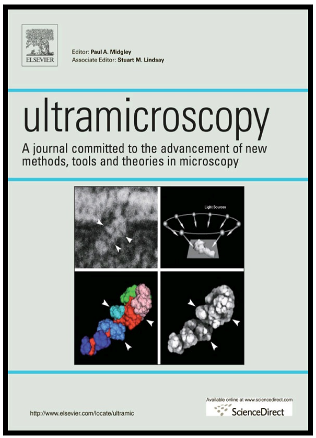

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Automated discrete electron tomography- Towards routine high-fidelity reconstruction of nanomaterials

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ABSTRACT

Electron tomography is an essential imaging technique for the investigation of morphology and 3D structure of nanomaterials. This method, however, suffers from well-known missing wedge artifacts due to a restricted tilt range, which limits the objectiveness, repeatability and efficiency of quantitative structural analysis. Discrete tomography represents one of the promising reconstruction techniques for materials science, potentially capable of delivering higher fidelity reconstructions by exploiting the prior knowledge of the limited number of material compositions in a specimen. However, the application of discrete tomography to practical datasets remains a difficult task due to the underlying challenging mathematical problem. In practice, it is often hard to obtain consistent reconstructions from experimental datasets. In addition, numerous parameters need to be tuned manually, which can lead to bias and non-repeatability. In this paper, we present the application of a new iterative reconstruction technique, named TVR-DART, for discrete electron tomography. The technique is capable of consistently delivering reconstructions with significantly reduced missing wedge artifacts for a variety of challenging data and imaging conditions, and can automatically estimate its key parameters. We describe the principles of the technique and apply it to datasets from three different types of samples acquired under diverse imaging modes. By further reducing the available tilt range and number of projections, we show that the proposed technique can still produce consistent reconstructions with minimized missing wedge artifacts. This new development promises to provide the electron microscopy community with an easy-to-use and robust tool for high-fidelity 3D characterization of nanomaterials.

I. INTRODUCTION

Increasing interest in the modeling and development of advanced nanomaterials has fueled the demand for optimized imaging methods capable of accurate characterization of such systems. Electron tomography (ET) is an important and powerful technique for the investigation of the three-dimensional structures of nanomaterials [1,2], and has been widely applied to materials that include polymeric structures [3,4], inorganic materials [5,6] and organic materials [7].

Despite recent advances in instrumentation and automated image acquisition, ET is fundamentally limited by the accuracy of the reconstructions it can produce, largely due to the well-coined 'missing wedge' problem [8]. For most types of samples, the maximum tilt range, over which 2D projection images are acquired, is restricted to approximately ±70° (and sometimes less in practice) due to an increase in the effective thickness of a thin section at high tilt angles, shadowing by the sample grid and sample holder, and limited space between the polepieces of the objective lens in the transmission electron microscope (TEM). This limited tilt range results in an unavoidable missing gap of information in the Fourier representation of the reconstruction, which can lead to false vertical elongation of structures and to the disappearance of horizontal features. As a result, segmentation of the reconstructions needs to be performed manually to reduce the influence of artifacts, which is not only time-consuming but also affects the objectiveness and repeatability of quantitative structural analysis.

Significant efforts have been made by the electron microscopy community to address the missing wedge problem. Dual-axis ET is an alternative acquisition strategy, which involves the acquisition of additional projection images about a second tilt axis that is perpendicular to the original one [9,10]. Although this approach can partially reduce artifacts by decreasing the lost information to a 'missing pyramid', the doubled electron dose and difficulty in acquiring as well as aligning two tilt series add many complications. Needle-shaped specimens that have been prepared using focused ion beam (FIB) milling together with the use of a dedicated tomography holder, enable the acquisition of projection images over the complete tilt range of 180°, thereby eliminating missing wedge artifacts [11-13]. However, not all samples can be prepared and imaged using this method and the diameter of the specimen that one can image is also limited.

The development of advanced reconstruction algorithms is another important direction for alleviating the missing wedge problem. Weighted backprojection (WBP) [14] and iterative reconstruction algorithms, such as the simultaneous iterative reconstruction technique (SIRT) [15], are now widely used but do not offer solutions to the missing wedge problem. Furthermore, their performance degrades significantly when the number of projection images is limited. Compressive sensing ET (CS-ET)