

Deep Retinex Decomposition Enhanced with Traditional Digital Image Processing

Low-Light Image Enhancement

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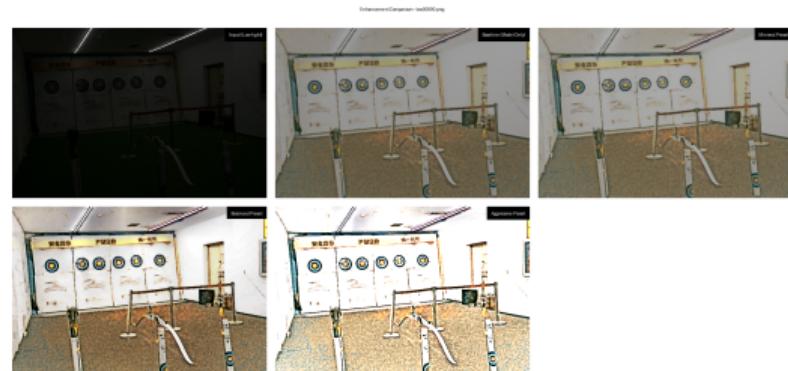
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GitHub: <https://github.com/firearc7/Deep-Retinex-Decomposition-Extension>

Why Low-Light Enhancement Matters

The Problem:

- Low-light conditions degrade image quality
- Reduced contrast and suppressed colors
- Increased noise levels
- Impacts critical applications



Applications:

- Surveillance systems
- Autonomous vehicles
- Medical imaging
- Consumer photography

Limitations of Existing Approaches

Traditional Methods:

- Histogram Equalization → Unnatural results
- SSR/MSR → Complex tuning, halo artifacts
- LIME → Limited adaptability

Deep Learning Methods:

- RetinexNet → Color artifacts
- EnlightenGAN → Inconsistent enhancement
- Zero-DCE → Over/under enhancement

Key Insight

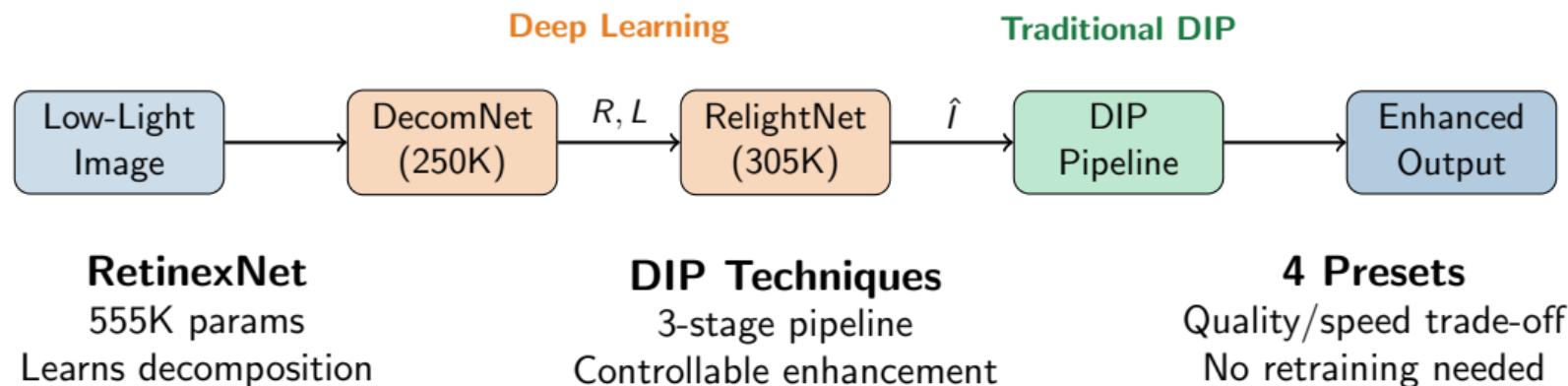
Neither approach alone is sufficient!

Deep learning: Good at learning patterns
Traditional DIP: Good at fine-grained control



Hybrid Approach
“Train Once, Experiment Forever”

Our Approach: Hybrid Framework



Retinex Decomposition

Retinex Theory (Land & McCann, 1971):

$$I = R \circ L$$

where:

- I = Observed image
- R = Reflectance (intrinsic)
- L = Illumination (lighting)

Enhancement:

$$\hat{I} = R \circ \hat{L}$$

Loss Functions:

Reconstruction:

$$\mathcal{L}_{recon} = \|R \circ \hat{L} - I_{gt}\|_1$$

Smoothness:

$$\mathcal{L}_{smooth} = \sum_i \|\nabla L_i\|_1 \cdot e^{-\lambda \|\nabla R_i\|}$$

Total:

$$\mathcal{L} = \mathcal{L}_{recon} + \lambda_1 \mathcal{L}_{smooth} + \lambda_2 \mathcal{L}_{mutual}$$

Three-Stage DIP Enhancement Pipeline

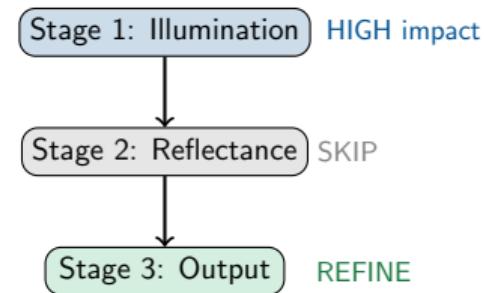
Stage 1: Illumination Enhancement (Primary)

- **CLAHE**: Adaptive contrast, clip=2.0
- **Bilateral Filter**: Edge-preserving smoothing
- **Adaptive Gamma**: Content-aware brightness
- **Guided Filter**: $O(N)$ complexity
- **Multi-Scale Retinex**: $\sigma \in \{15, 80, 250\}$

Stage 2: Reflectance (Skip—already good)

Stage 3: Output Enhancement

- Unsharp Mask, Color Balance
- Local Contrast, Tone Mapping



Key Design Decision:
Illumination > Reflectance
(RetinexNet R is already good)

DIP Techniques: Mathematical Formulations

4. Unsharp Masking

1. CLAHE (Contrast Limited Adaptive HE)

- Applied to L channel in LAB space
- clip_limit=2.0, tile_grid=8×8

$$I_{sharp} = I + \alpha(I - G_\sigma * I)$$

- $\alpha = 1.0, \sigma = 1.0$ for edge enhancement

2. Bilateral Filter

$$I_{bf}(x) = \frac{1}{W} \sum_{x_i} I(x_i) \cdot G_s \cdot G_r$$

- G_s : Spatial, G_r : Range Gaussian

3. Adaptive Gamma

$$\gamma = -0.3 / \log_{10}(\mu), \quad I_{out} = I_{in}^{1/\gamma}$$

5. White Balance (Gray World)

$$I_c = I_c \times \frac{\bar{I}_{gray}}{\bar{I}_c}$$

6. Multi-Scale Retinex

$$MSR = \sum_{\sigma} w_{\sigma} \cdot [\log I - \log(G_{\sigma} * I)]$$

- $\sigma \in \{15, 80, 250\}$

Additional DIP Techniques Available

Illumination Techniques:

- Histogram Equalization
- Multi-Scale Retinex
- Tone Mapping (Reinhard)
- Anisotropic Diffusion
- Guided Filtering

Output Techniques:

- Local Contrast Enhancement
- Multi-Scale Detail (Laplacian)
- Shadow Enhancement
- Contrast Stretching

Edge-Preserving Smoothing:

Technique	Complexity
Bilateral Filter	$O(N \cdot r^2)$
Guided Filter	$O(N)$
Anisotropic Diff.	$O(N \cdot k)$
Domain Transform	$O(N)$

Key Point:

All techniques implemented and available for experimentation via preset configuration.

Enhancement Presets

Parameter	None	Min	Bal	Agg
CLAHE Clip	–	–	2.0	3.0
Bilateral d	–	–	7	9
Bilateral σ	–	–	50	75
Unsharp Amt	–	–	1.2	2.0
Time (s)	0.005	0.011	0.089	0.134

Preset Use Cases:

None: Raw model output
Benchmark comparison

Minimal: Subtle improvement
Real-time video, mobile

Balanced (Best): Best quality/speed
Production default

Aggressive: Maximum enhancement
Extremely poor inputs

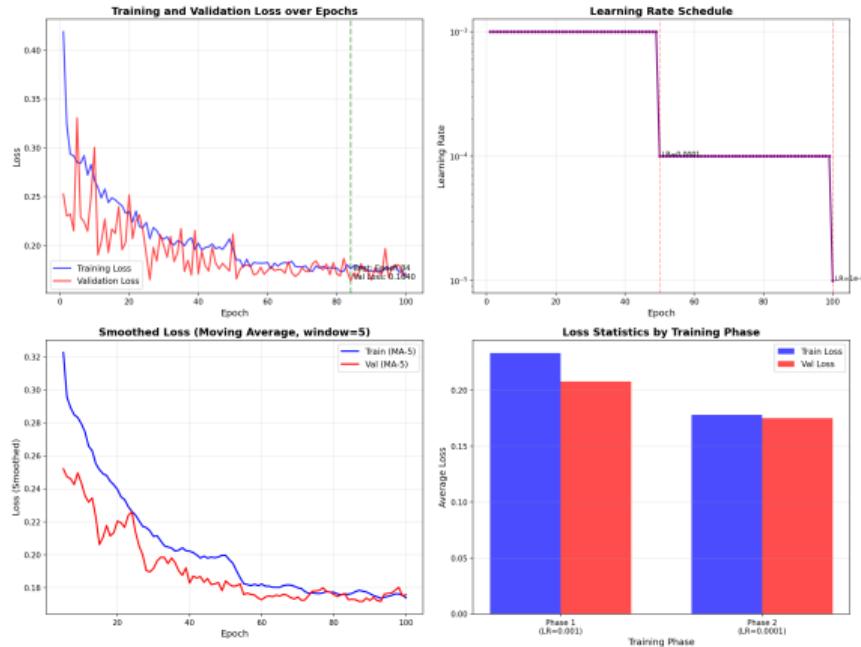
Training Configuration

Dataset: LOL (Low-Light)

- 689 training pairs
- 100 validation pairs
- Resolution: 400×600
- Paired low/normal-light images

Training Setup:

- Epochs: 100 (best at epoch 84)
- Batch size: 16, Patch size: 48
- Optimizer: Adam ($\beta_1 = 0.9$, $\beta_2 = 0.999$)
- LR: 10^{-3} with step decay at epoch 50
- Training time: ~ 18 minutes



Best Val Loss: 0.1640
Loss Reduction: 59.8%

Evaluation Metrics (8 Metrics)

No-Reference Metrics:

1. Entropy: $H = -\sum p(x_i) \log_2 p(x_i)$

- Information content
- Optimal: 7.5-8.0

2. Contrast: $\sigma(L)$

- Standard deviation of luminance
- Higher = better separation

3. Sharpness: $\sum |G_x|^2 + |G_y|^2$

- Sobel gradient magnitude
- Edge strength indicator

4. Colorfulness: Hasler-Süsstrunk

- Perceptual color vividness

5. Brightness: Mean luminance

- ITU-R BT.601 weights
- Optimal: 0.4-0.6

Reference-Based:

6. PSNR: $20 \log_{10}(MAX/\sqrt{MSE})$

- Standard benchmark

7. SSIM: Luminance + Contrast + Structure

- Better perceptual correlation

Practical:

8. Processing Time

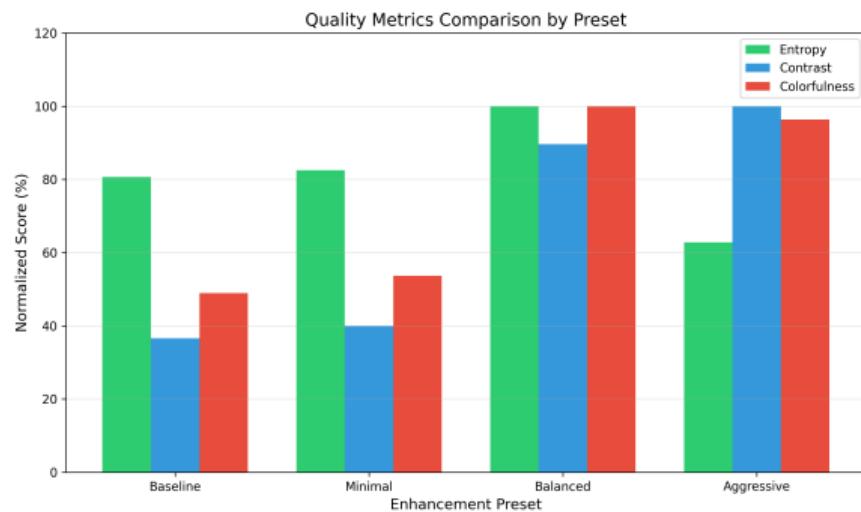
- Real-time constraint

Quantitative Results (100 Test Images)

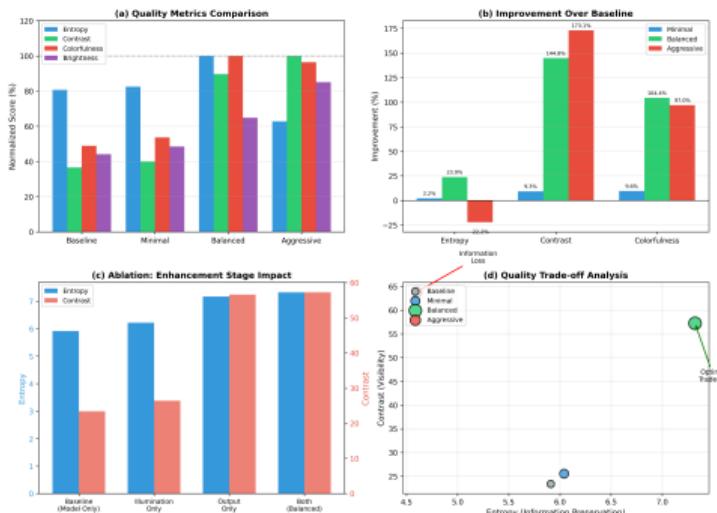
Preset	Ent.	Cont.	Color.	Time
Baseline	5.91	23.37	25.05	0.005
Minimal	6.04	25.53	27.47	0.011
Balanced	7.32	57.22	51.20	0.089
Aggressive	4.60	63.82	49.36	0.134
Illum Only	6.22	26.40	28.16	0.043
Output Only	7.17	56.57	50.49	0.071

Balanced Improvements:

- Entropy: **+23.9%**
- Contrast: **+144.8%**
- Colorfulness: **+104.4%**
- Sharpness: **+866%**



Ablation Study: Why Balanced Works Best



1. Information Preservation

- Highest entropy (7.32); Aggressive destroys tonal info (4.60)

2. Optimal Contrast (+144.8%)

- CLAHE + Gamma synergy without saturation artifacts

3. Natural Sharpness

- No halo artifacts; Aggressive causes edge overshoot

4. Color Fidelity (+104.4%)

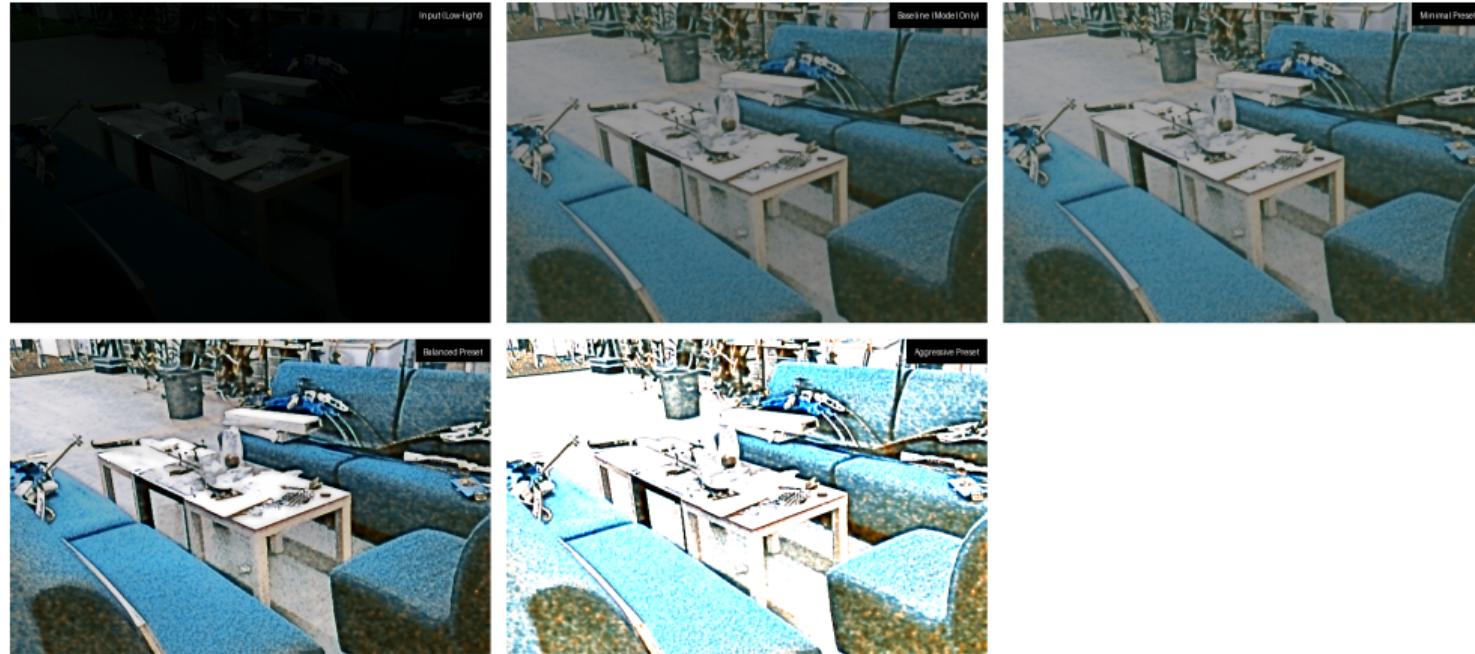
- Highest colorfulness (51.20) with natural relationships

5. Appropriate Brightness

- Preserves highlight headroom

Visual Results

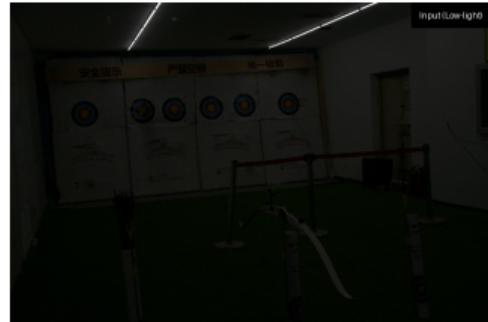
Enhancement Comparison - low00698.png



Progressive enhancement: Input → RetinexNet → DIP Pipeline → Output

More Visual Comparisons

Enhancement Comparison - low00690.png



Natural-looking enhancement with improved visibility, enhanced colors, and preserved details

DEMO

Live demonstration of the enhancement system

- Custom image enhancement
- Preset comparison (None vs Balanced vs Aggressive)
 - Real-time processing

Key Design Decisions

Why CLAHE on Illumination?

- Illumination is smooth (no texture)
- CLAHE won't amplify texture noise
- Output has reflectance texture

Why Skip Reflectance?

- RetinexNet R is already high quality
- No consistent improvement observed
- Risk of color shifts

Why Post-Processing?

- No retraining needed
- 100+ configurations instantly
- Flexibility > Optimality

Stage Separation Results:

Configuration	Sharpness
Baseline	150.84
Illumination Only	186.31 (+23.5%)
Output Only	2370.22 (+1471%)
Balanced (both)	2069.40 (+866%)

Key Insight:

Output enhancement amplifies illumination improvements

Advantages Over Existing Methods

vs. Pure Deep Learning

- Controllable parameters
- No retraining needed
- Interpretable processing
- Adapt to use cases

vs. Pure Traditional

- Handles complex lighting
- Learned decomposition
- More robust
- Better generalization

vs. Other Hybrids

- Modular architecture
- Independent updates
- Flexible presets
- Three-stage pipeline

Component	Specification
Total Parameters	555,205
Training Time	~18 minutes
Inference	Real-time capable
DIP Techniques	16 implemented

Future Work

Enhancement Techniques:

- Frequency domain processing
- Homomorphic filtering
- FFT-based denoising
- Advanced color space processing

Content-Aware Processing:

- Adaptive preset selection
- Semantic segmentation-guided
- Automatic parameter tuning

Quality Assessment:

- NIQE, BRISQUE metrics
- LPIPS perceptual metric
- Automated optimization

Applications:

- Video processing
- Temporal consistency
- Mobile deployment
- GPU acceleration

Conclusion

Summary

- Proposed a **hybrid framework** combining deep Retinex decomposition with **traditional DIP techniques**
- **“Train Once, Experiment Forever”**: No retraining for new enhancement combinations
- **Three-stage pipeline**: Illumination, Reflectance (skip), Output enhancement
- **Balanced preset** achieves optimal results:
 - +23.9% entropy, +144.8% contrast, +104.4% colorfulness
- **Key insight**: Illumination enhancement > Reflectance enhancement

Code Available

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Thank You!

Questions?

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