Turn-Key Compressed Sensing System For Electron Microscopy

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INTRODUCTION

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. The sparse sampling performance is dictated by a combination of the CSSG hardware, the CS sampling strategy and scanning system dynamics.

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 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). 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 based upon a fractional real-time dose. This CS platform provides a framework to explore a rich environment of use cases in CS electron microscopy that benefit from the combination of faster acquisition and reduced probe interaction.

DESIGNING A COMPRESSED SENSING SYSTEM FOR ELECTRON MICROSCOPY

The hardware design architecture of the CSSG is dependent on the CS serial sparse sampling scan strategies, as the latter informs the requirements for the former. Evolution of the CS sparse sampling scan strategies will be described as segue into the CSSG hardware architecture overview, followed by example data.

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 envisioned hardware became reality when 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 were developed and the CS software reconstruction methods were integrated into a universal control platform with a Python-based user interface.

Evolution Of An Idealized Compressed Sensing Matrix For Electron Microscopy

As mentioned, 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. 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. Invoking a random perturbation about the indices of any SFC was found, again 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. In this manner, 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. Sparse sampling paths are optionally smoothed with a maximum curvature driven by the scan criteria, and random perturbations are not restricted to vertices. Note, the schema does not generally require any beam blanking along the scan path! Conceptually, a continuous (seamless) montage pattern may also be formed by extending the fill area in contiguous blocks. The fill blocks do not need to be orthogonal, square or even Euclidean (i.e., fill primitives can be triangles, circles, or non-Euclidean geometries.). The system is compatible with scan paths which do require beam blanking, such as so-called "fly-back" scan patterns. 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.

Key Features Of The CSSG Architecture

The design objective was a state-of-art CS scan generator which would match or exceed capabilities of any electron microscope platform on the current market. The CSSG is FPGA-based with a PCIe bus architecture operating with 24-bit 50MHz hardware. The effective number of bits will be limited by the electronics (i.e., scan amplifiers) on the native SEM/STEM/FIB. 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 (i.e., FIB-SEM) 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 detection, all synchronized with the scanning signal. There are 12 GPIO ports for logic control. There is an automated built-in signal-to-noise ratio (SNR) function which will truncate the dwell time within ~140ns of a pre-determined SNR value being reached. This SNR function can further reduce CS acquisition time. Dwell times range from 20ns – 20.97ms. All scans are vector-based. Any generalized set of points may be user programmed as input. The CSSG hardware is housed in a small form factor thermally stabilized GPU style enclosure.

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. An API is available for extensibility and custom development.

CSSG Results & Discussion

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. It challenging to graphically display highly sparse sampled data, but 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 goldon-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.

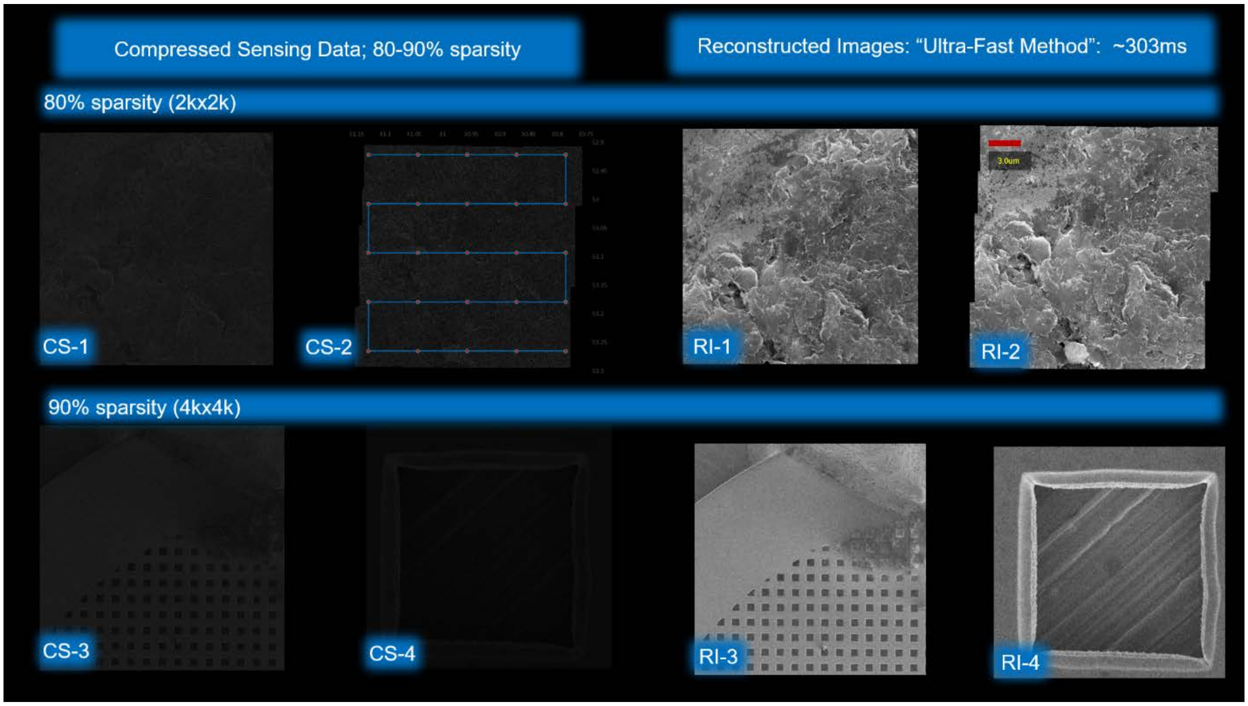

FIGURE 1. Compressively Sensed scanning electron microscope images are shown on the left (CS- #) and corresponding Reconstructed Images (RI-#) are shown on the right half of the graphic. See text for details.

A near real-time validation module currently in field testing estimates the 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 diagnostic module in field testing measures scan distortions from the microscope. The inverted pre-distortion fields are then applied through the CSSG to acquire a distortion corrected sparsely sampled scan. A third functional module in field testing measures the point spread function (PSF) of the microscope and applies this PSF kernel in post processing to correct beam distortions. In future, these modules could function as part of a health monitoring schema to track platform performance. Early adopters are being sought for collaboration.

REFERENCES

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KEYWORDS

Compressed Sensing, Sparse Sampling, Electron Microscopy