Structure-Aware Consistency Priors for Shape from Polarization in Complex Media

Kaimin Yu[1], Puyun Wang[1], Huayang He[2], Xianyu Wu[1†]

[1]Fuzhou University [2]Research Institute of Highway, Ministry of Transport

Motivation: Why is SfP in Ice Challenging?

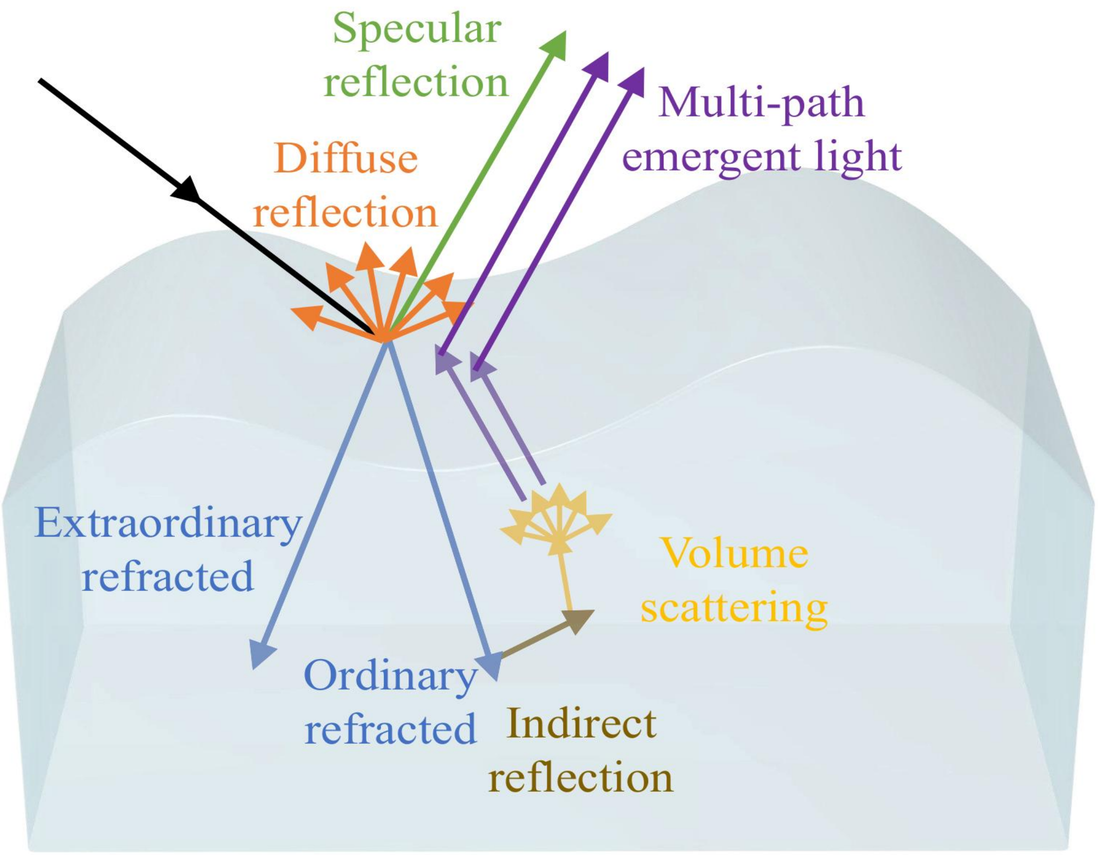
Ice exhibits complex light transport: birefringence, volume scattering, multipath

→ Nonlinear & unstable mapping between polarization and surface geometry

Classical SfP assumptions fail under these conditions

Existing 3D methods either require expensive hardware, controlled environments, or fail entirely

This work: First systematic SfP study targeting ice media



Surface reflection + birefringence + volume scattering → multipath emergent light

Key Insight: Structure Polarization Consistency Prior

Core observation: AoLP spatial coherence indicates reliability of polarization measurements

Surface Reflection Dominated:

• Smoothly varying AoLP → high spatial autocorrelation

Volume Scattering Dominated:

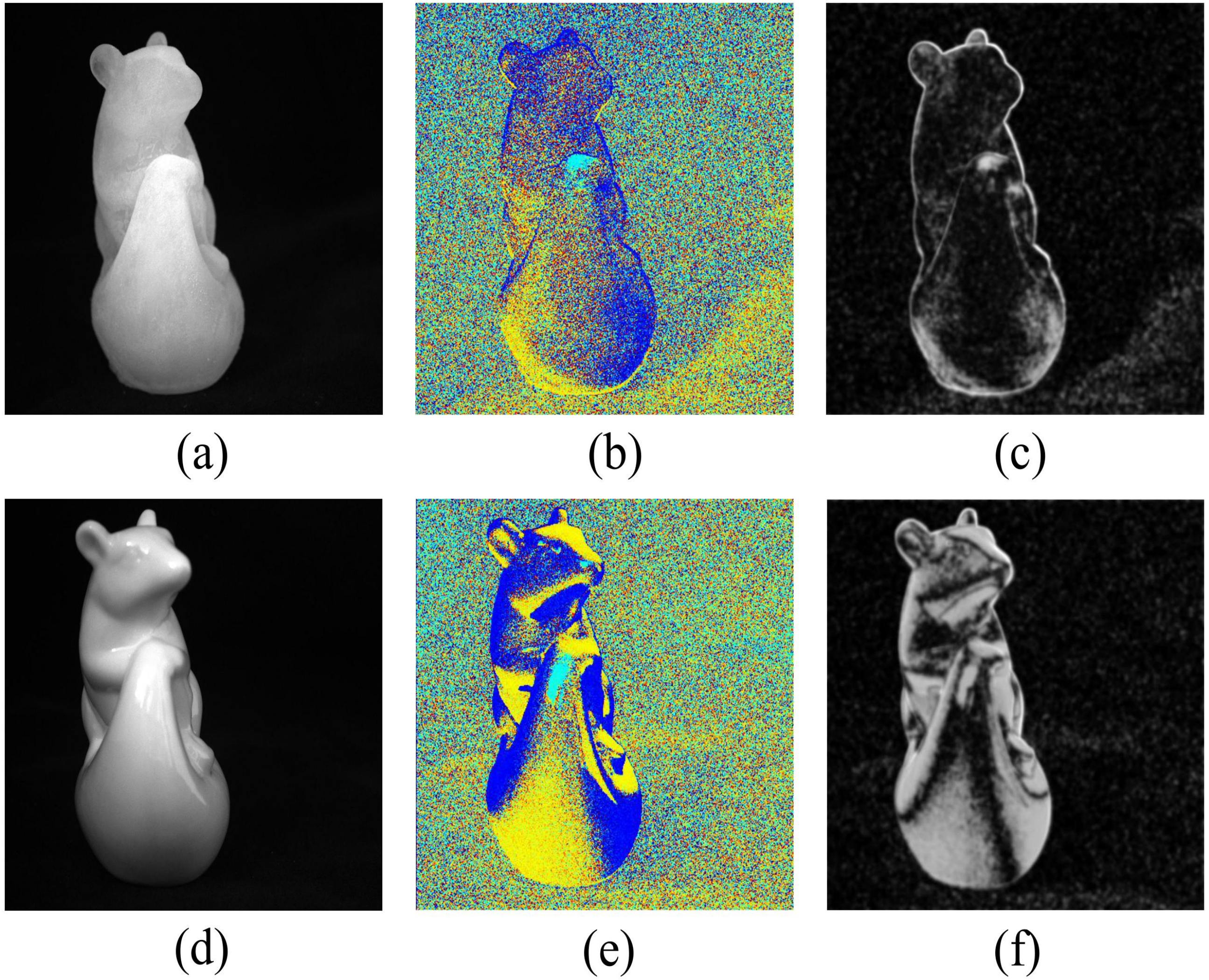
• Chaotic, abrupt AoLP shifts → low spatial autocorrelation

Proposed Consistency Prior C(x):

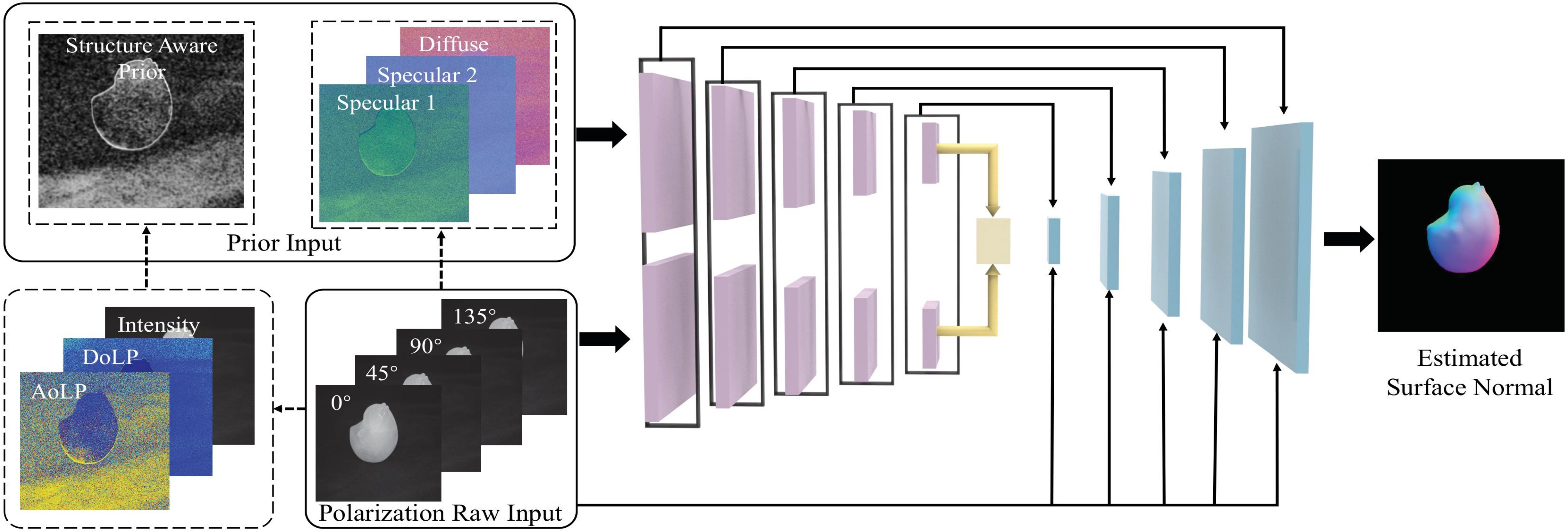
• ACF measures local AoLP spatial coherence

• SWT captures structural discontinuities

• Combined into pixel-wise consistency map



IceSfP: Dual-Branch Network Architecture



Raw Polarization Branch

- 4-channel polarization images (0°,45°,90°,135°)
- EPSANet50 backbone + ASPP for context enhancement

Physics Prior Branch

- 3 candidate normal maps + consistency prior C(x)
- CRA module adaptively modulates physics-based priors

Cross-modal Reliability Attention (CRA)

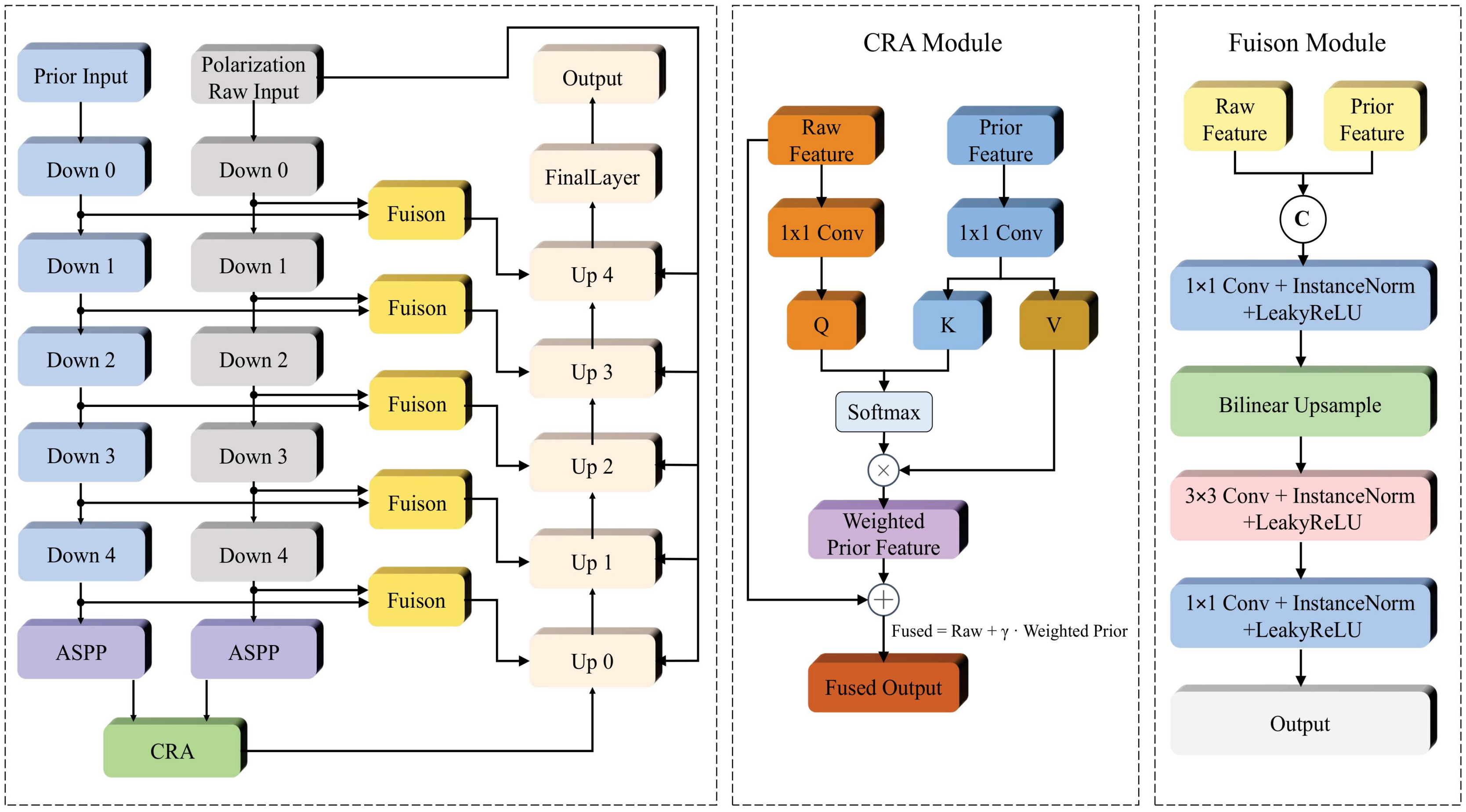
ICML International Conference On Machine Learning

Problem:

Physics-based normal priors are inherently ambiguous in complex media

CRA Solution:

- Cross-attention between raw polarization features and physics prior features
- Selectively enhance reliable physics cues, suppress unreliable ones
- Residual fusion preserves raw polarization information



(a) (b) (c)

$$\mathbf{F}_{\text{fused}} = \mathbf{F}_{\text{raw}} + \gamma \cdot \mathbf{Attention}(\mathbf{F}_{\text{raw}}, \mathbf{F}_{\text{physics}})$$

IceSfP Dataset: First Real-World Ice SfP Benchmark

Dataset Statistics:

- 16 different ice objects, 960 samples total
- 0°–360° rotation, 0°–10° increments
- Resolution: 2448 × 2048 pixels
- GT normals at 0.1 mm precision (structured-light scanner)

Acquisition Pipeline:

1. Silicone molds cast from real objects
2. Pure water slow-freezing (near 0°C)
3. FLIR polarization camera capture (low-temp)
4. Mutual-information registration + Mitsuba rendering

(a)

(b)

(c)

Experimental Results on IceSfP Dataset

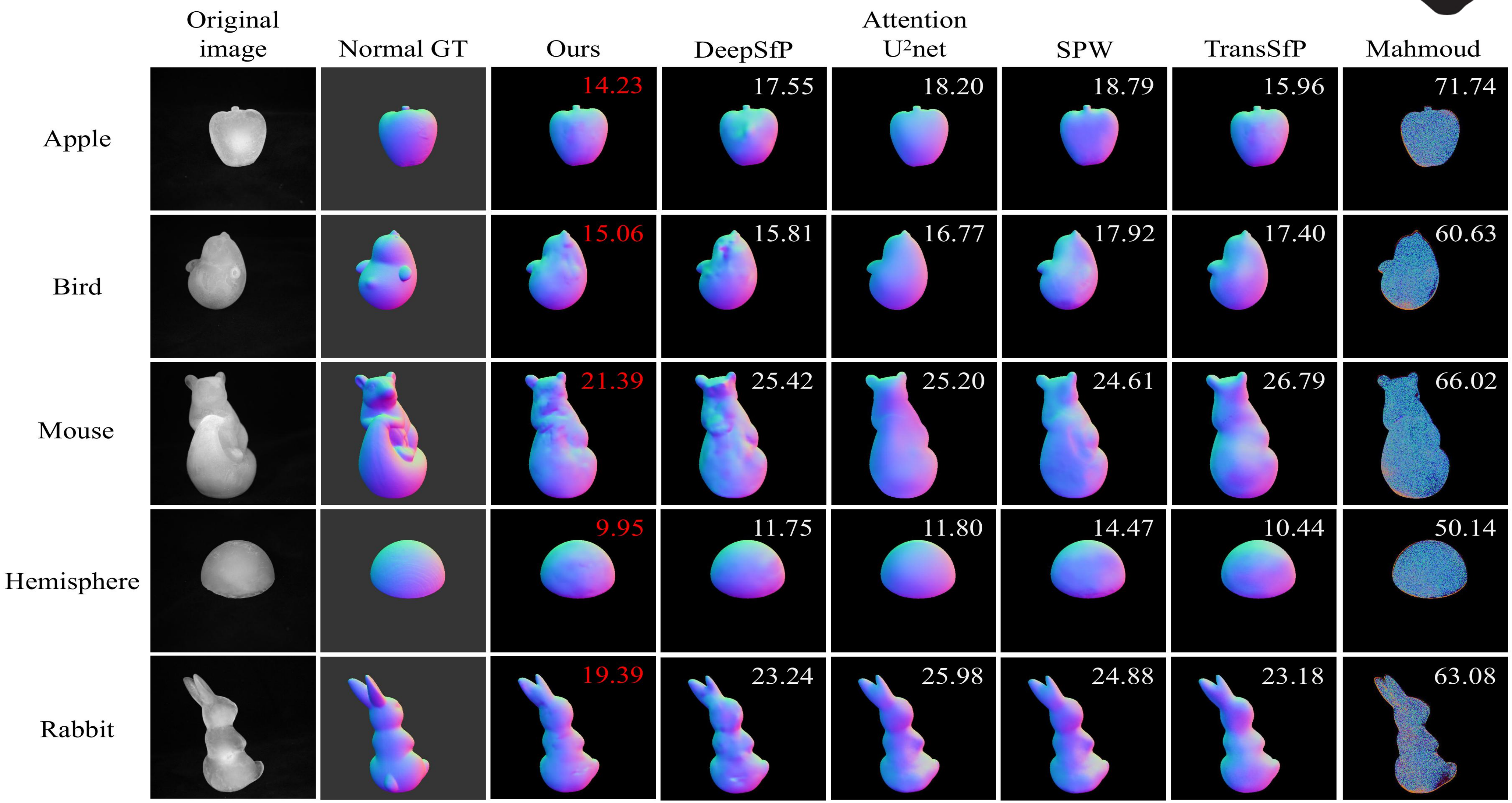
Our method achieves MAE 16.01° — 2.74° better than the second-best approach

Method	MAE↓	MedAE↓	<11.25°↑	<22.5°↑	<30°↑
Ours	**16.01°**	**13.93°**	**41.92%**	**79.58%**	**89.21%**
DeepSfP	18.76°	16.32°	34.35%	70.65%	82.80%
TransSfP	18.75°	16.48°	32.13%	73.26%	85.01%
Attn U^2Net	19.59°	17.62°	29.67%	71.17%	83.83%
SPW	20.13°	18.34°	25.29%	67.27%	82.95%
Mahmoud et al.	62.32°	60.09°	0.54%	2.75%	4.91%

- Physics-only method (Mahmoud) fails entirely — complex optics violate ideal modeling assumptions
- Learning-based methods partially compensate but still suffer from unstable polarization cues
- Our consistency prior + CRA effectively suppresses interference from unreliable polarization regions

Qualitative Comparison

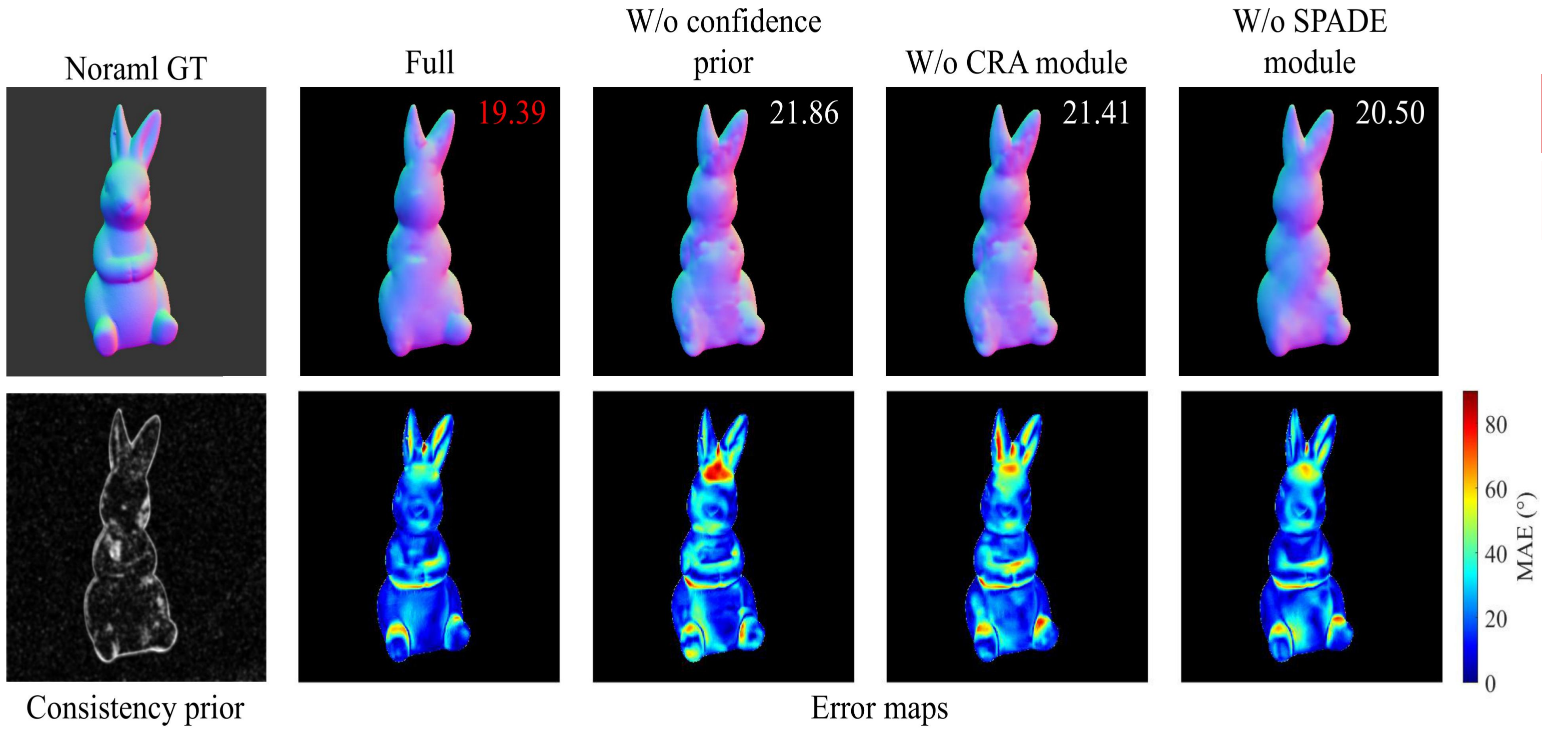
ICML
International Conference
On Machine Learning



Our method: Higher geometric consistency better local texture

Other methods: Disrupted normal distributions in complex optical regions

Ablation Study: Every Component Contributes



Configuration	MAE ↓	Δ
Full model	**16.01°**	—
W/o consistency prior	17.84°	+1.83°
W/o CRA module	17.44°	+1.43°
W/o SPADE module	17.45°	+1.44°

Consistency Prior contributes most (+1.83°):

Guides network to focus on structurally coherent polarization regions

CRA Module (+1.43°):

Cross-modal attention adaptively weights physics priors

Summary

What We Did

- First systematic SfP study in ice media
- Structure-aware polarization consistency prior
- IceSfP dual-branch network with CRA module
- First real-world IceSfP dataset

Key Results

- MAE 16.01° (2.74° improvement)
- Best across all metrics on IceSfP dataset
- Strong generalization to DeepSfP & TransSfP
- Each component validated via ablation

Future Work

- Extend to other translucent / scattering media
- Explicit Fresnel inversion uncertainty modeling
- Validate in uncontrolled outdoor lighting
- Broader complex media geometric perception

Thank You!

Contact: xwu@fzu.edu.cn & kaimin_yu@163.com | Code & Dataset available