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An Iterative Image Reconstruction for Differential X-ray Phase-contrast Computed Tomography ⋆

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Abstract

The last decade saw the growth of the use of X-ray Phase-contrast Computed Tomography (PCT) imaging. Differential X-ray Phase-contrast CT (DPCT) has shown bright prospect for clinical use in recent years, but how to best reconstruct the phase-contrast tomographic image from incomplete or inconsistent projections remains challenging. We designed an iterative image reconstruction method for DPCT utilizing compressed sensing. This proposed method reconstructs the phase-contrast tomographic image of the refractive index decrement gradient with acceptable accuracy and image quality even when the projection data is undersampled or noisy. Real data experiments indicate this proposed method is accurate and practical and outperforms the analytic filtered back-projection reconstruction. This method shows potential for X-ray DPCT facilities in low dose tomography and fast acquisition imaging.

Keywords: X-ray Phase-contrast Imaging; Computed Tomography (CT); Compressed Sensing; Low Dose Tomography; Fast Acquisition Imaging

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1 Introduction

Phase sensitive X-ray imaging, in which additional contrast is generated by the refraction of hard X-rays as they pass through the object under study, can provide substantially increased contrast over conventional absorption-based imaging and new and otherwise inaccessible information [1–3].

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It originates in the real part of the complex refractive index of hard X-rays for light- or medium-density materials is several orders of magnitude higher than its imaginary part which describes its absorption. The tomographic implementation of phase sensitive X-ray imaging, i.e., X-ray Phase-contrast Computed Tomography (PCT), bears tremendous potential for three-dimensional tomographic imaging of soft biological tissue and other specimens whose details exhibit very weak absorption contrast. PCT imaging techniques have seen significant growth recently. And differential X-ray Phase-contrast CT (DPCT) has shown promise for clinical use in medical imaging [4]. However, tomographic image reconstruction from incomplete (e.g., undersampled) or inconsistent (e.g., heavy noisy) projections is needed in DPCT modalities to ensure low dose tomography and faster acquisition. Such reconstruction with acceptable accuracy and image quality is challenging due to the violation of the Nyquist sampling criteria.

Iterative tomographic image reconstructions possess distinct advantages over their analytic counterparts when the projection data is incomplete or inconsistent. But iterative image reconstruction was not employed in modern commercial CT scanners until recently, owing to the prolonged computation time and the large storage requirement. With the rapid development of signal processing and computation technique as well as the fantastic decrease of computer hardware cost, these limitations are not a significant concern any more. We designed an iterative tomographic image reconstruction method for DPCT under the framework of Compressed Sensing (CS) theory [5, 6]. CS has been applied in conventional absorption contrast CT to address some diagnostic imaging issues [7–9], and also emerges recently in phase sensitive X-ray imaging [10, 11]. The previous work are significant, but we believe the exploration of CS-based iterative tomographic image reconstruction for DPCT still remains an open topic and has just begun.

The complex refractive index of X-rays for an object, generally, can be expressed as $n = 1 - \delta + i\beta$, where the refractive index decrement (i.e., δ) determines the phase shift of the X-rays passing through the object, while the absorption term (i.e., β) is correlated with the linear absorption coefficient. Let us denote the spatial distribution of the refractive index decrement as $\delta\left(x, y\right)$. Our method, which will be referred to as the RRL1 method in this paper, reconstructs the spatial distribution of the refractive index decrement gradient (i.e., $\nabla\delta = \left(\partial\delta/\partial x, \partial\delta/\partial y\right)$) from X-rays refraction angle data. Real data experiments along with the quantitive performance evaluation indicate the RRL1 method is practical and accurate and overperforms the FBP reconstruction. And the RRL1 method offers the potential for DPCT facilities in low dose tomography and fast acquisition imaging, as it is capable of generating phase-contrast tomographic images with satisfactory fidelity even when the projection data is undersampled and noisy.

2 Theory and Method

As illustrated in Fig. 1, we define the refraction angle of a X-ray beam as the angle of the downstream propagation direction relative to the initial one and denote it as θ. Eq. (1) reveals the relationship between the refraction angle θ and the integral of the directional derivative of $\delta\left(x, y\right)$ [12]. The directional derivative of $\delta\left(x, y\right)$ in Eq. (1) is with respect to $l_\perp$, which is perpendicular to the X-ray beam path l.

$$\theta = \int \frac{\partial\delta\left(x, y\right)}{\partial l_\perp} dl \tag{1}$$

According to the geometry diagramed in Fig. 1 and using angle ϕ to depict the direction of the