Single-Exposure, Single-Mask, Edge-Illumination X-ray Phase-Contrast Imaging Using a 7.8-μm Pixel Pitch Direct Conversion X-ray Detector

Abdollah Pil-Ali, *Student Member, IEEE*, Sahar Adnani, *Student Member, IEEE*, Christopher C. Scott, Alessandro Olivo, Karim S. Karim, *Senior Member, IEEE*

***Abstract*—Double-mask edge-illumination is a well-reported technique for phase-contrast x-ray imaging. Although phase retrieval using this technique is comparably easier than propagation-based phase-contrast x-ray imaging, edge-illumination can be inefficient in terms of dose efficiency and imaging time when it comes to computed tomography scanning. The illumination curve, which describes the beamlets' intensity profile impinging upon the detector, is a key parameter that contributes to retrieving phase and absorption information. To obtain the illumination curve, multiple exposures are typically required which decreases x-ray dose efficiency and, more importantly, increases imaging time. Moreover, sample motion can negatively impact the image and information retrieval process. In this research, we employ a single mask in conjunction with a 7.8-μm pixel pitch amorphous selenium-CMOS hybrid direct conversion x-ray detector to obtain the beamlets' intensity profile with only a single exposure. We demonstrate how using an ultra-high spatial resolution x-ray detector with a single-mask edge-illumination technique can potentially increase both dose efficiency and imaging time by at least a factor of 1.5X. Moreover, the resulting system using our approach is more compact with a source-to-detector distance of less than 30 cm. Single-exposure imaging can also help mitigate the impact of motion artifacts in the final image.**

***Index Terms*—X-ray imaging, Phase-Contrast X-ray Imaging, Edge-Illumination, Coded-Aperture, Illumination Curve, Single-Exposure, Dose-Efficient, Motion Artifact, Amorphous Selenium (a-Se), CMOS X-ray Detector, High-Resolution Imaging.**

I. Introduction

X-RAYS not only attenuate when they pass through an object, but also they refract when they exit the interface between two regions with different refractive indices. Explorations on the imaging applications associated with the refraction of x-rays and phase effects started three decades ago and are still on-going [1]. The introduction of phase contrast x-ray imaging has motivated imaging research using phase effects in applications ranging from industrial and material science to medicine and biology [2]–[5]. X-ray phase contrast imaging (XPCi) is an important alternative when conventional attenuation based x-ray imaging is insufficient, e.g. imaging low atomic number materials. Soft tissues such as cancerous tumors and fats can be picked up with much higher contrast through XPCi techniques.

Among the different methods reported for XPCi, edge-illumination (EI), or coded-aperture, stands out because it has worked well with both synchrotron and laboratory sources. EI has advantages over other methods of XPCi because of its comparable dose efficiency, sensitivity, and image contrast in a variety of imaging scenarios. Phase and absorption retrieval in EI depend on a parameter called the illumination curve (IC) – which is simply the intensity profile of beamlets on the detector. The IC plays a central role in EI-XPCi performance, especially in quantifying the imaging information acquired. Not having enough information on IC results in partially missing quantitative information about the sample. Obtaining the IC requires multiple, typically at least three, exposures per projection so that the beam intensity profile can be extracted [6], [7]. In computed tomography, where a large number of projections (e.g. 1000) at different angles are captured, obtaining the IC can lead to at least three times the number of exposures to the sample, increasing radiation exposure and lengthening imaging times. Moreover, sample motion during the three exposures can negatively impact the IC, which consequently decreases the imaging performance due to blurring.

Despite the potential advantages of EI techniques over other XPCi methods, EI's practicality is limited in imaging dose-sensitive and living samples [8]. In this research, we demonstrate how employing a very high-resolution direct conversion x-ray detector can potentially help obtain more accurate beamlet shape through only a single-exposure in a compact low-dose imaging system geometry. A novel, high resolution, x-ray camera called BrillianSe developed by our research group and recently commercialized by a University of Waterloo spin-off company, KA Imaging, is used to enable a single-mask EI configuration following the beam tracking method. As is to be expected, motion artifact is also mitigated since only a single-exposure is performed.

II. Methods and Results

We first simulated a single-mask (SM) EI system (Fig. 1) in MATLAB® through the model explained in [5]. Intensity

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A. Pil-Ali, S. Adnani, and K. S. Karim are with the Department of Electrical and Computer Engineering, and Centre for Bioengineering and Biotechnology; University of Waterloo; 200 University Ave W; Waterloo; ON N2L3G1; CA (email: apilali@uwaterloo.ca).

C. C. Scott and K. S. Karim are with KA Imaging Inc., 560 Parkside Dr #3, Waterloo, ON N2L5Z4, CA.

Alessandro Olivo Department of Medical Physics and Biomedical Engineering, University College London, Gower St, London, WC1E 6BT, UK.

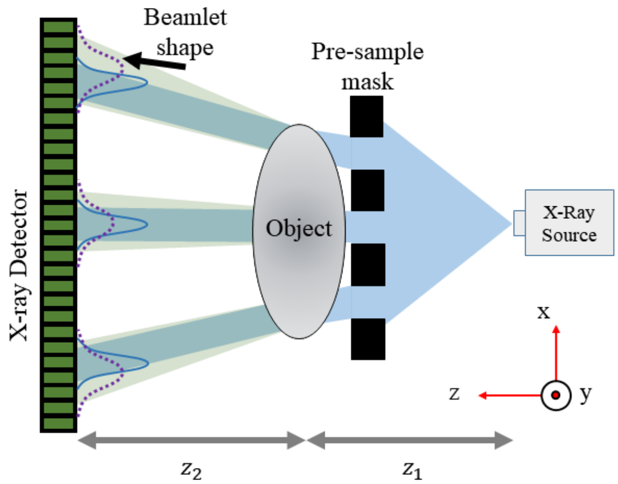

Fig. 1. Illustration of the SM-EI XPCi system model used for simulation. The Gaussian profiles on the detector are the intensity profile distribution of beamlets before (solid blue line) and after (dashed purple line) definition of the object.

profile of the beamlets are measured through reading the corresponding pixel values, which is described in (1). This beamlet shape is related to absorption and phase information where it can be expressed through (2):

$$I_{SM-EI}(x) = S_r(\frac{x}{M-1}) * T_M(\frac{x}{M}) * PSF_d(x) \quad (1)$$

$$I(x) = I_0 T(x - z_2 \Delta\theta_R) * s(x) \quad (2)$$

where $S_r(x)$ is the source spatial intensity distribution, $T_M(x)$ is the transmission function of pre-sample mask, $PSF_d(x)$ is the detector point spread function, $M = (z_1 + z_2)/z_1$ is the magnification (with z_1 and z_2 being the distance between source to object and object to detector), I and I_0 are the intensity profile distribution of beamlets with and without the sample, T is the transmitted portion of beam after the sample, $\Delta\theta_R$ is refraction angle of the beam, and $s(x)$ is the scattering introduced by the sample.

Fig. 2 shows the experimental set-up including the Thermo Scientific™ PXS5-927 microfocus x-ray source (from Thermo Fisher Scientific Inc.) working at 60 kVp, 134 μA, 8 μm spot size, 8 W; pre-sample absorption mask with 10μm opening and 79μm period; as well as our high-resolution detector with 7.8μm pixel size and pixel pitch. The z_1 and z_2 are 18 cm and 8 cm, respectively.

The simulation result of the intensity profile distribution of beamlets without the sample present is illustrated in Fig. 3, from which the beamlets' profile, the horizontal Gaussian patterns, that are detected by groups of pixels through only a single-exposure are clearly noticeable. Fig. 4 depicts the relative intensity profile registered at the detector (in experimental set-up). The agreement between simulation result and experimental data (Fig. 5) confirms the fact that a single-mask EI-XPCi system employing the high-resolution BrillianSe x-ray camera provides an accurate intensity profile distribution of beamlets through a single-exposure. The final EI setup is also a compact system (with less than 30 cm source-to-detector distance) thanks to the ultra-high resolution x-ray detector.

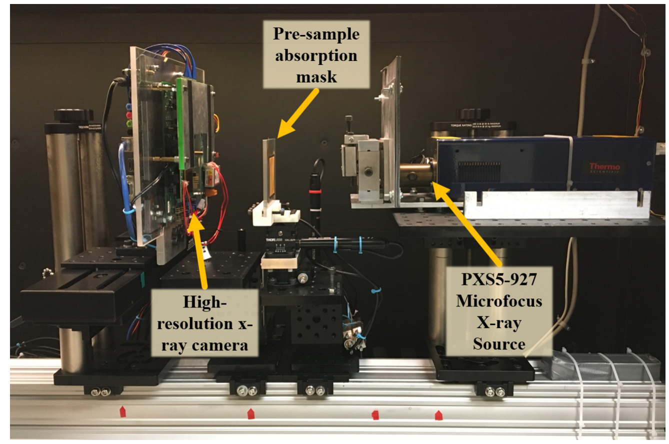

Fig. 2. SM-EI experimental set-up used in this work.

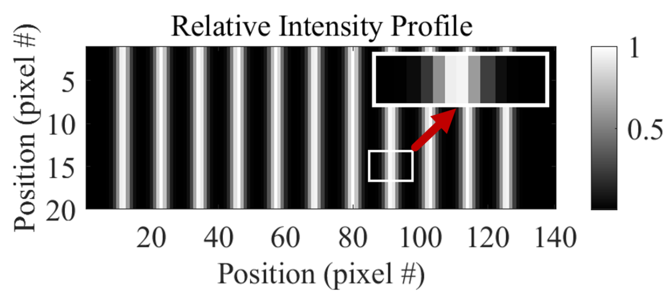

Fig. 3. Simulation result of relative intensity profile clearly highlights the beamlet's profile (the Gaussian pattern) detected by groups of pixels.

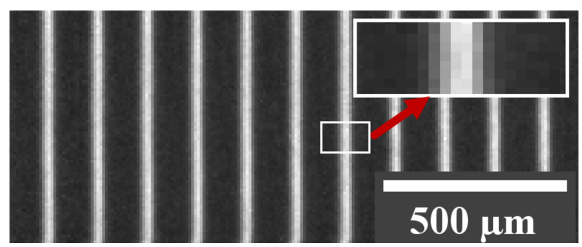

Fig. 4. Experimental data of relative intensity profile registered at the detector shows the beamlets' profile (the Gaussian pattern) obtained from groups of pixels.

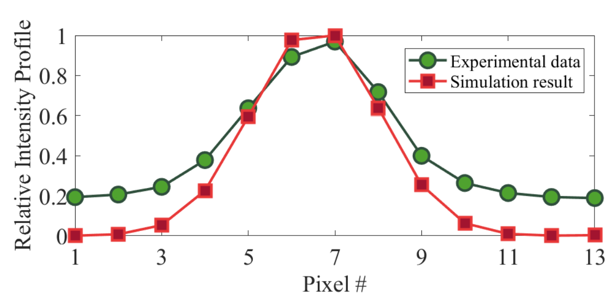

Fig. 5. The agreement between beamlet shape from experimental data and simulation result. The higher value of lower left and right tails of experimental data is related to pre-sample mask imperfection and detector PSF.

III. CONCLUSION

We employed an ultra-high special resolution x-ray detector in a coded-aperture x-ray phase-contrast x-ray imaging technique to increase dose efficiency and imaging time by at least a factor of 1.5X. Illumination curve in coded-aperture XPCi can be extracted through only a single-shot using a high-resolution detector. The proposed method is beneficial in imaging dose-sensitive samples, and where sample's motion can negatively impact imaging performance. Using an ultra-high spacial resolution detector also leads to a compact imaging system.

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