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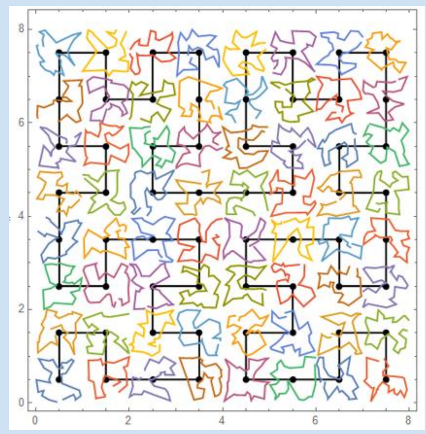
Turn-Key Compressed Sensing System For Scanning Microscopy

Technological Challenge & Solution

Compressed Sensing (CS) in serial scanning instruments involves sampling a minority fraction (i.e., 20%) of the full pixel density while allowing a faithful reconstruction of the object. A number of requirements must be satisfied to achieve a faithful reconstruction. Among these requirements is a high degree of statistical randomness in the sparse sampling strategy. Executing a highly random, high speed, precise scan pattern has presented a barrier to implementing a practical CS Scan Generator (**CSSG**) for electron microscopy. One of the common issues when designing a CS serial scan strategy is to mitigate effects tied to scan system dynamics [1]. An approach to overcome barriers to practical CS implementation in serial scanning electron microscope (SEM) or scanning transmission electron microscopes (STEM) was developed which integrates scan generator hardware specifically developed for CS, a novel and generalized CS sparse sampling strategy, and an ultra-fast reconstruction method, to form a complete CS system for electron microscopy. The system is also compatible with other serial scanning characterization techniques, such as AFM, EDS, Auger and even 3D sparse sampling applied to techniques such as laser scanning microscopy (LSM).

CSSG Principles of Operation

To minimize hysteresis, slew and other scan distortions, CS scan matrices were explored which ensured predominantly smooth and largely continuous scan pattern properties. Space-filling curves (SFCs) represent a family of topological curves which possess such properties. It was found through simulated reconstruction that SFCs in general "worked", but as a mathematical family are prone to non-idealities when applied directly as a CS sampling matrix. Namely, SFCs are pseudo random, which does not satisfy a highly statistically random sampling. SFCs are also discretized in degree of sparsity, as dictated by the order of the SFC and the pixel density.



Cartoon of FAST-SLOW DAC Concept

The optimal patent-pending solution was to employ the SFC as a "slow" carrier signal modulated by a "fast" randomized perturbation signal. In this manner, by combining the "slow" continuous carrier and "fast" random modulation, a programmable highly randomized pattern may be invoked with any fractional degree of sparsity and with a high geometrical degree of freedom (DOF) in 2D or 3D. And **no beam blanking is required!** Stage scanning is also possible to form a continuous scan.

The ratio of work performed by the carrier signal relative to the randomized modulated signal may be regulated to accommodate physical constraints of native hardware, such as amplifier circuits and scan coil response. The schema also does not generally require any beam blanking along the scan path! Fill blocks do not need to be orthogonal, square, or even Euclidean. A wide variety of SFCs may be applied with this system, including serpentine curves, spiral curves, Lissajous curves and other parametric curves. A module estimates resolution from the Fourier transform of the sparse data and the SNR from the Gaussian noise estimated from eigenvalues of the patch covariance. A second module measures and corrects scan distortions. A third module measures the point spread function and applies this kernel to correct beam distortions. See figures for examples of sparse sampling and reconstruction.

Ultra-Fast Reconstruction

The CSSG hardware is integrated with a Python-based GUI and software which combines to create a complete turn-key system for CS data acquisition and reconstruction. The hardware and software is compatible with nearly any scanning probe system (SEM, FIB-SEM, AFM, STM, LSM). With a SEM or STEM, the integration is identical to interfacing with the external scan inputs utilized by x-ray spectroscopy (EDS) systems.

The proprietary reconstruction method is termed **"ARTI"**, which stands for Adaptive Real-Time Inpainting. This ultra-fast method allows real-time observation of reconstructed images in a reduced raster window such that an operator can observe a fully reconstructed image based upon the sparse dose (i.e., 20%). See the central panel for comparisons of ARTI with other well-known CS reconstruction methods (described below) for relative speed and performance.

CS Reconstruction Background

InPainting

Inpainting is the process of "painting in" the gaps in an image. Applied to digital imaging: an inpainting algorithm uses available information such as non-missing pixels and their surrounding in that same image, or in other, non-sparse, images of a similar nature, to infer the missing information and reconstruct the image. Two methods from the literature, Nesta (faster) and BPFA (higher quality) are used to benchmark the new method proposed in this work (ARTI)

Nesta (Nesterov's Algorithm)

Nesta is a textbook compressive sensing method and uses the standard approach of decomposing the observed sparse signal as:

$X_{sp}=AX_0+\varepsilon$ (with A: sampling matrix; X_0: signal of interest)

and minimizing some regularizing function f(X) while keeping

$$\|X_{sp}-AX_0\|_{L2}\leq\varepsilon$$

This Fourier-based algorithm is relatively fast but tends to yield artifacts due to the nature of the Fourier basis, and these issues can be seen in the reconstructions compared in the central panel to the right.

BPFA (Beta Process Factor Analysis)

BPFA is a Bayesian process where the unknown reconstructed image is approximated as combination of 3 factor arrays and a noise array:

$$X=D*(S*Z)+\varepsilon$$

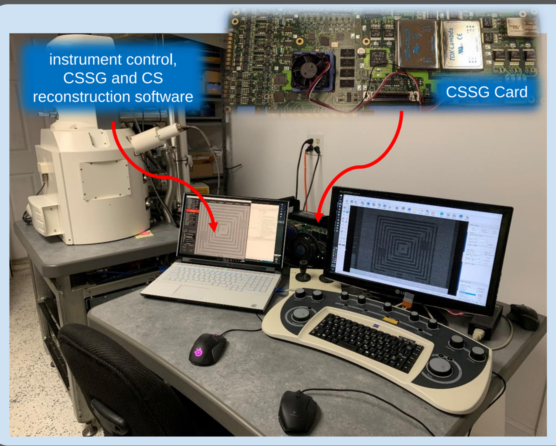
The iteratively estimates each factor D, S, and Z based on a similarly calculated previous estimation of the other two. X converges towards the desired reconstructed image, and that convergence is evaluated based on the stabilization of the residuals R=X-D*(S*Z) or executed for a fixed number of iterations. This relatively slow iterative process can be accelerated with additional parallel processing but a good quality BPFA reconstruction imposes a heavy computational burden.

Compressed Sensing Scan Generator (CSSG) Hardware & Software Highlights

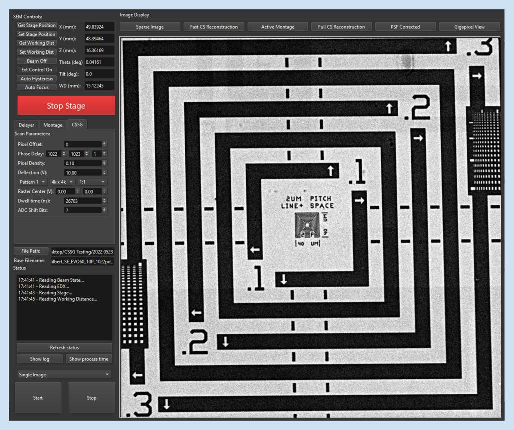
- 24-bit 50MHz hardware
- FPGA creates 50MHz "data pipe"
- 4x DAC channels
  - ➢ control two columns (FIB-SEM)
- 8x 12-bit ADC
- ➢Up to 8 synchronized detectors!

- Dwell: 20 ns – 20.97 ms
- 12 GPIO ports for logic & sensors
- Thermal stabilized enclosure
- PCIe data bus on a single card
- 3 on board temp sensors
- Scan distortion correction

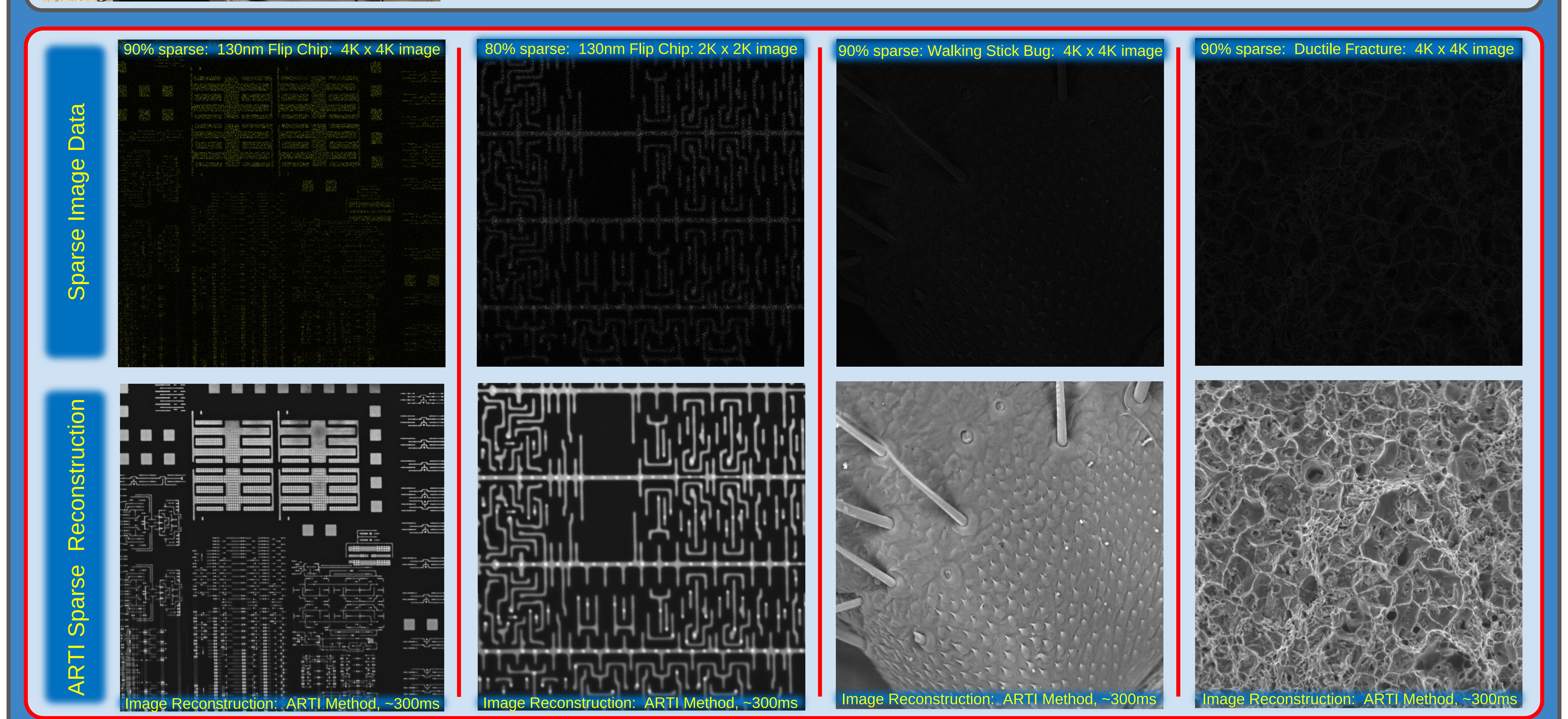
- PSF measurement & correction
- ➢ Measured scan and lens distortions are corrected during scan automatically
- Any fractional sparsity 0-99.9%
- Up to 8K x 8K scan areas

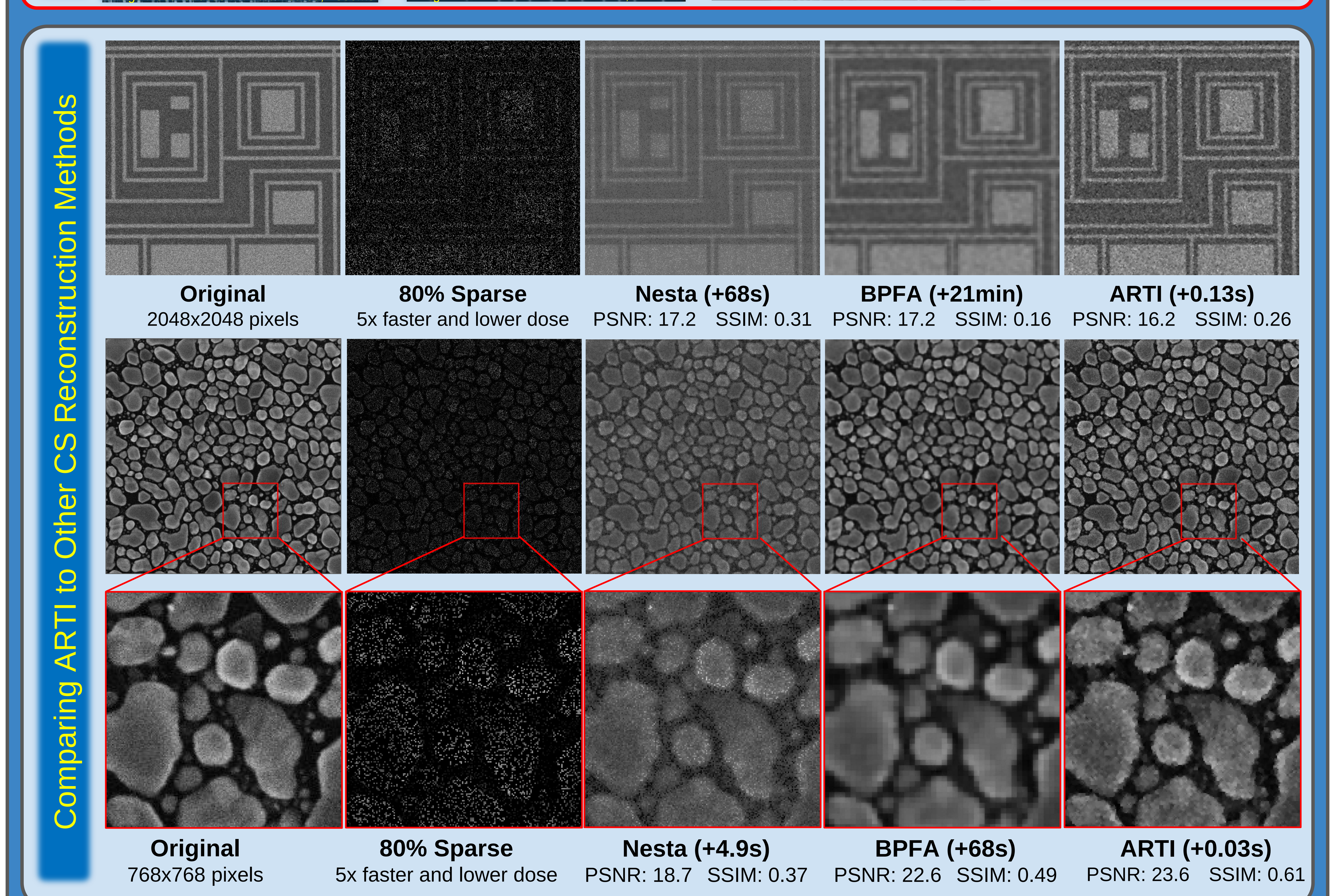


- Data shown taken on Zeiss EVO60
- CSSG interfaces with Ext Scan
- API allow remote control of SEM
- Similar to integration of EDS
- May be interfaced to a FIB-SEM
  - ➢ 3D sparsity is possible in 3D FIB-SEM reconstructions!
- May be interfaced to a STEM
- 10X faster and 10X lower dose

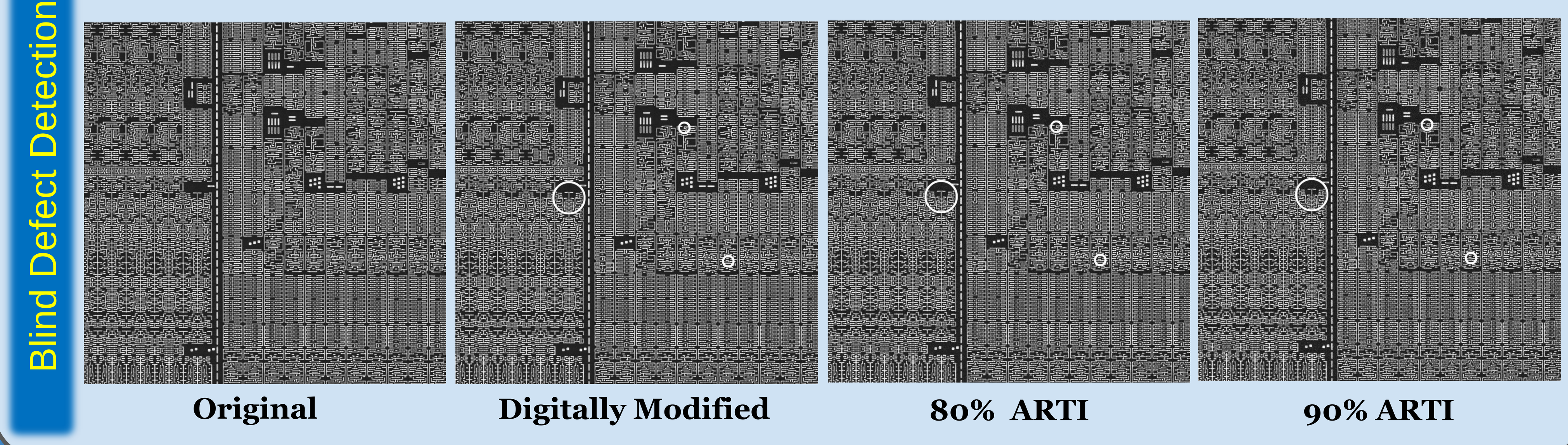


- Python user interface
- Compact & easy to use
- Displays sparse image
- Displays reconstructed image
- Optional PSF corrected image
- Sparse montage image display
- Automated sparse delayering!
  - ➢ requires FIB-SEM CSSG
- Fractional sparsity (0-99.9%)
- Up to 8K x 8K image





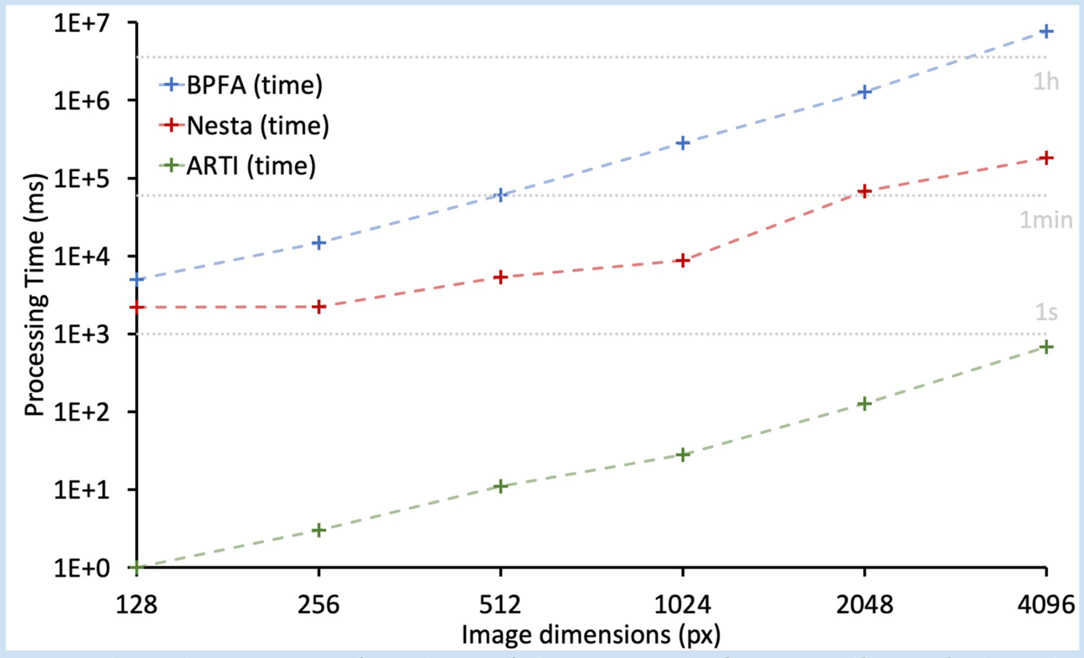
Blind digital feature modifications were created on an SEM image to verify capture of features on reconstructed images with varying sparsity



Discussion

Processing times

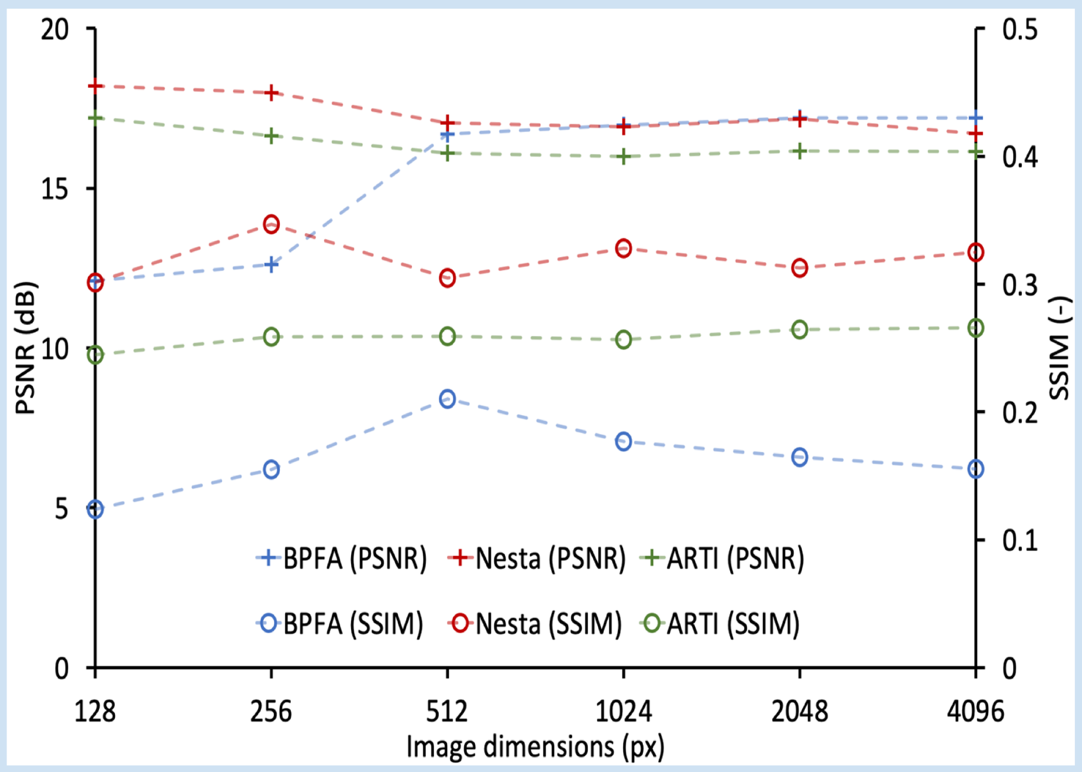
BPFA is consistently several times slower than Nesta, and several orders of magnitude slower than ARTI, as illustrated in the plots below.



Processing times as a function of image size show similar relative time differences across the size spectrum. BPFA is highly tunable, however, e.g. smaller patch sizes or number of iterations to reduce its processing time. However, BPFA speed increase comes with a very steep cost in reconstruction quality in testing performed thus far.

Calculated reconstruction quality

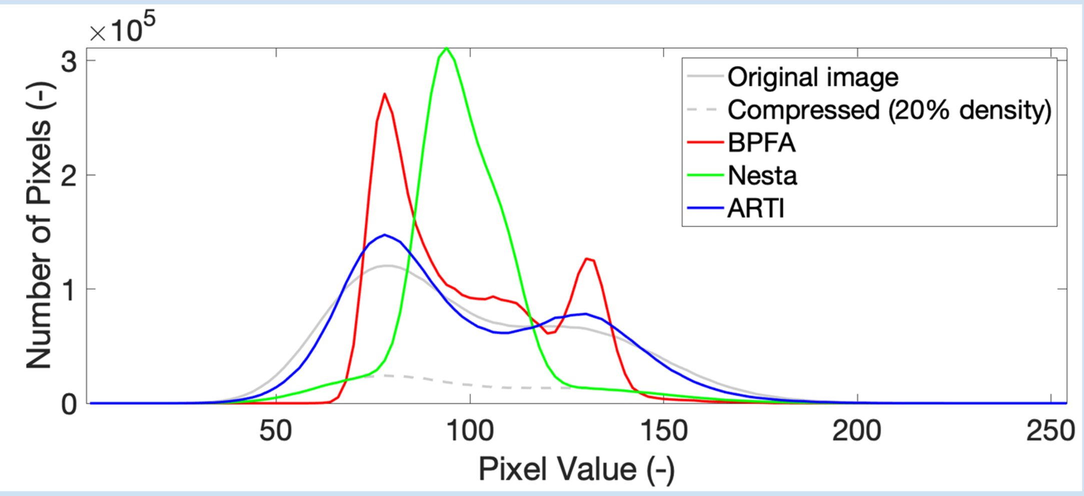
For integrated circuit (IC) scans, the quality metrics calculated from original and recon-structed images indicate that Nesta consistently yields a higher quality output than ARTI regardless of metrics or image size. On the other hand, while the mean structural similarity index (SSIM) consistently rank BPFA the lowest, its relative PSNR changes with size, from the lowest for small sizes to on par with Nesta for larger ones.



Perceived reconstruction quality

Visually gauging the relative quality of an entire reconstructed images is not necessarily consistent with the information provided by a single metric. In particular, both PSNR and SSIM indicate that Nesta yields the best output in the images shown on the central panel, yet BPFA and ARTI are better at reproducing brightness and contrast, and consequently look closer to the original image. Closeups further reveal that the reconstruction artifacts from Nesta make it difficult to read some of the finer details of the images.

The histograms (below) for the ICs confirm that the missing pixels recon-structed by Nesta have much narrower dynamic range than original images, hence the reduced contrast. ARTI histogram levels are closest to the originals.



For gold on carbon images, the relative quality metrics are consistent with visual inspection. These observations suggest that metrics commonly used to compare images may be inadequate, possibly even misleading, to gauge the effectiveness of reconstruction methods. The randomness resulting from the higher degree of freedom enabled by our methods have distinct advantages over line-hopping methods [2] applied to CS electron microscopy. These advantages manifest both in quality & speed of the results shown.

References

[1]. Anderson, et al. "Sparse imaging for fast electron microscopy." *Computational Imaging X1. Proceedings of* SPI-*IS&T Electronic Imaging, SPIE*. Vol 8675 (2013).

[2]. L. Kovarik, et al., "Implementing An Accurate And Rapid Sparse Sampling Approach For Low-Dose Atomic Resolution Stem Imaging", Appl. Phys. Lett. **109**, 164102 (2016); https://doi.org/10.1063/1.4965720

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Early Adopter Opportunities

We seek early adopters to acquire CSSG systems. These would include corrected STEM instruments, Cryo-STEM applications, AFM and other innovative applications. Contact support@panosciedu.com