What Is a Good Day for Outdoor Photometric Stereo?

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Photometric Stereo

Images of object under different light directions

Surface normals
Photometric Stereo in the lab

- Non-parametric, spatially-varying reflectance
  - [Alldrin et al., CVPR '08]

- Unknown (smooth) lighting
  - [Basri et al., IJCV '07]

- Robust under specularities, shadows, and noise
  - [Ikehata et al., CVPR '12]
Photometric Stereo — point light sources

\[ b_j = l_j^T n \]

\[
\begin{bmatrix}
  b_1 \\
  b_2 \\
  \vdots \\
  b_m
\end{bmatrix} = \begin{bmatrix}
  l_1^T \\
  l_2^T \\
  \vdots \\
  l_m^T
\end{bmatrix} \quad n = Ln
Outdoor Photometric Stereo

- Cannot control the lighting!
- Sun moves on a plane during the course of a day
Outdoor Photometric Stereo

Uncontrolled illumination!

Months of data

Wait for a particular day

[Abrams et al., ECCV’12]  [Ackermann et al., CVPR’12]  [Shen et al., Pacific Graphics ’14]
Richer lighting models

[Yu et al., ICCP’13]

The quality of their results were degraded outdoors
When does Photometric Stereo work outdoors?
Summary of our findings

• Best stability is obtained when:

1) the sky is partially cloudy throughout the day
2) surface patches are pointing south, above the horizon
3) the sun path is low in the sky
Outline

- theoretical analysis
- data
- results
Photometric stereo — environment map lighting

\[ b_j = \overline{I}_j^T n \]
Point light source vs environment map lighting

**Point light source**

\[
b = \begin{bmatrix}
  b_1 \\
  b_2 \\
  \vdots \\
  b_m \\
\end{bmatrix} = \begin{bmatrix}
  l_1^T \\
  l_2^T \\
  \vdots \\
  l_m^T \\
\end{bmatrix} \quad n = Ln
\]

**Environment map**

\[
b = \begin{bmatrix}
  b_1 \\
  b_2 \\
  \vdots \\
  b_m \\
\end{bmatrix} = \begin{bmatrix}
  \overline{l}_1^T \\
  \overline{l}_2^T \\
  \vdots \\
  \overline{l}_m^T \\
\end{bmatrix} \quad n = Ln
\]

Matrix of **light directions**

Matrix of **mean light vectors**
How well does Photometric Stereo work?

\[ \delta_k = 1.96 \frac{\sigma \lambda_k}{\rho} \]

• Assume Gaussian noise on observations
• Reconstruction quality linked to:
  • noise variance
  • albedo of surface
  • related to the conditioning of matrix \( L \)
• Intuitive measure: 95% confidence interval in normal estimation error
Example of confidence interval sphere

more stable

less stable

Degrees
Run this analysis on real-world illumination conditions.
Over 3800 captures
23 days
10 months
Influence of cloud cover—quantitative

Sun visibility throughout the day (%)
Influence of cloud cover—quantitative

Sun visibility throughout the day (%)
Influence of cloud cover—quantitative

Sun visibility throughout the day (%)
Influence of cloud cover—quantitative

Sun visibility throughout the day (%)
Influence of cloud cover

Mean light directions
Sun position
Real data

Owl statuette

Corresponding Sky Capture

Normal map
Results on real data

95% upper bound on error

Error with ground truth
When will Photometric Stereo work outdoors?

- Reconstruction stability is a function of:
  - Noise, surface albedo and lighting conditions
- Best to use mixed skies

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<tr>
<th>Day</th>
<th>Time</th>
<th>Weather</th>
<th>Chance</th>
<th>Wind</th>
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<tr>
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<td>70°</td>
<td>50%</td>
<td>SW 8 mph</td>
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<td>90°</td>
<td>73°</td>
<td>10%</td>
<td>S 10 mph</td>
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<tr>
<td>MON</td>
<td>83°</td>
<td>66°</td>
<td>80%</td>
<td>E 11 mph</td>
</tr>
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