Close Range Photometric Stereo with Point Light Sources

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Problem statement
Photometric Stereo (PS) is a popular paradigm for reconstructing surface details based on shading variations. Recently it has become a competitive alternative to other shape reconstruction methods. However to fully realize the potential of PS, more realistic capture conditions need to be dealt with. In this work we tackle the problem of formulating PS to take into account natural lighting attenuation, near light sources, non-uniform albedo, non-parallel light rays and multiple images all observed by a single perspective camera. Our quasi-linear PDE formulation permits a robust numerical scheme that relies only on a single known depth point.

Endoscopic perspective setup
We capture \( N \) images \( I_j \) all obtained under a different lighting condition and defined in the image domain \( \Omega_p \). We model the images using the standard formulation for image irradiance while also adding a general multiplicative factor \( a_j(x, y) \) to account for lighting attenuation such that
\[
I_j(x, y) = \rho(x, y)(n(x, y) \cdot l_j(x, y, \ldots))a_j(x, y).
\]
The perspective parametrization \([3, 1]\),
\[
M(x, y) = \{[x, y, \zeta, \eta] \mid \zeta = -x z/f, \eta = y z/f, z(x, y) \},
\]
yields the outgoing normal \( n(x, y) = z[f \nabla z, z(x, y) \cdot \nabla z]/f^2 \) and the point light source as
\[
I_j(x, y) = \left[ -\frac{\zeta_j f}{z(x, y)} - x, -\frac{\eta_j f}{z(x, y)} - y, f \right],
\]
where \( I_j(x, y) = q_j(x, y) \).
Using the image ratio strategy \( \bar{I} \) of \([5]\), each of the \( \binom{n}{2} \) pairs of source images defines a first order quasi-linear PDE in the form
\[
\begin{align*}
\bar{b}(x, y, z) \cdot \nabla z(x, y) &= s(x, y, z), & \text{on } \Omega_p \\
(z(x, y) &= g(x, y), & \text{on } \partial \Omega_p.
\end{align*}
\]

Attenuation model
We model lighting dropoff as a result of distance with the factor \( 1/r_j^2 \)
where \( r_j(x, y) = \sqrt{(x - x_j)^2 + (y - y_j)^2} \).
Radial attenuation with sharpness coefficient \( \mu \) exhibited by typical point-like light sources can be modeled with \( (I_1(x, y) \cdot (0, 0, 1))^p = f^p/q_j^p(x, y) \). For this setup we have that
\[
\begin{align*}
\bar{b} &= [I_{1q_1^{+2/3}} - I_{2q_2^{+2/3}} & I_{1q_1^{+2/3}} - I_{2q_2^{+2/3}}] \\
\bar{s} &= (I_{1q_1^{+2/3}} - I_{2q_2^{+2/3}})/f.
\end{align*}
\]

Upwind scheme
We wish to directly solve for \( z \) and as such we build an upwind update scheme in the same way as \([3]\). The final scheme for each image pixel \((i, j)\) is thus
\[
Z_{i+j}^{t+1} = \frac{|[b_{ij}(Z_{i,j})]_{Z_{i,j} < \text{min}} + b_{ij}(Z_{i,j})]_{Z_{i,j} = \text{min}} + \Delta s_{ij}(Z_{i,j})|}{|b_{ij}(Z_{i,j})| + |b_{ij}(Z_{i,j})|}
\]
\[(4)\]

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Contributions
- A well-posed mathematical model based on quasi-linear PDEs using a physically based PS point light source parametrization.
- A numerical solver for direct surface reconstruction without first explicitly solving for normals and then integrating.
- A parallel multi-core implementation of the method.

Results on natural images

Figure 1: We use a simple experimental setup with a wide field of view lens that is fitted with nearby, in-plane, orthogonally oriented SMD LED light sources. Multiple sets of four images are taken and averaged with one non-lit to account for ambient light.

Synthetic results

Figure 2: This experiment demonstrates the ability of the proposed method to handle both missing data, multiple images, non-uniform albedo and non-parallel light rays from nearby sources.

Figure 3: Reconstruction with no noise is similar to that for 2% and 5% noise. Global features remain intact but local deformation begin to occur. The graph illustrates the effect on MSE for these 3 scenarios.

Figure 4: The 4 images on the left are synthesized from the ground truth surface in gray. When using these as input, our method to the right of the gray surface performs better than other indirect surface integration methods such as \([2]\) and \([4]\).

Characteristic steering and parallelization

Figure 5: The left side shows a characteristic expansion front that is used in the update of \((4)\). For 3 or more images we choose the image pairs which permit explicit expansion. Each location on the wave front is independent and the effect of parallelization speedup over multiple cores can be seen on the right.

References
[4] A. Agostini, R. Rucker and M. Schlegel, What is the range of surface reconstruction from a gradient field?, In ECV, 2005