End-to-end Learning for Computational Imaging

Realization of Diffractive Achromat and Super-resolution SPAD Camera

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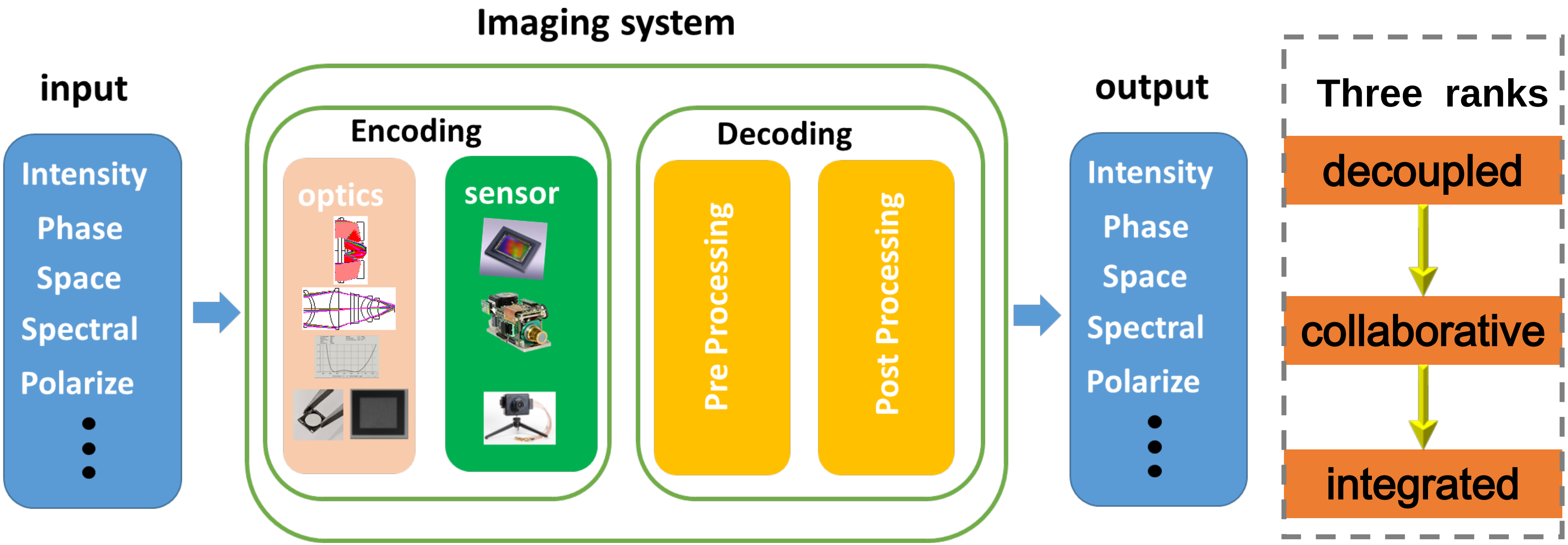
Outline

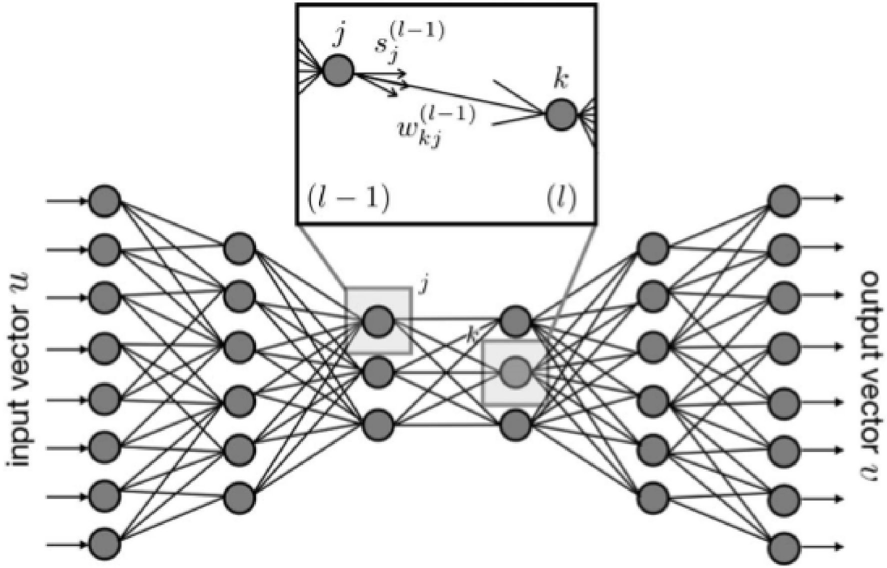
- ❖ **Define and Background**
- ❖ **Two examples**
  1. **Learned achromatic DOE for full spectrum computational imaging**
  2. **Optically Coded Super-resolution SPAD Camera**
- ❖ **Conclusion**

Computational Imaging



Solving an optimization problem: $\mathbf{i} \approx \arg\min_{\mathbf{i}} \frac{\mu}{2}\left\|\mathbf{b}-\mathbf{P}\cdot\mathbf{i}\right\|_2^2 + \Gamma(\mathbf{i})$

Deep Learning



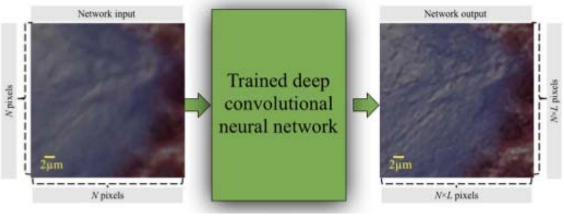
GEORGE BARBASTATHIS,2019

Based on neural network (NN).
Composed by lots of simple nonlinear processing units,
Each unit receives its inputs as weighted sums from the previous

Deep Learning based computational imaging

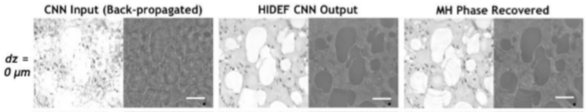
Deep leaning used as a solver

deblur



Rivenson et al. 2017

PR

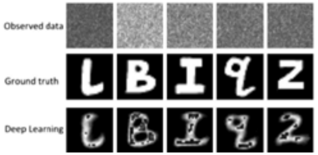


Wu et al. 2018

Denoise

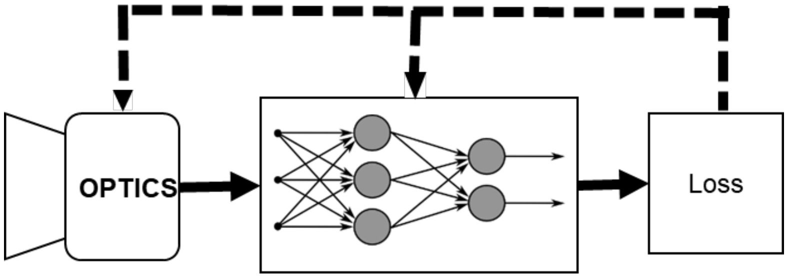
Chen et al. 2018

See diffuser

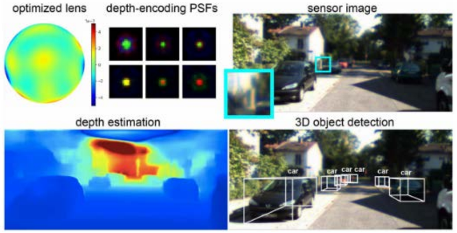


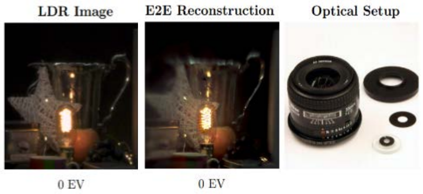
Lyu et al. 2017

Deep leaning as a design framework



Sitzmann et al. 2018





Chang et al. 2019

Metzler et al. 2019

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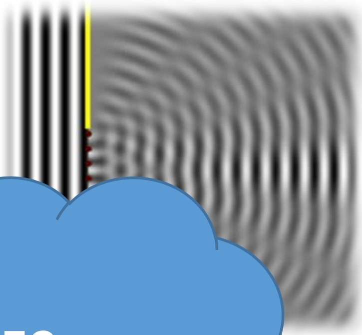
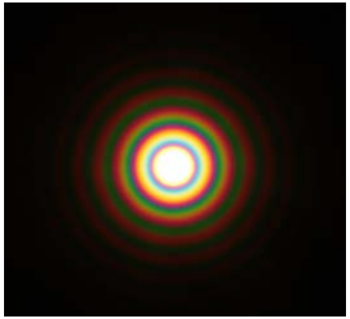
Problem statement

Diffractive Optical Elements (DOEs)

- **Amplitude & Phase modulation**





Need realize achromatic design

Thin; Great, flexible
& operatio

Wavelength sensitive → color dispersion

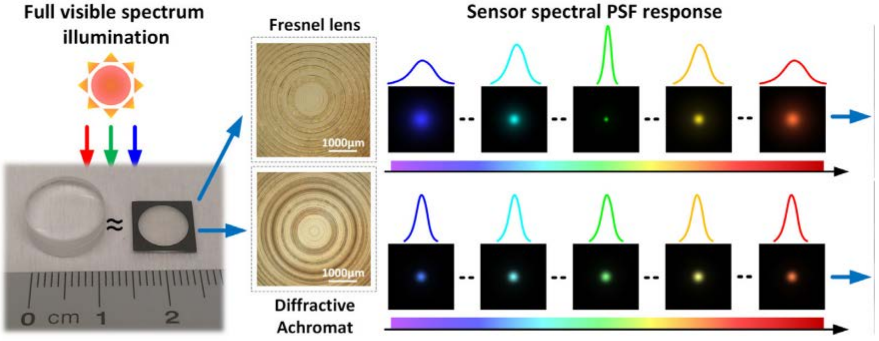
amerism problem

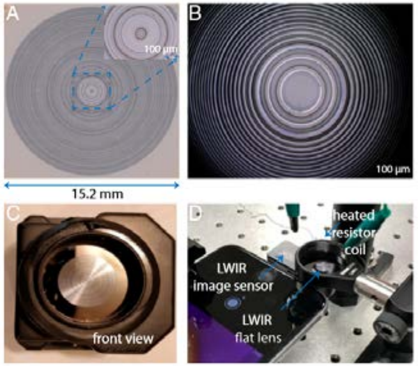
Peng et al. 2016

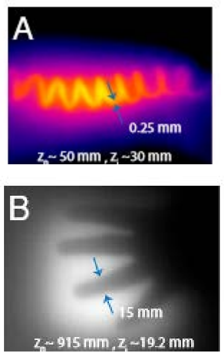
Previous methods

Belong to collaborate. Design achromatic based on Handed-craft target PSF.

Peng et al. 2016



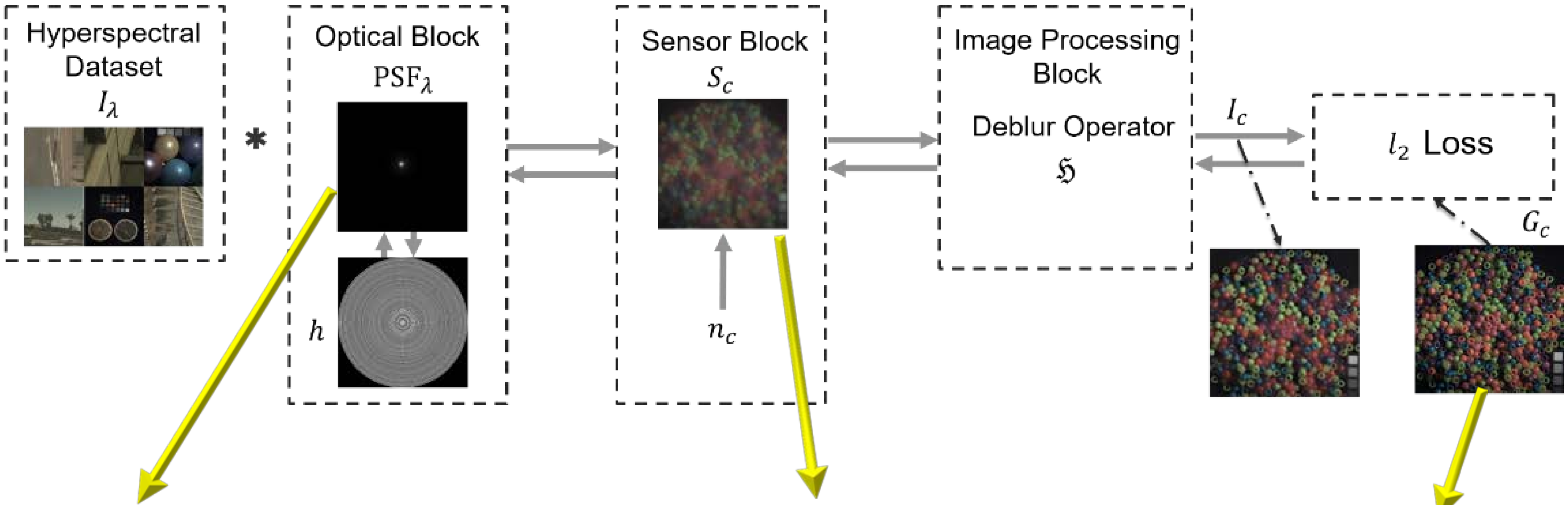




May not the optimal PSF for latter image processing

Meem et al. 2019

Proposed method



1D PSF simulator

$$I_c(r') = \int_{\lambda=\lambda_1}^{\lambda=\lambda_2} I(r',\lambda) * PSF(r',\lambda) R_c(\lambda) d\lambda + n_c,$$

$$G_c(r') = \int_{\lambda=\lambda_1}^{\lambda=\lambda_2} I(r',\lambda) R_c(\lambda) d\lambda.$$

Proposed method

1D PSF simulator → Solve the problem of Heavy memory consumption

Origin rotational symmetric

Fresnel propagation

$$f_{z',\lambda} = \left| \exp\left(jk\left(\sqrt{x^2+y^2+z'^2} + (n-1)h(x,y)\right)\right) * \exp\left(j\frac{k}{2z}(x^2+y^2)\right)\right|^2$$

↓

Discrete Hankel transform

$$f_{z',\lambda} = \sum_i G(r_i)\left[r_i J_1(2\pi\rho r_i) - r_{i-1} J_1(2\pi\rho r_i)\right]$$

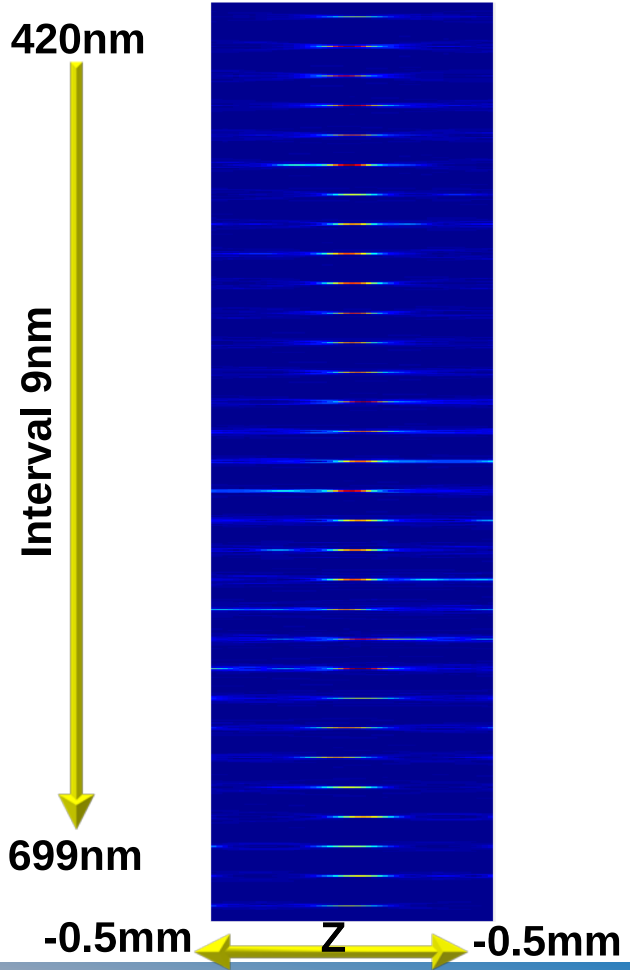
Past

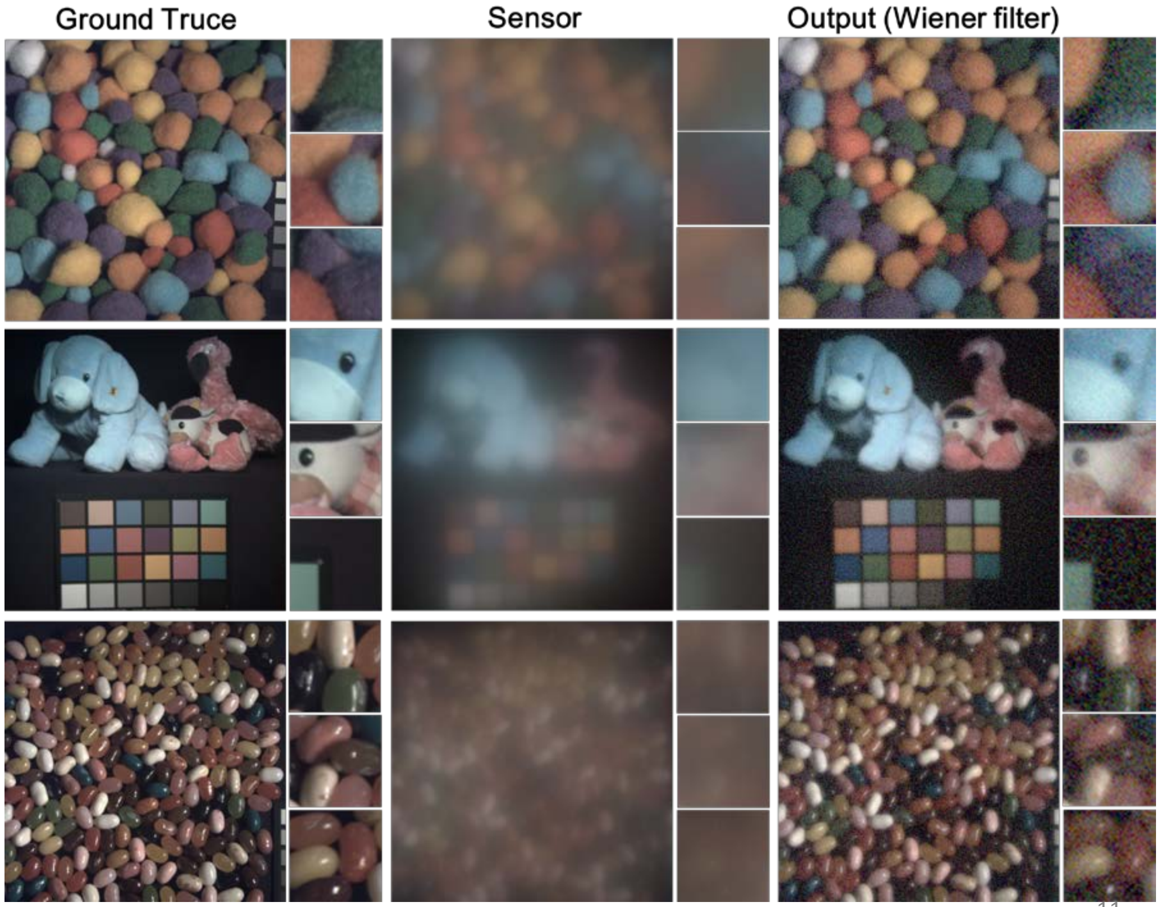
For Nvidia 1080TI GPU, the largest pixel sample numbers are 2500 by 2500 with 3-wavelength channels

With proposed 1 D simulator

Can design pixel number of 8000 by 8000 with 31-wavelength channels

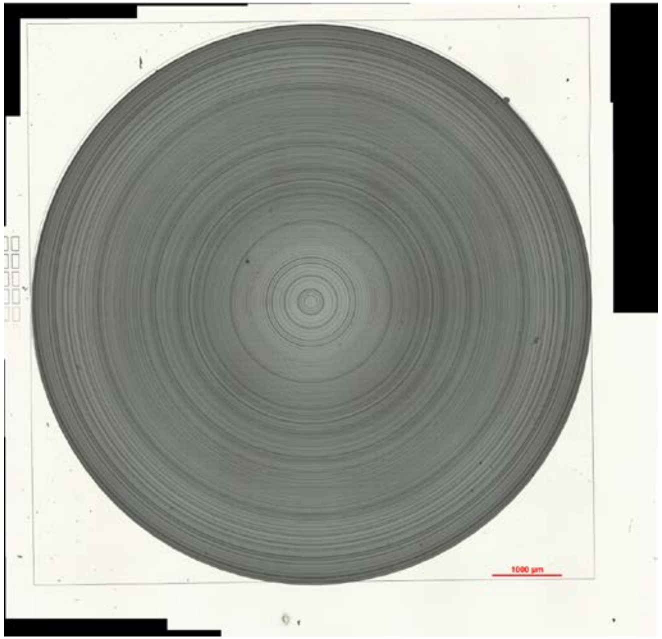
Simulation results





Real capture (FLIR GS3-23S6C-C)

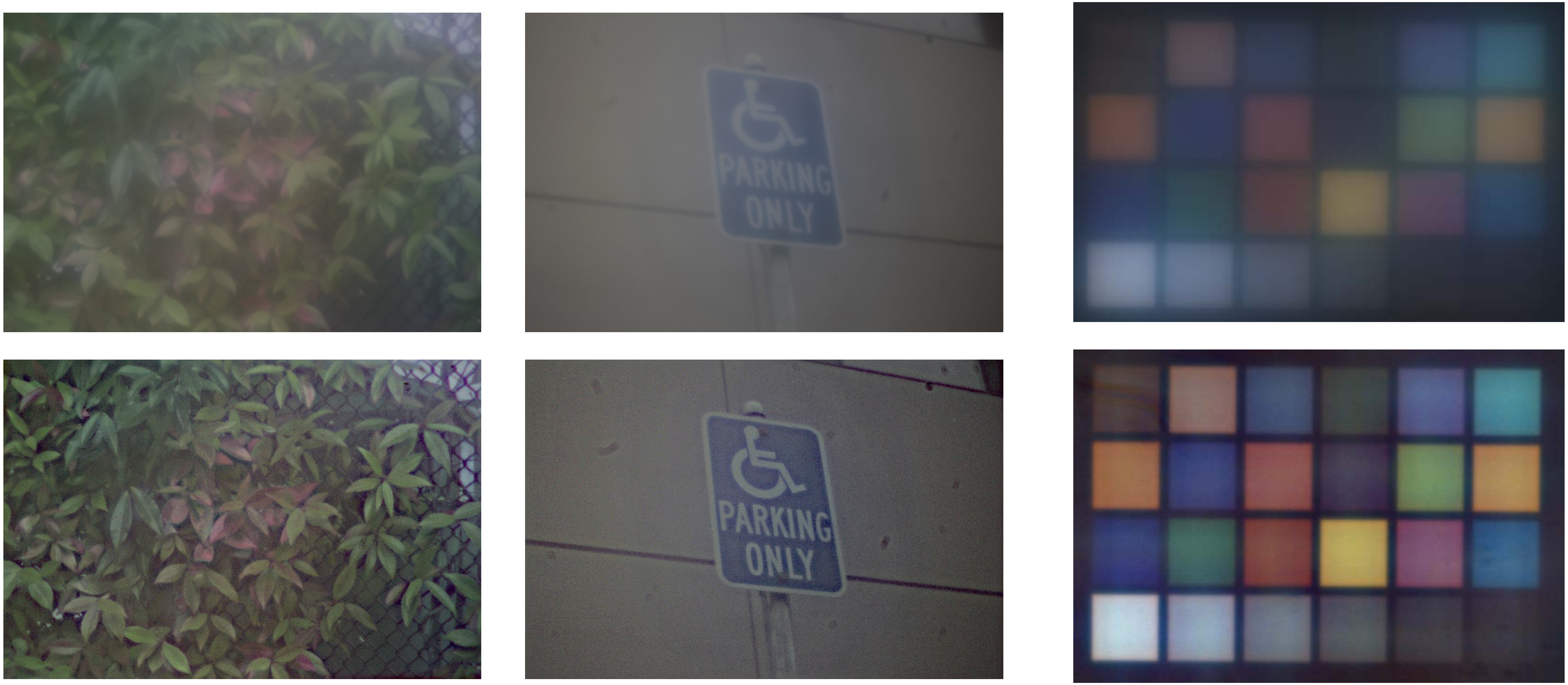
Fabricated DOE



Sensor output

proposed

Real capture (cannon D60)



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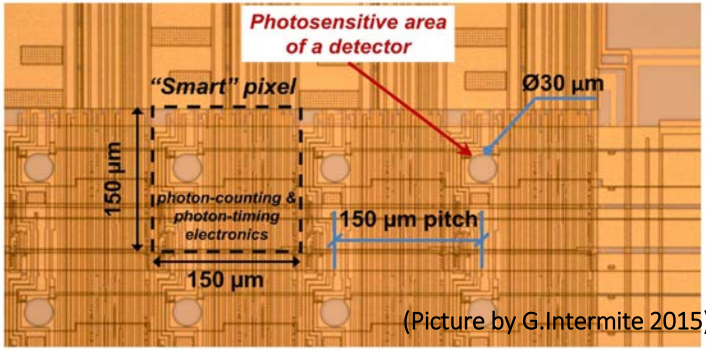
Problem statement

SPAD array sensor

(Picture from MPD)

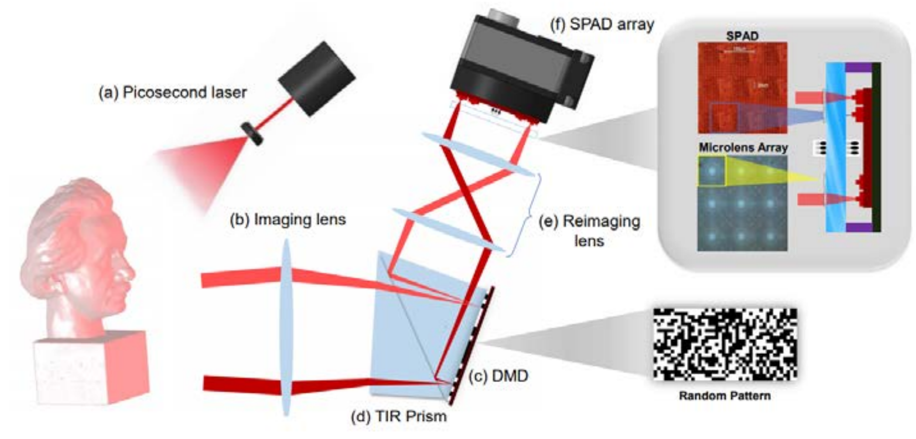


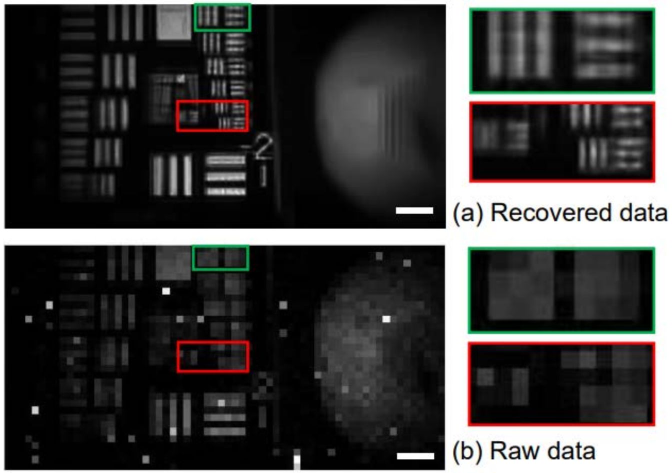
(Picture by G.Intermite 2015)

- **Single photon level sensitivity**
- **Pico-second level time resolution**
- **Low spatial resolution(32*64)**
- **Low fill-factor(3.15%)**

Need realize super-resolution and anti-aliasing

Previous methods

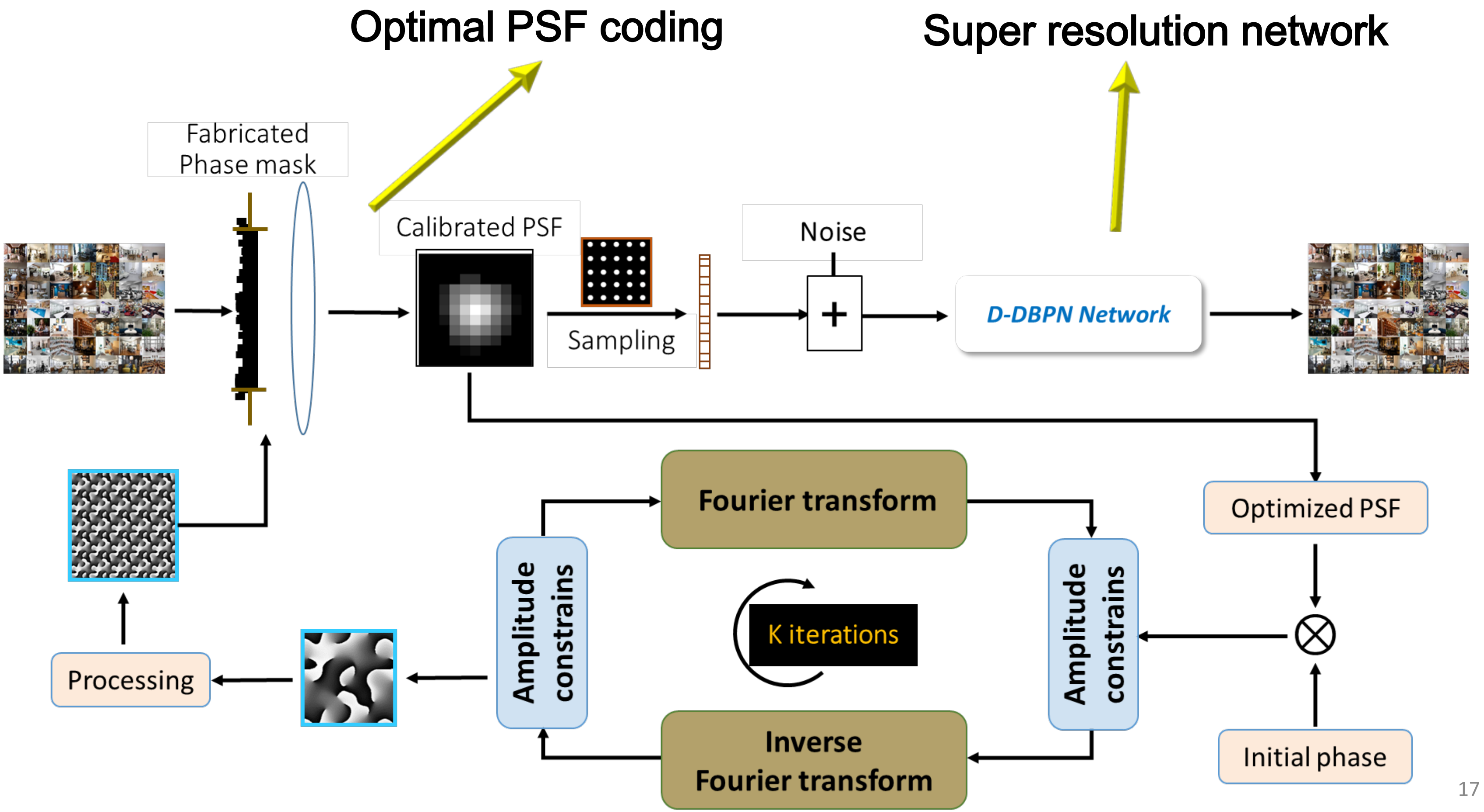




Sun et al. 2018

Based on Compressive sensing, the system is very complicated

Proposed method

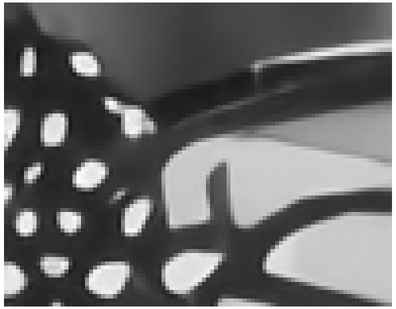


Simulation result

model	Set5 PSNR	Set14 PSNR	BSDS100 PSNR
Low fill-factor	27.13	24.12	23.95
Full fill-factor	29.48	25.93	25.55
Ours	30.76	26.91	26.23

Low fill-factor

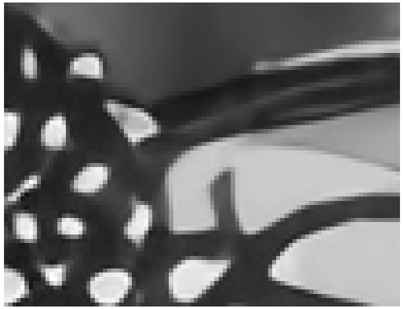
Low fill-factor (no mask)



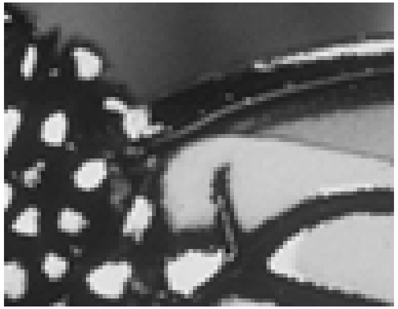
With phase mask

Ours

Full fill-factor

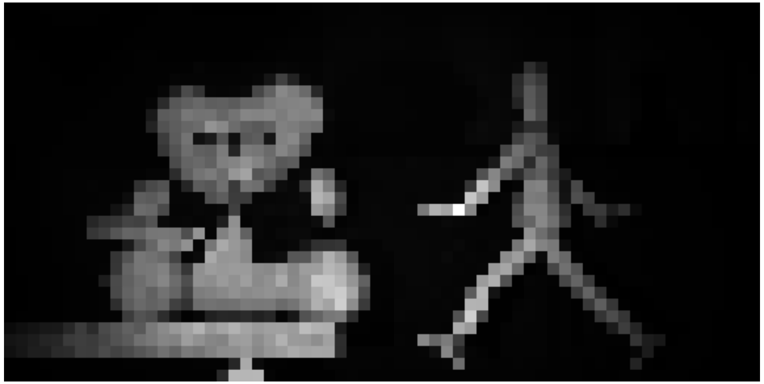


Full fill-factor



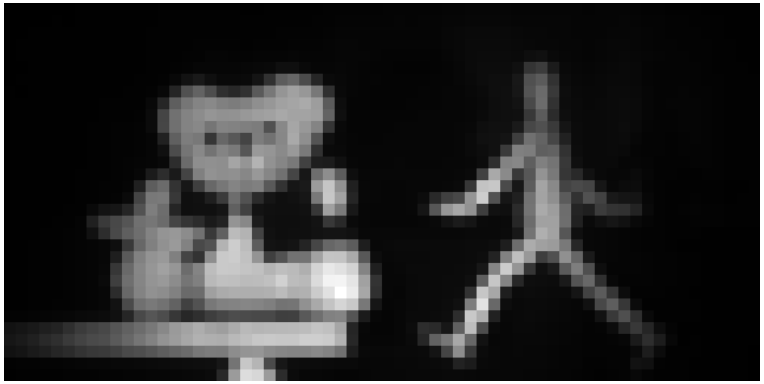
Ground Truth

Real capture (the optimized mask is helpful)

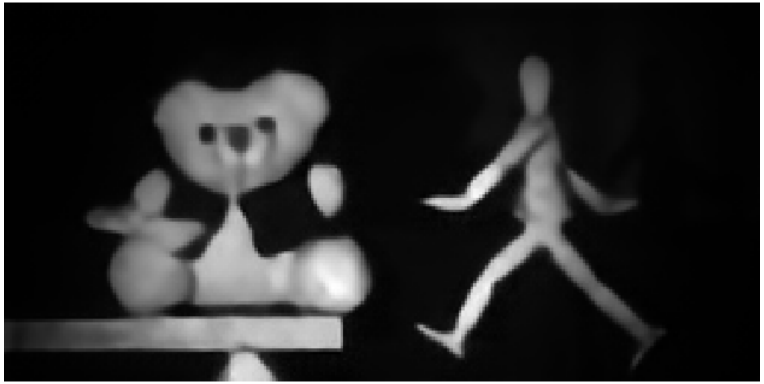


Raw image without mask

Result without mask



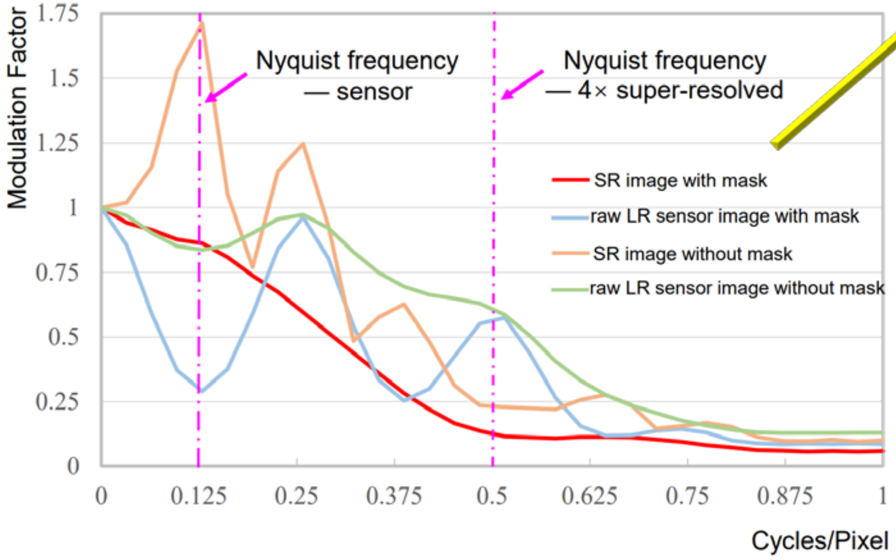
Raw image with mask

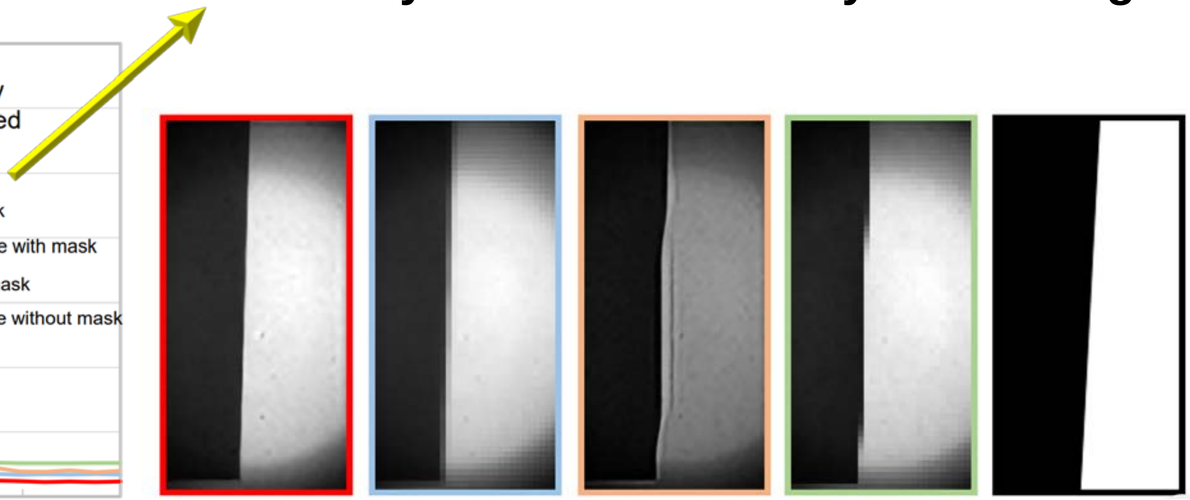


Result with mask

Real capture (MTF test)

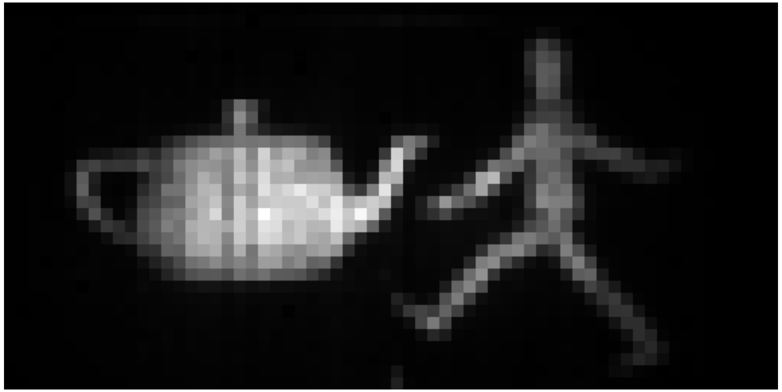
Smoothly and monotonously decreasing



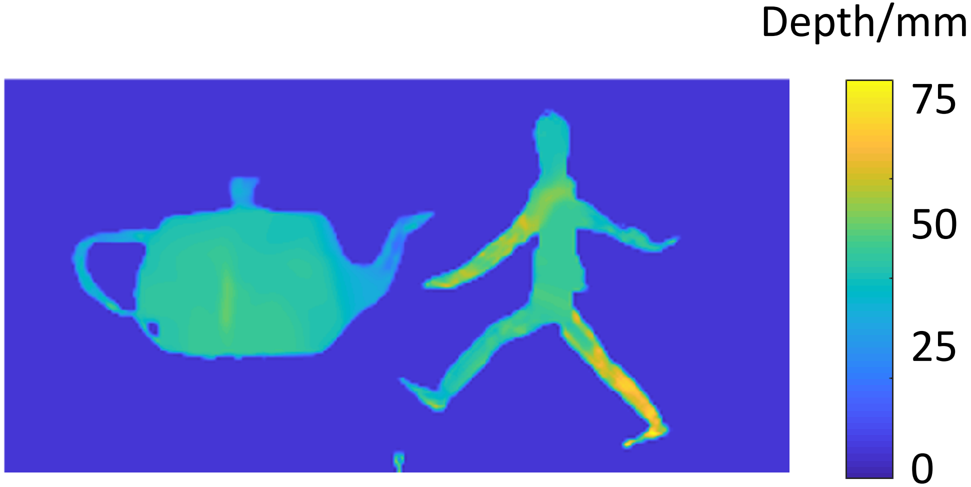


Real capture (more results)

Real capture (more results)



SPAD measurement
summed over time axis



Reconstruction depth map

Real capture (more results)

**SPAD measurement
(time resolved 20ps)**

Reconstruction result

Reference

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Conclusion

Benefit from the end to end design framework

Example 1

1. **Automatic seek the best-fit PSFs instead of non-optimized hand-crafted PSFs**
2. **Obtain good results even with a relatively simple image processing algorithm**

Example 2

1. **Achieve an spatial resolution enhancement of 4×**
2. **Optimized compromise between sharpness and anti-aliasing for a given pixel fill-factor.**

Conclusion

- Performance & robustness gains
- Domain-specific hardware reduce footprint, cost, power, capture time…

we envision the end to end design can boost lots of applications

Relative papers

1. Q.L. Sun, J. Zhang, X. Dun, B. Ghanem, Bernard, Y.F. Peng, Yifan and Heidrich, W. Heidrich, End-to-End Learned, Optically Coded Super-resolution SPAD Camera, ACM Transactions on Graphics, 2020
2. Y.F. Peng*, Q.L. Sun*, X. Dun*, G. Wetzstein, W. Heidrich, F. Heide. Learned Large Field-of-View Imaging With Thin-Plate Optics. ACM Transactions on Graphics, 2019.
3. X. Dun, Z.S. Wang, Y.F. Peng. Joint-designed achromatic diffractive optical element for full-spectrum computational imaging (Invited Paper). Proc. of SPIE (2019).
4. D. S. Jeon, S.H. Baek, S. Yi, Q. Fu, X. Dun, W. Heidrich, M.H. Kim, Compact Snapshot Hyperspectral Imaging with Diffracted Rotation, ACM Transactions on Graphics, (2019).
5. V. Sitzmann, S. Diamond, Y.F. Peng, X. Dun, S. Boyd, W. Heidrich, Felix Heide, Gordon Wetzstein. End-to-end Optimization of Optics and Image Processing for Achromatic Extended Depth of Field and Super-resolution Imaging. ACM Transactions on Graphics, 2018.
6. Q.L. Sun, X. Dun, Y.F. Peng, W. Heidrich, Depth and Transient Imaging with Compressive SPAD Array Cameras, in CVPR. 2018

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Thank you!

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