End-to-end optimization of coded aperture for extended depth of field

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Motivation

- Deep optics by combining optics and post-processing methods provides a new pathway towards optimizing images, compared with the traditional purely image post-processing pipelines or only lens optimization.
- Such end-to-end optimization can be applied to a variety of applications including extended depth of view and super-resolution imaging.
- In this study, we would like to apply the end-to-end framework to optimize the coded aperture for extended depth of field.

Related Work

- End-to-end Lens Design: [1] used optimized refractive optical element to change the phase of the obtained image, and eventually achieves both depth and chromatic invariance, followed by an image processing pipeline.
- Wave-front coding: [2] built a phase masks for an extended- depth-of-field incoherent optical system based on the ambiguity function and the stationary-phase method.
- Image dataset: The INRIA Holidays dataset in [3] as a benchmark.

References

[1] Sitzmann, Diamond, Peng, Dun, Boyd, Heidrich, Heide, and Wetzstein. “End-to-end optimization ofoptics and image processing for achromatic extended depth offield and super-resolution imaging”. ACM Trans. Graph. (SIG-GRAPH), 2018.
[2] Dowski and Cathey. Extended depth of field through wave-front coding.Appl. Opt., 34(11):1859–1866,Apr 1995
[3] Jegou, Douze and Schmid, "Hamming Embedding and Weak geometry consistency for large scale image search”, Proceedings of the 10th European conference on Computer vision, October, 2008

New Technique

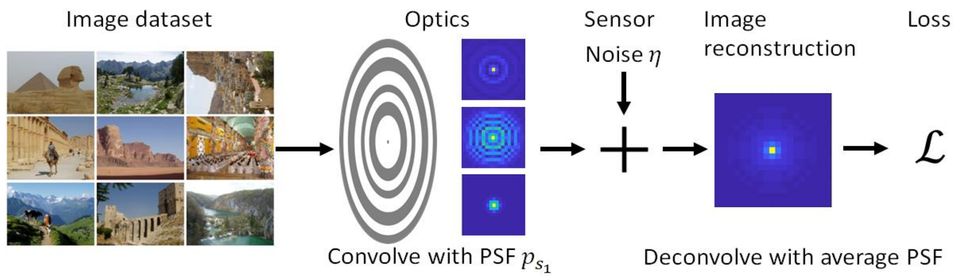

Fig. 1 End-to-end optimization schematic of Extended Depth of Field (EDOF)

Point-spread function: $p_{s_1} \propto \left|\mathcal{F}\left[A(x',y')\exp\left(-\frac{ik\delta}{2s_0}\right)\right]\right|^2$

$$\frac{1}{s_0}+\frac{1}{z}=\frac{1}{f} \qquad \delta=(1/s_0-1/s_1)s_0 \qquad k=2\pi/\lambda_0$$

Average PSF: $p_{avg}=\frac{1}{N_s}\sum_{i=1}^{N_s} p_{s_1^{(i)}}$

Reconstruction loss: $\mathcal{L}^{(j)}=\frac{1}{N_s}\sum_{i=1}^{N_s}\|I^{(j)}-\tilde{I}_i^{(j)}\|^2$

Optimization: gradient descent to minimize loss

Diffraction coded aperture: $\frac{kr_n^2\delta_{n1}}{2s_0}=\phi_0+2\pi n$

New focal depth: s_{n1} $\quad \delta_{n1}=(1/s_0-1/s_{n1})s_0$

Experimental Results

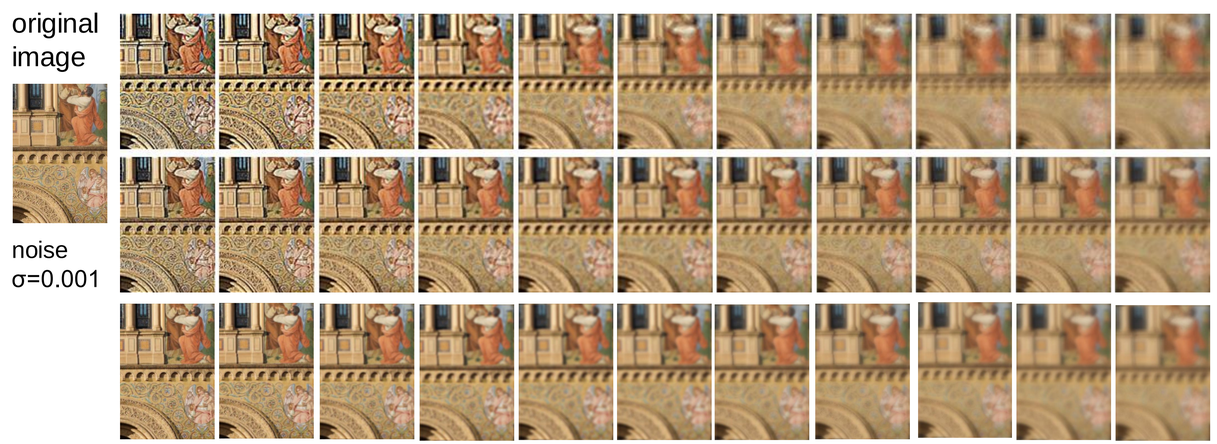

Fig. 2 Image processing result. From left to right δ = 0, 0.1, 0.2, … 0.9, 1

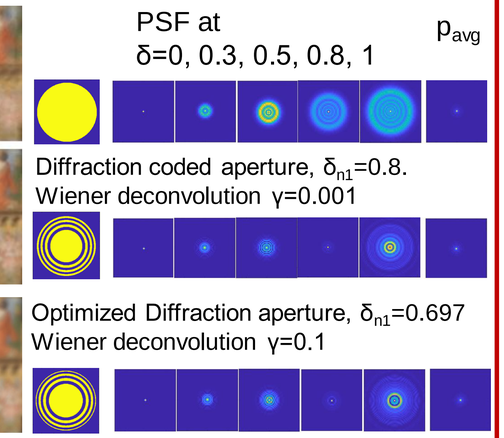

Fig. 3 PSF comparison.

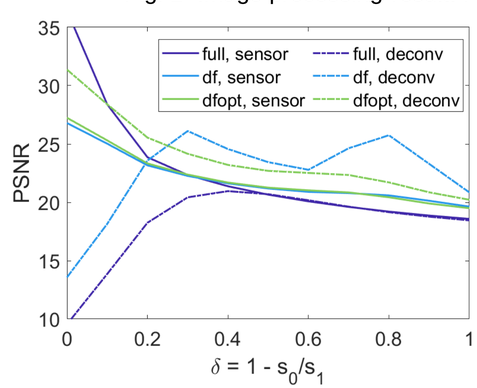

Fig. 4 PSNR comparison for the full aperture, diffraction coded aperture and the end-to-end optimized aperture.

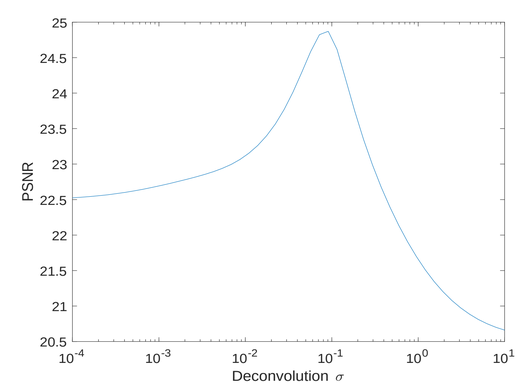

Fig. 5 Parameter sensitivity to deconvolution parameter γ.

Conclusions

- The coded aperture is capable of extend the depth of field.
- The coded aperture designed based on diffraction optics successfully creates the second focal plane.
- With end-to-end optimization, we obtain the optimized aperture together with the parameter γ in the Wiener filter.