Near-Light Photometric Stereo using Circularly Placed Point Light Sources

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ICCP 2018

Motivation

Circularly placed light sources are common

Surveillance Cameras

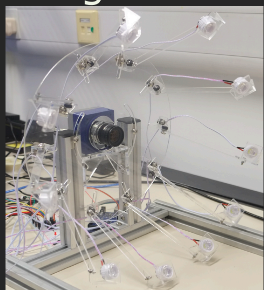
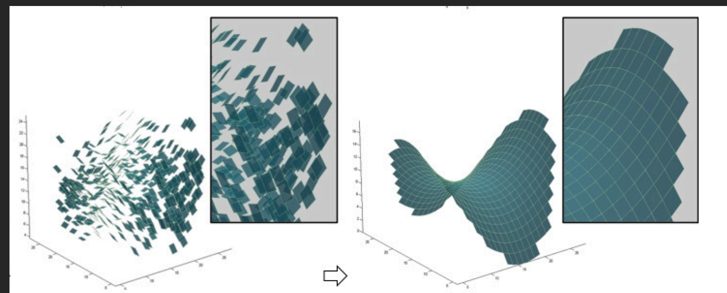
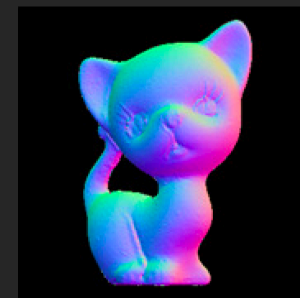
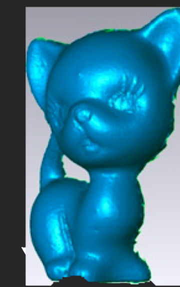
Medical Imaging

Photography

Motivation

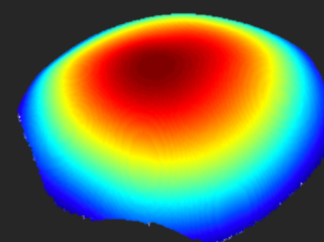
Circularly placed light sources are common and could be useful

Near-light Photometric Stereo

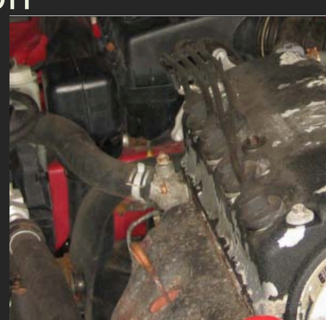
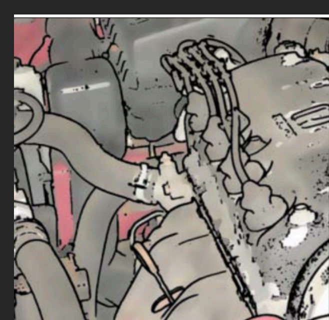
[Xie et.a 14 15]

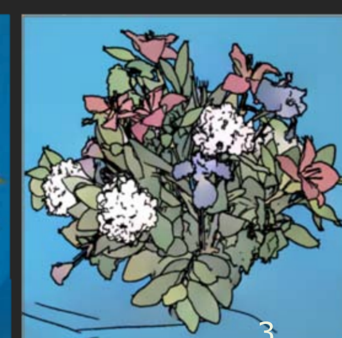
BRDF-invariant Shape Analysis


[Chandraker 11]

Depth Edge Detection



[Raskar et.al 04]

Motivation

Circularly placed light sources are common and could be useful

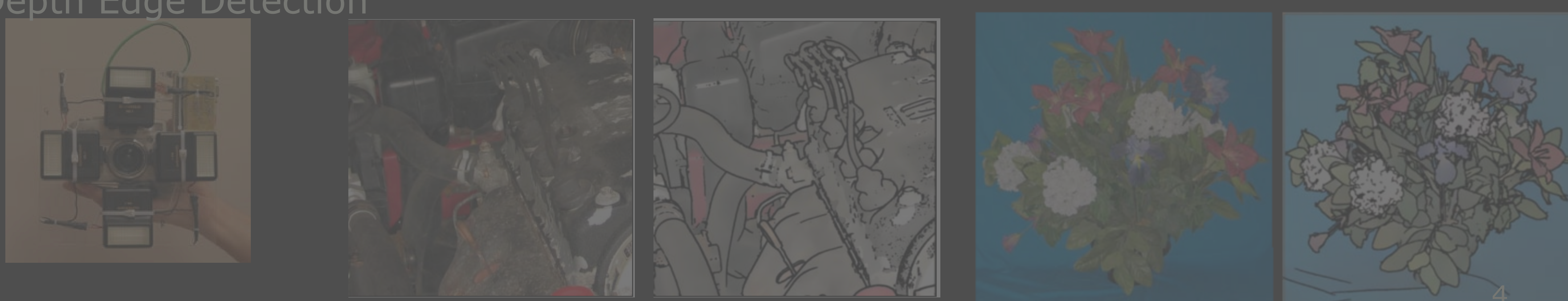
Near-light Photometric S

BRDF-invariant Shape Analysis

[Xie et.a 14 15]

[Chandraker 11]

Depth Edge Detection



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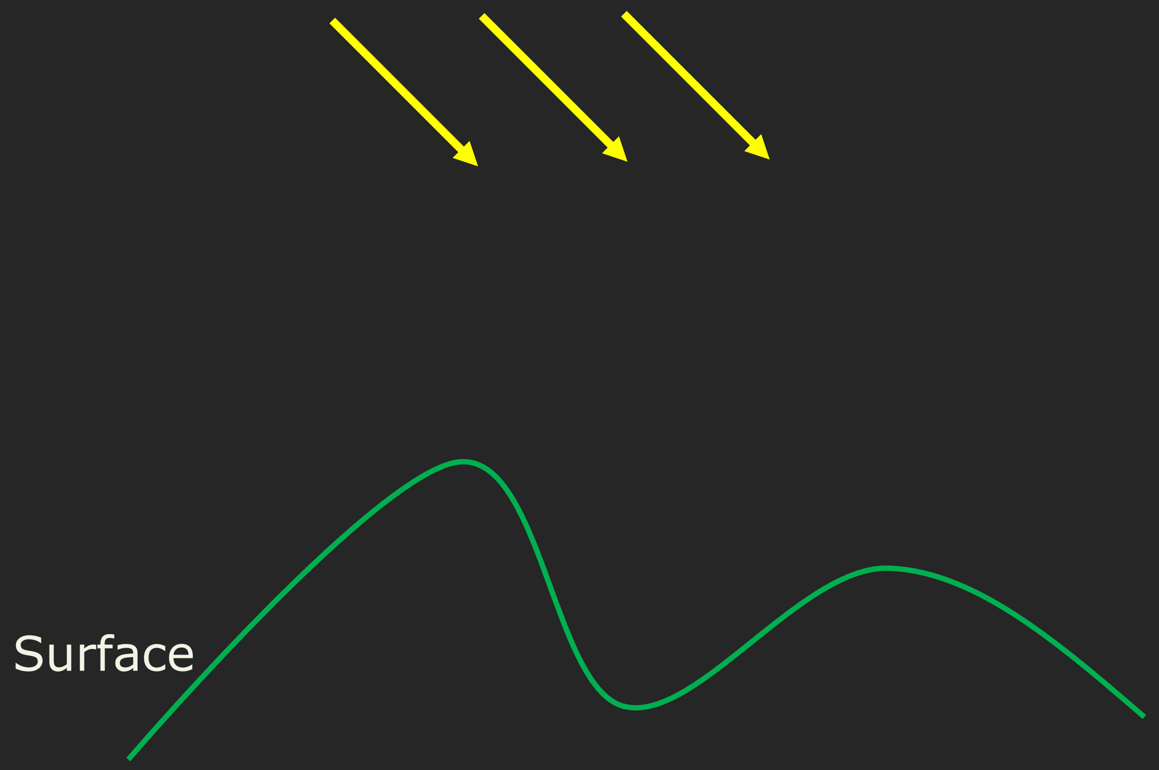
[Raskar et.al 04]

Challenges

Near-light Photometric Stereo using circularly placed light sources:

Near-field Lighting: Distant light assumption fails



Challenges

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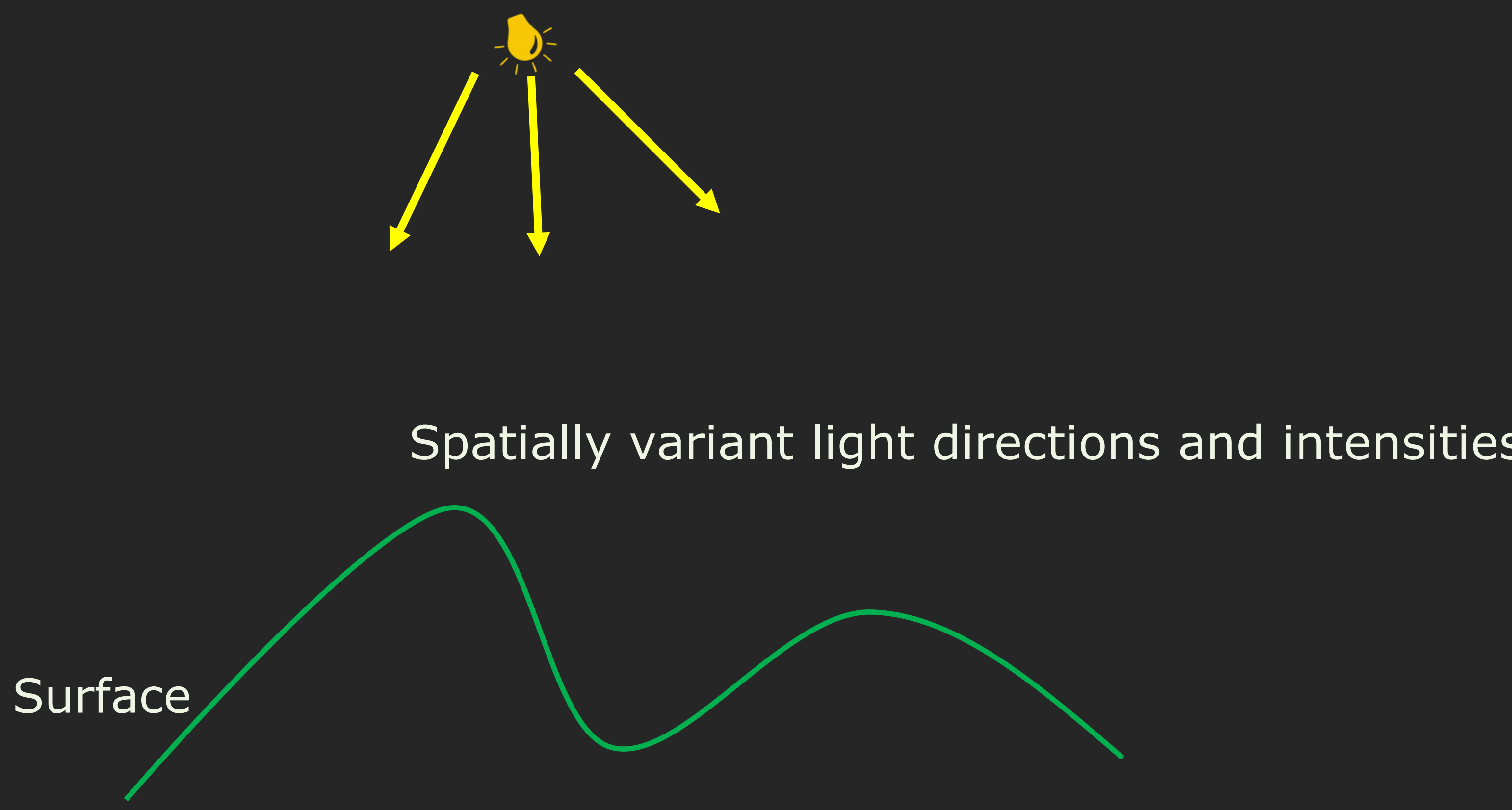


Challenges

Near-light Photometric Stereo using circularly placed light sources:

Small light source baseline: subtle intensity changes

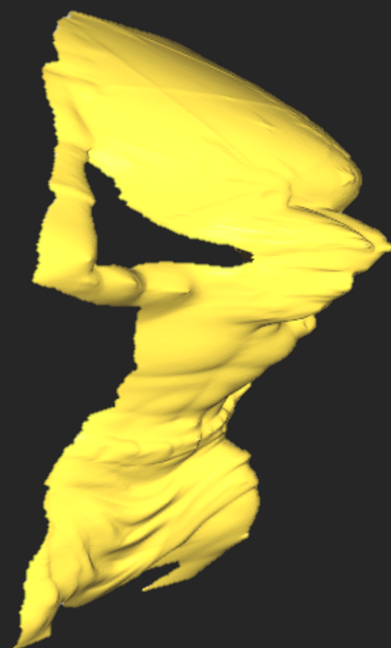
LED ring radius: 30mm; Object distance: 400mm

Challenges

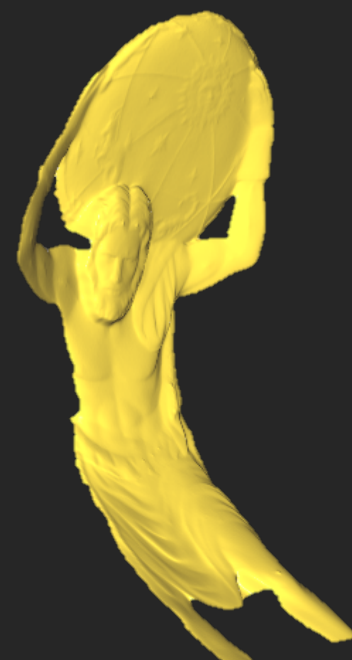
Difficult to estimate the shape with near lights in small baselines

Reconstruction

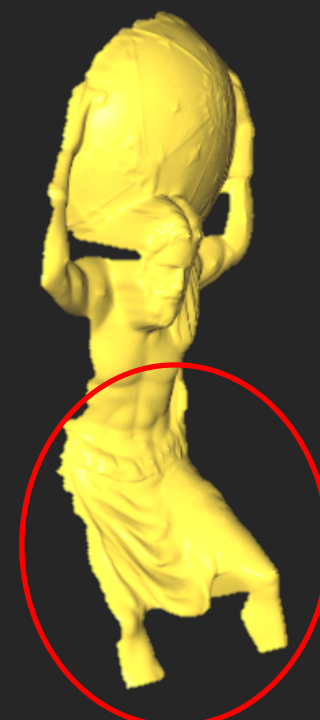
Profile of object



Distant Light



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



Near Light
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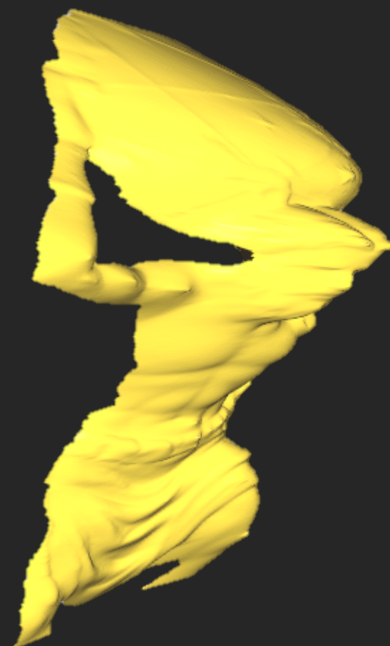
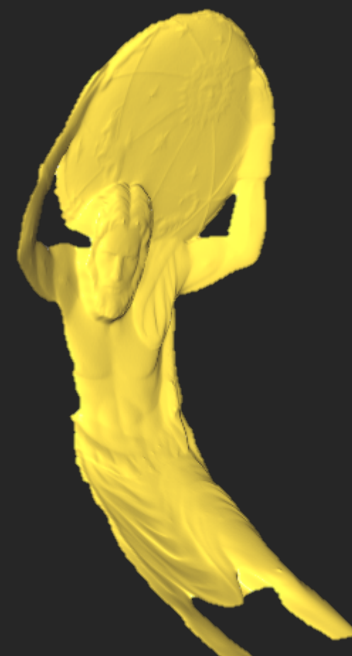
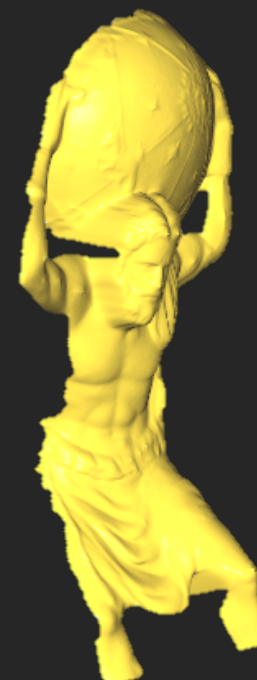


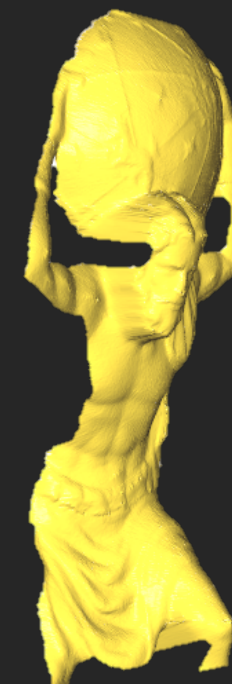
Distant Light



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

Photometric Stereo with Distant Light

Image intensity

Light direction

$$I = \rho(p)\boldsymbol{l}^T\boldsymbol{n}(\boldsymbol{p})$$

Photometric Stereo with Distant Light

Image intensity

$$I = \rho(p) l^T n(p)$$

Surface normal

Photometric Stereo with Distant Light

Image intensity

$$I = \rho(\boldsymbol{p})\boldsymbol{l}^T\boldsymbol{n}(\boldsymbol{p})$$

Albedo

Photometric Stereo with Near Light

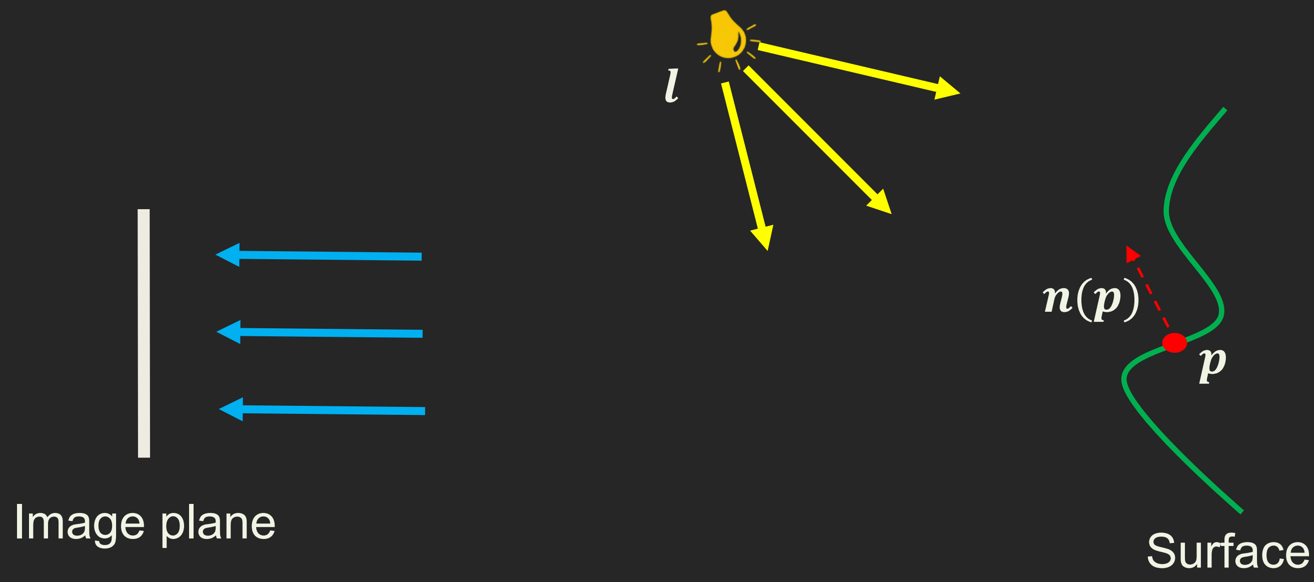


Image intensity

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

Photometric Stereo with Near Light

Image intensity

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

Intensity fall off

Photometric Stereo with Near Light

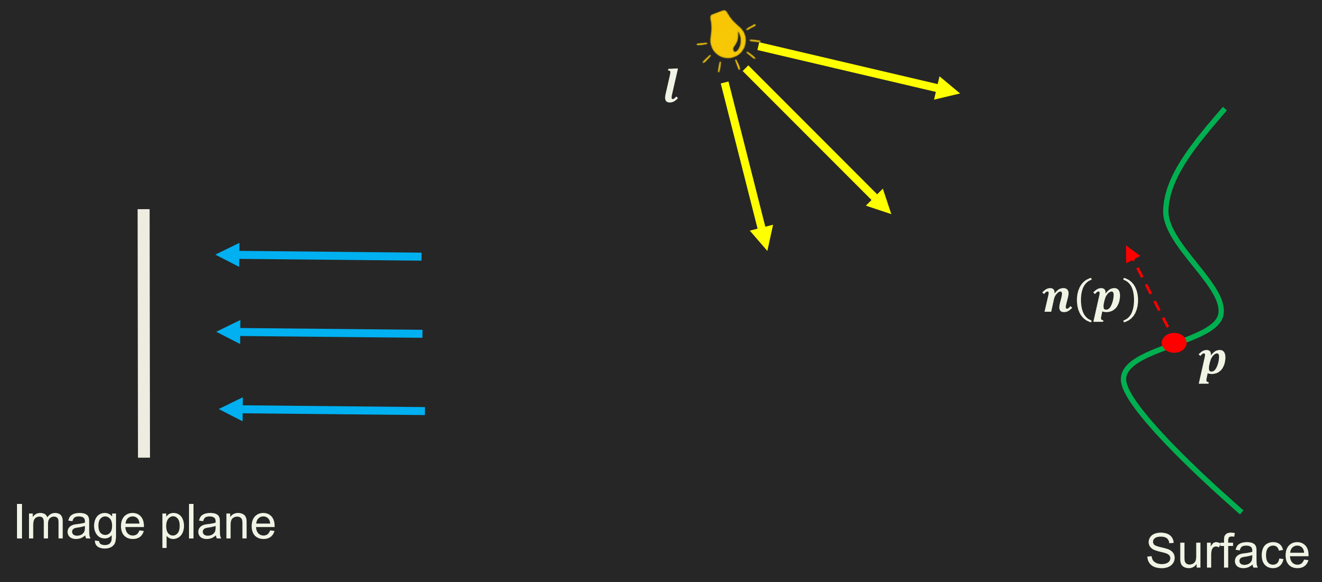


Image intensity

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Light direction

Photometric Stereo with Near Light

Projective camera model

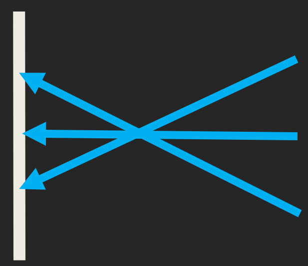
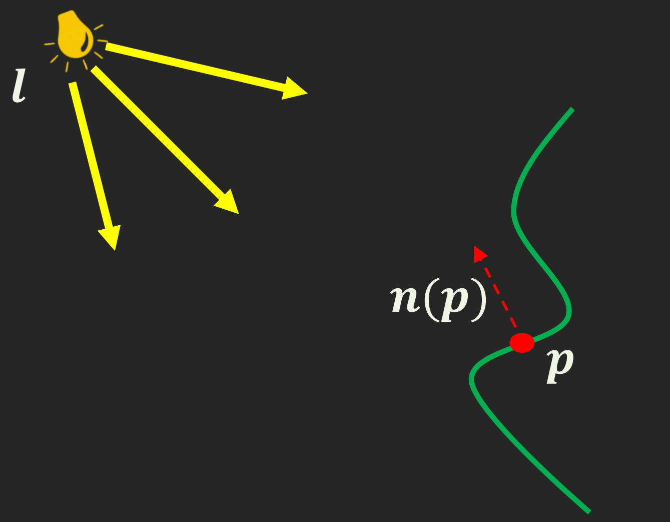


Image plane



Surface

Image intensity

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

Photometric Stereo with Near Light

Projective camera model

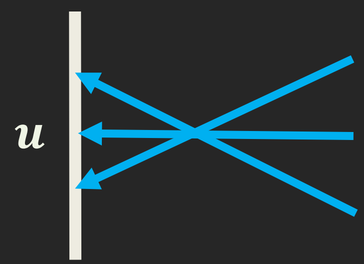
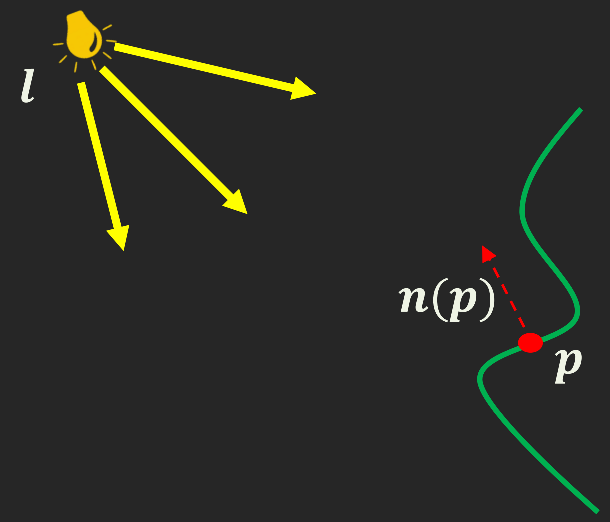


Image plane



Surface

Image intensity

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

Photometric Stereo with Near Light

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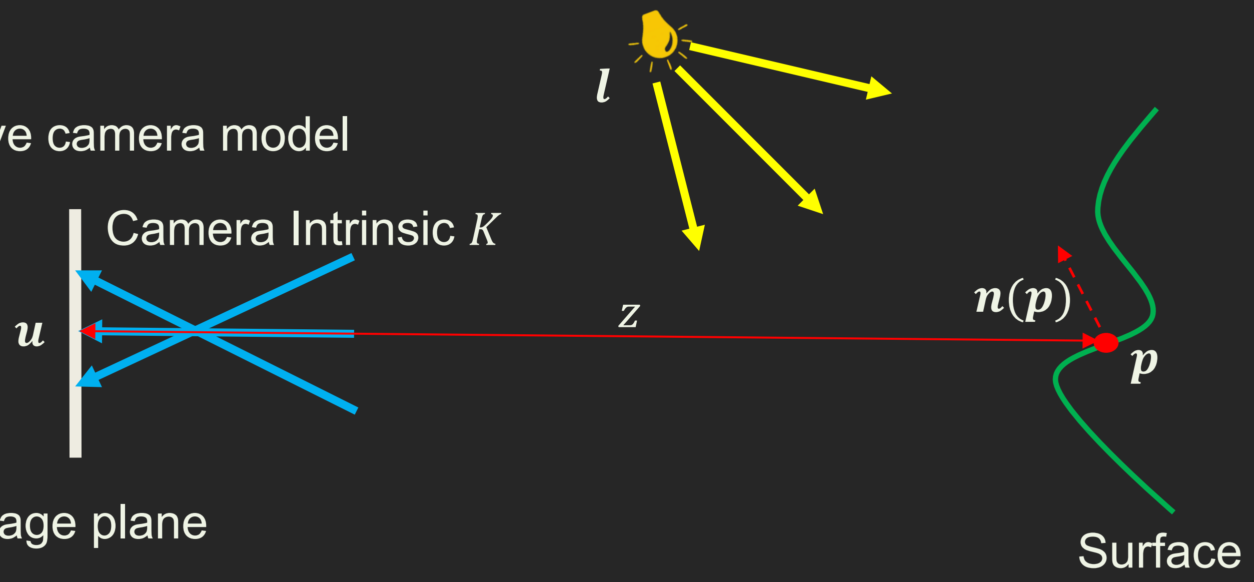


Image intensity

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

Back-projection:

$$\boldsymbol{p}(z) = K^{-1}\boldsymbol{u}\mathrm{z}$$

Photometric Stereo with Near Light

Projective camera model

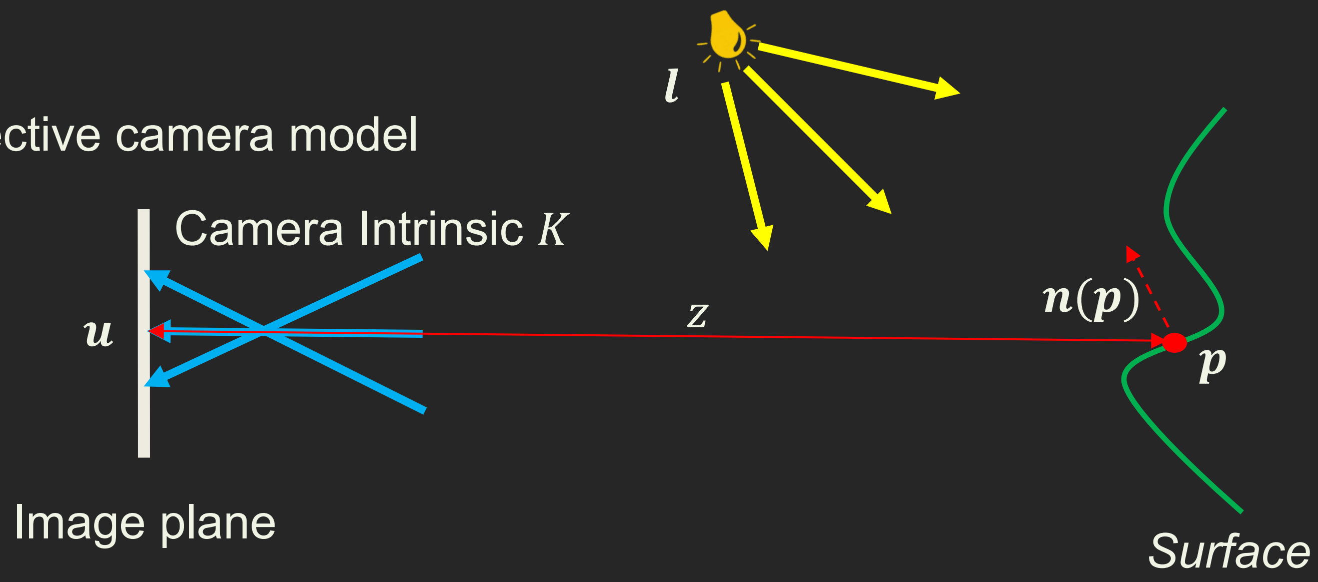


Image formation model

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

Photometric Stereo with Near Light

Projective camera model

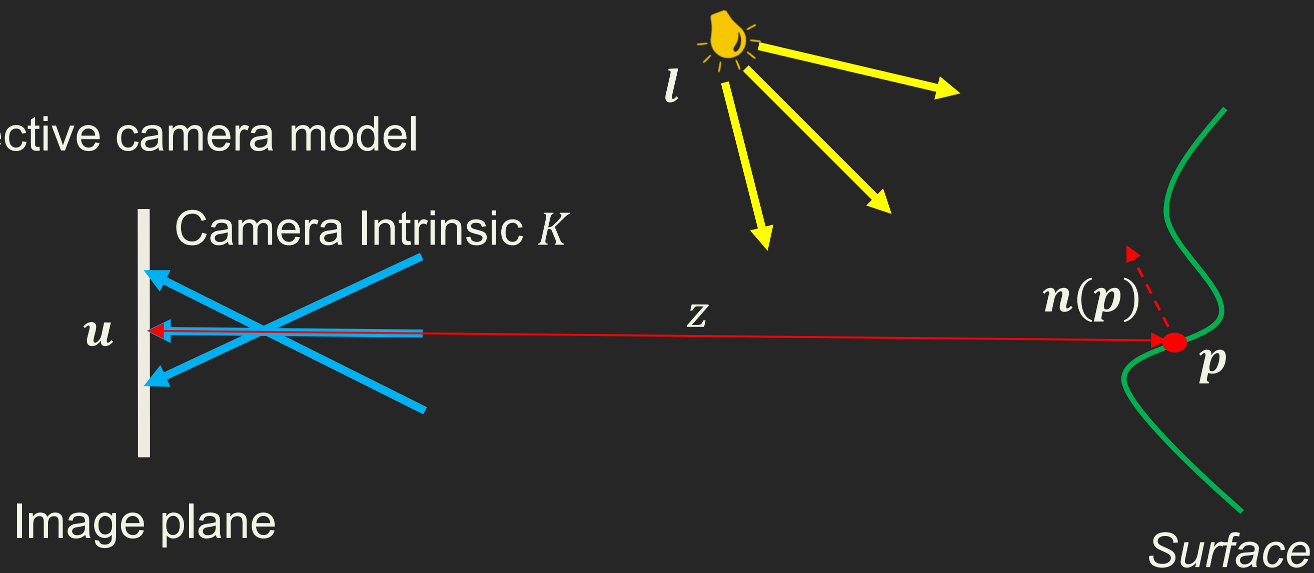


Image formation model

Camera Intrinsics

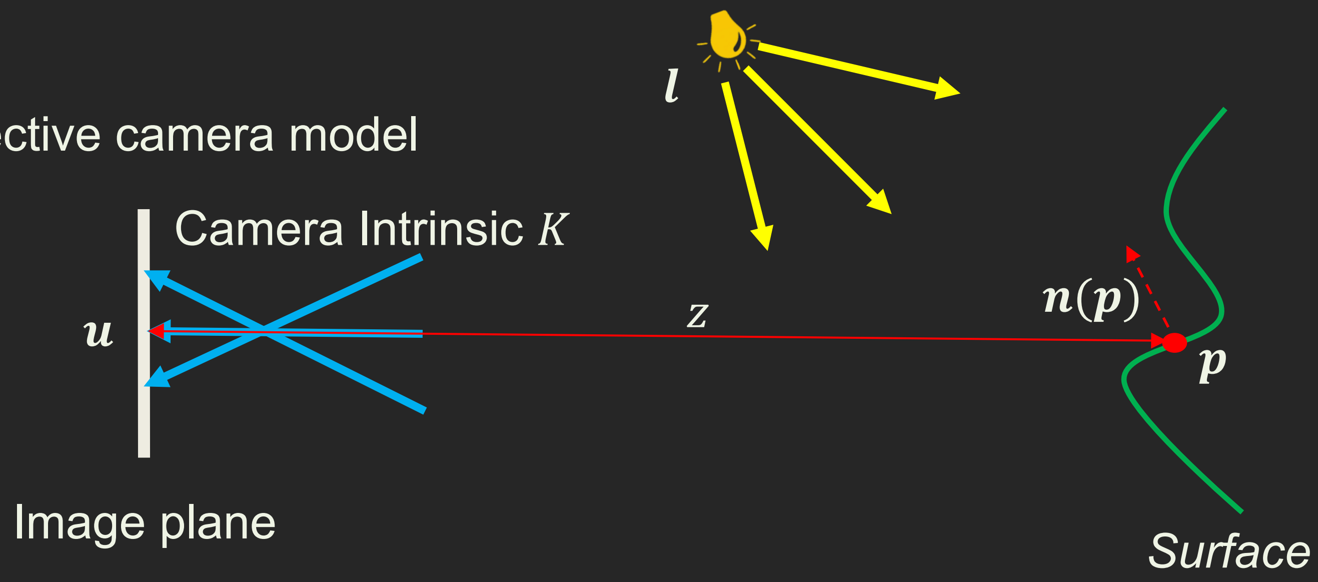
$$I(\boldsymbol{u}) = \rho(\boldsymbol{u}) \frac{(\boldsymbol{l} - K^{-1}\boldsymbol{u}z)^T}{|\boldsymbol{l} - K^{-1}\boldsymbol{u}z|^3} \boldsymbol{n}(\boldsymbol{u})$$

Normal

Albedo Light Position Depth

Photometric Stereo with Near Light

Projective camera model



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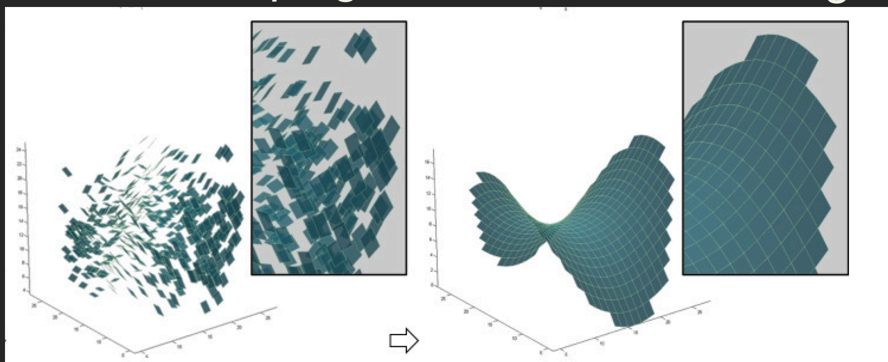
Albedo

Depth

Related Works on Near Light PS

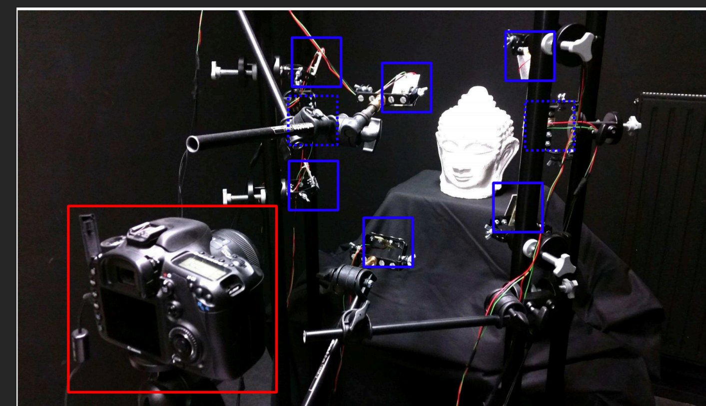
Solve for ***n*** and *z* separately

Local shaping Global blending

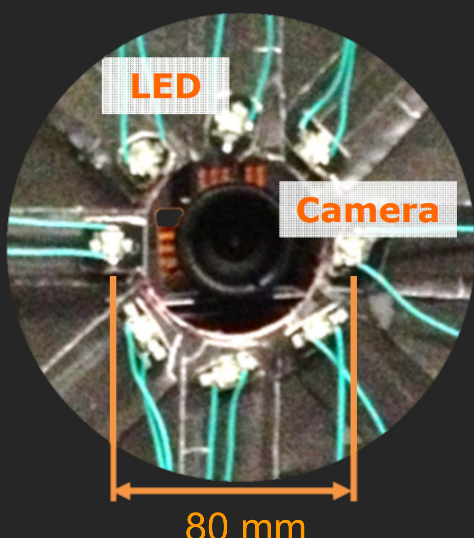


[Xie et.al 15]

Solve for *z* directly



[Queau et.al 16, 17]



[Wang et.al 15]

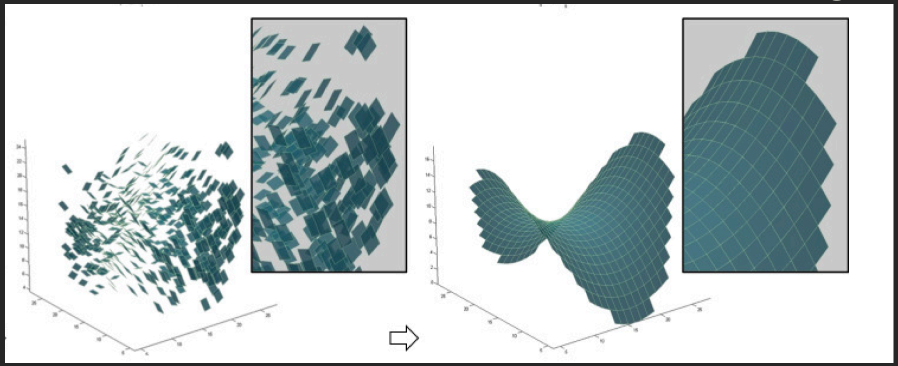
$$\boldsymbol{n} = \frac{\left[\frac{\partial z}{\partial x(z)}, \frac{\partial z}{\partial y(z)}, -1\right]^{\boldsymbol{T}}}{\left\|\left[\frac{\partial z}{\partial x(z)}, \frac{\partial z}{\partial y(z)}, -1\right]\right\|_{\mathbf{2}}}$$

[Wu et.al 11] [Fotios et.al 17]

Related Works on Near Light PS

Solve for ***n*** and *z* separately

Local shaping   Global blending



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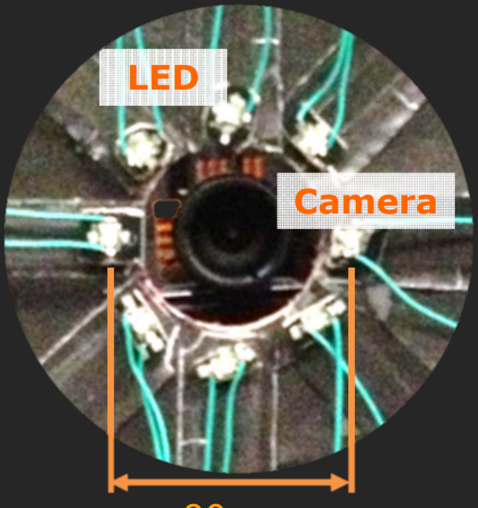

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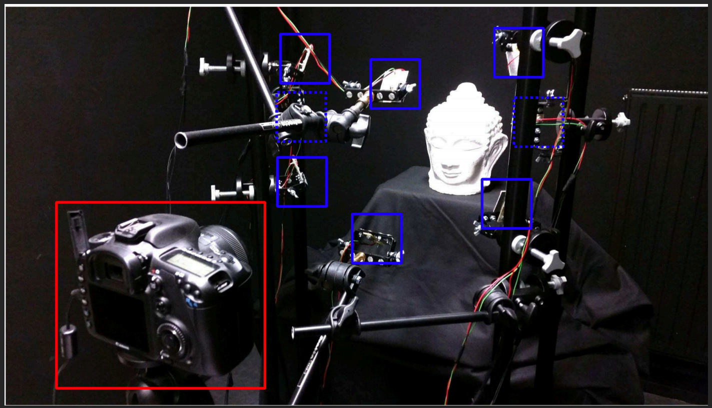

[Queau et.al 16, 17]

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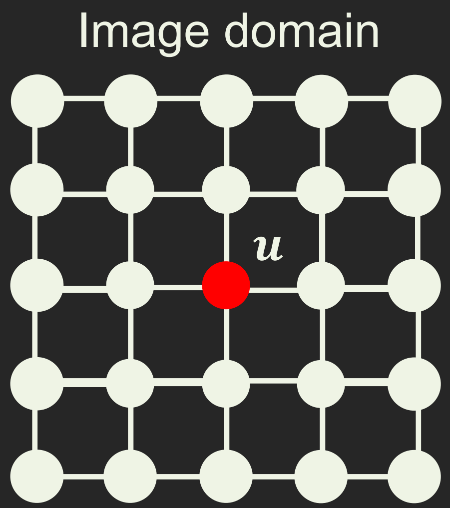
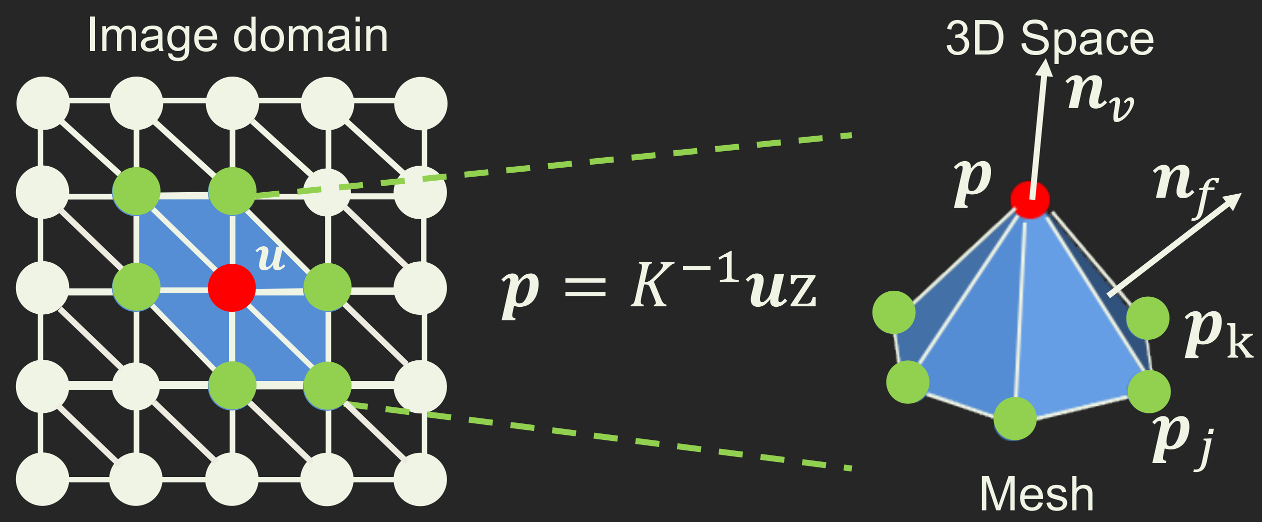
[Wu et.al 11] [Fotios et.al 17]

Represent Normal in terms of Depth



Represent Normal in terms of Depth



Surface normal as function of depths

$$\boldsymbol{n}(\boldsymbol{u}) = \boldsymbol{n}_v(\boldsymbol{u}, \boldsymbol{z}) = \sum_{\boldsymbol{p}_k, \boldsymbol{p}_i \in N_1(\boldsymbol{p})} w_f \boldsymbol{n}_f(\boldsymbol{p}, \boldsymbol{p}_k, \boldsymbol{p}_j)$$

Vertex position as back-projecting

$$\boldsymbol{p} = K^{-1}\boldsymbol{u}\mathrm{z}$$

Problem Formation

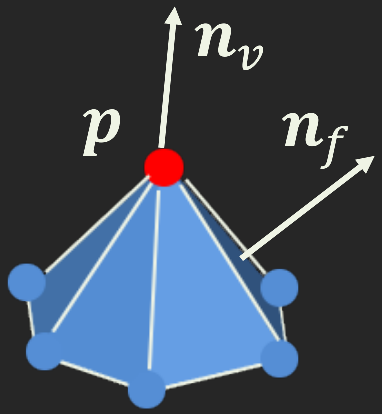
Given the captured images $\hat{I}$, estimate depth and albedo:

$$\min_{\boldsymbol{z},\boldsymbol{\rho}} \left| \hat{I}(\boldsymbol{u}) - I(\boldsymbol{u}; \boldsymbol{n}, z, \rho) \right|^2 + \boldsymbol{R_s}(z)$$

Photometric difference Regulization for depth

with

$$I(\boldsymbol{u}; \boldsymbol{n}, z, \rho) = \rho(\boldsymbol{u}) \frac{(\boldsymbol{l} - K^{-1}\boldsymbol{u}\mathrm{z})^T}{|\boldsymbol{l} - K^{-1}\boldsymbol{u}\mathrm{z}|^3} \boldsymbol{n_v}(\boldsymbol{u}, \boldsymbol{z})$$



Sensitive to Initial Guess

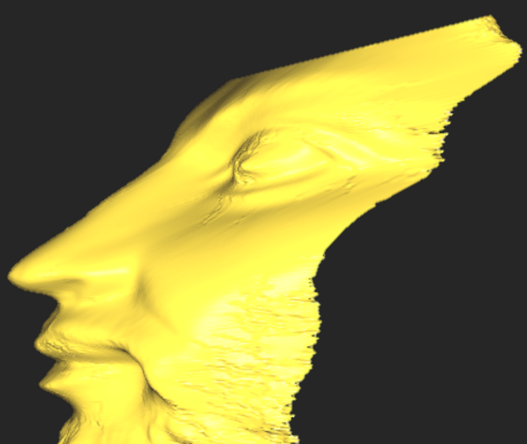
Reconstructed object is place at depth about 200 *mm.* LED ring radius is 30 mm

Two of 24 captured images

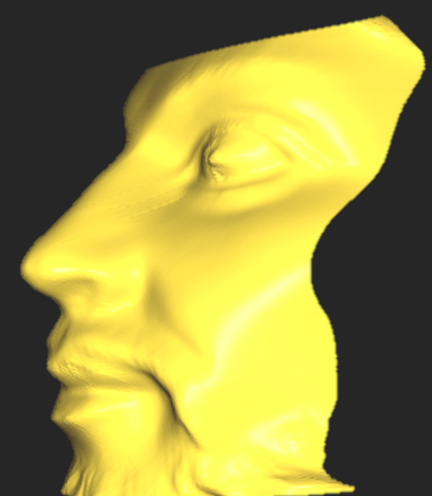
Object Profile

z_{opt}

z_{init}=100 mm

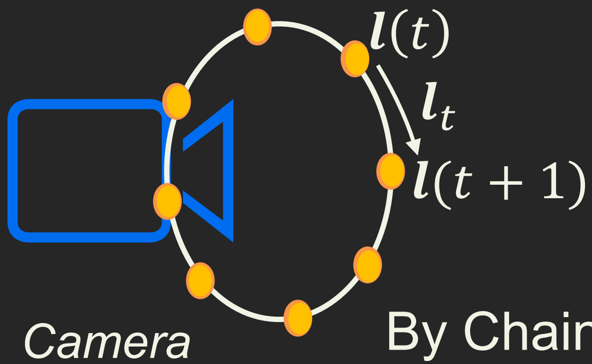


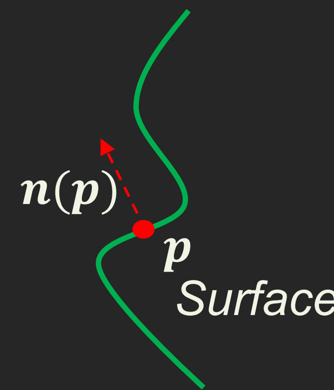
z_{init}=400mm



z_{init}=250 mm

Modelling Differential Image





By Chain Rule:

Direction Change   Distance Change

$$I_t = \frac{\partial I}{\partial t} = \frac{\partial I}{\partial \boldsymbol{l}} \boldsymbol{l}_t = I \frac{\boldsymbol{n}^T \boldsymbol{l}_t}{\boldsymbol{n}^T (\boldsymbol{l} - \boldsymbol{p})} - 3I \frac{(\boldsymbol{l} - \boldsymbol{p})^T \boldsymbol{l}_t}{|\boldsymbol{l} - \boldsymbol{p}|^2}$$

$\boldsymbol{l}^T \boldsymbol{l}_t \approx 0$ for light on a circle

$$\approx I \frac{\boldsymbol{n}^T \boldsymbol{l}_t}{\boldsymbol{n}^T (\boldsymbol{l} - \boldsymbol{p})} + 3I \frac{\boldsymbol{p}^T \boldsymbol{l}_t}{|\boldsymbol{l} - \boldsymbol{p}|^2}$$

$\boldsymbol{p}^T \boldsymbol{l}_t$ is small and attenuated by inverse squared distance

$$\approx I \frac{\boldsymbol{n}^T \boldsymbol{l}_t}{\boldsymbol{n}^T (\boldsymbol{l} - \boldsymbol{p})}$$

Initialize using Differential Image

Using Differential Images to initialize

$$\min_{\boldsymbol{z}} \left| \hat{I}_t \boldsymbol{n}^T(\boldsymbol{z})(\boldsymbol{l} - \boldsymbol{p}(\boldsymbol{z})) - \hat{I} \boldsymbol{n}^T(\boldsymbol{z}) \boldsymbol{l}_t \right|^{\boldsymbol{2}} + \boldsymbol{R_s}(z)$$

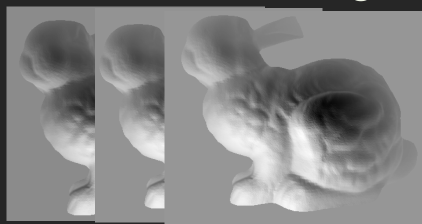
By using Differential Images to initialize depths

1. Free from albedo estimation

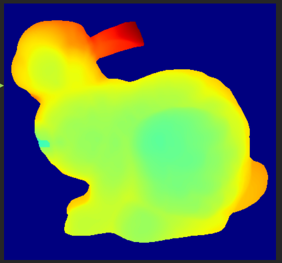
2. Free from inverse square attenuation term

Two Stage Near-light Photometric Stereo

Differential Images



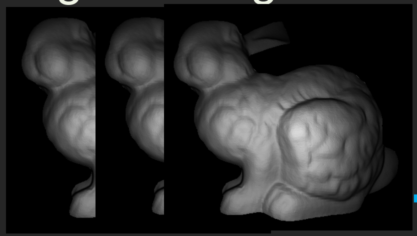
Initial Depth Map



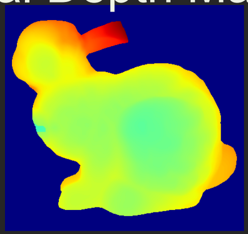
Use Differential Images to initialize

$$\min_{\boldsymbol{z}} \left| \hat{I}_t \boldsymbol{n}^T(\boldsymbol{z})(\boldsymbol{l}-\boldsymbol{p}(\boldsymbol{z})) - \hat{I}\boldsymbol{n}^T(\boldsymbol{z})\boldsymbol{l}_t \right|^{\boldsymbol{2}} + \boldsymbol{R_s}(z)$$

Original Images



Initial Depth Map

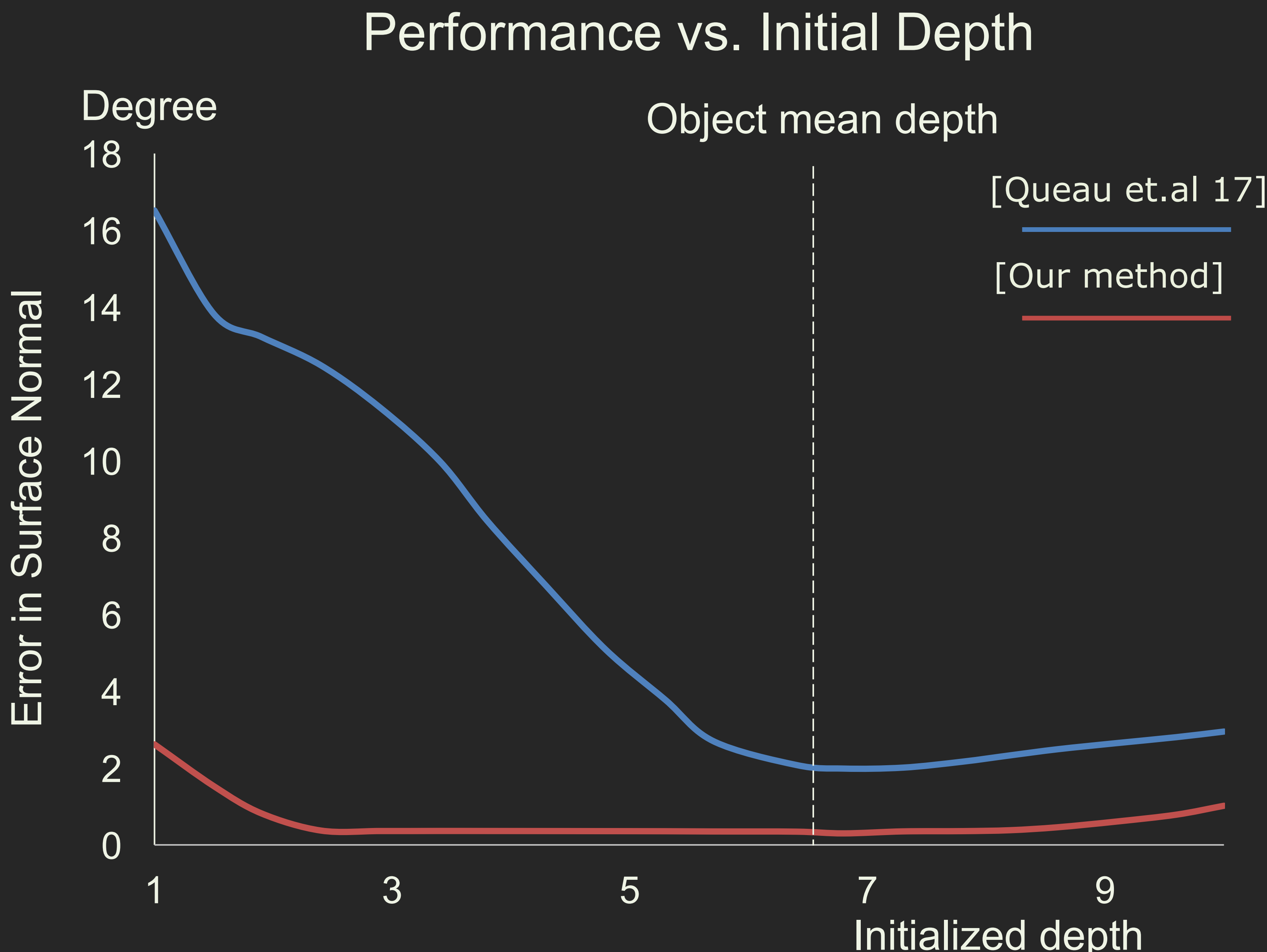


3D shape

Use Original Images directly to refine

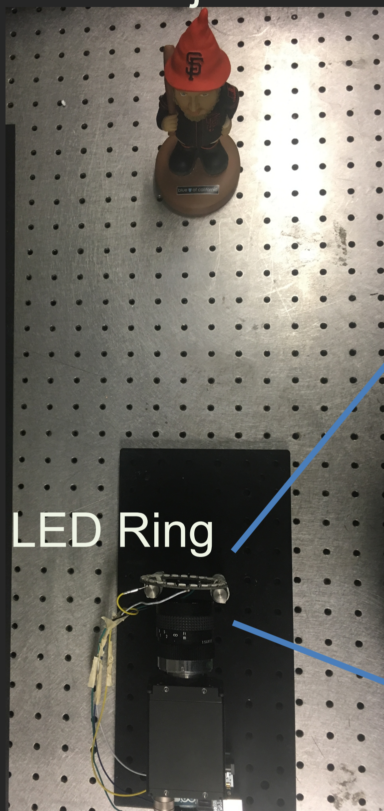
$$\min_{\boldsymbol{z},\rho} \left| \hat{I}_m - \rho(\boldsymbol{u}) \frac{(\boldsymbol{l}_m - \boldsymbol{p}(\boldsymbol{z}))^T}{|\boldsymbol{l}_m - \boldsymbol{p}(\boldsymbol{z})|^3} \boldsymbol{n}(\boldsymbol{z}) \right|^{\boldsymbol{2}} + \boldsymbol{R_s}(z)$$

Simulation: Different Initials



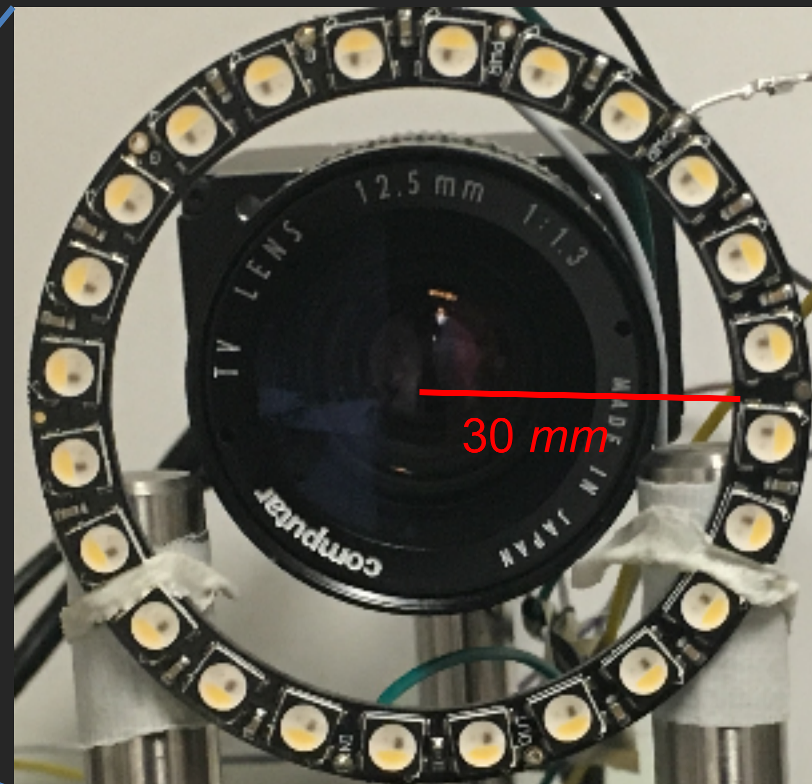
Experiment Setup

Object



LED Ring

Camera

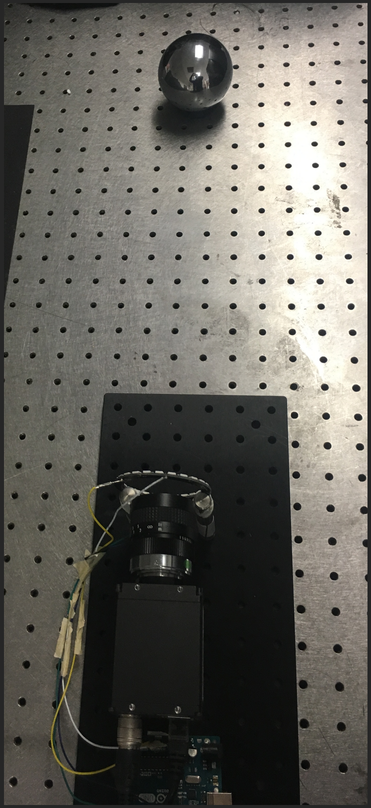


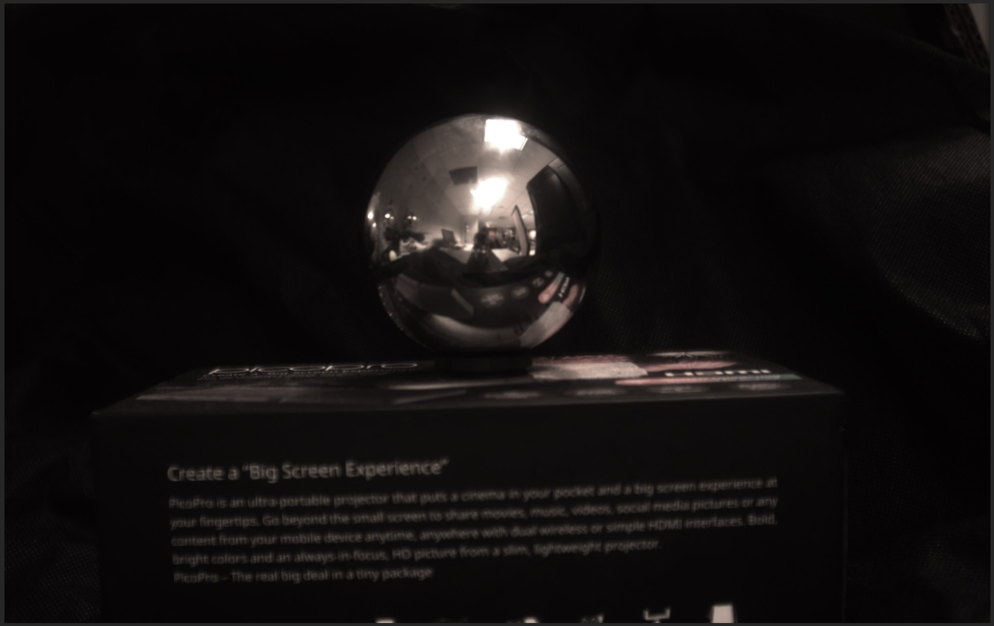
24 LEDs

Light Source Position Calibration

Accurate light source positions are needed.

Chrome Sphere





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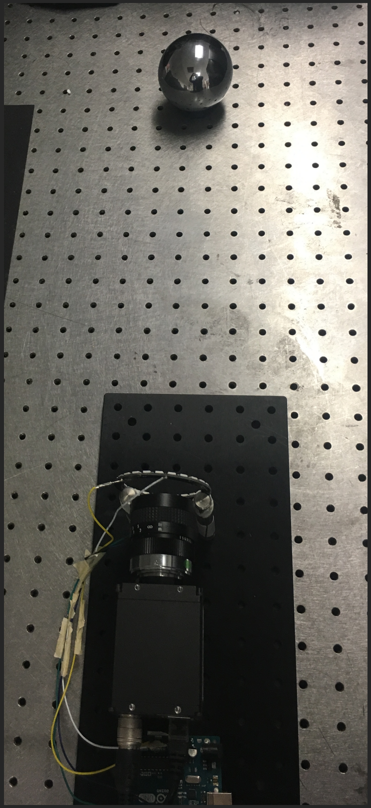


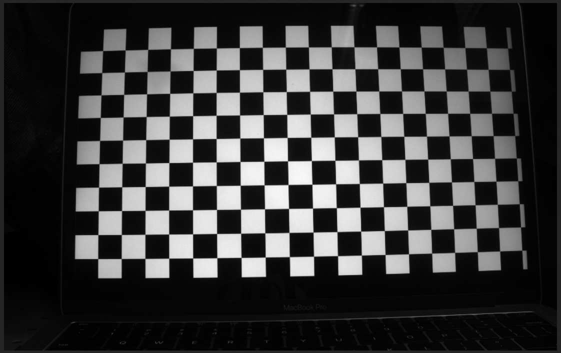
Reflection of light sources

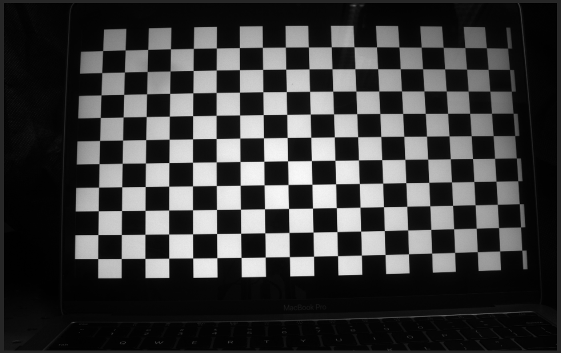
Light Source Position Calibration

Accurate light source positions are needed.

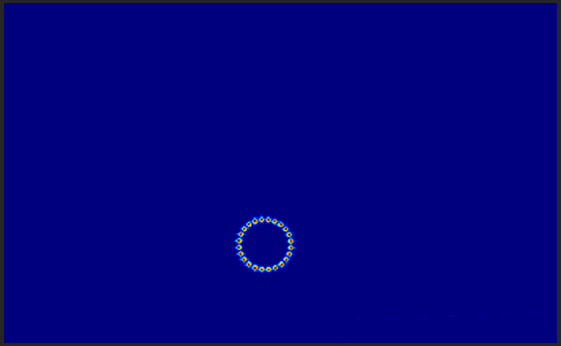
Specular Display

Displayed Checkerboard



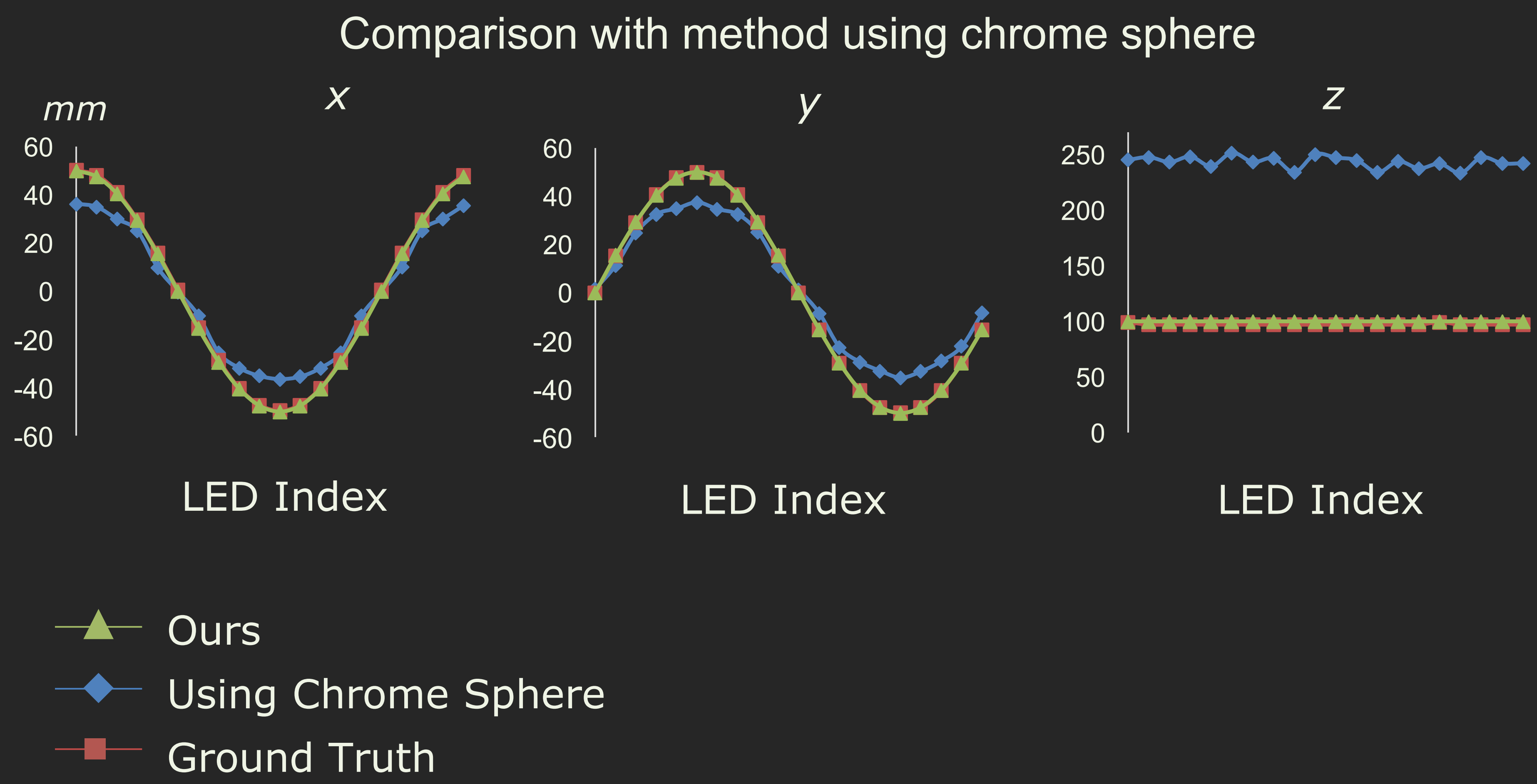


Reflected Light (color encoded)



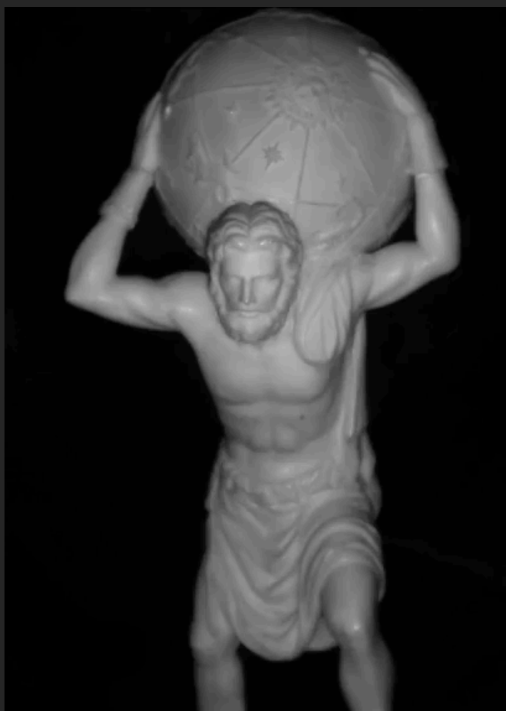
The light positions are estimated by triangulate the reflected rays

Simulation Results on Light Calibration

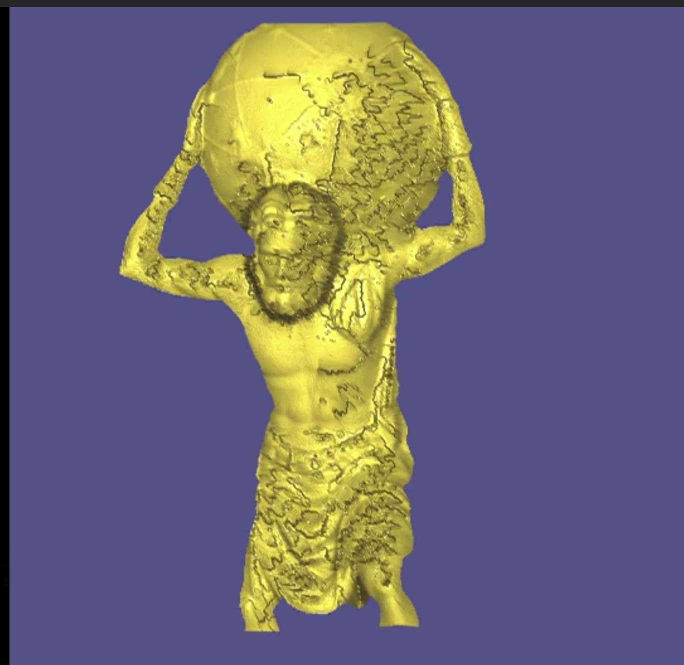


Real Experiment Results

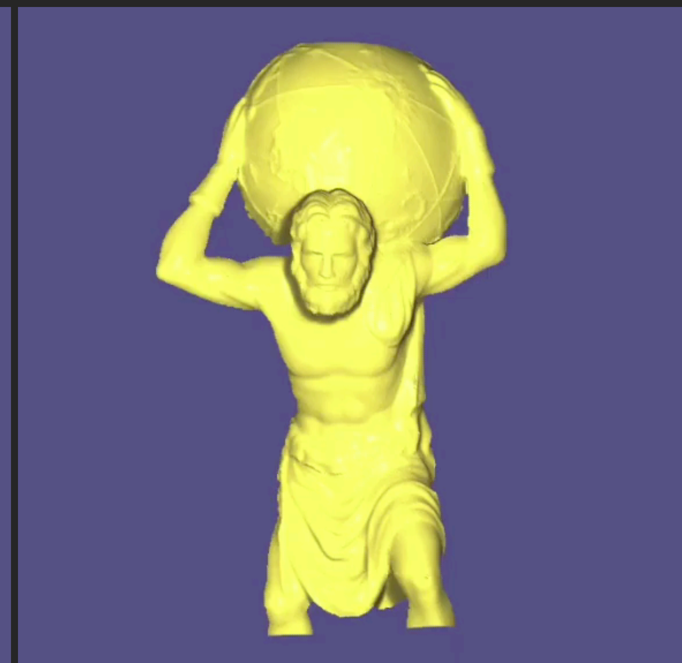
Input images



Initial Depth using
Differential Images



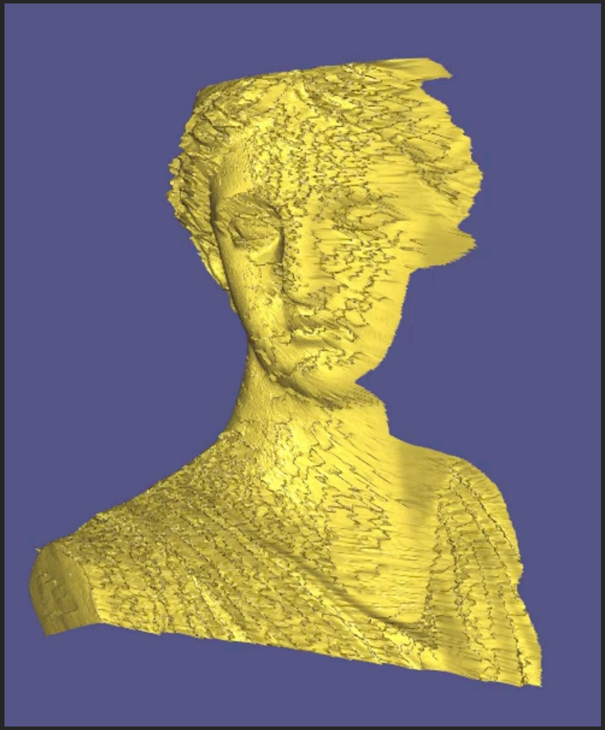
Refined using
Original Images



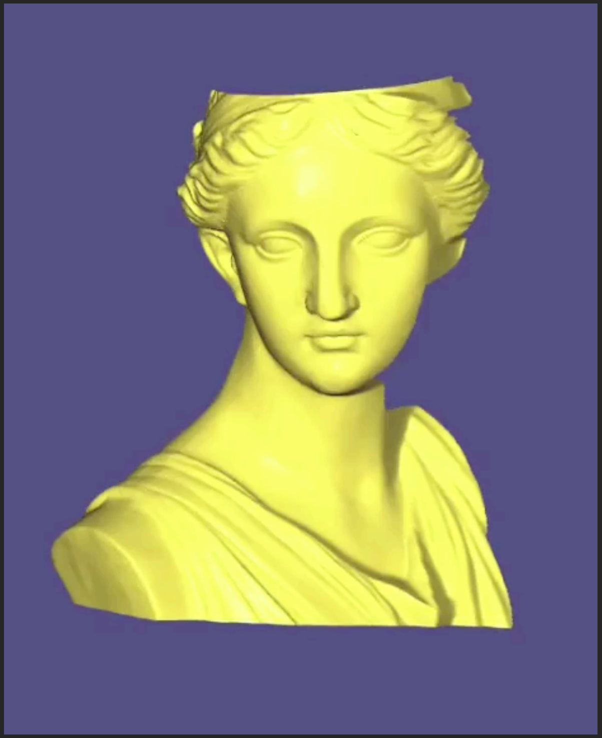
Real Experiment Results

Input images

Initial Depth using Differential Images

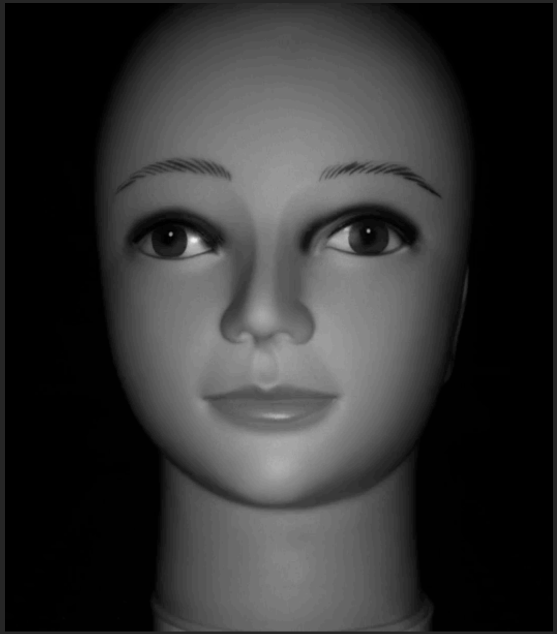


Refined using Original Images

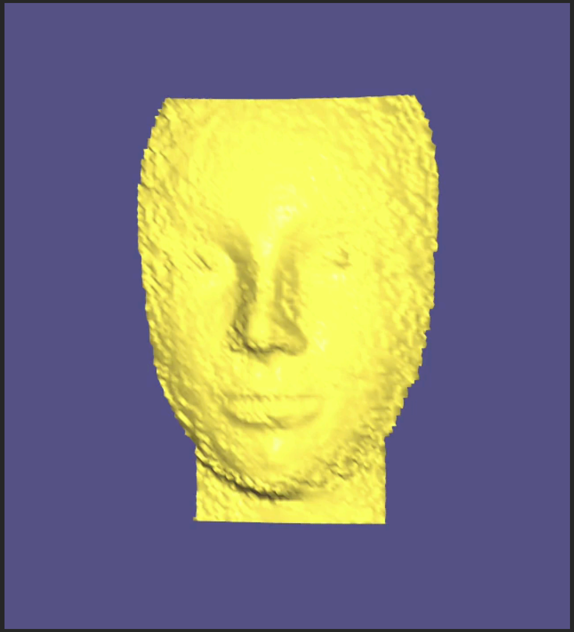


Real Experiment Results

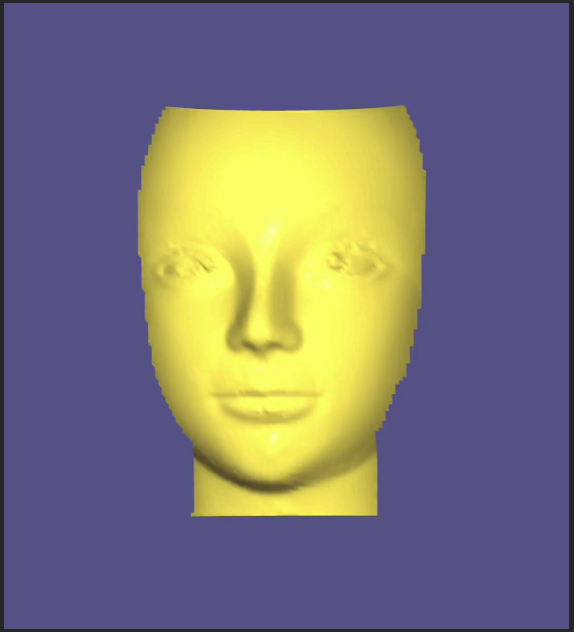
Input images



Initial Depth using
Differential Images

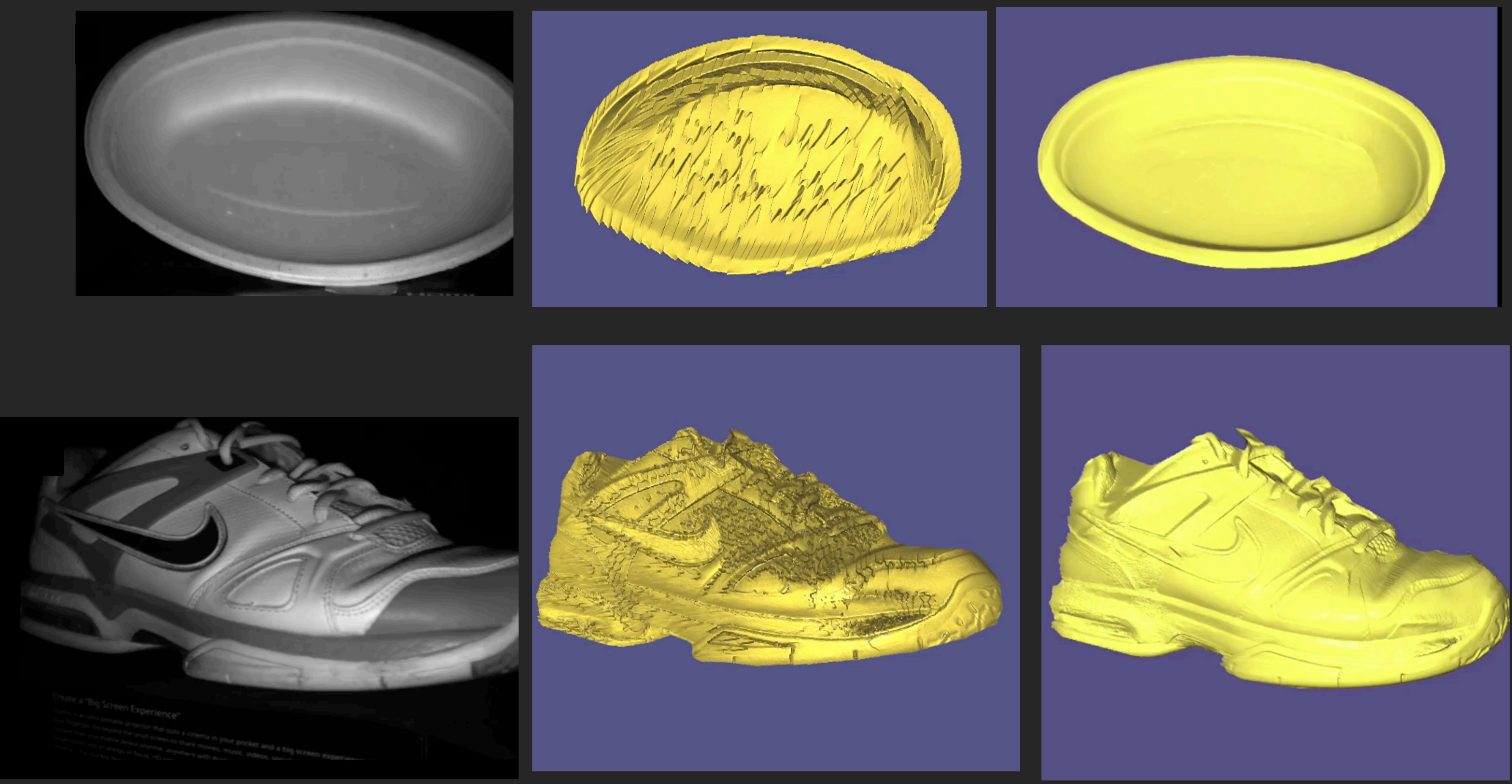


Refined using
Original Images



Real Experiment Results

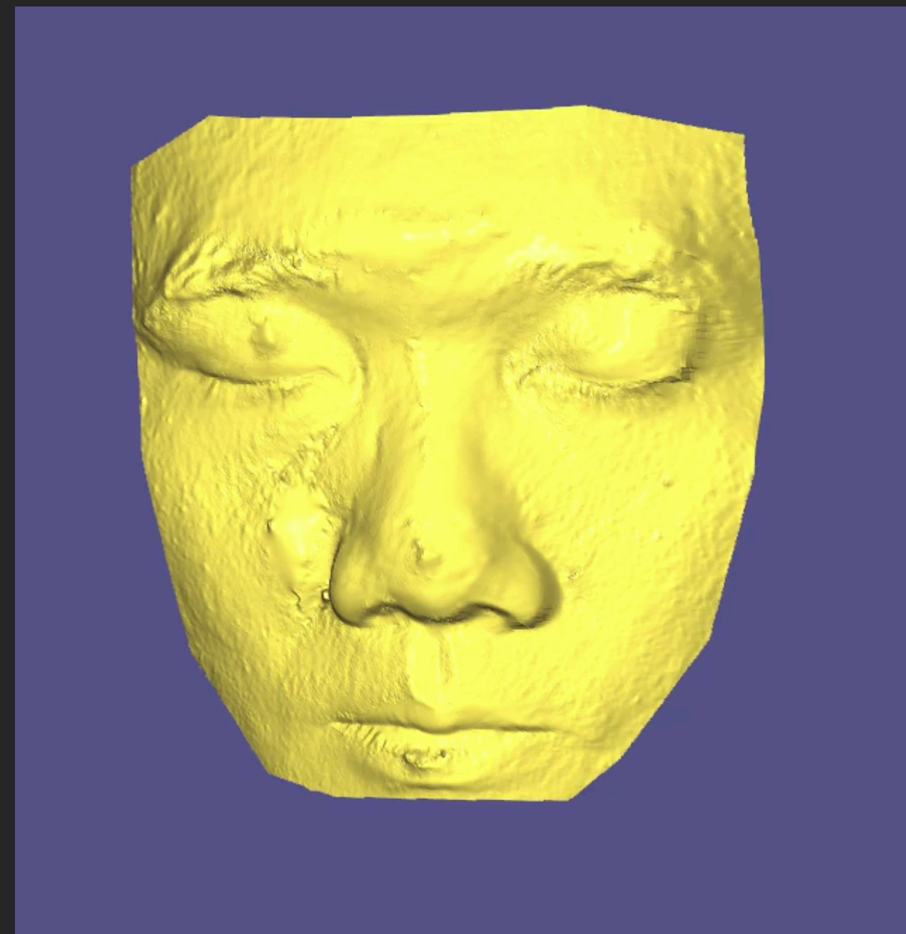
Input images | Initial Depth using Differential Images | Refined using Original Images



Real Experiment Results

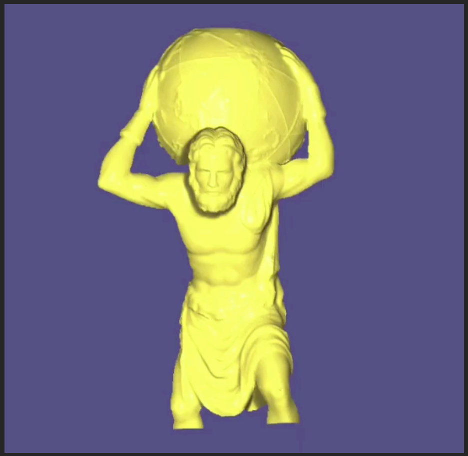
Input images

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 limitationf