Binary Coded Aperture Design by Sphere Packing in Compressive Ultrafast Photography






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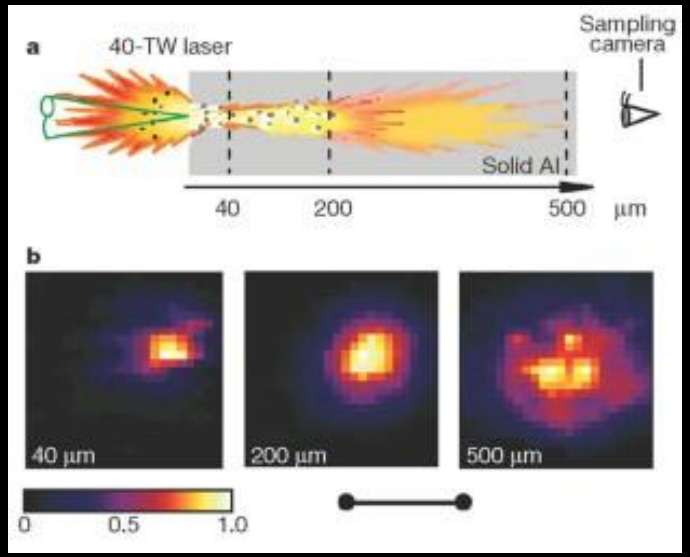
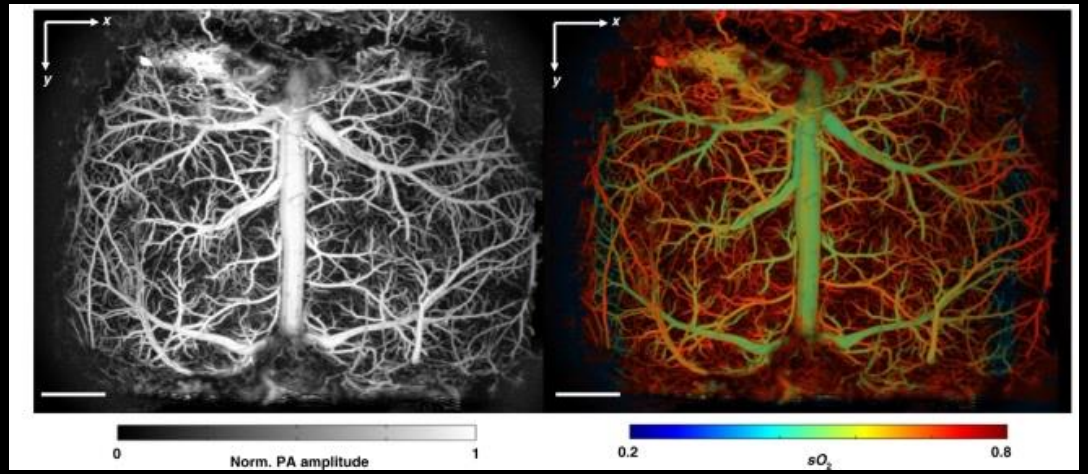
OPTOLAB

Sensing Transient Events



Nuclear fusion: Fast-heating plasma



Neuroscience for monitoring neural activity

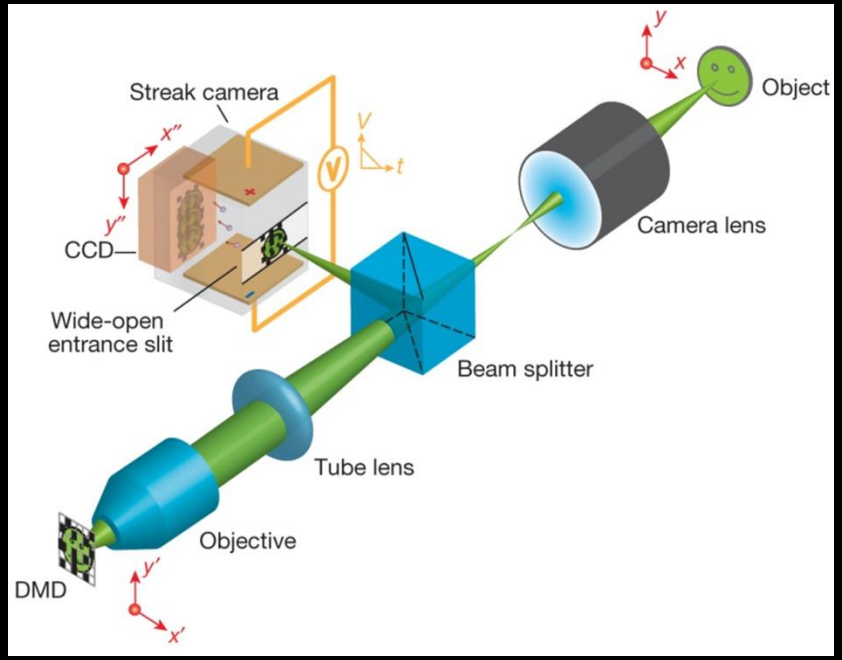
Conventional cameras capture up to 10^7

R. Kodama, P. Norreys, K. Mima, A. Dangor, R. Evans, H. Fujita, Y. Kitagawa, K. Krushelnick, T. Miyakoshi, N. Miyanaga et al., “Fast heating of ultrahigh-density plasma as a step towards laser fusion ignition,” Nature 412, 798–802 (2001)

X. Zhu, Q. Huang, A. DiSpirito, T. Vu, Q. Rong, X. Peng, H. Sheng, X. Shen, Q. Zhou, L. Jiang et al., “Real-time whole-brain imaging of hemodynamics and oxygenation at micro-vessel resolution with ultrafast wide-field photoacoustic microscopy,” Light. Sci. & Appl. 11, 138 (2022).

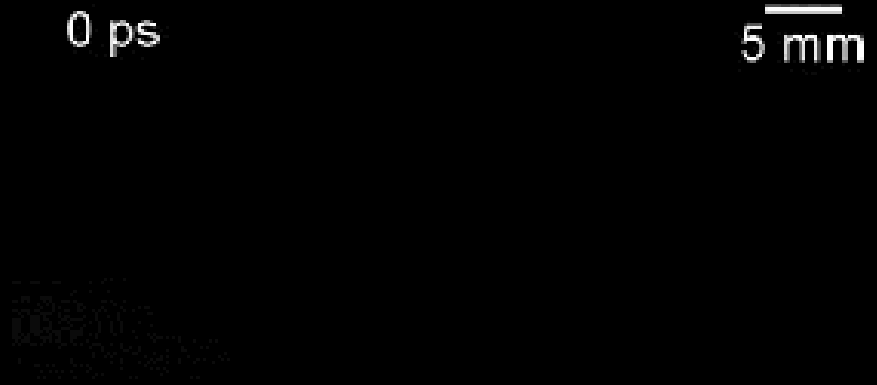
Compressive Ultrafast Photography (CUP)

The scene is encoded using a binary coded aperture. Then, the encoded scene is sheared by the temporal shearing operator. The encoded and sheared scene is captured in the detector.

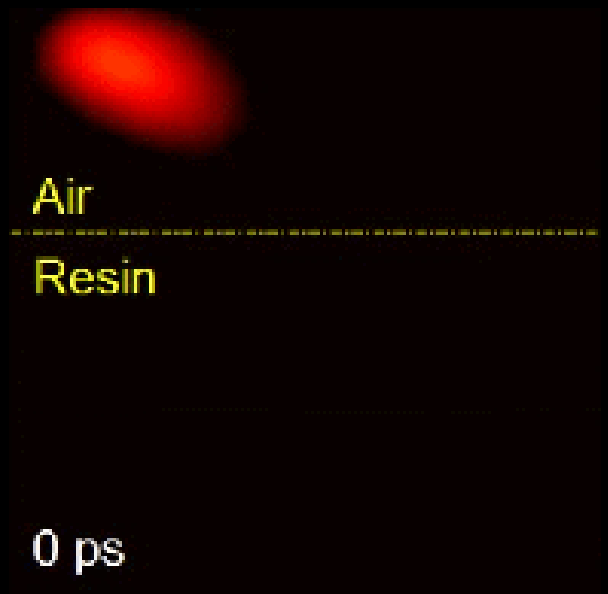


L. Gao, J. Liang, C. Li, and L. V. Wang, “Single-shot compressed ultrafast photography at one hundred billion frames per second,” Nature 516, 74–77 (2014).

Compressive Ultrafast Photography (CUP) Applications



Optical Mach cone using CUP



Single-shot CUP pulse refraction

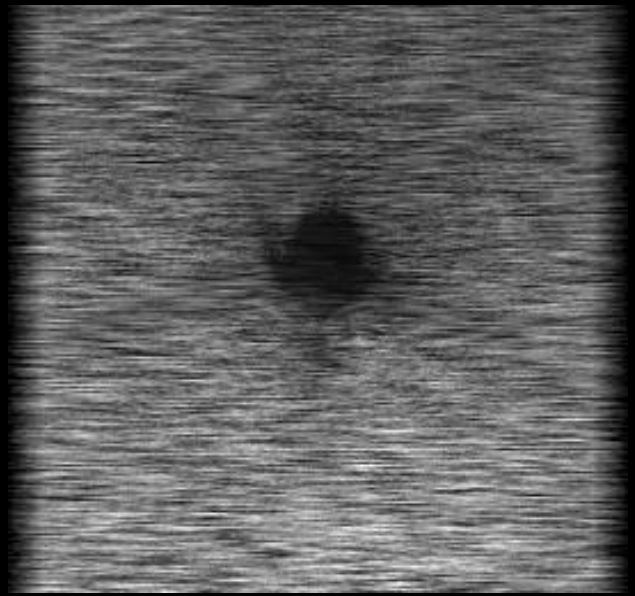
Real-time applications is limited by reconstruction

L. Gao, J. Liang, C. Li, and L. V. Wang, “Single-shot compressed ultrafast photography at one hundred billion frames per second,” Nature 516, 74–77 (2014).

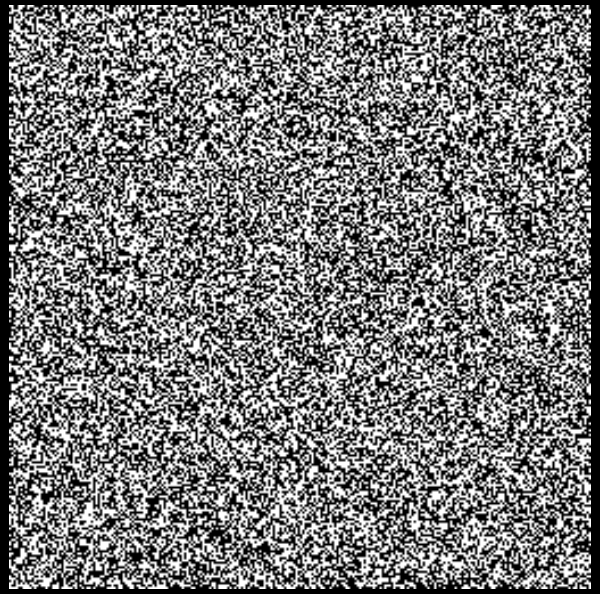
CUP Discrete Model

$$Y_{(:,\bar{t})} = \sum_{t=0}^{T-1} X_{(:,:,\bar{t})} \odot C_{(:,:,\bar{t})} + \Omega$$

designing the encoding is critical for real-time applications



measurement



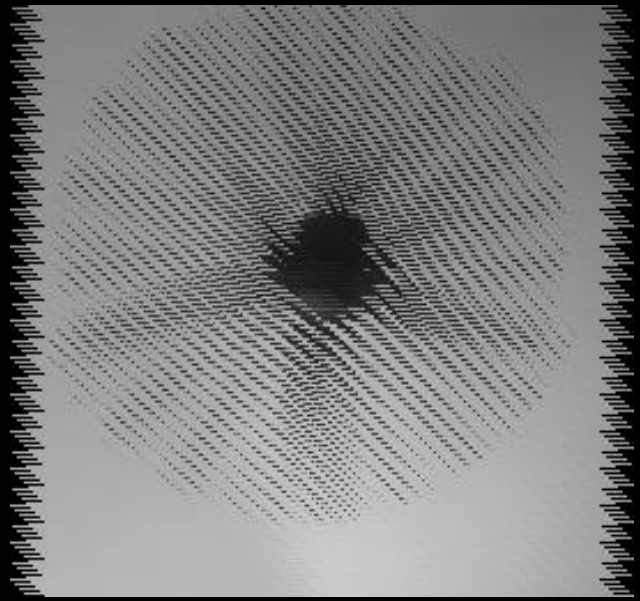
traditional coded aperture

video

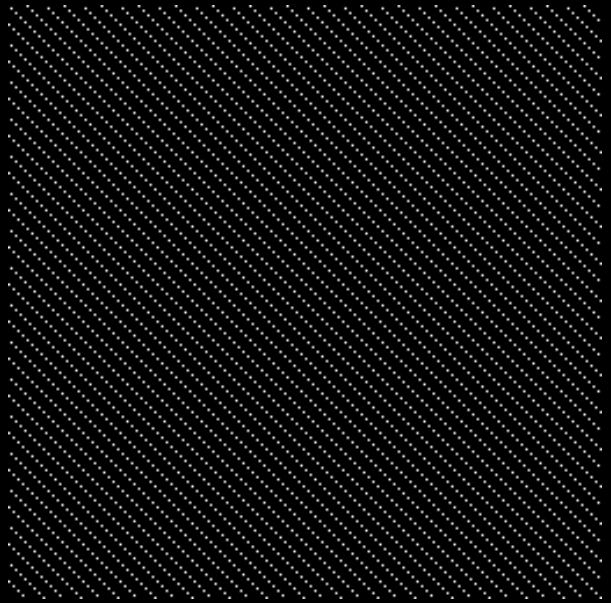
Discrete model

$$Y_{(:,\bar{t})} = \sum_{t=0}^{T-1} X_{(:,:,\bar{t})} \odot C_{(:,:,\bar{t})} + \Omega$$

novel aperture design



measurements



coded aperture

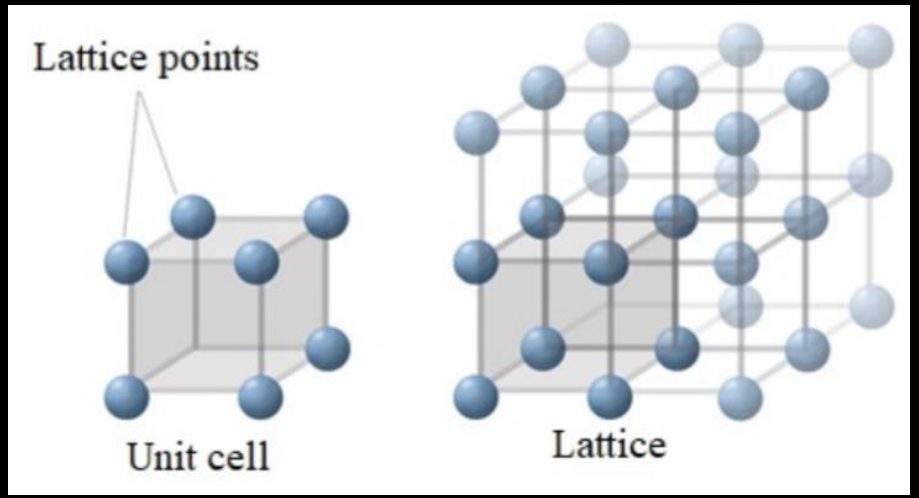
video

What is Sphere Packing?

- Ask for the densest packing of R^n
- Faced-center cubic lattice is optimal in 3D

$$\rho_{\Lambda_3} = \frac{\pi}{\sqrt{18}} \approx 0.74 \ldots$$

stacking cannonballs

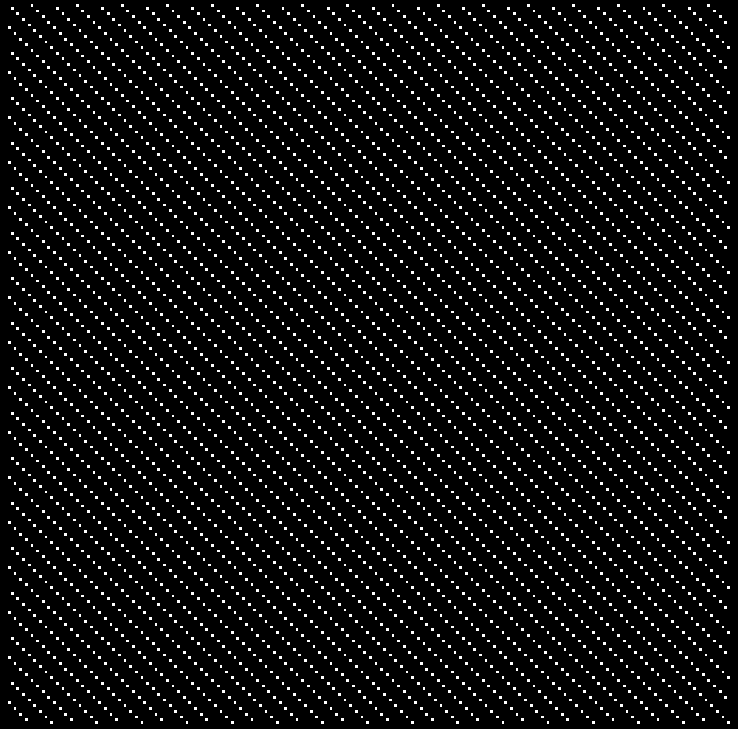


Tiling the space by replicating the unit cell

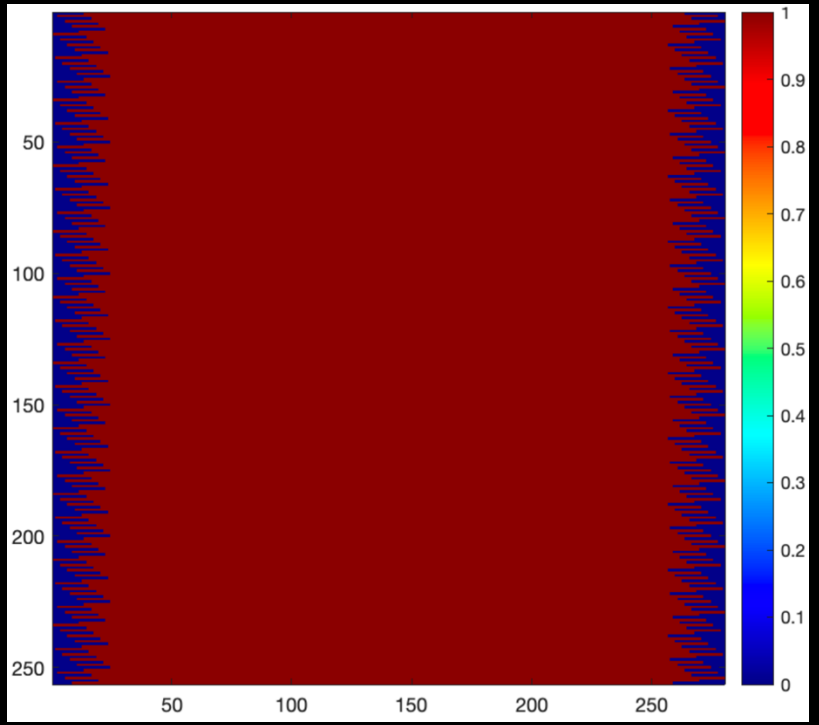
J. Kepler, The six-cornered snowflake (Paul Dry Books, 2010).
T. Hales, M. Adams, G. Bauer, T. D. Dang, J. Harrison, H. Le Truong, C. Kaliszyk, V. Magron, S. McLaughlin, T. T. Nguyen, and et al., “A formal proof of the kepler conjecture,” Forum Math. Pi 5, e2 (2017).

Coded Aperture Design

- The coded aperture exploits the shifting induced by the galvanometer scanner.
- Our design guarantees uniform sampling.



uniform coded aperture

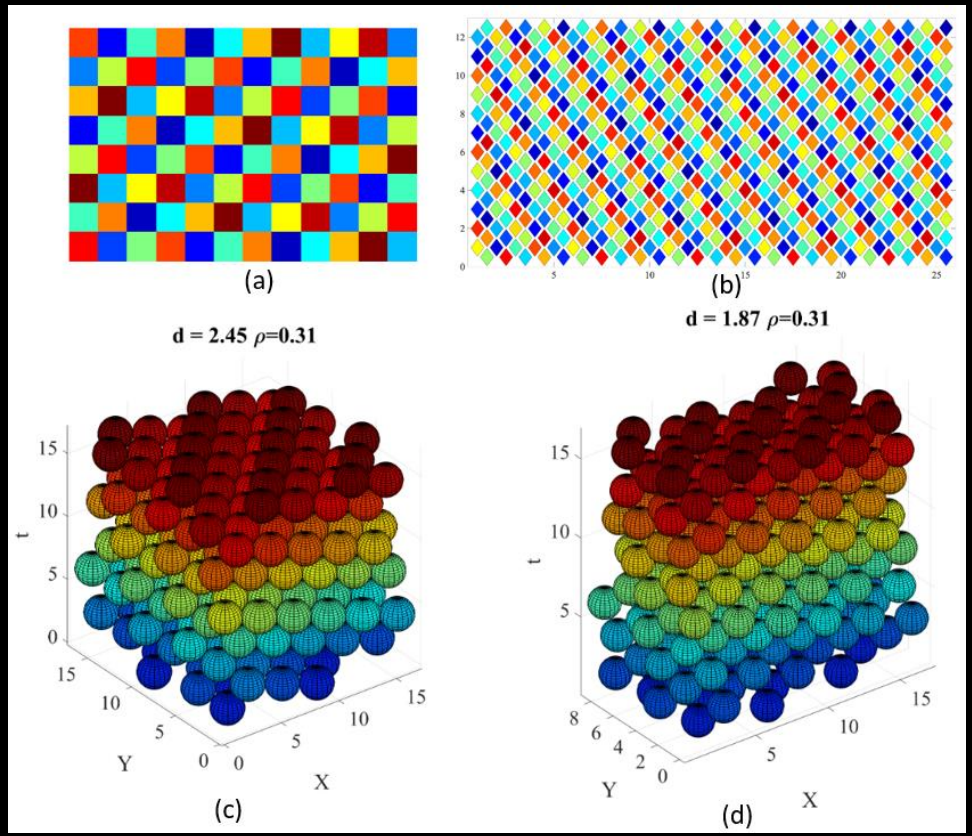


uniform sensing

Sphere Packing Comparison Between DMDs

orthogonal DMD

diamond DMD

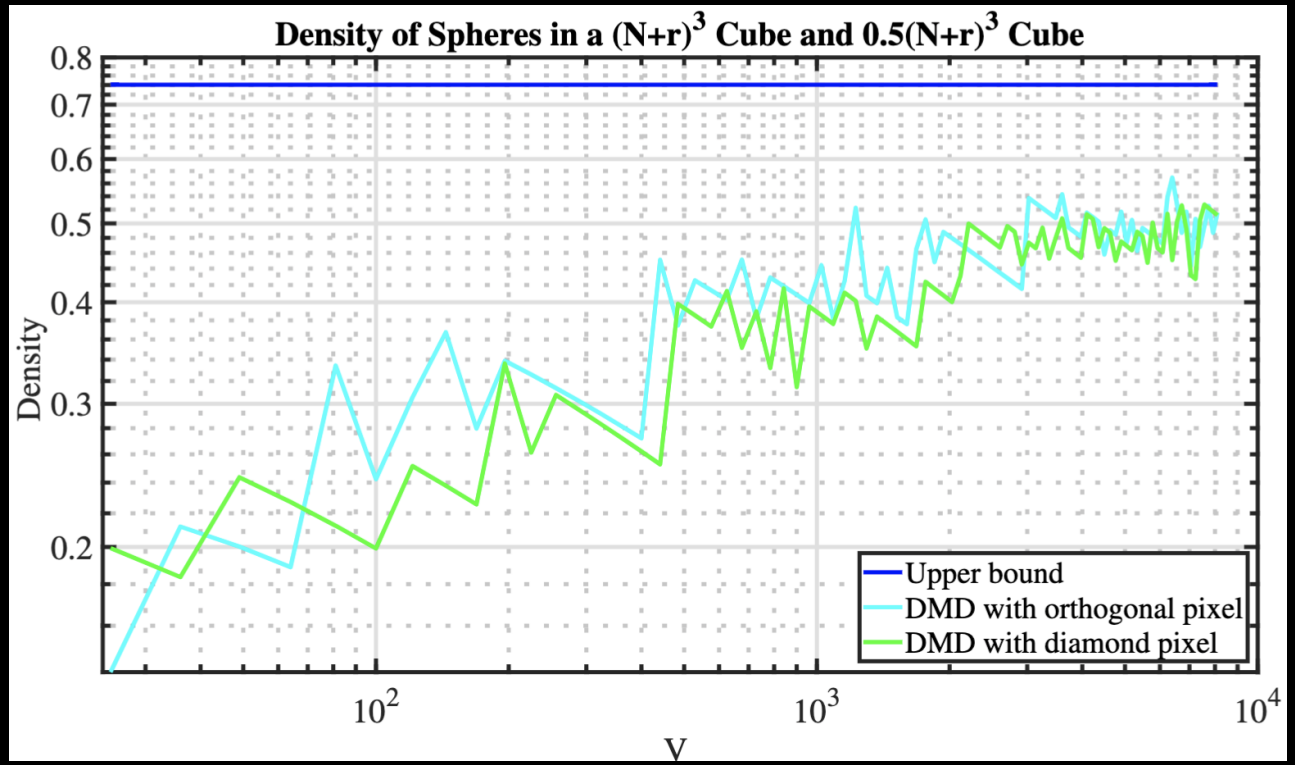


Texas instruments

orthogonal: DLP3010LC
diamond: DLP® 0.45 WXGA DMD

	Orthogonal DMD	Diamond DMD
radius	2.45	1.87
density	0.31	0.31

Sphere Packing Bound

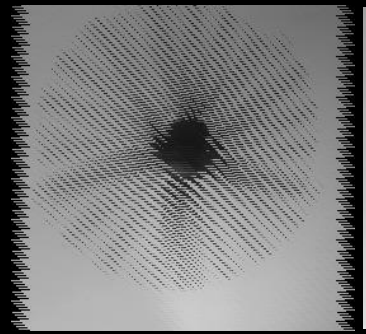


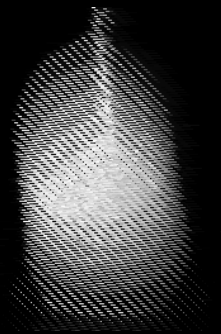
$$\rho_{\Lambda_3} = \frac{\pi}{\sqrt{18}} \approx 0.74 \ldots$$

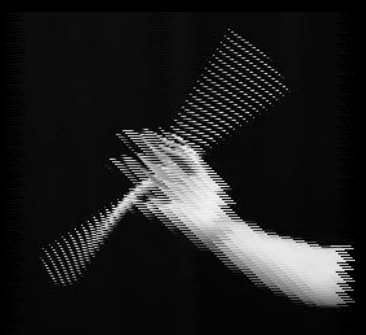
Both spheres densities are comparable as the number of spheres grows

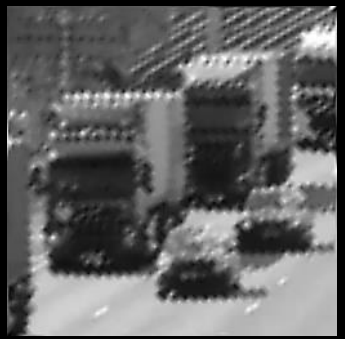
E. Vera, F. Guzmán, and N. Díaz, "Shuffled rolling shutter for snapshot temporal imaging," Opt. Express 30, 887–901, (2022).
E. Vera, F. Guzman, and N. Diaz, Shuffled Rolling Shutter Camera (Springer International Publishing, Cham, 2024), pp. 499–513.
N. Diaz, A. Alvarado, P. Meza, F. Guzmán, and E. Vera, "Multispectral filter array design by optimal sphere packing,"IEEE Transactions on Image Process. 32, 3634–3649 (2023)

Simulation Results









measurements

reconstruction

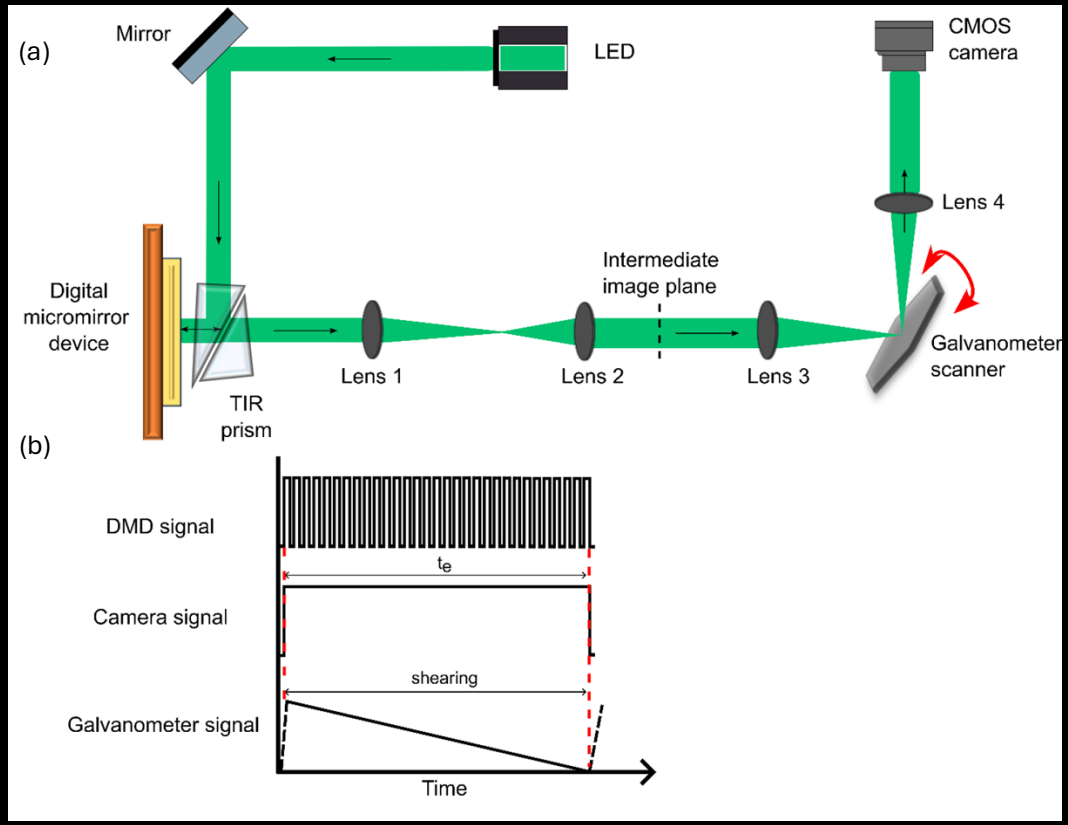
measurements

reconstruction

Algorithm	CA	Number of frames		
		$T = 16$	$T = 25$	$T = 31$
NNI	random CA PSNR (dB)	27.59	25.75	24.98
	random CA SSIM	0.91	0.87	0.83
	SPCA PSNR (dB)	28.33	26.9	25.06
	SPCA SSIM (dB)	0.92	0.89	0.85

I. Amidror, “Scattered data interpolation methods for electronic imaging systems: a survey,” J. Electron. Imaging 11,157–176 (2002).

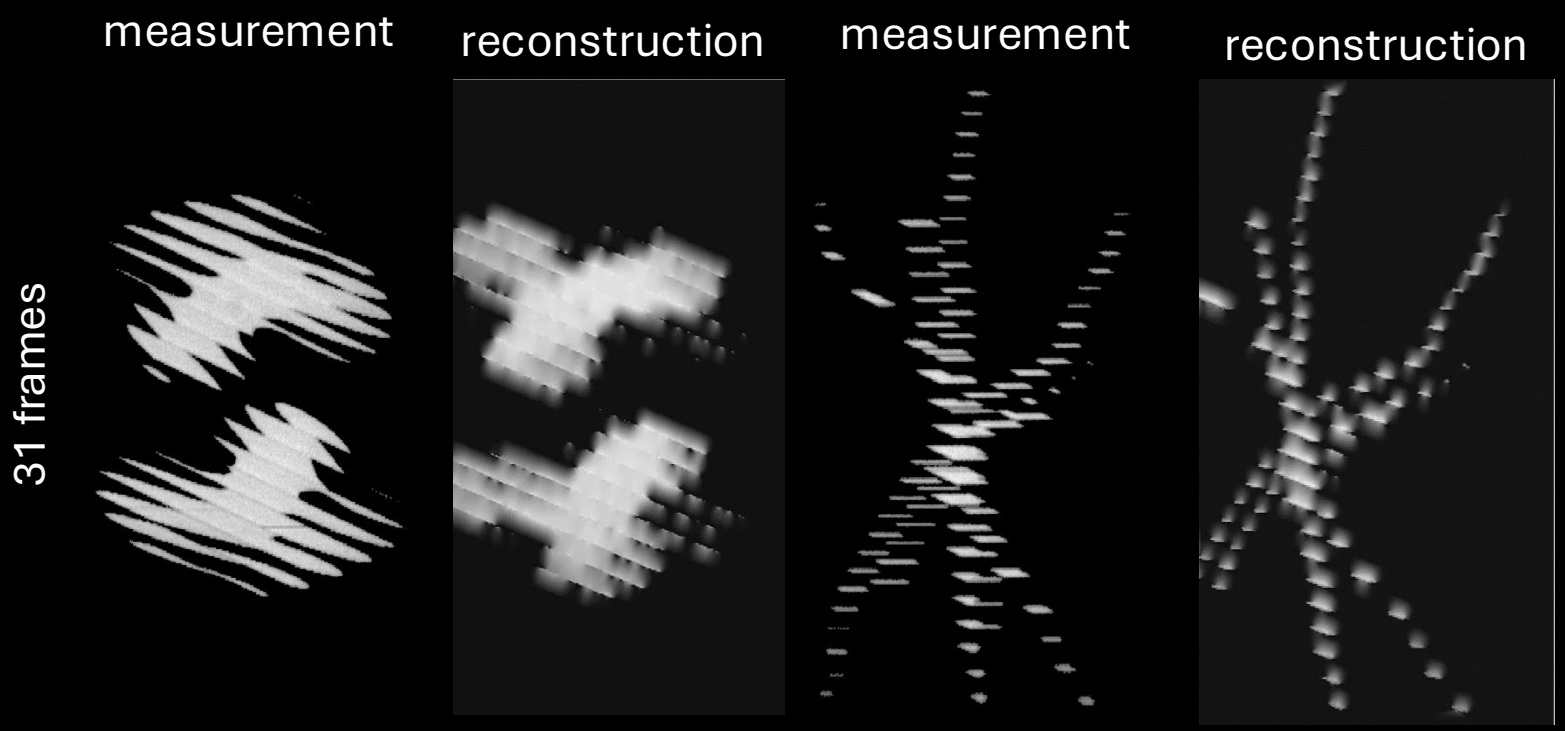
Experimental implementation



- Architecture: compressed optical-streaking ultra-high-speed photography
- Encoding: single binary mask
- Shearing operator: Galvanometer

X. Liu, J. Liu, C. Jiang, F. Vetrone, and J. Liang, "Single-shot compressed optical-streaking ultra-high-speed photography," Opt. Lett. 44, 1387–1390 (2019).

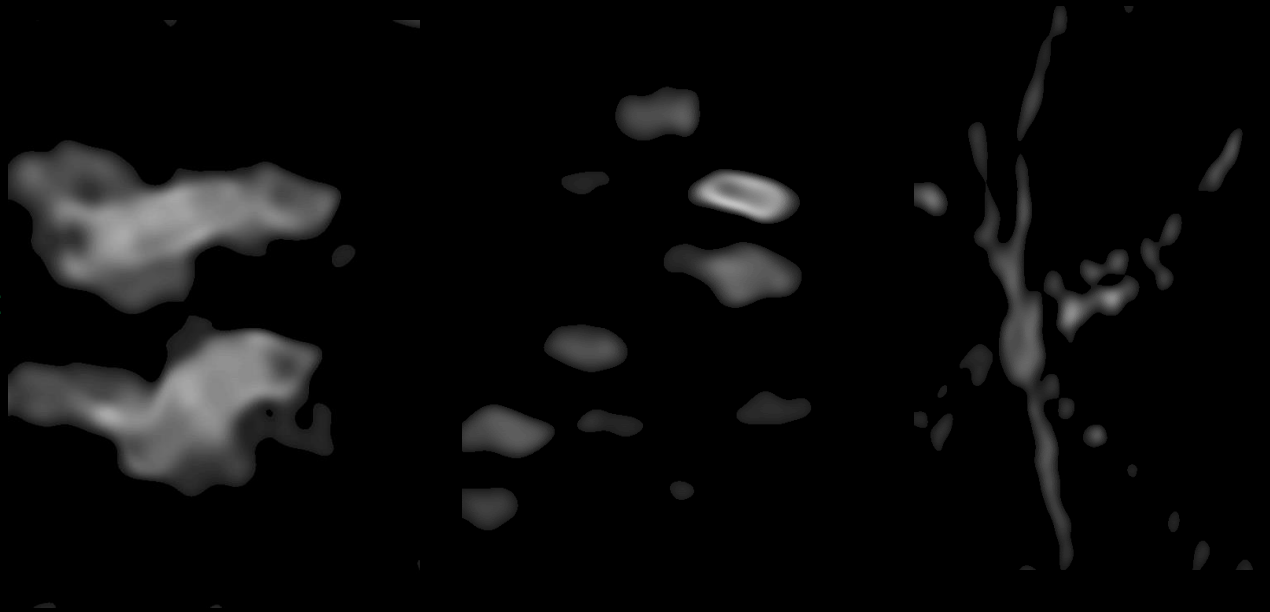
Real-data: Interpolation



I. Amidror, “Scattered data interpolation methods for electronic imaging systems: a survey,” J. Electron. Imaging 11,157–176 (2002).

Real-data with Implicit Neural Representation

reconstruction reconstruction reconstruction



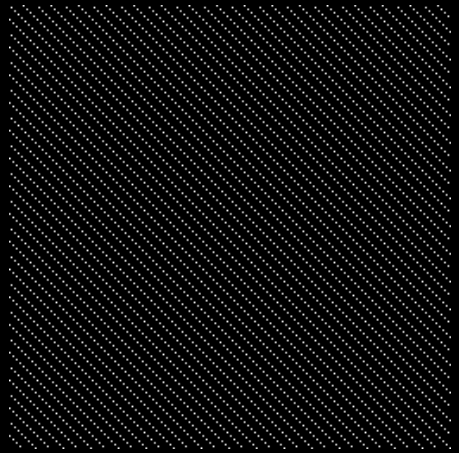
Parameters

- Initial learning rate: 0.0005
- Iteration: 1500
- Resolution: 714 x 574 x 31
- Training: a single measurement
- Training time: 1.7 s
- Testing time: 2.5 ms
- Layers: Two hidden layers

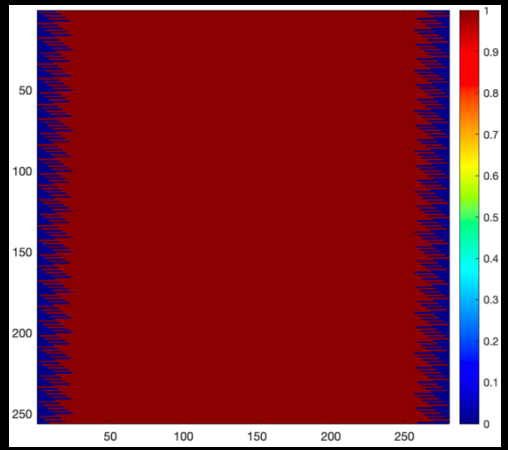
V. Sitzmann, J. Martel, A. Bergman, D. Lindell, and G. Wetzstein, “Implicit neural representations with periodic activation functions,” in Advances in Neural Information Processing Systems, vol. 33 H. Larochelle, M. Ranzato, R. Hadsell, M. Balcan, and H. Lin, eds. (Curran Associates, Inc., 2020), pp. 7462–7473

Conclusions

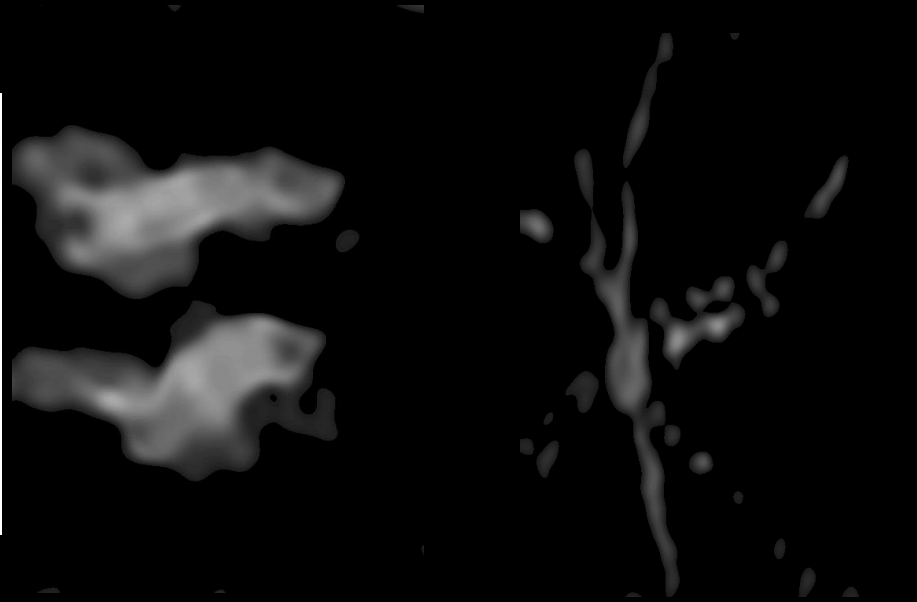
- We introduced a novel binary coded aperture for compressed optical-streaking ultra-high-speed photography
- Our designed coded aperture samples uniformly the video
- We recover the underlying video using interpolation and implicit neural representation



uniform coded aperture



uniform sensing



Thanks

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