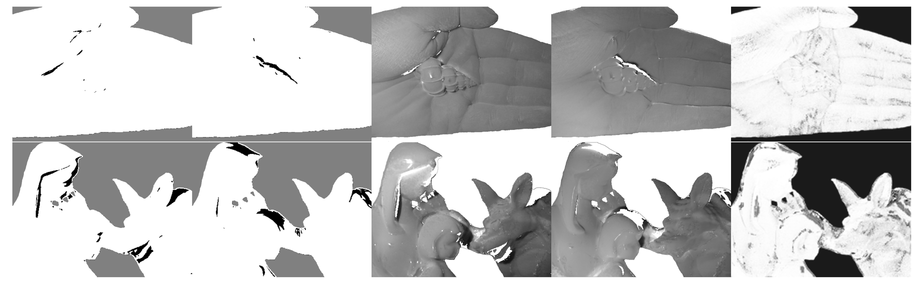

Figure 7: Sample shadowmaps, light attenuation maps and specularity parameter ($c = 1$ for Lambertian is white; the darker the more specular). Note that the shadowmaps are calculated by ray-tracing using current estimates of the geometry.

3D reconstructions

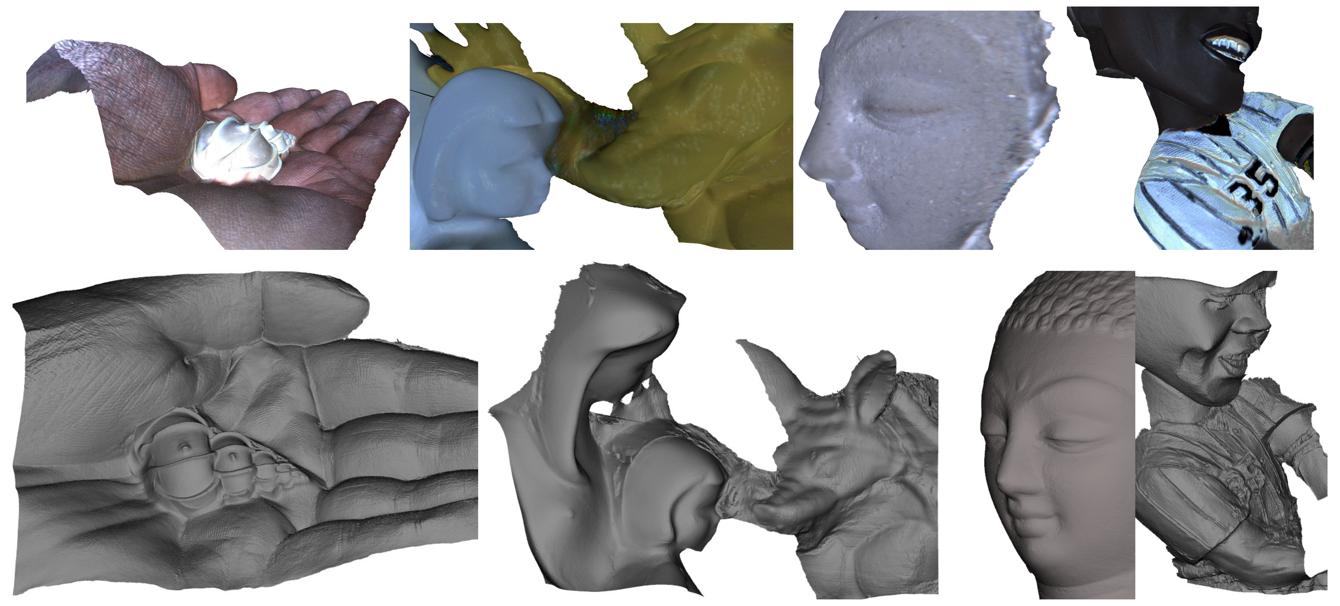

Figure 8: Two views of the obtained reconstructions.

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