# Quaternion Factorized Simulated Exposure Fusion

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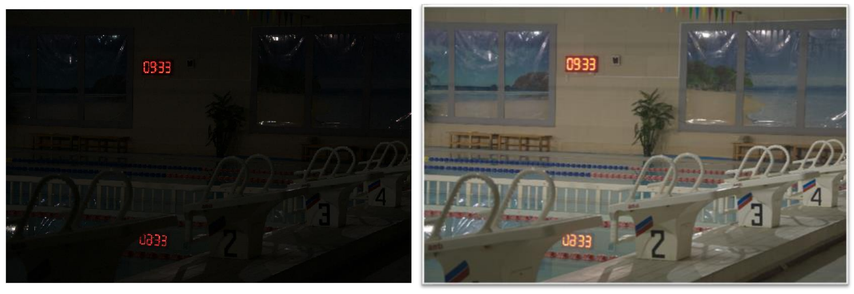
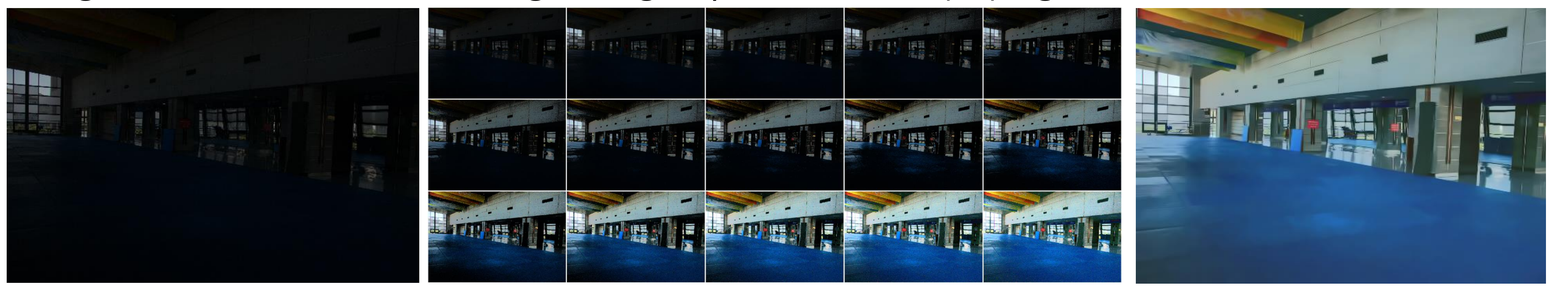
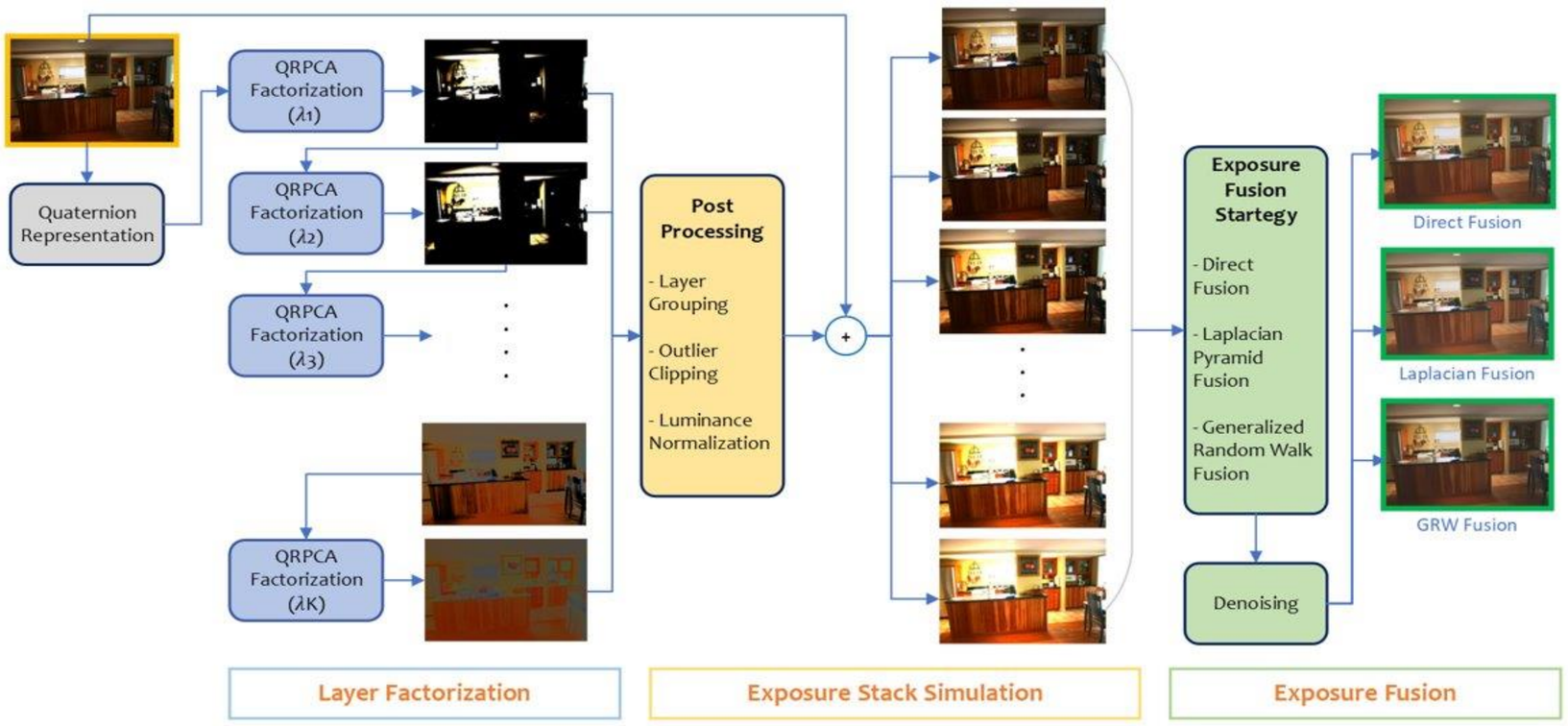
**Low Light Enhancement (LLE):** Enhance a poorly illuminated input image into a well-lit result.



**Simulated Exposure Fusion (SEF):** Render virtual *exposure stack* from the single image ⟶ global enhancement ⟶ merge using Exposure Fusion (EF) algorithms.



**QFSEF:** Iterative *Quaternion RPCA factorization* for progressive specularity removal & SEF.




## Quaternion Image Representation:

- 4D Hypercomplex universal algebra
- Non-commutative

$$i^2 = j^2 = k^2 = i.j.k = -1$$
$$i.j = k; \quad j.k = i; \quad k.i = j$$
$$i.k = -j; \quad j.i = -k; \quad k.j = -i$$

- Pure Quaternion space (scalar = 0)
- Direct Mapping:

$R \rightarrow i \quad G \rightarrow j \quad B \rightarrow k$

- **Motivation:**
  a) Geometric color space representation
  b) Inter-channel correlation
  c) 3D ⟶ 2D matrix (no vector calculus)
  d) Spatial and inter-color spectral analysis
  e) Complex algorithms
- **Apps:** inpainting, saliency, smoothing, edge detection, segmentation, denoising etc.

**Layer Factorization:** Split image into multiple *illumination consistent* layers.

$$I = I_{specular} + I_{diffuse}$$

- **Robust Principle Component Analysis (RPCA):**

$I = E + A$ *where A: low-rank & E: sparse*

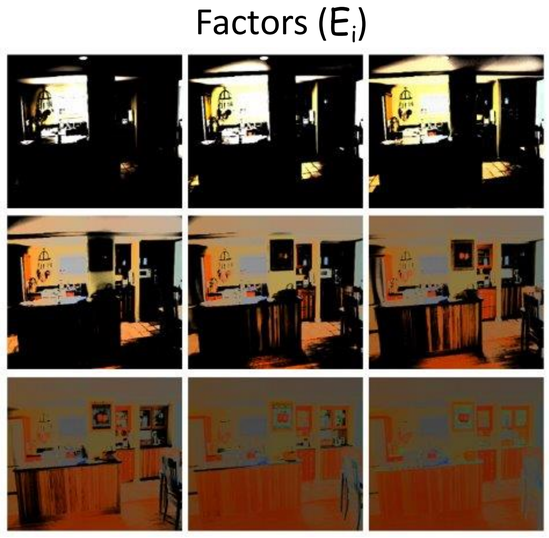
$\text{argmin } \|A\|_* + \lambda \|E\|^1 \quad \text{s.t.} \quad I = A + E$

Solved by *Quaternion Principle Component Pursuit*

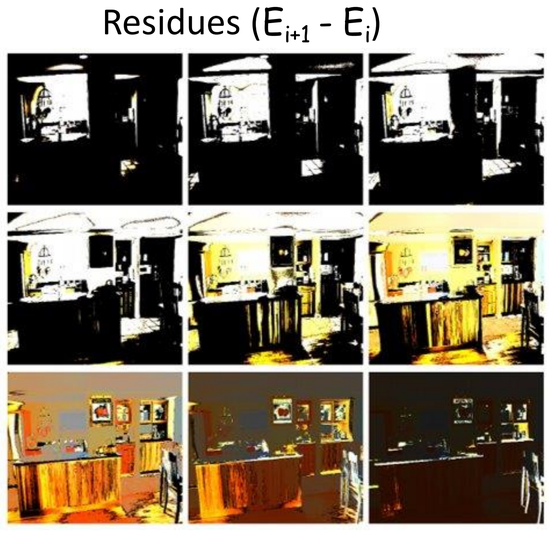
- **Iterative Factorization:**

$$I = E_1 + A_1 = E_1 + (E_2 + A_2) = E_1 + E_2 + (E_3 + A_3) = \Sigma_i^K E_i$$


Factors ($E_i$)



Residues ($E_{i+1} - E_i$)



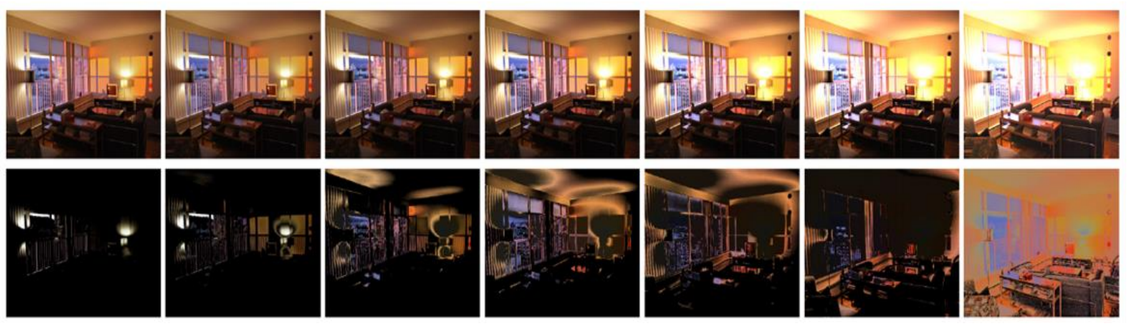
**Stack Simulation:** Clean & Combine factors.

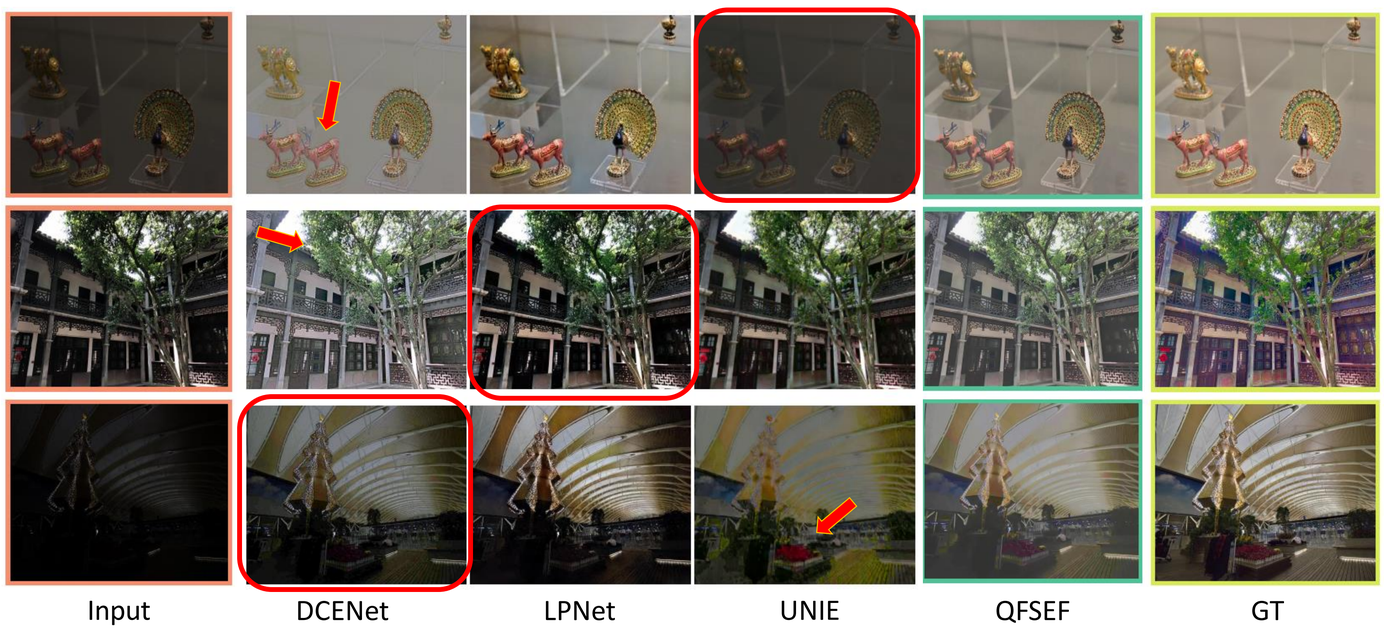
- **Post Processing:**
  a) Layer Grouping: ($\tau$ = 1% of I energy )
  b) Outlier Removal: (>99.9 & <0.1 %-ile)
  c) Luminance Normalization: (0-mi)
- **Combine**

$S_{i+1} = (1 - \alpha).S_i + \alpha.E_i, \quad where\ i \in [0, K] \quad \& \quad S_0 = I$

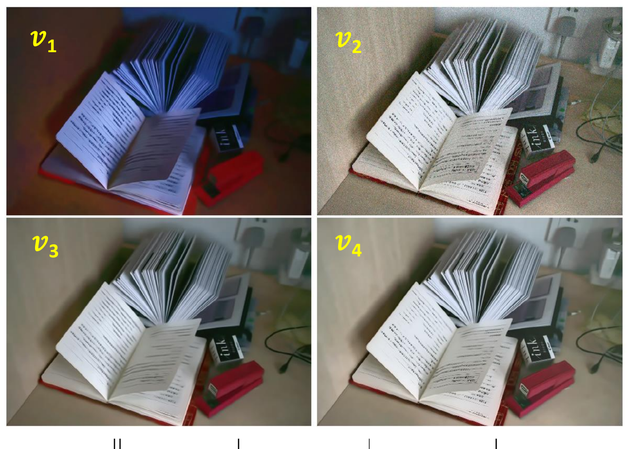
**Exposure Fusion:** Fuse simulated stack images.

- Direct ($I_D$)
- Laplacian Pyramid Fusion ($I_L$)
- Generalized Random Walk Fusion ($I_G$)

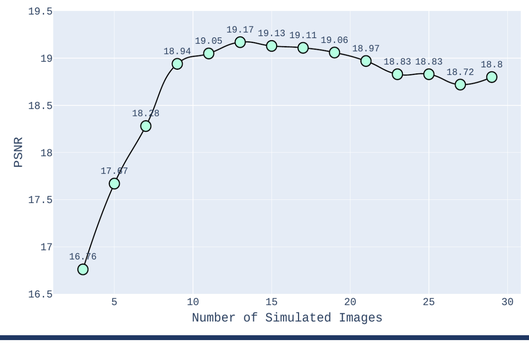






| Methods | Testset ⟶ Trainset ↓ | LOLv1 test (15) | LOLv2 test (100) | SICE Part 2 (767) | Adobe5k (3543 + 2362 = 5905) Overexp. | Underexp. | Complete | **Average** ($S_a$) | **Generaliz -ability** ($S_g$) |
|---|---|---|---|---|---|---|---|---|---|
| RetinexNet | LOLv1 train | 16.77 - 0.46 | 15.47 - 0.56 | 15.99 - 0.53 | 11.06 - 0.60 | 12.49 - 0.62 | 11.63 - 0.61 | 12.19 - 0.60 | 12.18 - 0.60 |
| DCENet | SICE Part 1 | 14.86 - 0.59 | 20.54 - 0.78 | 16.57 - 0.59 | 11.02 - 0.52 | 14.96 - 0.59 | 12.60 - 0.55 | 13.17 - 0.56 | 12.74 - 0.55 |
| LPNet | raw Adobe5k | 15.3 - 0.56 | 16.38 - 0.53 | 14.55 - 0.50 | **19.35 - 0.74** | 19.69 - **0.74** | **19.48 - 0.74** | **18.87 - 0.71** | 14.77 - 0.51 |
| UNIE | LOLv1 train | **21.52** - 0.76 | **25.53 - 0.88** | 13.72 - 0.46 | 16.93 - 0.66 | 15.65 - 0.60 | 16.41 - 0.64 | 16.26 - 0.62 | 16.42 - 0.62 |
| $I_D$ (*ours Direct*) | _ | 20.39 - **0.77** | 19.12 - 0.67 | 16.82 - **0.62** | 17.90 - 0.71 | **19.87** - 0.72 | 18.69 - 0.71 | 18.49 - 0.70 | 18.49 - **0.70** |
| $I_L$ (*ours Laplacian*) | _ | 19.28 - 0.75 | 18.16 - 0.67 | **17.75** - 0.60 | 15.60 - 0.65 | 17.94 - 0.69 | 16.78 - 0.67 | 16.92 - 0.66 | 16.92 - 0.66 |
| $I_G$ (*ours GRWF*) | _ | 17.72 - 0.70 | 19.01 - 0.69 | 15.64 - 0.56 | 18.71 - 0.71 | 19.34 - 0.70 | 18.96 - 0.71 | 18.58 - 0.69 | **18.58** - 0.69 |




| Variants ⟶ | real RPCA $v_1$ | w/o Denoise $v_2$ | w/o LNorm. $v_3$ | Full $v_4$ |
|---|---|---|---|---|
| $I_D$ | 12.83 - 0.5 | 18.35 - 0.6 | 20.86 - 0.75 | 20.39 - 0.77 |
| $I_L$ | 14.54 - 0.56 | 18.14 - 0.59 | 20.11 - 0.76 | 19.28 - 0.75 |
| $I_G$ | 12.66 - 0.48 | 15.83 - 0.53 | 17.48 - 0.69 | 17.72 - 0.70 |




## Summary:

- Novel single image exposure fusion method.
- Novel iterative quaternion RPCA factorization scheme for exposure stack simulation.
- Qualitative & quantitative SOTA comparisons on multiple datasets.
- Ablation analysis with multiple variants.

## Future Work:

- Simulations for LLE self-supervision.
- End-to-end unrolled LLE.
- Beyond LLE: relighting, shadow removal, white balancing, object compositing, image harmonization etc.