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Turn-Key Compressed Sensing System for Electron Microscopy

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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. Among the requirements to achieve a faithful reconstruction 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.

An approach to overcome barriers to practical CS implementation in serial scanning electron microscopes (SEM) or scanning transmission electron microscopes (STEM) is presented 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 capable of producing a wide variety of highly random sparse sampling scan patterns with any fractional degree of sparsity from 0-99.9% while not requiring fast beam blanking. Reconstructing a 2kx2k or 4kx4k image requires ~150-300ms. The ultra-fast reconstruction means it is possible to view a dynamic reduced raster reconstructed image using a fractional real-time dose.

The origins of this project reach back to 2012 when Synchrotron Research Inc. (SRI) was seeking to use CS as part of a scanning option on a hyperspectral imaging NEXAFS spectrometer developed by SRI for the NIST beamline suite, now operating at NSLS II. CS for electron microscopy concepts progressed steadily over time through NIST funding [1] and methods were written which permitted the simulation of theoretical sparse sampling patterns and CS reconstruction. As best methods crystallized, it became clear a custom scan generator would yield optimal performance, while simultaneously allowing the greatest experimental liberty to explore CS electron microscopy. The hardware funding to fabricate the CSSG hardware was supported by the Sensors Directorate of Air Force Research Labs (AFRL/RYD) under Contract No. FA8650-17-F-1047. External hardware interfaces and CS software reconstruction methods are integrated into a universal control platform with a Python-based user interface.

One of the common issues when designing a CS serial scan strategy is to mitigate effects tied to scan system dynamics [2]. 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. Through simulated reconstructions it was determine SFCs in general “worked”, but are prone to non-idealities when applied directly as a CS sampling matrix. Namely, SFCs are pseudo random, which doesn’t satisfy a highly statistically random sampling. SFCs are also discretize in degree of sparsity, according to the order of the SFC and the pixel density. Invoking a random perturbation about the indices of any

SFC was found through simulation, to improve the reconstruction performance but still did not optimize the randomness, nor eliminate the discretization in scan sparsity.

The solution was to employ the SFC as a “slow” carrier signal modulated by a “fast” randomized perturbation signal. By combining the “slow” continuous carrier and “fast” random modulation, a programmatic 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. The DOF enabled by this method is a distinct advantage over line-hopping methods applied to CS electron microscopy [3].The ratio of work performed by the carrier signal relative to the randomized modulated signal may be regulated as one of multiple handles to accommodate physical constraints of native hardware, such as amplifier circuits and scan coil response. The schema does not generally require any beam blanking along the scan path. Fill blocks do not need to be orthogonal, square or even Euclidean (i.e., fill primitives can be triangles, circles, or non-Euclidean geometries.). A wide variety of SFCs may be applied with this system, including serpentine curves, spiral curves, Lissajous curves and other parametric curves. Given a-priori information derived from either lower resolution full field imaging data (i.e., optical image) or digital design files (i.e., GDSII) congestion maps can guide adaptive sparse sampling strategies which dynamically adjust sparsity and pixel density to further optimize information collection efficiency.

The CSSG is FPGA-based with a PCIe bus architecture operating with 24-bit 50MHz hardware. Each “fast” randomized modulated signal converter is referenced to a “slow” carrier signal converter to form a compound carrier-modulator output. Four compound carrier-modulator DACs standard on each CSSG can control two columns simultaneously at full speed, or two pair of scan coils on a STEM, or a X-Y-Z CS scan on a 3D LSM. The FPGA functions as a bi-directional 50MHz data pipe synchronizing the outgoing DAC signals controlling the scan pattern with the incoming 12-bit ADC signals from SE detectors, BSE detectors or electrical probes. Up to eight ADCs can be combined for simultaneous synchronized detection. There are 12 GPIO ports for logic control. An automated built-in signal-to-noise ratio (SNR) option will truncate the dwell time within 140ns of a pre-determined SNR value being reached. All scans are vector-based. Any generalized set of points may be user programmed as input. Interfacing the CSSG is similar to any EDS or external scan generator for electron beam lithography. A Python-based GUI allow users to control basic microscope functions, including stage control for montage acquisition and basic column control.

Panels CS-1 through CS-4 a of Figure 1) show a series of compressively sensed images. CS-1 and CS-2 were acquired at 80% sparsity in a 2Kx2K pixel array and CS-3 and CS-4 were acquired at 90% sparsity in a 4Kx4K array. Features can be correlated to the reconstructed images RI-1 through RI-4 on the right side of the graphic. CS/RI-1 and CS/RI-2 are overlapping regions from a gold-on-carbon specimen acquired on a thermal emitter and Everhart-Thornley style secondary electron detector. CS-1 is 80% sparse, ~25um FOV and 12.2nm pixel size. CS-2 is an 80% sparse 5x5 serpentine montage, and the blue solid line and red dots representing the montage tile path are for visualization purposes only. Each montage tile is 6.1um FOV and 3.1nm pixel size. Comparing varying pixel size for the same sparsity in the ROI is a method to compare CS sampling parameters. CS-3 and CS-4 are 90% sparsity sampling images on a regular grid acquired on a Schottky field emitter platform using a through-lens detector. All scans shown were performed using a Hilbert style SFC.

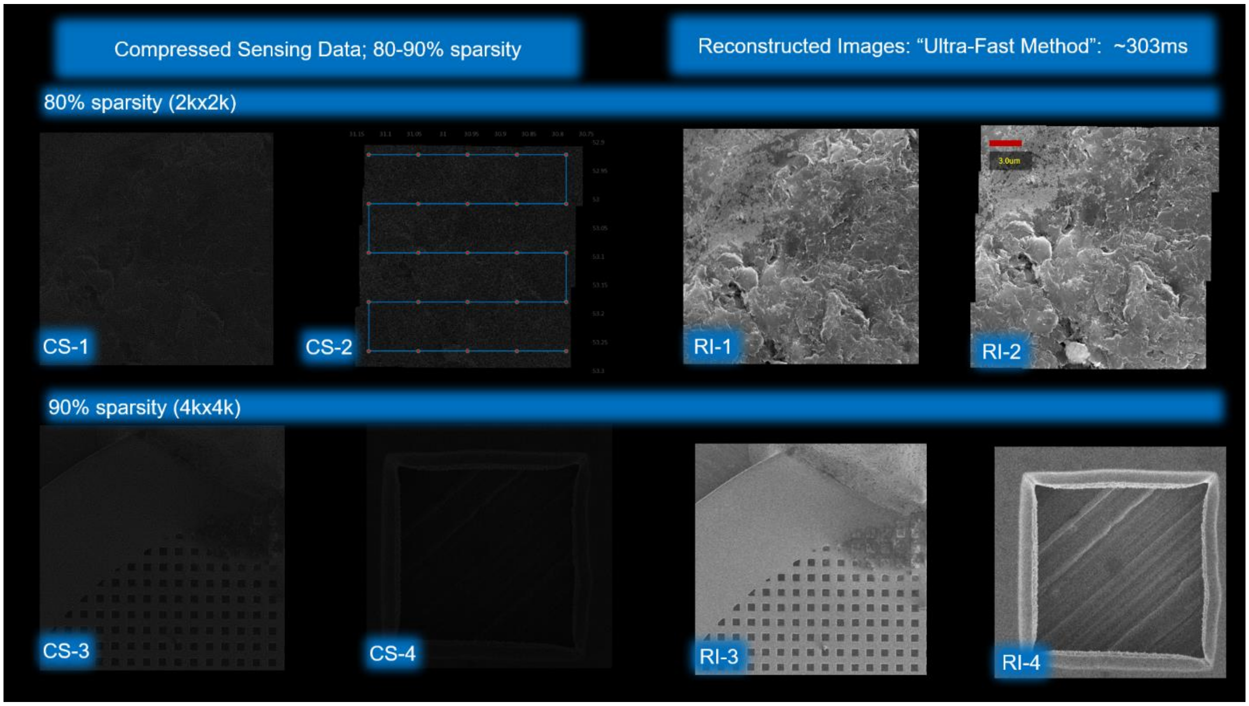

Figure 1. Compressively Sensed scanning electron microscope images are shown on the left (CS- #) and corresponding Reconstructed Images (RI-#) are shown on the right half of the graphic. See text for details.

References:

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