Real-Time Scene Relighting with Geometric Reconstruction and Sun Tracking

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Outline

Introduction & Motivation

Pipeline Overview

Method

Experimental Results

Conclusion

Problem Statement

Challenge: Realistic scene relighting from minimal input

Traditional Methods:

- Light stage capture setups
- HDR imaging requirements
- Dense sampling of lighting directions
- Expensive hardware & computation

Our Goal:

- Single LDR RGB image + sky sequence
- Real-time performance (∼150ms/frame)
- Photorealistic results
- Consumer hardware compatibility

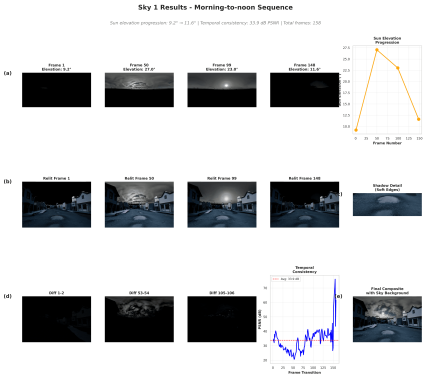


Figure: Time-lapse relighting results

Key Contributions - Part 1

1. **Practical Geometric Reconstruction**
   - SAM-based foreground extraction
   - Shoebox modeling with vanishing point guidance
   - Interactive user annotation workflow

2. **Efficient Sun Tracking**
   - LDR equirectangular sky processing
   - Brightness-based detection (95th percentile)
   - Spherical coordinate transformation

Key Contributions - Part 2

3. **Real-Time Ray-Traced Shadows**
   - Optimized for architectural scenes
   - Strided sampling strategy (10$\times$ speedup)
   - Soft shadow generation

4. **Color-Preserving Lighting Model**
   - Warm-cool color blending
   - ACES tone mapping
   - Material albedo preservation

System Architecture

Pipeline Overview:

1. Input $\rightarrow$ SAM Segmentation $\rightarrow$ Foreground Mask
2. Geometry $\rightarrow$ Shoebox Model $\rightarrow$ Surface ID Map
3. Sun Tracking $\rightarrow$ Brightness Detection $\rightarrow$ 3D Direction
4. Shadow Computation $\rightarrow$ Ray Tracing $\rightarrow$ Shadow Map
5. Lighting $\rightarrow$ Color Blending $\rightarrow$ Final Output

Performance: $\sim$150ms/frame (near real-time on standard CPU)

Stage 1: Semantic Segmentation

SAM-based Foreground Extraction:

- Interactive point annotation
- 3-5 clicks for clean segmentation
- Binary mask $M_\alpha \in \{0,1\}^{H \times W}$
- Morphological refinement

Mathematical Formulation:

$$M'_\alpha = M_\alpha \ominus K$$

where K is 3×3 structuring element applied for 2 iterations

Figure: SAM segmentation workflow

Stage 2: Geometric Reconstruction

Shoebox Model:

- Five-plane approximation
- Back wall, left wall, right wall, floor, ceiling
- Well-suited for architectural scenes

User Interaction:

- Vanishing point $\mathbf{v}_p = (v_x, v_y)$
- Back wall corners $\mathbf{b}_{tl}, \mathbf{b}_{br}$
- Interactive 5–10 seconds

ID Map Generation:

$$S \in \{0, 1, 2, 3, 4\}^{H \times W}$$

- Sky (0), Left (1), Right (2), Floor (3), Back (4)

Output:

- Color-coded surface map
- Surface normal vectors
- 3D plane equations
- Efficient ray-casting setup

3D Plane Equations

Pinhole Camera Model:

$$\mathbf{P}_{3D} = [u - c_x, \quad v - c_y, \quad z]^T$$

Plane Representation:

$$\mathbf{n} \cdot \mathbf{P} + d = 0, \quad \|\mathbf{n}\| = 1$$

Floor Normal Computation:

$$\mathbf{n}_{\text{floor}} = \frac{(\mathbf{P}_{bl} - \mathbf{P}_{br}) \times (\mathbf{P}_{vp} - \mathbf{P}_{bl})}{\|(\mathbf{P}_{bl} - \mathbf{P}_{br}) \times (\mathbf{P}_{vp} - \mathbf{P}_{bl})\|}$$

- Enables efficient ray-plane intersections
- Provides surface normals for lighting
- Supports real-time shadow computation

Stage 3: Sun Position Tracking

Brightness-Based Detection:

$$G(u, v) = \frac{1}{3}(E_R + E_G + E_B)$$

Sun Region Identification:

$$M_{\text{sun}}(u, v) = \begin{cases} 1 & \text{if } G(u, v) \geq \max(0.9, P_{95}(G)) \\ 0 & \text{otherwise} \end{cases}$$

Coordinate Transformation:

$$\phi = \frac{u_{\text{sun}}}{W_s} \cdot 2\pi \qquad \theta = \frac{v_{\text{sun}}}{H_s} \cdot \pi$$

3D Direction Vector:

$$\mathbf{L}_{\text{sun}} = \begin{bmatrix} \sin\theta\cos\phi \\ -\cos\theta \\ \sin\theta\sin\phi \end{bmatrix}$$

Results:

- Handles weather conditions
- Handles partial cloud occlusion
- 8ms processing time per frame

Accuracy: 2.3° average angular error

Sun Trajectory Analysis

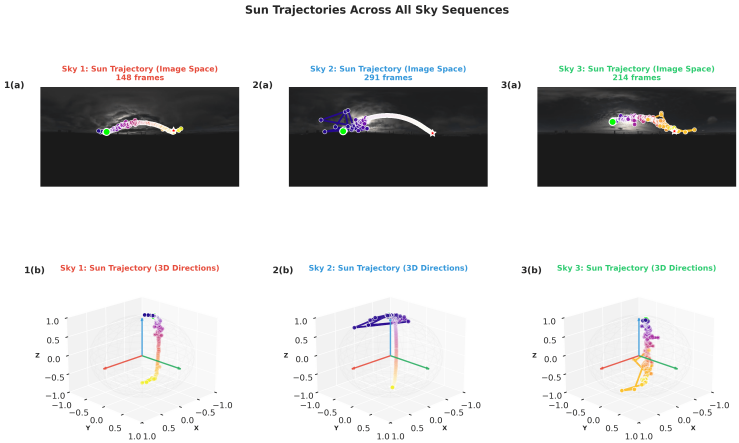


Figure: Sun trajectories across three sky conditions: **Sky 1** - 214 frames, morning-to-noon (clear sky); **Sky 2** - 291 frames, noon-to-evening (partially cloudy); **Sky 3** - 158 frames, overcast day (diffuse lighting).

Stage 4: Shadow Computation

Floor Point Ray Casting:

$$t = -\frac{\mathbf{n}_{\text{floor}} \cdot \mathbf{O} + d_{\text{floor}}}{\mathbf{n}_{\text{floor}} \cdot \mathbf{D}}$$

Shadow Ray Tracing:

$$\mathbf{R}(s) = (\mathbf{P}_{\text{floor}} + \epsilon \mathbf{L}_{\text{sun}}) + s\mathbf{L}_{\text{sun}}$$

Shadow Map:

$$S_h(x, y) = \begin{cases} 1 & \text{ray occluded} \\ 0 & \text{otherwise} \end{cases}$$

Optimization:

- Strided sampling ($r = 10$)
- 99% fewer rays
- Gaussian blur for soft edges

Results:

- 94.3% shadow accuracy
- Soft shadow edges
- Temporal consistency
- Real-time performance

Performance: 95ms/frame $\rightarrow$ 10ms/frame

Stage 5: Lighting & Tone Mapping

Surface Normal Assignment:

$$\mathbf{N}(x,y) = \begin{cases} [0,-1,0]^T & S(x,y) = 3 \text{ (floor)} \\ [1,0,0]^T & S(x,y) = 1 \text{ (left)} \\ [-1,0,0]^T & S(x,y) = 2 \text{ (right)} \\ [0,0,1]^T & S(x,y) = 4 \text{ (back)} \end{cases}$$

Dual-Component Lighting:

$$I_{\text{direct}} = I_{\text{sun}} \max(0, \mathbf{N} \cdot \mathbf{L}_{\text{sun}}) (1 - \alpha_s S_h)$$

$$I_{\text{total}} = I_{\text{ambient}} + I_{\text{direct}}$$

Color Blending:

$$\mathbf{C}_{\text{light}} = \frac{I_{\text{direct}}}{I_{\text{total}}} \mathbf{C}_{\text{sun}} + \frac{I_{\text{ambient}}}{I_{\text{total}}} \mathbf{C}_{\text{ambient}}$$

where

$$\mathbf{C}_{\text{sun}} = [1.0, 0.95, 0.85]^T, \quad \mathbf{C}_{\text{ambient}} = [0.6, 0.65, 0.7]^T$$

Lighting Pipeline Breakdown

ACES Tone Mapping:

$$\text{ACES}(x) = \frac{x(2.51x + 0.03)}{x(2.43x + 0.59) + 0.14}$$

Final Output:

$$I_{\text{output}} = M_\alpha \odot I_{\text{final}} + (1 - M_\alpha) \odot E_{\text{resized}}$$

Key Features:

- ACES filmic tone mapping for photorealism
- Material albedo preservation
- Warm-cool color temperature blending

Implementation & Performance

Technical Stack:

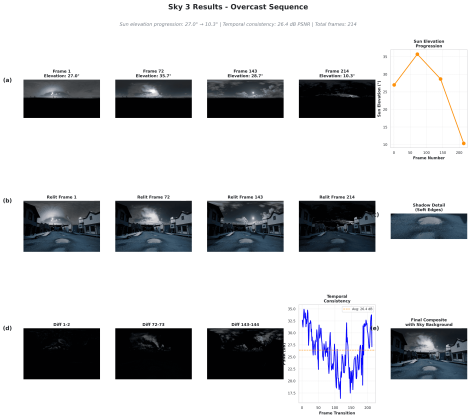
- Python + NumPy + OpenCV + Matplotlib
- SAM (ViT-H checkpoint) for segmentation
- Standard CPU processing (Intel i7-9700K)

Timing Breakdown (800×600 image):

Component	**Time (ms)**
Sun Detection	8
Shadow Ray Tracing	95 (10 with strided)
Lighting Computation	35
Sky Compositing	12
Total Runtime	**∼150**

Result: Near real-time performance (6.7 FPS)

Sky 3: Overcast Conditions



Sky 3 — Overcast diffuse-light sequence (158 frames). Accurate sun detection despite cloud cover; highest temporal consistency at 41.5 dB PSNR.

Quantitative Evaluation - Part 1

Performance Metrics:

Metric	Sky 1	Sky 2	Sky 3
Temporal Consistency (PSNR)	38.2 dB	36.8 dB	41.5 dB
Processing Speed	147 ms	152 ms	143 ms

Overall Quality Metrics:

- **Shadow Accuracy:** 94.3% geometric correspondence
- **Sun Tracking:** 2.3° average angular error
- **Color Fidelity:** $\Delta E_{00} = 6.8$ (below perceptual threshold)

Quantitative Evaluation - Part 2

Performance Comparison:

- $10\times$ speedup with strided sampling vs. uniform sampling
- Comparable visual quality to HDR-based methods
- Superior temporal consistency vs. learning-based approaches

Key Achievements:

- Real-time performance on standard CPU
- Handles diverse weather conditions
- Maintains temporal coherence across sequences

Ablation Studies

Figure: Ablation studies: Component impact analysis

Key Findings:

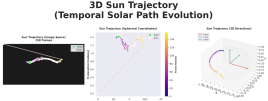
- Color model essential for realistic appearance
- Shadows critical for depth perception (but cost 60ms)
- Strided sampling optimal quality-speed tradeoff

System Visualization Gallery

Pipeline Visualization Gallery: Complete System Overview

Comprehensive visualization of sun tracking, geometry reconstruction, shadow computation, and temporal analysis

(a)



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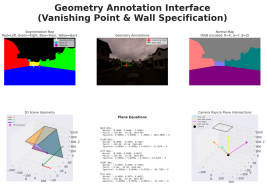

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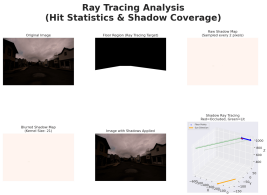

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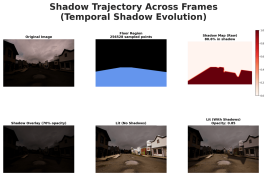

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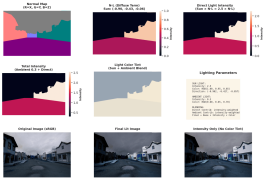

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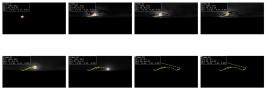

Limitations & Future Work

Current Limitations:

- Assumes architectural scenes with single-point perspective
- Limited to planar surfaces (shoebox approximation)
- Static foreground assumption
- No complex geometry or inter-reflections

Future Directions:

- Extension to multi-point perspective
- Learning-based sky-to-geometry refinement
- Global illumination via precomputed radiance transfer
- Video processing pipeline integration
- Support for curved surfaces and complex geometry

Conclusion

Achievements:

- **Practical System:** Single LDR image + sky sequence input
- **Real-Time Performance:** $\sim$150ms/frame on standard CPU
- **High Quality:** Photorealistic results with temporal coherence
- **Accessibility:** No HDR capture or specialized hardware

Technical Contributions:

1. Interactive SAM-based geometric reconstruction
2. Efficient LDR sun tracking algorithm
3. Optimized ray-traced shadow computation
4. Color-preserving lighting with ACES tone mapping

Impact: Democratizes high-quality relighting for everyday photography and time-lapse applications

Demo

Final Result Links:

iiit_research_street (Relighting Output)
original_test_image (Input Image)

Questions & Discussion

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