ECCV'20 ONLINE
23-28 AUGUST 2020

Polarimetric Multi-View Inverse Rendering (Polarimetric MVIR)

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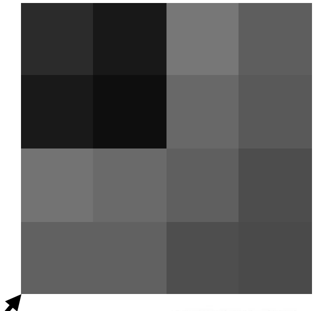
Introduction

Polarization Camera

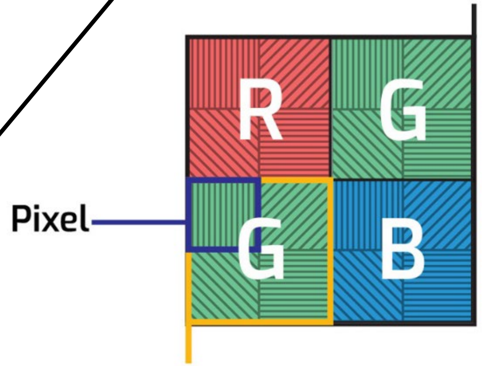
Scene

One-shot polarization camera
(Lucid PHX050S-Q camera)

Captured mosaic raw data



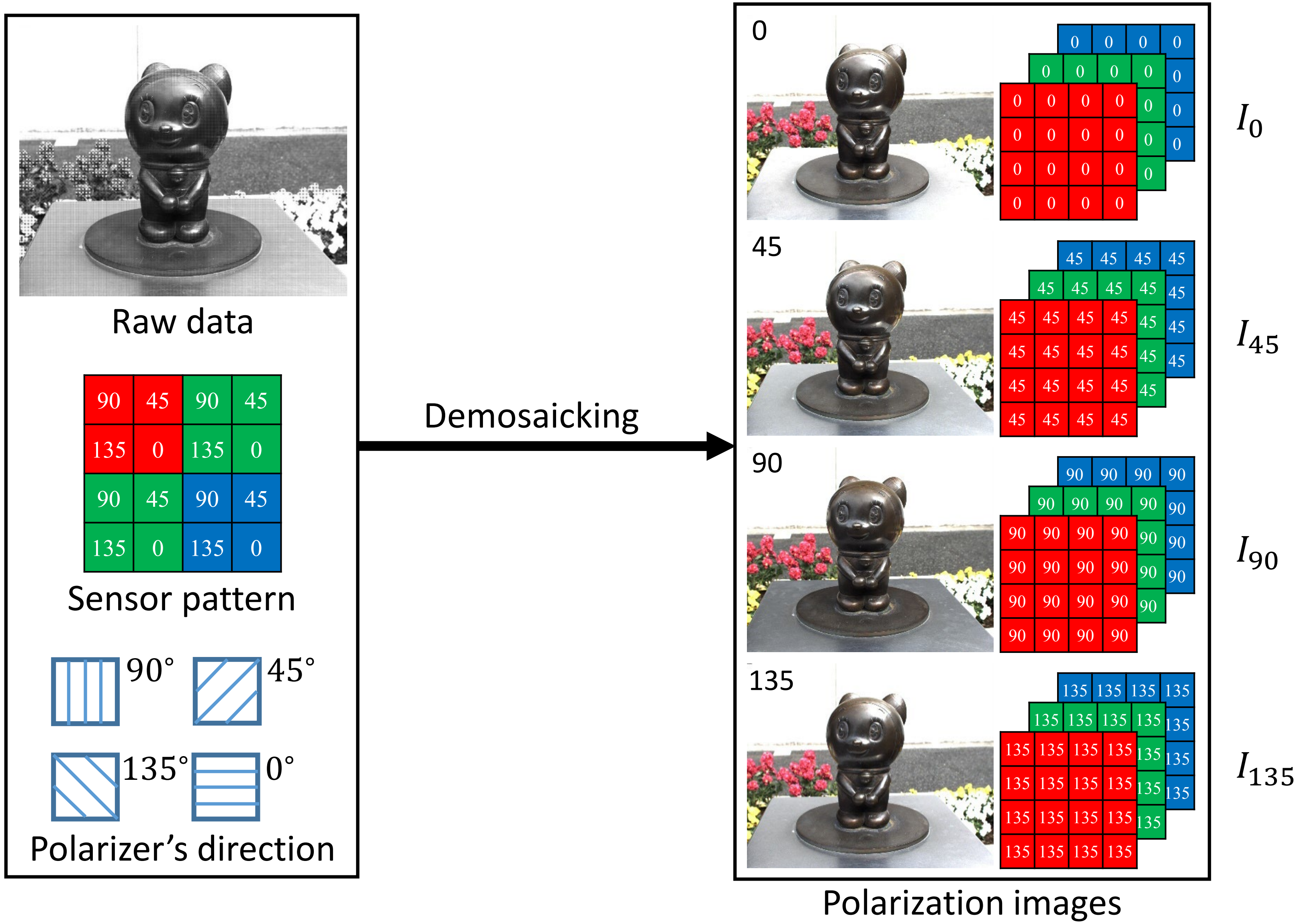
RGGB 16 pixels
calculation unit



Polarization 4 pixels
calculation unit
(4 different wire-grid directions)

Sensor pattern

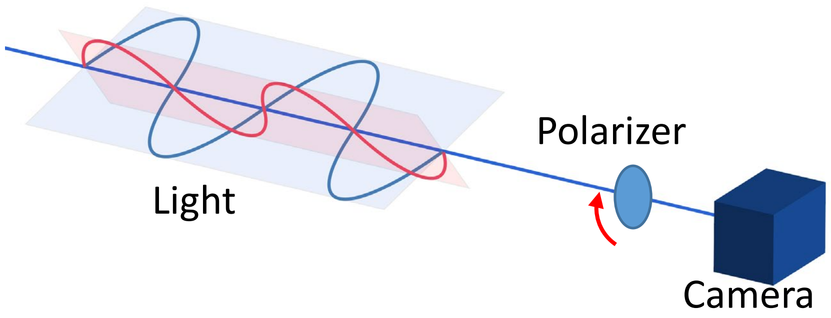
Polarization Data Acquisition



Polarization Data Acquisition

Stokes vector

$$\boldsymbol{s} = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} I_{max} + I_{min} \\ (I_{max} - I_{min})\cos(2\phi) \\ (I_{max} - I_{min})\sin(2\phi) \\ 0 \end{bmatrix} = \begin{bmatrix} I_0 + I_{90} \\ I_0 - I_{90} \\ I_{45} - I_{135} \\ 0 \end{bmatrix}$$



$$I\left(\phi_{\mathrm{pol}}\right) = \frac{I_{\max} + I_{\min}}{2} + \frac{I_{\max} - I_{\min}}{2} \cos\left(2\left(\phi_{\mathrm{pol}} - \phi\right)\right)$$

ϕ: Angle of polarization

ϕ_{pol}: Polarizer angle of the sensor

➢ Intensity information

$$I = s_0$$

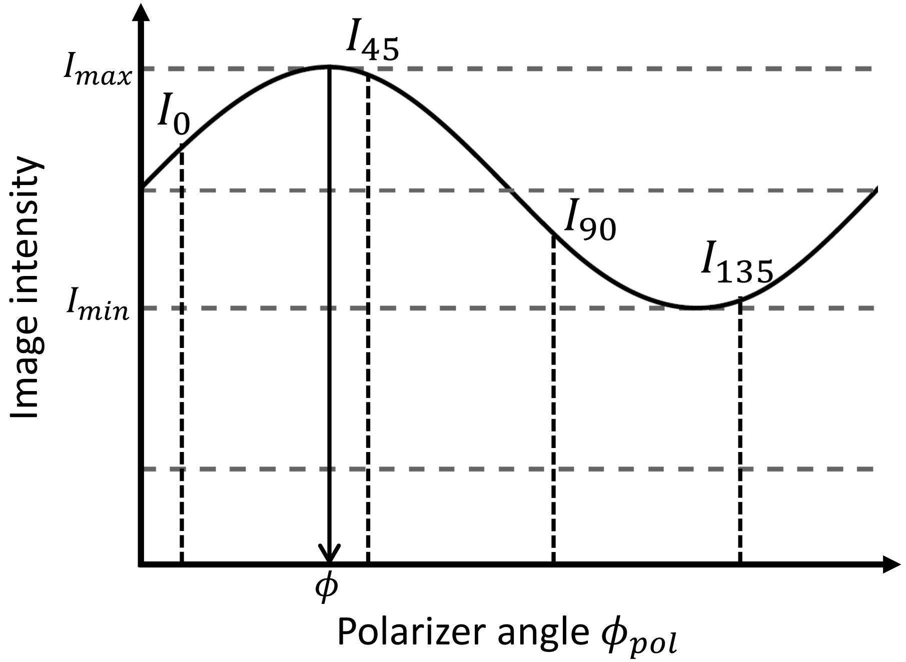
➢ Polarimetric information

- Angle of Polarization (AoP)

$$\phi = \frac{1}{2}\tan^{-1}\frac{s_2}{s_1}$$

- Degree of Polarization (DoP)

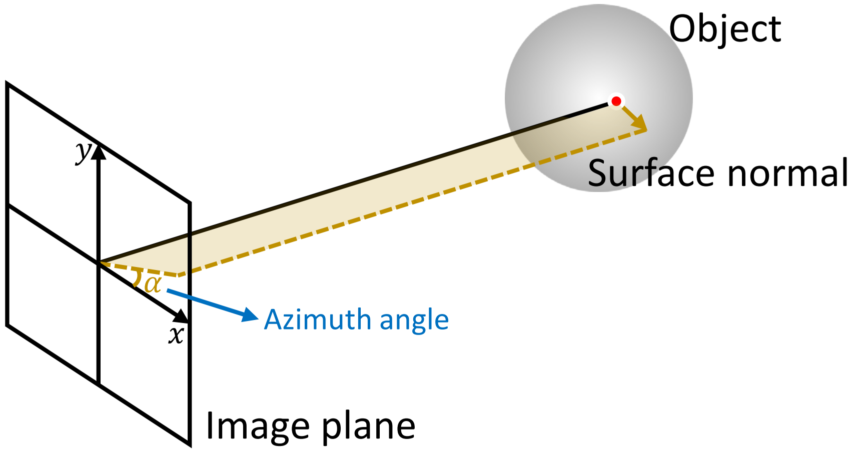
$$\rho = \frac{\sqrt{s_1^2 + s_2^2}}{s_0}$$



Relationship Between AoP and Surface Normal

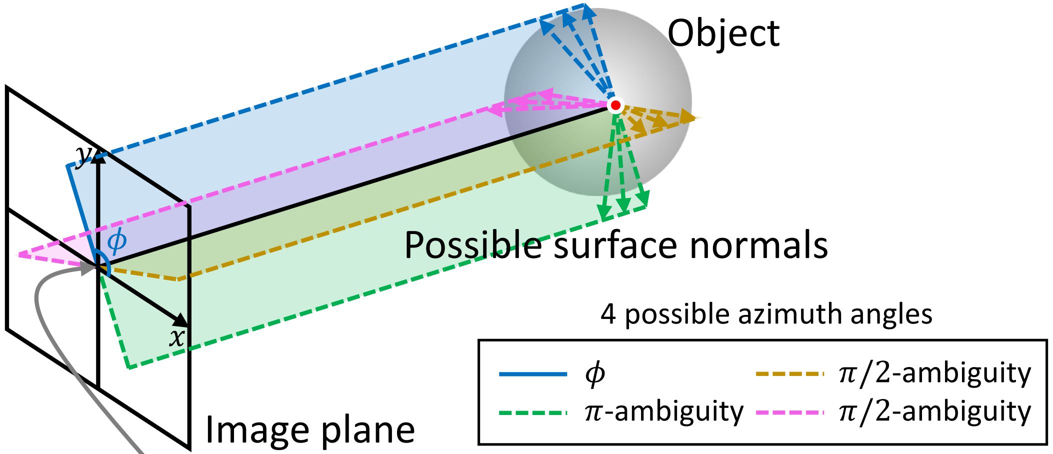
- **Azimuth angle (α)**

The angle between x-axis and projection of the surface normal to the image plane.



- **AoP (ϕ) and possible azimuth angles**

Polarized specular reflection dominates: $|\phi - \alpha| = \pi/2$
Polarized diffuse reflection dominates: $|\phi - \alpha| = 0$ or π



Azimuth angle map

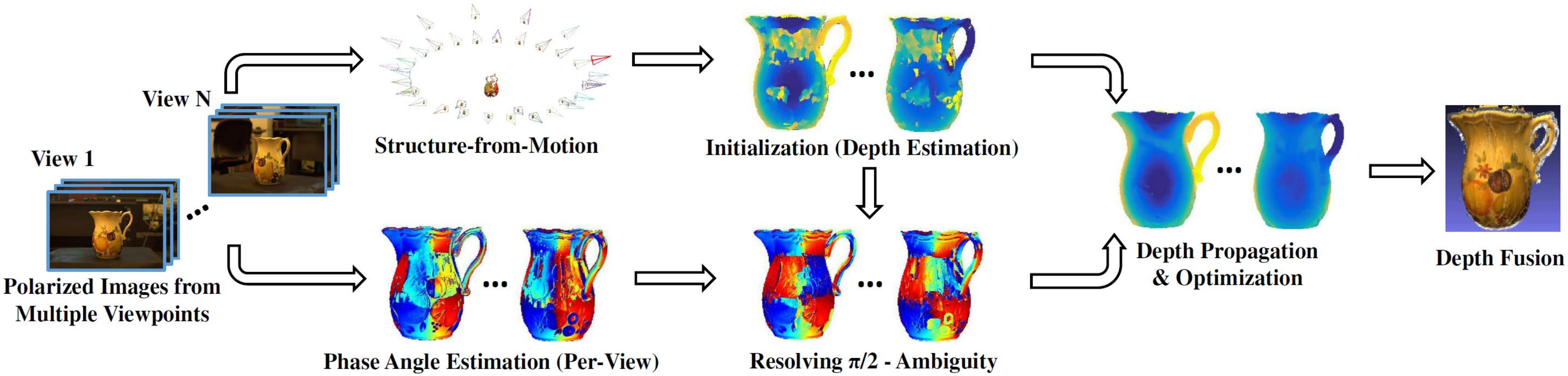
Related with ambiguities

AoP image

Related Work: Polarimetric Multi-View Stereo

➢ **State-of-the-art multi-view stereo method using polarization camera**

- Calculate AoP and resolve ambiguities
- Propagate the depth according to disambiguated AoP
- Optimize and fuse the depth

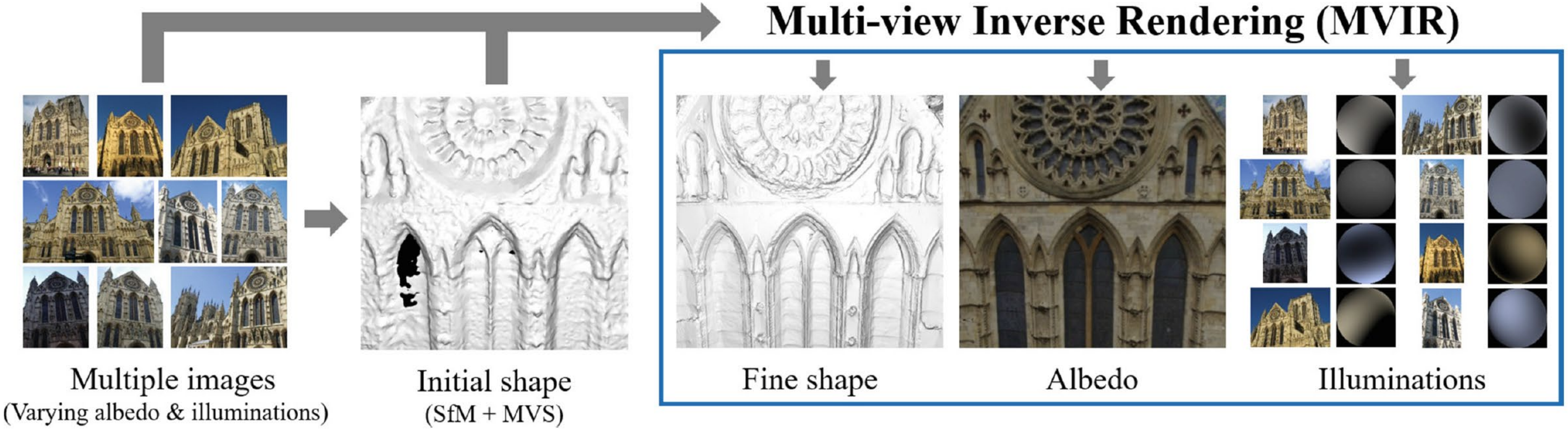


Cui, Z., Gu, J., Shi, B., Tan, P., Kautz, J.: Polarimetric multi-view stereo. (CVPR 2017)

Related Work: Multi-View Inverse Rendering

➢ **State-of-the-art method combining photometry and geometry**

- Input RGB images, camera poses and initial 3D shape
- Solve an optimization problem using photometric and geometric information
- Derive detailed shape, albedo and illumination



Kim, K., Torii, A., Okutomi, M.: Multi-view inverse rendering under arbitrary illumination and albedo. (ECCV 2016)

Our Contributions

We propose Polarimetric MVIR:

- The first method based on multi-view photometric and polarimetric optimization with an inverse rendering framework.

Method	Geometry	Photometry	Polarimetry
Polarimetric MVS	✓		✓
MVIR	✓	✓	
Polarimetric MVIR (Ours)	✓	✓	✓

- A novel polarimetric cost function is proposed to effectively constrain the surface normal while considering ambiguities as an optimization problem.

Proposed Method

Polarimetric MVIR: Input Data

Scene

Raw image

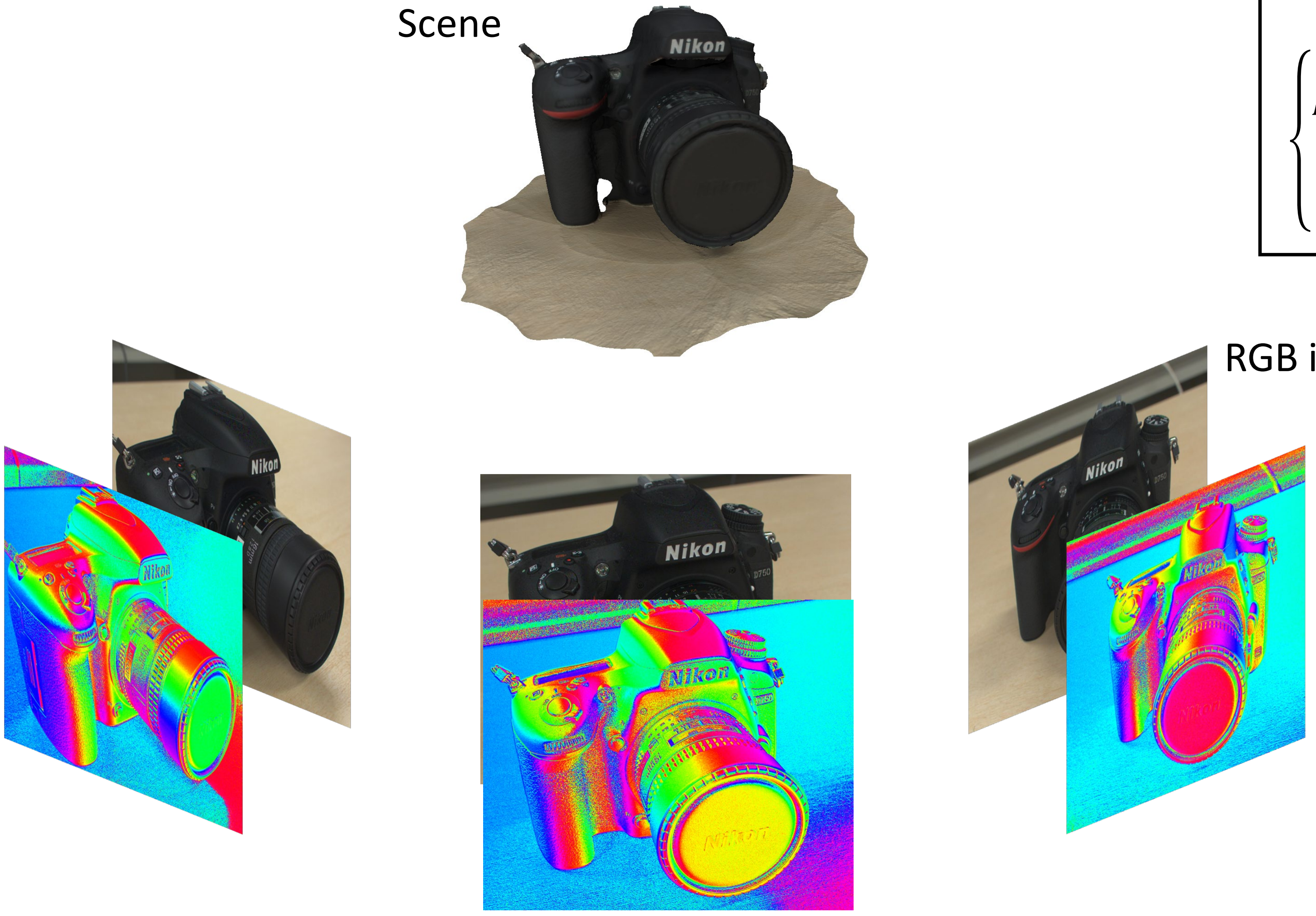
Polarimetric MVIR: Input Data

I_{min} and ϕ's calculation

$$\boldsymbol{s} = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} I_0 + I_{90} \\ I_0 - I_{90} \\ I_{45} - I_{135} \end{bmatrix}$$

$$\begin{cases} I_{min} = \dfrac{s_0 - \sqrt{s_1^2 + s_2^2}}{2} \\ \phi = \dfrac{1}{2}\tan^{-1}\dfrac{s_2}{s_1} \end{cases}$$

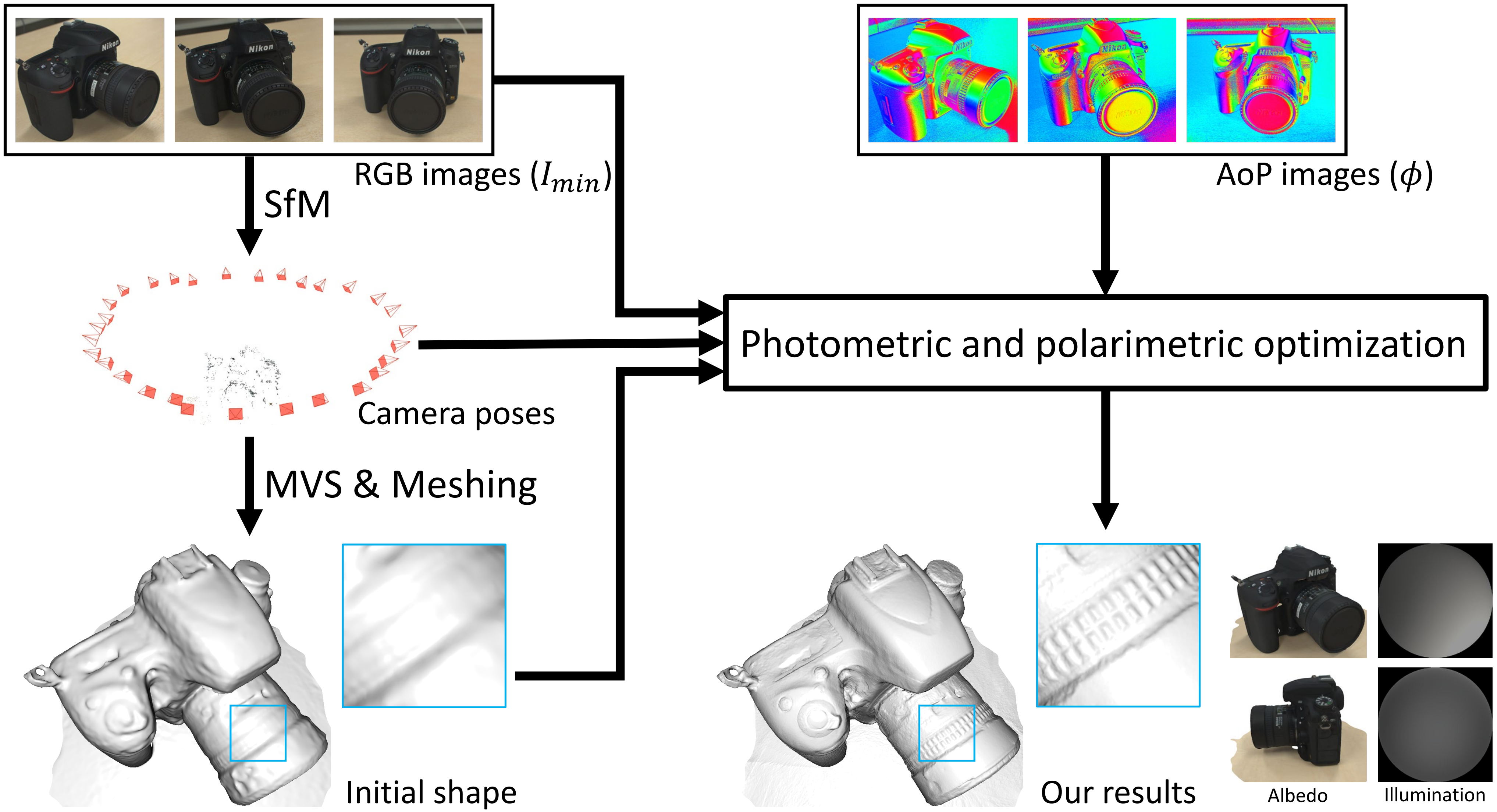
Scene



RGB image (I_{min})

AoP image (ϕ)

Polarimetric MVIR: Overview

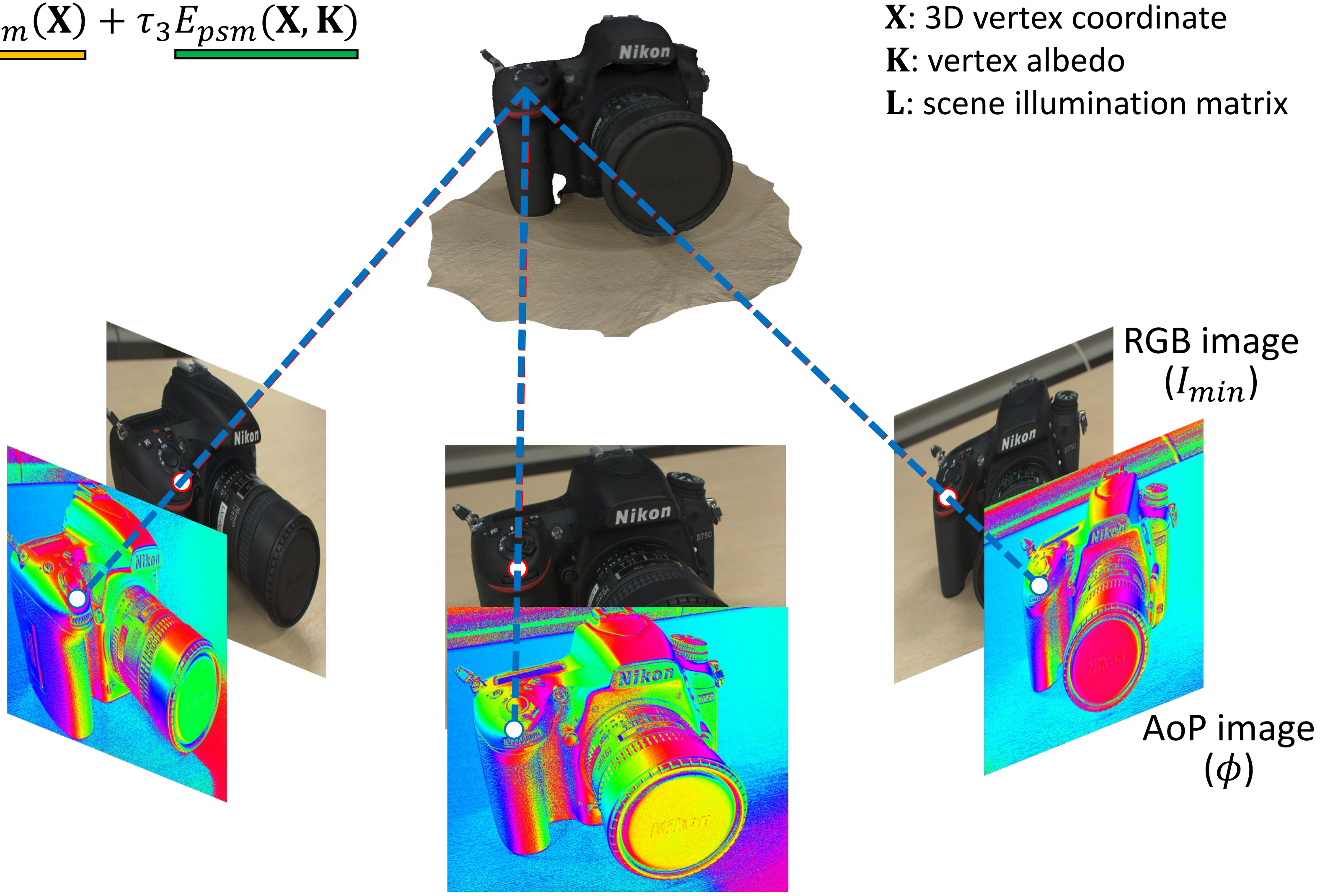


Multi-View Photometric and Polarimetric Optimization

$$\underset{\mathbf{X},\mathbf{K},\mathbf{L}}{\arg\min}\ \underline{E_{pho}(\mathbf{X},\mathbf{K},\mathbf{L})} + \tau_1 \underline{E_{pol}(\mathbf{X})} + \tau_2 \underline{E_{gsm}(\mathbf{X})} + \tau_3 \underline{E_{psm}(\mathbf{X},\mathbf{K})}$$

- Photometric error term
- Polarimetric error term
- Geometric smoothness term
- Photometric smoothness term

X: 3D vertex coordinate
K: vertex albedo
L: scene illumination matrix



Multi-View Photometric and Polarimetric Optimization

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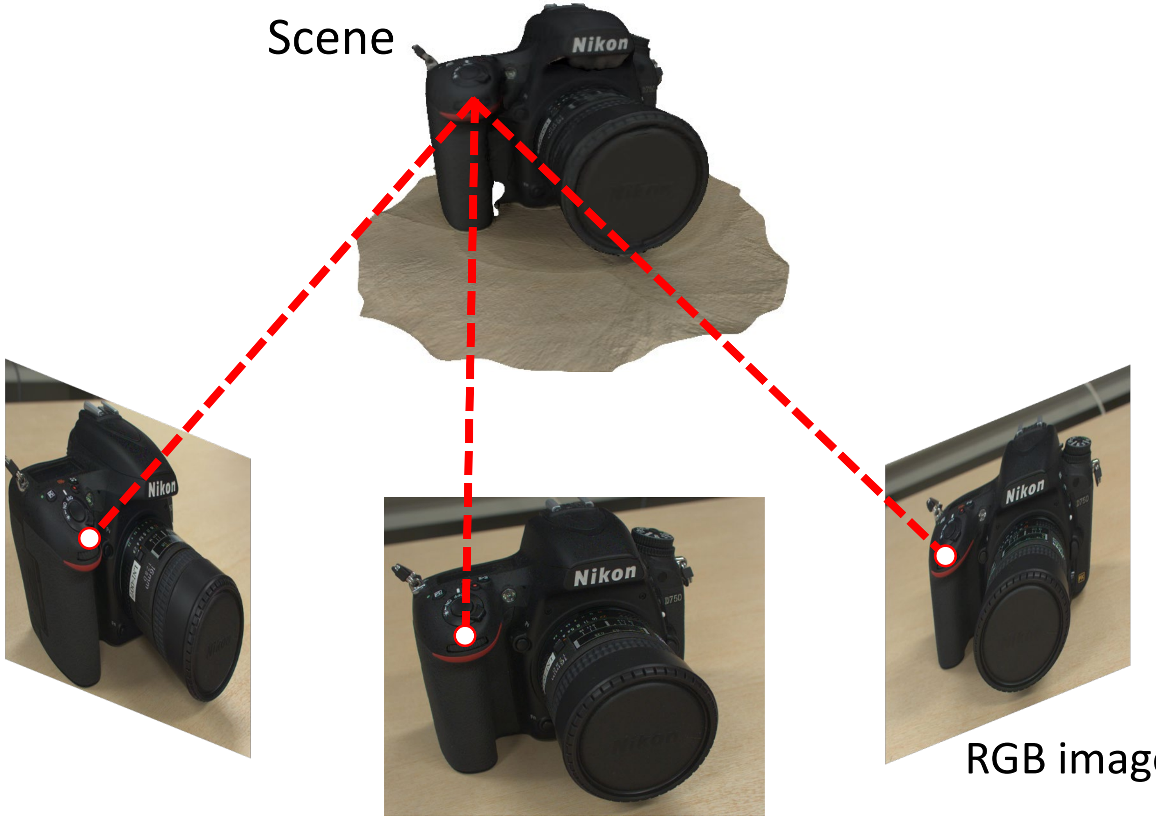
- Photometric error term



RGB image $\mathbf{I}$

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Multi-View Photometric and Polarimetric Optimization

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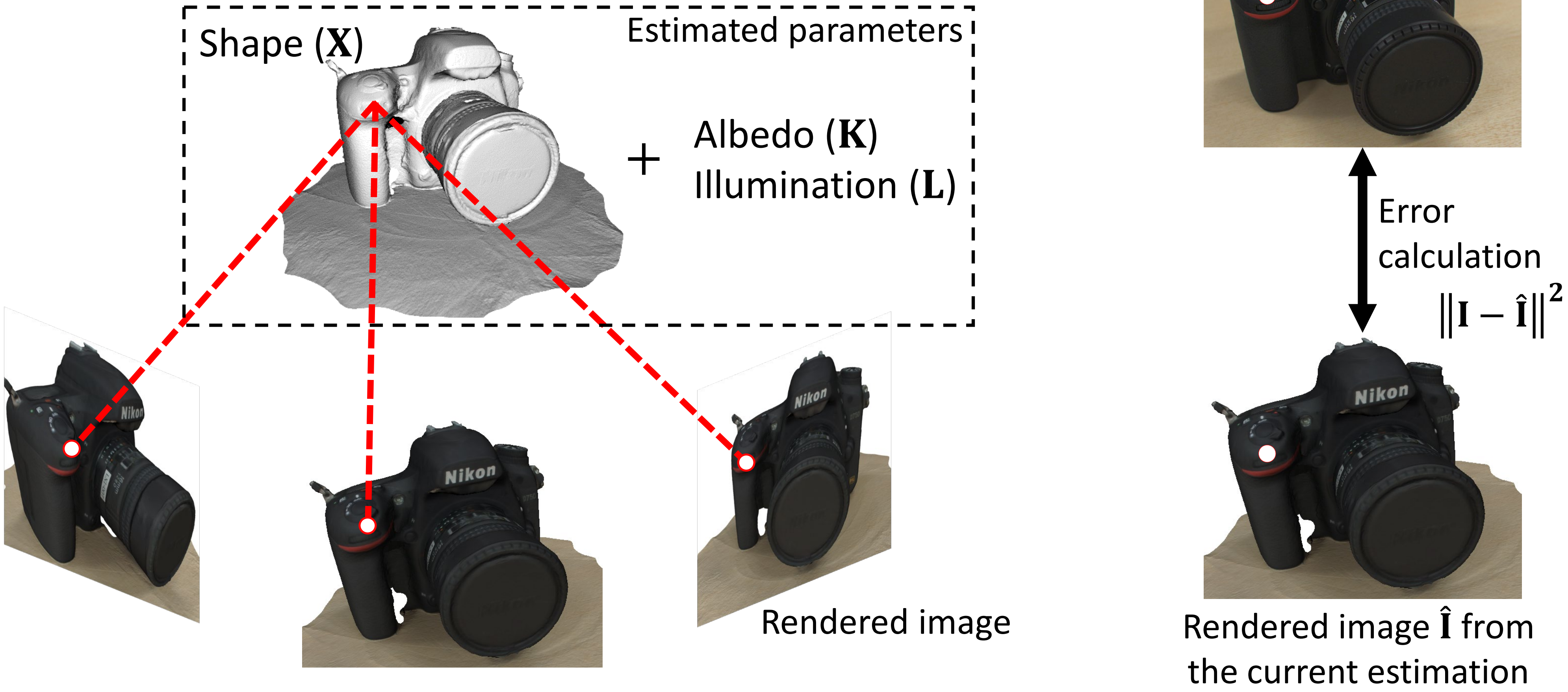
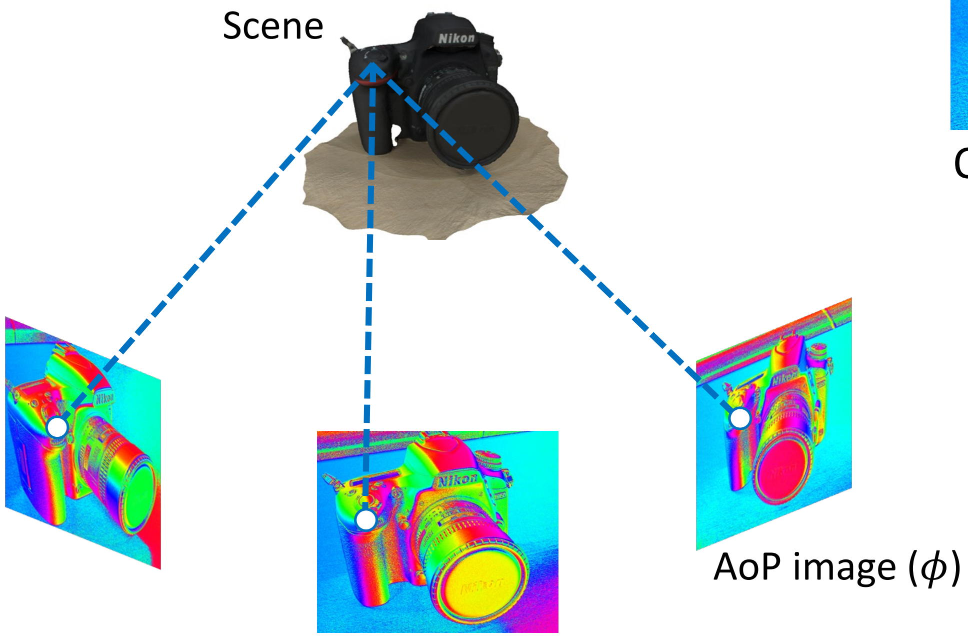


Multi-View Photometric and Polarimetric Optimization

$$\underset{\mathbf{X},\mathbf{K},\mathbf{L}}{\arg\min}\, E_{pho}(\mathbf{X},\mathbf{K},\mathbf{L}) + \tau_1 \underline{E_{pol}(\mathbf{X})} + \tau_2 E_{gsm}(\mathbf{X}) + \tau_3 E_{psm}(\mathbf{X},\mathbf{K})$$

- Polarimetric error term

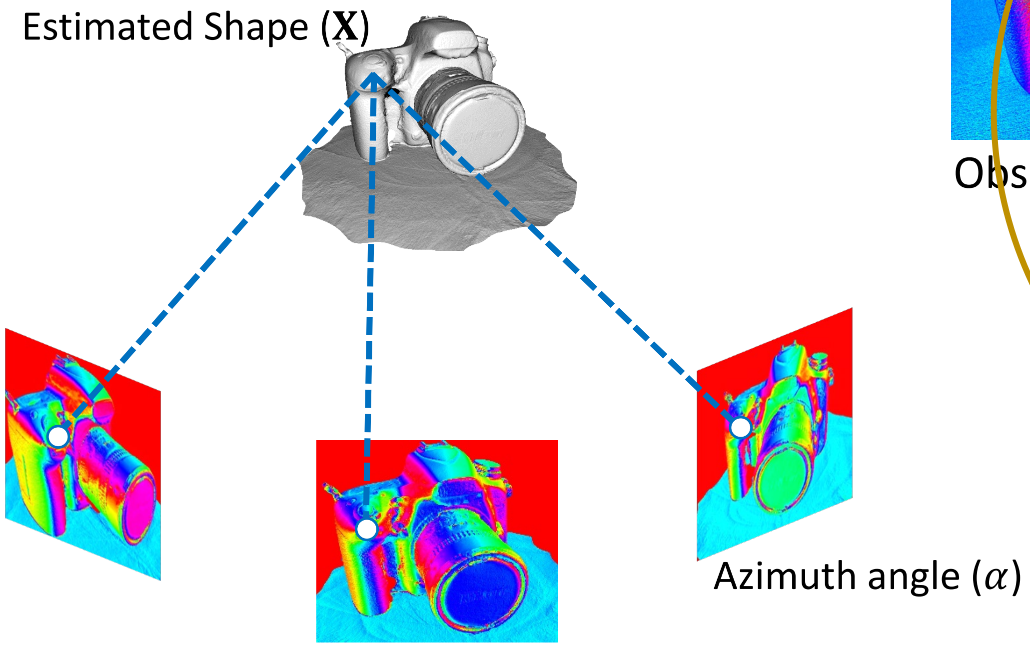


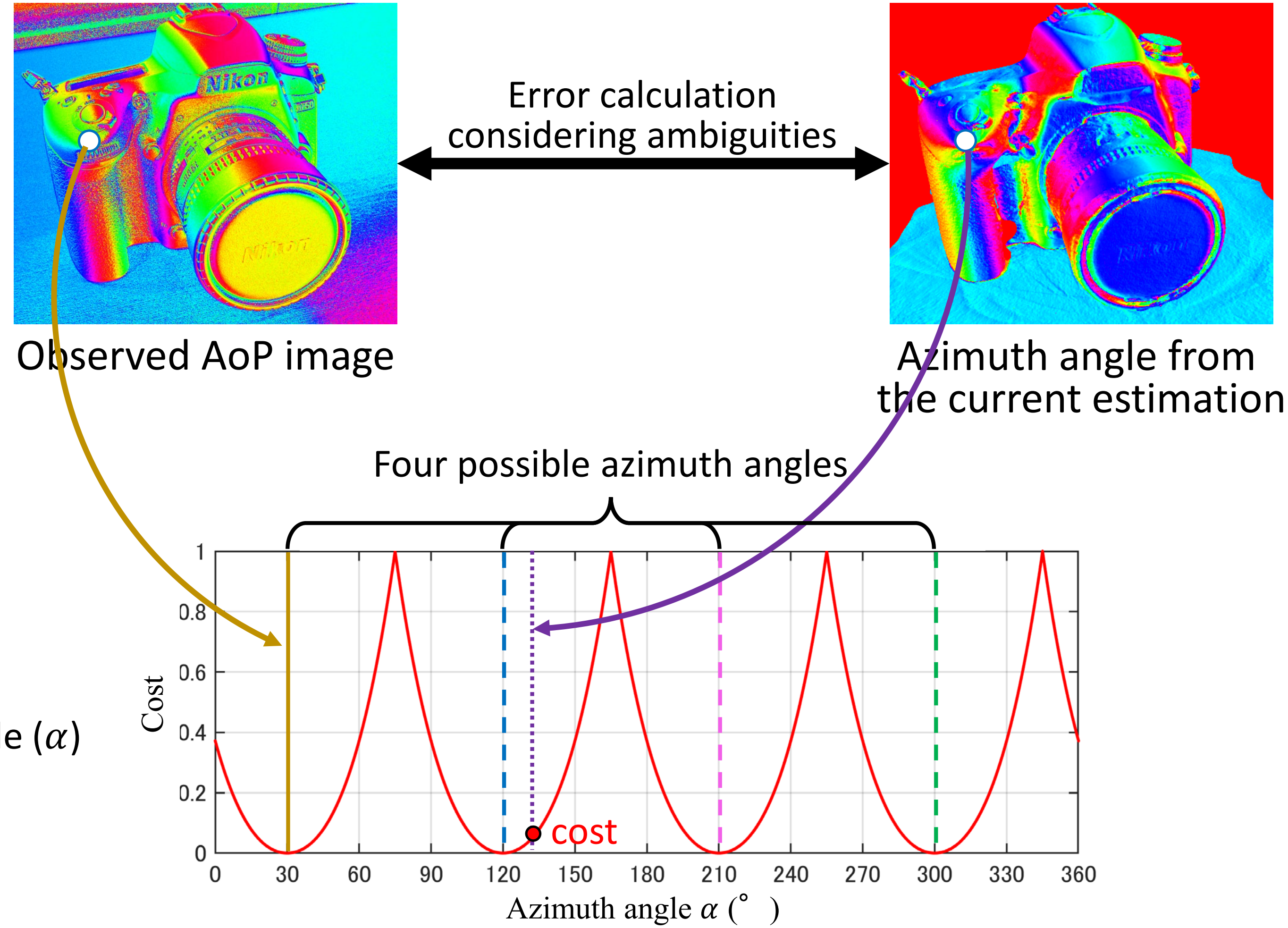
Observed AoP image

Multi-View Photometric and Polarimetric Optimization

$$\underset{\mathbf{X},\mathbf{K},\mathbf{L}}{\arg\min}\, E_{pho}(\mathbf{X},\mathbf{K},\mathbf{L}) + \tau_1 \underline{E_{pol}(\mathbf{X})} + \tau_2 E_{gsm}(\mathbf{X}) + \tau_3 E_{psm}(\mathbf{X},\mathbf{K})$$

- Polarimetric error term





Our proposed cost function ($\phi = 30°$)

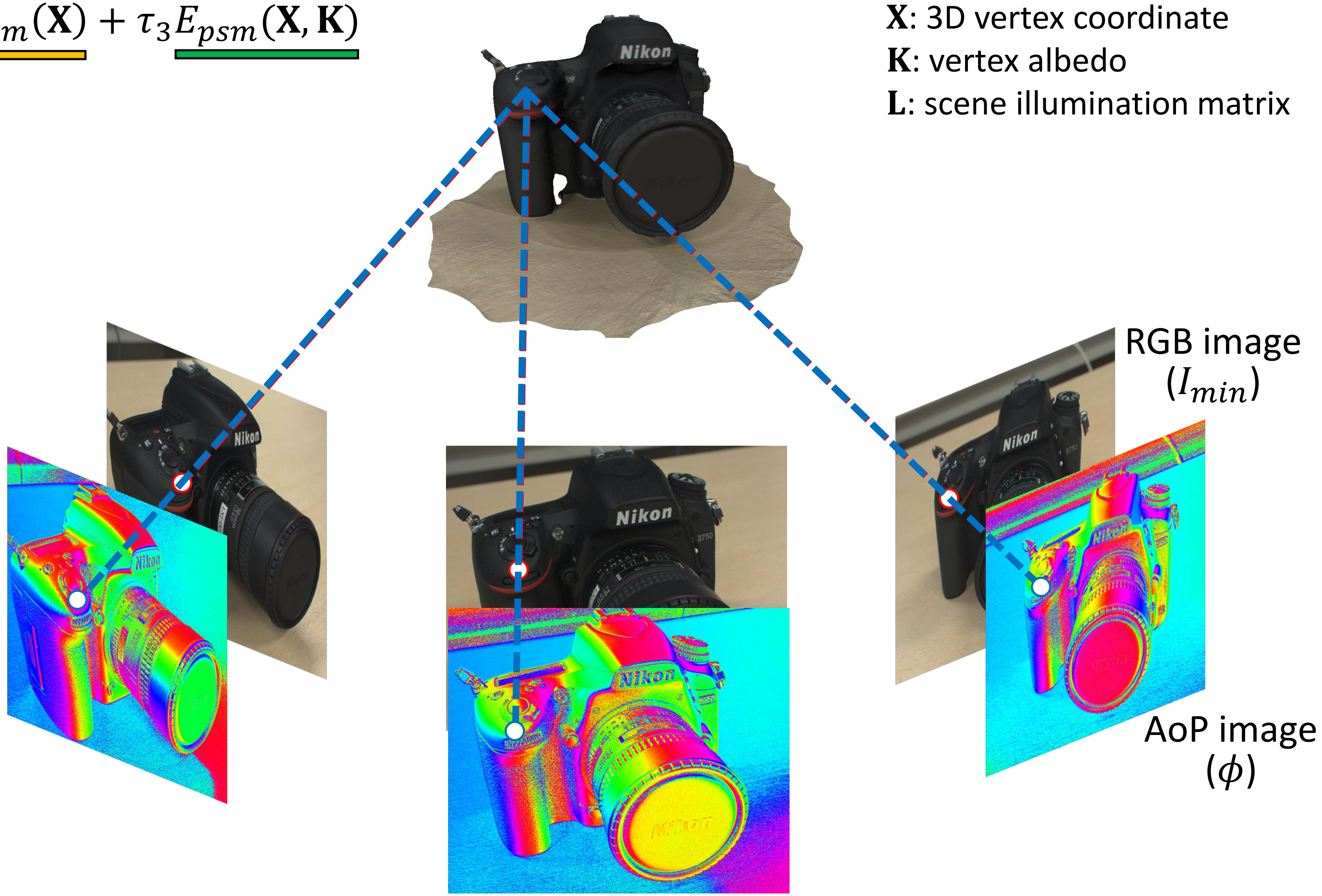
Multi-View Photometric and Polarimetric Optimization

$$\underset{\mathbf{X},\mathbf{K},\mathbf{L}}{\arg\min}\ \underline{E_{pho}(\mathbf{X},\mathbf{K},\mathbf{L})} + \tau_1 \underline{E_{pol}(\mathbf{X})} + \tau_2 \underline{E_{gsm}(\mathbf{X})} + \tau_3 \underline{E_{psm}(\mathbf{X},\mathbf{K})}$$

- Photometric error term
- Polarimetric error term
- Geometric smoothness term
- Photometric smoothness term

Equations and more details can be seen in our paper.

X: 3D vertex coordinate
K: vertex albedo
L: scene illumination matrix

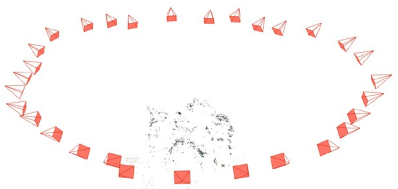


Real Scene Results

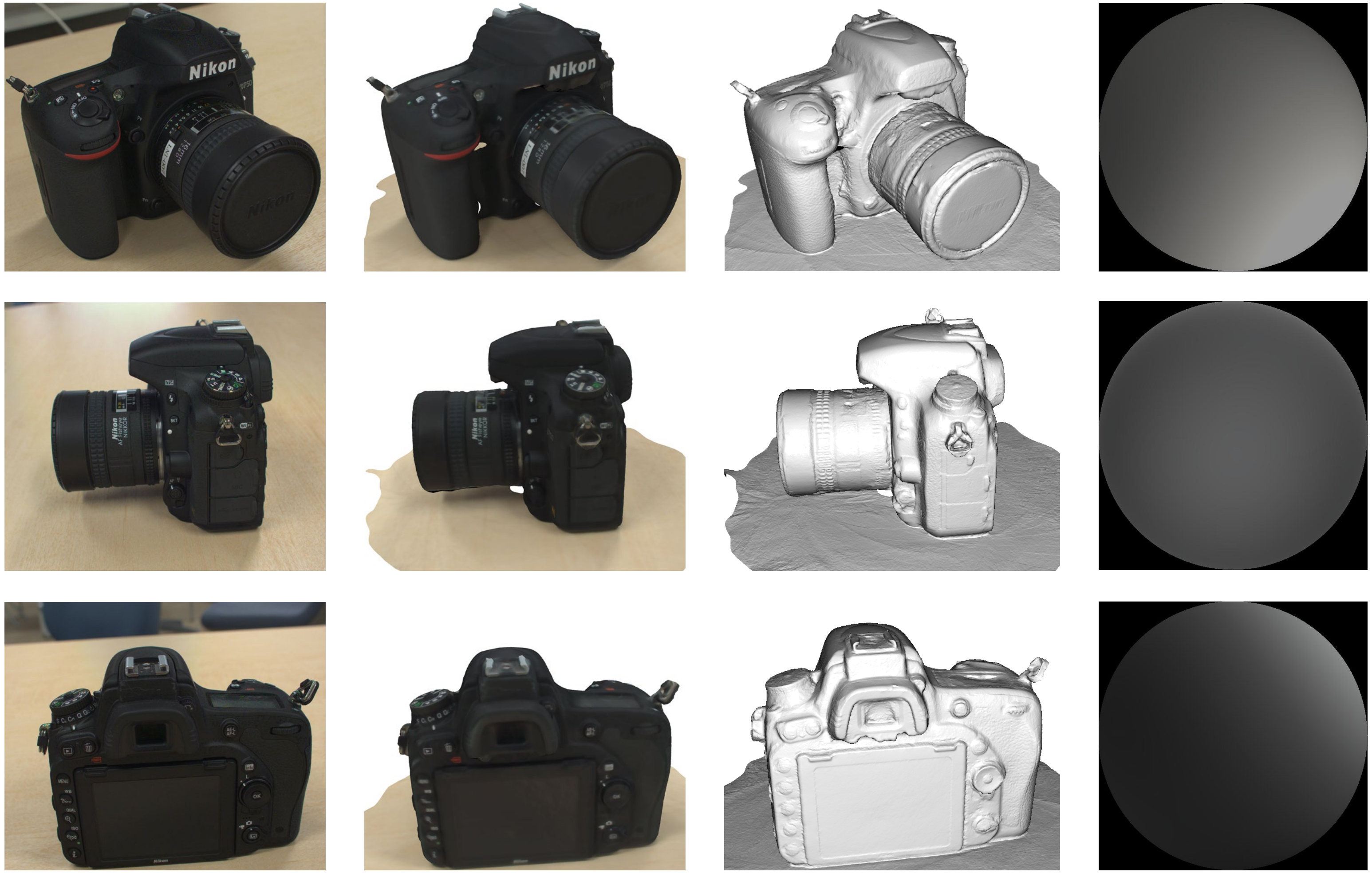
Camera (31 views) - Our Results

RGB images

AoP images



Estimated camera poses



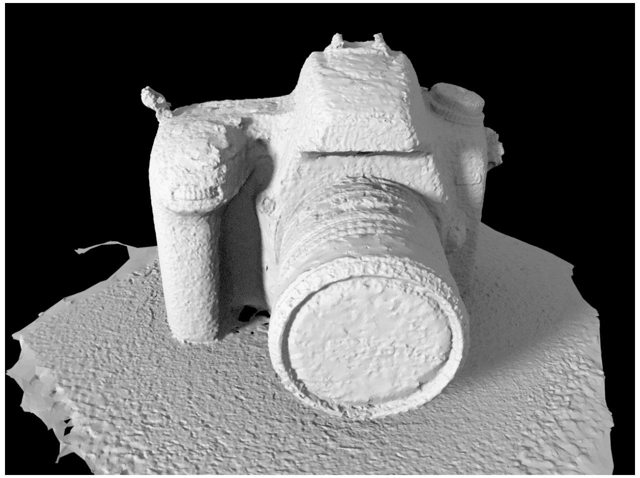
Input image | Estimated albedo | Estimated shape | Estimated illumination

Camera (31 views) - Comparison

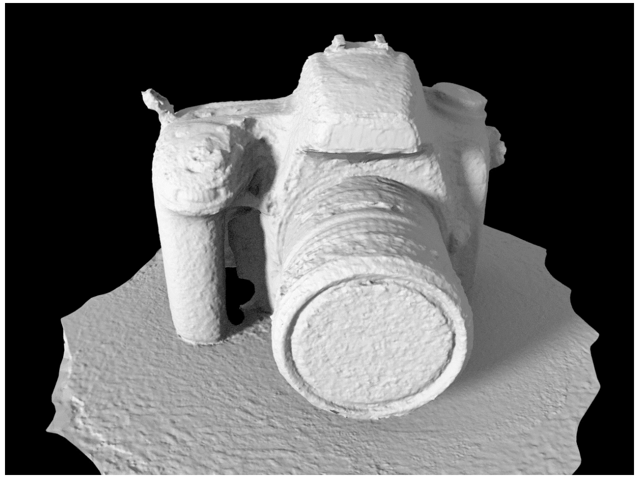
RGB images

AoP images

Estimated camera poses



CMPMVS



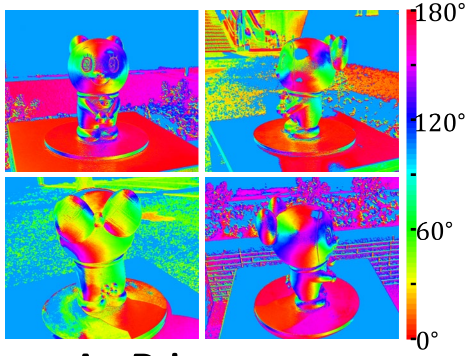
OpenMVS

MVIR

Polarimetric MVIR (Ours)

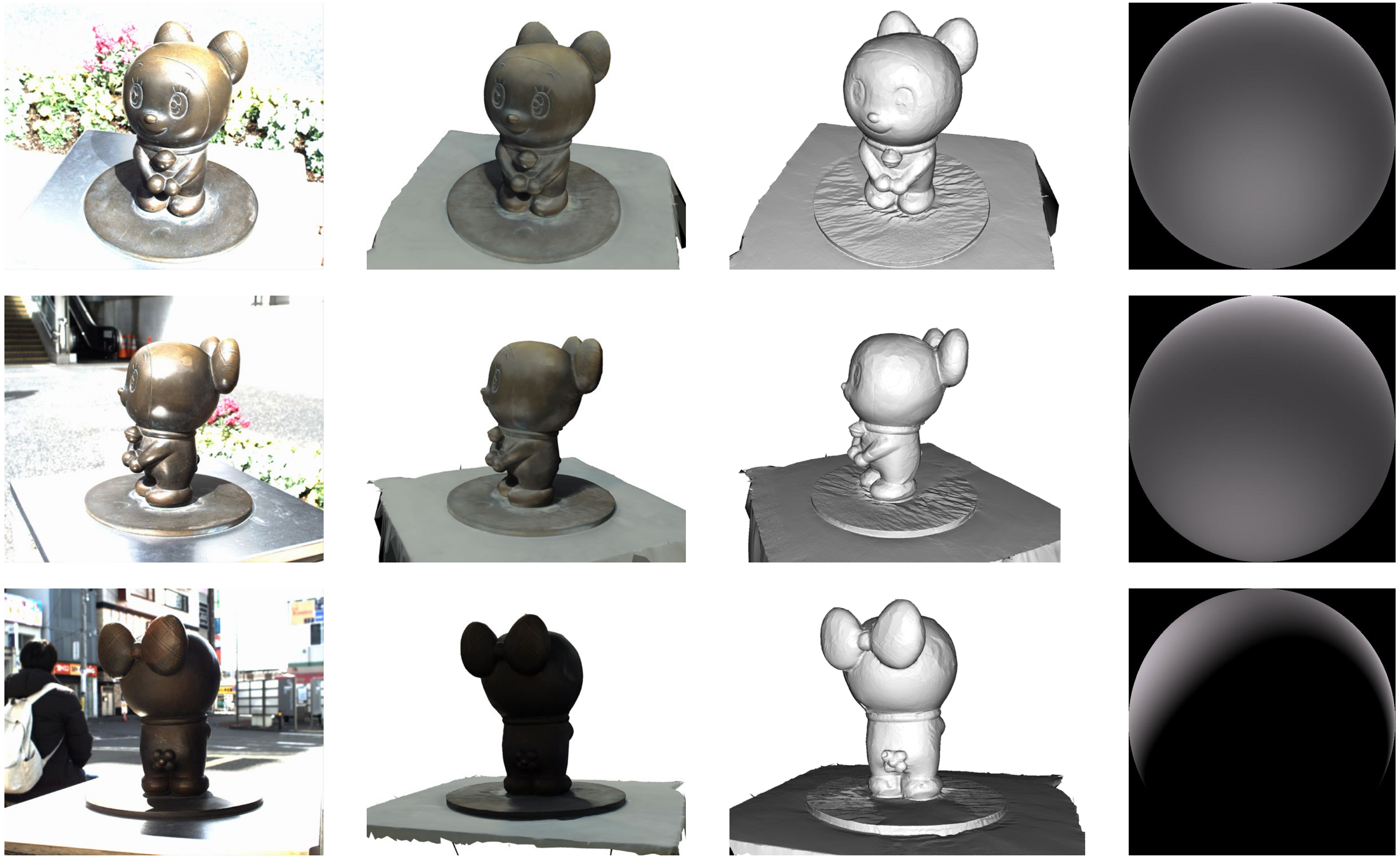
Statue (43 views) - Our Results

RGB images



AoP images

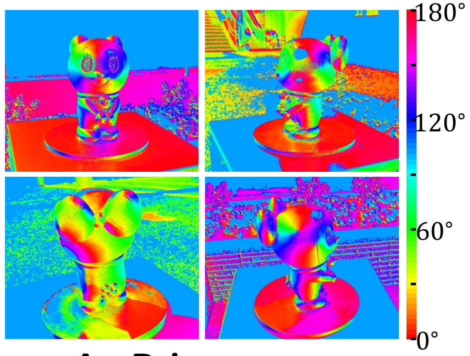
Estimated camera poses



Input image | Estimated albedo | Estimated shape | Estimated illumination

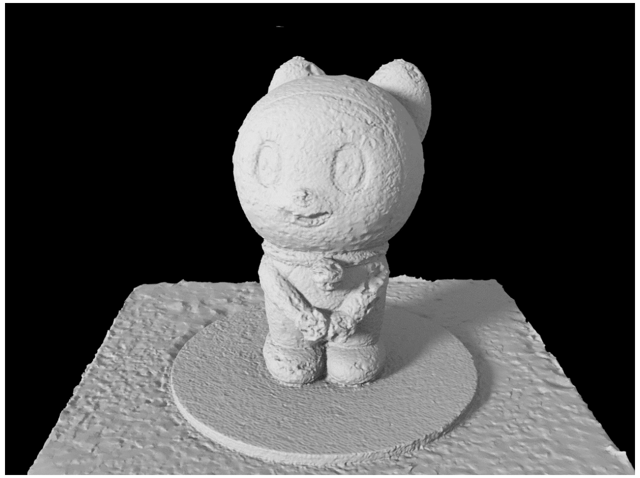
Statue (43 views) - Comparison

RGB images

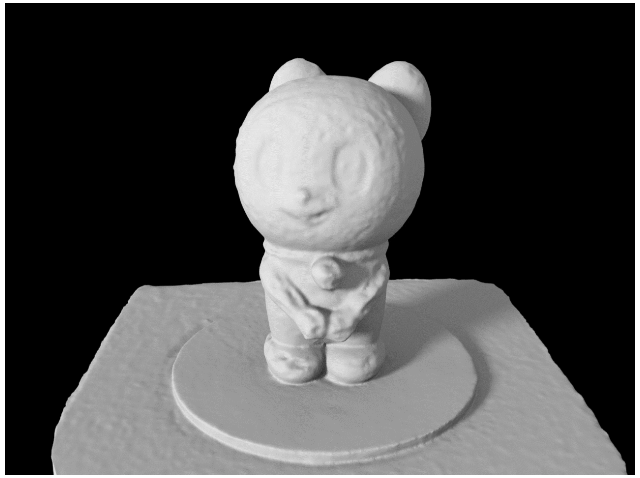


AoP images

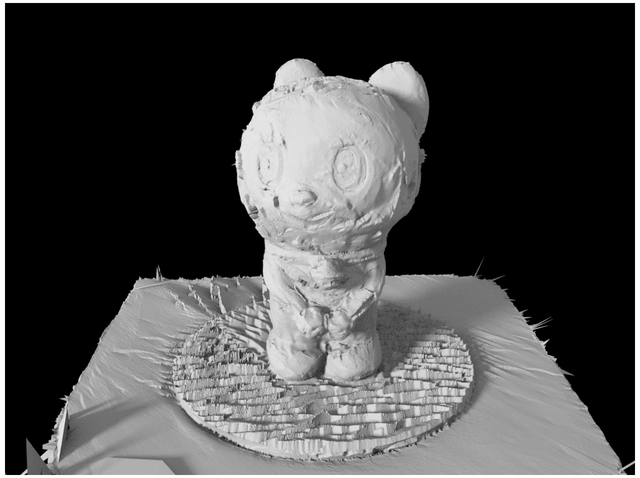
Estimated camera poses



CMPMVS



OpenMVS

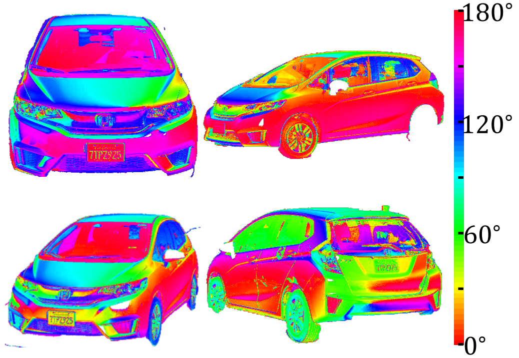


MVIR

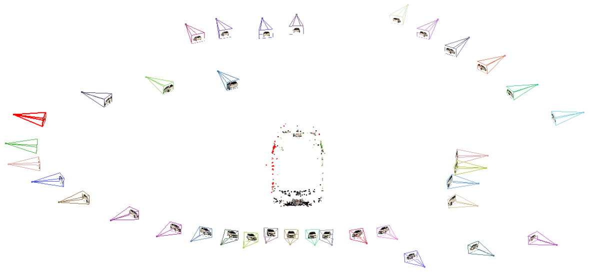
Polarimetric MVIR (Ours)

Refinement for Polarimetric MVS: Car (36 views)

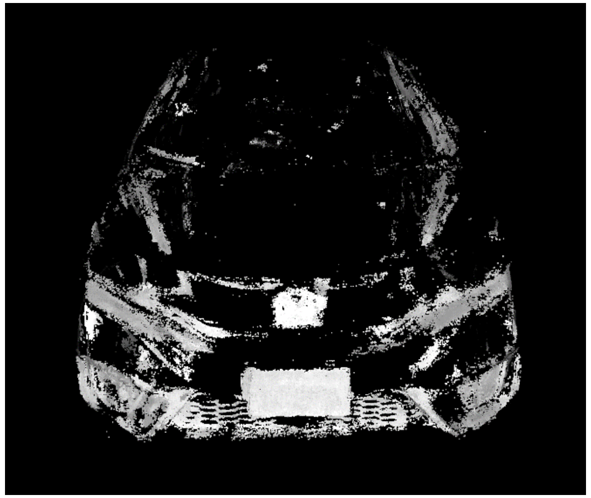
RGB images



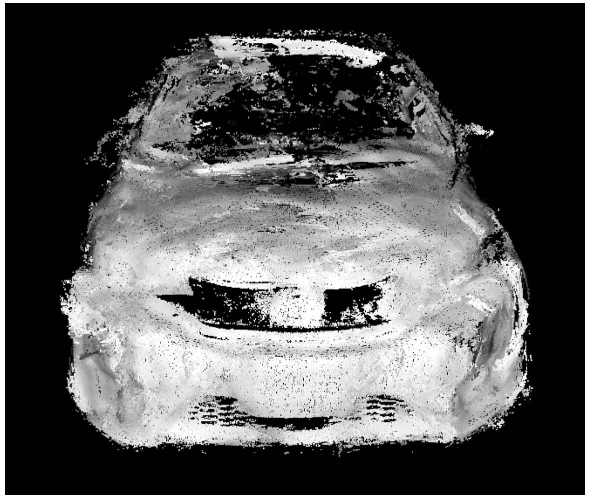
AoP images



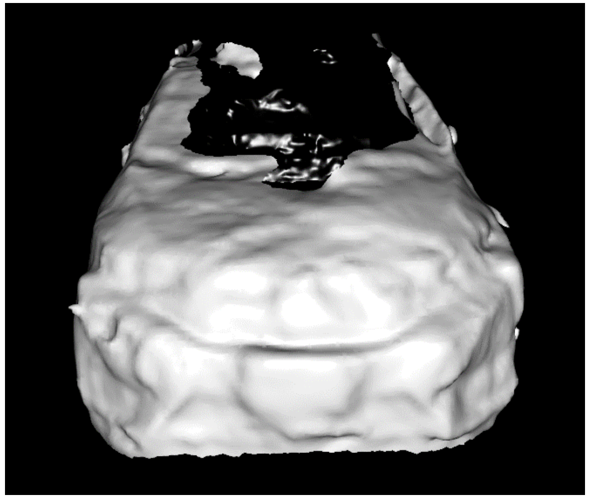
Estimated camera poses



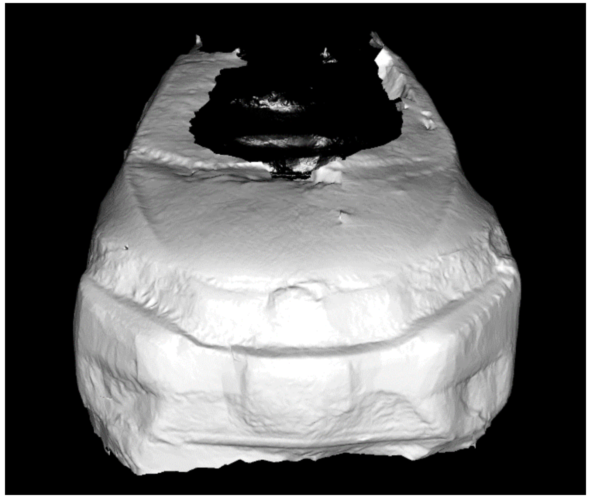
MVS (Gipuma)
without polarization



Polarimetric MVS



Polarimetric MVS + Poisson

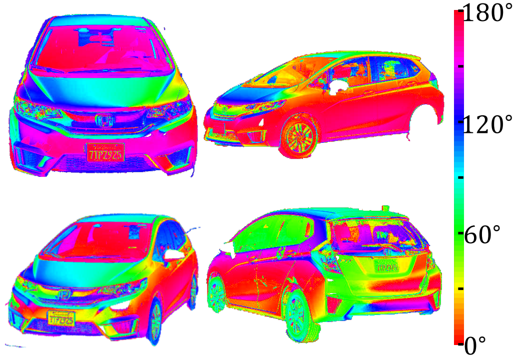


Polarimetric MVIR (Ours)

Data is provided by the author of Polarimetric Multi-View Stereo (CVPR 2017).

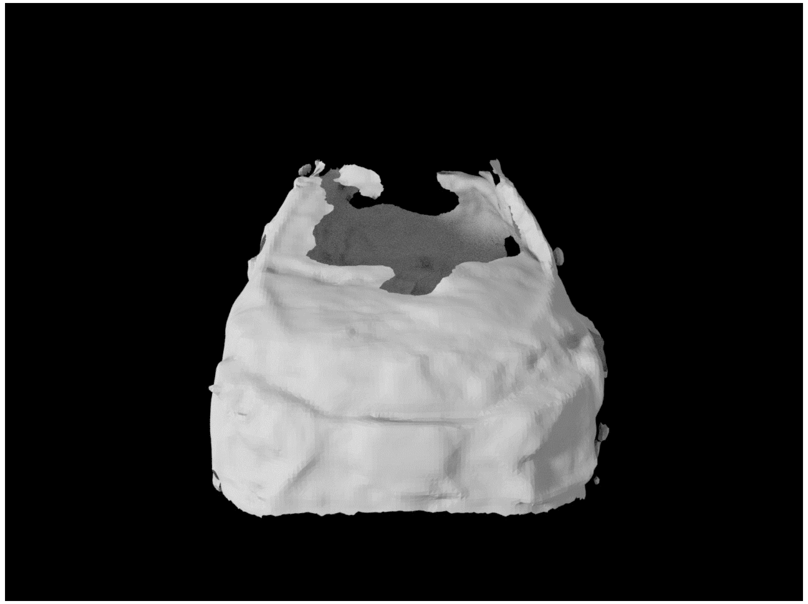
Refinement for Polarimetric MVS: Car (36 views)

RGB images

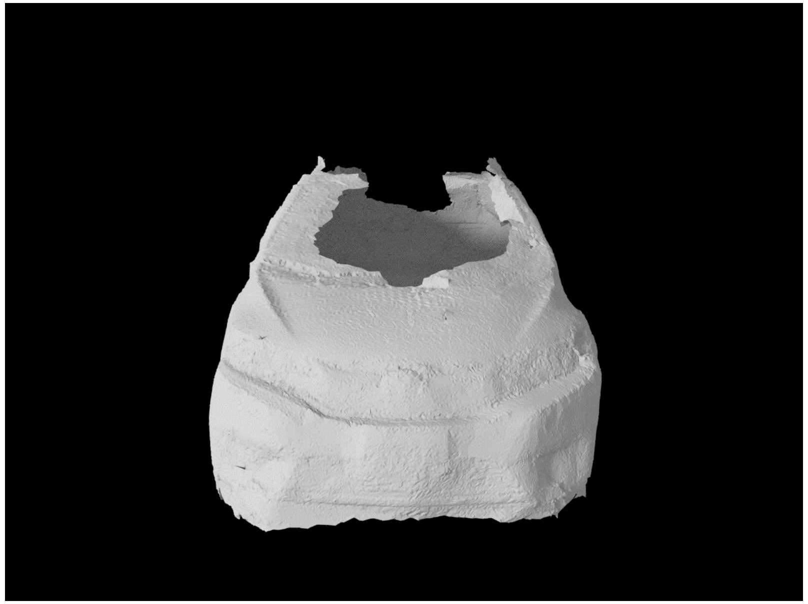


AoP images

Estimated camera poses



Polarimetric MVS + Poisson



Polarimetric MVIR (Ours)

Conclusions

We have proposed Polarimetric MVIR:

- Use a one-shot polarization camera to capture the data and perform SfM and MVS. Data and results are input to a photometric and polarimetric optimization problem.
- Reconstruct high-quality 3D models by optimizing multi-view photometric rendering errors and polarimetric errors.
- Resolve ambiguities implicitly as an optimization problem, making the proposed method fully passive and applicable to various materials under different situations.
- Robust to ambiguities and noise, and can generate more detailed 3D models compared with existing state-of-the-art multi-view reconstruction methods.

THANK YOU FOR LISTENING