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Exemplar-based inpainting as a solution to the missing wedge problem in electron tomography

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A B S T R A C T

A new method for dealing with incomplete projection sets in electron tomography is proposed. The approach is inspired by exemplar-based inpainting techniques in image processing and heuristically generates data for missing projection directions. The method has been extended to work on three dimensional data. In general, electron tomography reconstructions suffer from elongation artifacts along the beam direction. These artifacts can be seen in the corresponding Fourier domain as a missing wedge. The new method synthetically generates projections for these missing directions with the help of a dictionary based approach that is able to convey both structure and texture at the same time. It constitutes a preprocessing step that can be combined with any tomographic reconstruction algorithm. The new algorithm was applied to phantom data, to a real electron tomography data set taken from a catalyst, as well as to a real dataset containing solely colloidal gold particles. Visually, the synthetic projections, reconstructions, and corresponding Fourier power spectra showed a decrease of the typical missing wedge artifacts. Quantitatively, the inpainting method is capable to reduce missing wedge artifacts and improves tomogram quality with respect to full width half maximum measurements.

1. Introduction

Electron tomography is one of the main methods for three-dimensional (3D) imaging at the nano-scale. It is extensively used both in structural biology and material science. The resolution is in the range of 1–20 *nm*, thereby filling a critical length scale gap for biological applications between atomic resolution of X-ray crystallography and single particle electron tomography [1] on the one hand, and high-resolution confocal light microscopy [2] and X-ray microscopy [3] on the other. In material science, the methods fill the gap between atom probe tomography [4] on the one side and Focused Ion Beam Scanning Electron Microscopy (FIB-SEM) [5] respectively X-ray Tomography techniques on the other.

In Electron tomography, projections from different directions are acquired by means of a transmission electron microscope and tilting the sample. A three-dimensional volume is numerically generated from these projections. Electron tomographic reconstructions often suffer from different restrictions, like opacity, limited field of view, limited number of projections, or missing wedge artifacts. A comprehensive review of computational methods involved in electron tomography studies with all these problems can be found in [6], and an evaluation of accuracy of several reconstruction algorithms with tubular objects as example was conducted in [7].

One of the most severe problems is the non-availability of projections covering the whole angular range. Most electron tomography datasets have a maximum angular range of about −75°–75°, because of mechanical limitations of the specimen holder, shading of the area of interest by the support grid and the increasing projected thickness of the tilted specimen. This leads to elongation artifacts of reconstructed details along the symmetry center of projections. This is also visible in the Fourier domain as missing wedge, because no data is present in the angular range not imaged during data acquisition as predicted by the Fourier slice theorem [8]. This so called missing wedge problem introduces prominent

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elongation artifacts along the beam direction of reconstructed objects [9] leading to an anisotropic spatial resolution [10].

2. Related work

Different approaches on tackling the missing wedge problem have been proposed, based mainly on (i) data collection, i.e. the way images are taken like using dual axis schemes, (ii) enabling a complete rotation of the specimen by using cylindrical samples geometries, and (iii) specialized reconstruction methods that address reconstructing missing information.

Changing the way of data acquisition by extending standard approaches of single axis tomography leads to better results regarding the missing wedge issue. Lee et al. [11] experimentally demonstrated, that equally sloped tomography (EST) can reduce missing wedge artifacts by constraining acquired images in a tilt series to have equally sloped angle increments. Another approach is double-tilt tomography, also called dual axis tomography (cf. [12,13]), where data is acquired from two perpendicular tilt axes. This technique reduces the missing wedge to a missing pyramid due to the fact that more information is present because of the two mutually perpendicular tilt series for one reconstruction. Dahmen et al. [14] proposed a combined tilt- and focal series as a new recording scheme for high-angle annular dark-field scanning transmission electron microscopy (STEM) tomography. Hereby, a tilt series with limited tilt range is supplemented by a through-focal series per tilt direction. The method results in a better sampling of the Fourier space and, thus, to a reduction of axial elongation artifacts.

Instead of using slab-like flat specimens for electron tomography, which restricts viewing angles, Kawase et al. [15] used a cylindrical specimen. The cylindrical shape allows imaging from a full range of viewing angles around the tilt axis, so that no missing wedge exists. They quantitatively analyzed the effect of the missing wedge on the volume fraction in a composite and the elongation due to the missing wedge. The work was extended by Kato et al. [16] who used rod-shaped specimens with different diameter for transmission electron tomography to evaluate the maximum usable rod diameter for the tomography specimen. While effective at avoiding the missing wedge problem altogether, the approach is not applicable in many situations, because manufacturing the rod-shaped specimen requires making a decision on the field of view prior to initial imaging and, thus, selecting the area of interest becomes difficult and the statistical sampling is limited. Furthermore, fabrication of such needle-shaped samples requires the material to be mechanically sufficiently strong, which is not the case for many materials.

Adapted reconstruction methods to handle missing information may also be capable of fighting the missing wedge. Baba et al. [17] performed a topographic analysis by stereo-photogrammetry to get pre-determined voxel arrangements for thin film-like replica-type specimens with some known properties. Using this prior knowledge as constraint in the reconstruction process reduces an infinite number of solutions due to the missing wedge to a finite number. Qualitatively enhanced reconstructions revealing fine structural parts showed no missing wedge effects. Zürner et al. [18] also used prior knowledge by adding a mask in each reconstruction step setting all voxels known to be vacuum in the samples to zero. A stronger assumption is made in the field known as discrete tomography. Hereby, the assumption is that the solution of the reconstruction problem has a sparse gradient, i.e. the sought tomogram consists of only a limited number of a priori known materials. The assumption obviously simplifies the problem and can be used to reduce missing wedge artifacts. A heuristic approach to discrete tomography is taken by the discrete algebraic reconstruction technique (DART) [19] and consecutive work. Another group of algorithms based on the sparse gradient assumption are total variation minimization (TVM) techniques [20]. Contrary to DART, TVM techniques do not require the gray values to be known a priori, which can be an advantage for some applications.

Some algorithms that work without additional assumptions have also been reported to improve on missing wedge artifacts. A combination of the weighted back projection and SIRT, also called W-SIRT, claims an improved reconstruction with reduced elongated point spread in the direction of the missing tilt angles for a simple geometrical phantom, i.e. an improved reconstruction of spatial frequencies in the vicinity of the missing wedge [21]. The DIRECTT method (cf. [22,23]) is an iterative algorithm based on a sequence of alternating reconstructions and virtual projections of intermediate results, which are subsequently enhanced using residual sinograms instead of filtered back projections. DIRECTT reduces the typical missing wedge artifacts by variation of reconstruction parameters in the course of iterations.

In this study, we propose a heuristic method to estimate data from the missing projection directions using image processing techniques. The approach is orthogonal to reconstruction techniques that aim to generate better tomograms from incomplete data and could in principle be combined with any tomographic reconstruction algorithm.

3. Materials and methods

3.1. Inpainting algorithm

Our algorithm is inspired by the approach of Criminisi et al. [24]. The method originates from the field of image processing and was originally developed to fill missing regions in photographs in a way that this is not perceivable for the human eye after using the so called exemplar-based inpainting. Based on the surroundings, a hole is filled step by step by inserting small parts of the known image regions, called patches.

We found that the capability of the method to replicate both texture and structure can also be utilized to generate data for the missing tilt angle range. This seemingly surprising result can intuitively be understood from the fact that sinograms generated from a tilt series consist of the superposition of continuous curves. A reasonable guess on how the data in the missing wedge looks like should respect continuity, particularly in the angular dimension. Additionally, many samples exhibit some degree of local self-similarity. In the absence of additional data, continuing structures with patterns observed elsewhere in the sinogram, thus, results in better estimates than statistical methods, such as filling in the average gray value or using random distributions of gray values, are able to achieve. The method generates data in the missing wedge by computing the most likely continuation of the sinogram under the assumption that tilt series are both continuous and to some degree redundant.

A pseudo-code of the algorithm (Fig. 1) give a summary of the inpainting algorithm for 3D ET data.

In many cases, the TEM sample and respectively the ET data has an approximately slab-like geometry, which means that the thickness of a specimen as seen by the electron beam differs with the tilt angle. As the missing wedge inpainting assumes a cylindrical geometry, ET data has to be normalized in a preprocessing step. By dividing each projection through its mean intensity, the original geometry is mapped to a cylindrical geometry with uniform distances. Hereby, the imaging mode has to be considered. In HAADF-STEM, the intensity is proportional to the sample thickness, so the simple division should work. In BF-TEM the intensity is proportional to the log of the sample thickness and would have to be linearized prior to the division. The normalized data is then used as input for the inpainting algorithm.