Near-Light Photometric Stereo using Circularly Placed Point Light Sources

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Motivation

Circularly placed light sources are common

- Surveillance Cameras
- Photography
- Medical Imaging
Motivation
Circularly placed light sources are common and could be useful

Near-light Photometric Stereo

BRDF-invariant Shape Analysis

Depth Edge Detection

[Xie et.a 14 15]

[Chandraker 11]

[Raskar et.al 04]
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Circularly placed light sources are common and could be useful

Near-light Photometric Stereo

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[Xie et al. 14 15]

[Chandraker 11]

[Raskar et al. 04]
Challenges

Near-light Photometric Stereo using circularly placed light sources:

Near-field Lighting: Distant light assumption fails
Challenges

Near-light Photometric Stereo using circularly placed light sources:

Near-field Lighting: Distant light assumption fails

Spatially variant light directions and intensities

Surface
Challenges

Near-light Photometric Stereo using circularly placed light sources:

Small light source baseline: subtle intensity changes

LED ring radius: 30mm; Object distance: 400mm
Challenges

Difficult to estimate the shape with near lights in small baselines

Reconstruction

Profile of object

Distant Light

Near Light [Queau et.al 17]
Depth initialized at 200 mm

Near Light [Queau et.al 17]
Depth initialized at 400 mm
Challenges

Difficult to estimate the shape with near lights in small baselines

Profile of object

Distant Light

Near Light
[Queau et.al 17]
Depth initialized at 200 mm

Near Light
[Queau et.al 17]
Depth initialized at 400 mm

Proposed Method
Photometric Stereo with Distant Light

Image plane

Surface

$l$
Photometric Stereo with Distant Light

Image intensity

\[ I = \rho(p) l^T n(p) \]
Photometric Stereo with Distant Light

\[ I = \rho(p)l^T n(p) \]

Surface normal
Photometric Stereo with Distant Light

Image plane

Image intensity

\[ I = \rho(p) l^T n(p) \]

Albedo
Photometric Stereo with Near Light

Image intensity

\[ I = \rho(p) \frac{1}{|l - p|^2} \frac{(l - p)^T}{|l - p|} n(p) \]
Photometric Stereo with Near Light

\[ l = \rho(p) \frac{1}{|l - p|^2} \frac{(l - p)^T}{|l - p|} n(p) \]

Image intensity

Intensity fall off
Photometric Stereo with Near Light

\[ I = \rho(p) \frac{1}{|l-p|^2} \frac{(l-p)^T}{|l-p|} n(p) \]

Image intensity

Image plane

Surface
Photometric Stereo with Near Light

Projective camera model

Image plane

Light source $l$

Surface

Image intensity

\[ I = \rho(p) \frac{1}{|l - p|^2} \frac{(l - p)^T}{|l - p|} n(p) \]
Photometric Stereo with Near Light

Projective camera model

Image plane

Surface

Image intensity

\[ I = \rho(p) \frac{1}{|l - p|^2} \frac{(l - p)^T}{|l - p|} n(p) \]
Photometric Stereo with Near Light

Projective camera model

Camera Intrinsic $K$

Image plane

Surface

Image intensity

$$ I = \rho(p) \frac{1}{|l - p|^2} \frac{(l - p)^T}{|l - p|} n(p) $$

Back-projection:

$$ p(z) = K^{-1} uz $$
Photometric Stereo with Near Light

**Projective camera model**

- Image plane
- Camera Intrinsic $K$

**Image formation model**

$$I(u) = \rho(u) \frac{(l - K^{-1}uz)^T}{|l - K^{-1}uz|^3} n(u)$$
Photometric Stereo with Near Light

Projective camera model

Camera Intrinsic $K$

Image plane

Image formation model

Camera Intrinsic $K$

Albedo
Light Position
Depth

Normal

$$I(u) = \rho(u) \frac{(l - K^{-1}uz)^T}{|l - K^{-1}uz|^3} n(u)$$
Photometric Stereo with Near Light

Projective camera model

$\mathbf{u}$

Camera Intrinsic $K$

Image plane

$\mathbf{z}$

$l$

$\mathbf{n}(p)$

$p$

Surface

Image formation model

$$I(\mathbf{u}) = \rho(\mathbf{u}) \frac{(l - K^{-1}u\mathbf{z})^T}{|l - K^{-1}u\mathbf{z}|^3} \mathbf{n}(\mathbf{u})$$

Albedo

Depth

Normal
Related Works on Near Light PS

Solve for $n$ and $z$ separately

Local shaping

Global blending

[Xie et.al 15]

Solve for $z$ directly

[Wang et.al 15]

\[ n = \begin{bmatrix} \frac{\partial z}{\partial x(z)} & \frac{\partial z}{\partial y(z)} & -1 \end{bmatrix}^T \begin{bmatrix} \frac{\partial z}{\partial x(z)} & \frac{\partial z}{\partial y(z)} & -1 \end{bmatrix} \]  

[Queueu et.al 16, 17]

[Queau et.al 16, 17]

[Wu et.al 11] [Fotios et.al 17]
Related Works on Near Light PS

Solve for $n$ and $z$ separately

Local shaping

Global blending

Solve for $z$ directly

$$n = \frac{\begin{bmatrix} \frac{\partial z}{\partial x(z)} & \frac{\partial z}{\partial y(z)} & -1 \end{bmatrix}^T}{\left\| \begin{bmatrix} \frac{\partial z}{\partial x(z)} & \frac{\partial z}{\partial y(z)} & -1 \end{bmatrix} \right\|_2}$$

[Queau et.al 16, 17]

[Xie et.al 15]

[Wang et.al 15]

[Queau et.al 16, 17]

[Wu et.al 11] [Fotios et.al 17]
Represent Normal in terms of Depth

Image domain

\[ \mathbf{u} \]
Represent Normal in terms of Depth

Surface normal as function of depths

\[ n(u) = n_v(u, z) = \sum_{p_k, p_i \in N_1(p)} w_f n_f(p, p_k, p_j) \]

Vertex position as back-projecting

\[ p = K^{-1} uz \]
Problem Formation

Given the captured images $\hat{I}$, estimate depth and albedo:

\[
\min_{z, \rho} \left| \hat{I}(u) - I(u; n, z, \rho) \right|^2 + R_S(z)
\]

with

\[
I(u; n, z, \rho) = \rho(u) \frac{(l - K^{-1}uz)^T}{|l - K^{-1}uz|^3} n_v(u, z)
\]
Sensitive to Initial Guess

Reconstructed object is placed at depth about 200 mm. LED ring radius is 30 mm.

Two of 24 captured images

Object Profile

\( z_{\text{init}} = 100 \text{ mm} \)

\( z_{\text{init}} = 400 \text{ mm} \)

\( z_{\text{init}} = 250 \text{ mm} \)

\( z_{\text{opt}} \)
Modelling Differential Image

By Chain Rule:

\[ I_t = \frac{\partial I}{\partial t} = \frac{\partial I}{\partial l} l_t = \frac{n^T l_t}{n^T (l-p)} - 3I \frac{(l-p)^T l_t}{|l-p|^2} \]

\[ l^T l_t \approx 0 \text{ for light on a circle} \]

\[ p^T l_t \text{ is small and attenuated by inverse squared distance} \]
Initialize using Differential Image

Using Differential Images to initialize

\[
\min_z \left| \hat{l}_t n^T (z)(l - p(z)) - \hat{n}^T (z) l_t \right|^2 + R_s(z)
\]

By using Differential Images to initialize depths

1. Free from albedo estimation
2. Free from inverse square attenuation term
Two Stage Near-light Photometric Stereo

Use Differential Images to initialize
\[ \min_z \left| \hat{I}_t n^T(z)(l - p(z)) - \hat{n}^T(z)l_t \right|^2 + R_s(z) \]

Use Original Images directly to refine
\[ \min_{z, \rho} \left| \hat{l}_m - \rho(u) \frac{(l_m - p(z))^T}{|l_m - p(z)|^3} n(z) \right|^2 + R_s(z) \]
Simulation: Different Initials

Performance vs. Initial Depth

Error in Surface Normal

Degree

Object mean depth

[Queau et.al 17]

[Our method]
Experiment Setup

Object

LED Ring

Camera

24 LEDs

30 mm
Light Source Position Calibration

Accurate light source positions are needed.

Chrome Sphere
Light Source Position Calibration

Accurate light source positions are needed.

Chrome Sphere

Reflection of light sources
Light Source Position Calibration

Accurate light source positions are needed.

Specular Display

Displayed Checkerboard

Reflected Light (color encoded)

The light positions are estimated by triangulate the reflected rays.
Simulation Results on Light Calibration

Comparison with method using chrome sphere

- **mm**
- **x**
- **y**
- **z**

- LED Index
- LED Index
- LED Index

- **Ours**
- **Using Chrome Sphere**
- **Ground Truth**
Real Experiment Results

Input images

Initial Depth using Differential Images

Refined using Original Images
Real Experiment Results

Input images

Initial Depth using Differential Images

Refined using Original Images
Real Experiment Results

- **Input images**
- **Initial Depth using Differential Images**
- **Refined using Original Images**
Real Experiment Results

Input images

Initial Depth using Differential Images

Refined using Original Images
Real Experiment Results

Input images

Reconstruction
Conclusion

• Near-Light Photometric Stereo algorithm for circularly placed light sources with small baselines:

  – Use mesh representation to relate surface normal and depth
    • More trackable than the variational definition for surface normal

  – Two-stage photometric stereo algorithm
    • Use differential image for depth initialization
    • Refine the depths using the original images
Future Work

• Photometric Stereo for materials with subsurface scattering effects (e.g. human skin under NIR light)

• Take into account surface BRDF

• BRDF invariant shape analysis using differential image with near-field light and small light source baseline limitation