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Investigation of Moiré Pattern-based Phase Retrieval Approach for Differential Phase-contrast Cone Beam CT Imaging Using a Hospital-grade Tube

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Abstract

The phase stepping algorithm is commonly used for phase retrieval in grating-based differential phase-contrast (DPC) imaging, which requires multiple intensity images to compute one DPC image. It is not efficient for data acquisition, especially in the case of dynamic imaging using either DPC imaging or DPC-based cone beam CT (DPC-CBCT) imaging. A Fourier transform-based approach has been developed for fringe pattern analysis in optics, and it was recently implemented into a synchrotron-based DPC tomography system. In this research, this approach is further developed for a bench-top DPC-CBCT imaging system with a hospital-grade x-ray tube. The key idea is to separate carrier fringes and object information in Fourier domain of the interferogram and to reconstruct the differentiated phase information using the object information. Only one interferogram is required for phase retrieval at a cost of spatial resolution. The fringes of moiré patterns are used as the carrier fringes, and a phantom is scanned to evaluate the approach. Various interferograms with different carrier fringe frequencies are investigated and the reconstruction image quality is evaluated in terms of contrast, noise and sharpness. The results indicated that the DPC images can be effectively retrieved using the Fourier transform-based approach and the reconstructed phase coefficient showed better contrast compared to that of attenuation-based contrast. The spatial resolution is acceptable in the phantom studies although it is not as good as the results of phase-stepping approach. The Fourier transform-based phase retrieval approach is able to greatly simplify data acquisition, to improve the temporal resolution and to make it possible for dynamic DPC-CBCT imaging. It is promising for perfusion imaging where spatial resolution is not a concern.

Keywords

phase-contrast; differential phase-contrast; cone beam CT; moiré pattern

1. INTRODUCTION

Differential phase-contrast imaging (DPC) attracts increasing research interest as it makes phase imaging possible using a hospital-grade x-ray tube [1–5]. The commonly used phase-stepping algorithm requires at least three phase steps to retrieve one DPC image [2], and

consequently, a differential phase-contrast cone beam CT (DPC-CBCT) scan needs to acquire multiple intensity images (phase-stepping images) at each view angle. This is acceptable for static anatomy imaging. For a dynamic imaging procedure, however, the anatomy of the object changes with time, and therefore the multiple phase-stepping images taken at different moments at the same angular position cannot be used to faithfully retrieve the correct DPC image for DPC-CBCT reconstruction. There is a necessity to apply an alternative phase imaging approach that uses only one intensity image at each view angle for dynamic DPC-CBCT imaging.

A moiré pattern-based approach has been developed for fringe pattern analysis in optics [6], and it was recently implemented by Momose et al into a synchrotron-based DPC tomography system [7–9]. The key idea is to extract the phase information of x-rays through analyzing the distortion of interference fringes. The approach is to separate the carrier fringes from the first-order phase shift information in the Fourier domain of the interferogram and to retrieve the DPC information by inverse Fourier transform. The cone beam reconstruction is then performed using these DPC images to reconstruct the phase coefficient of the object. As only one interferogram is necessary for phase retrieval, this approach potentially solves the difficulty inherent with the phase-stepping approach for dynamic imaging. The tradeoff is that the spatial resolution of the reconstructed DPC image is limited by the spatial frequency of the carrier fringes.

In this research, the moiré pattern-based approach is implemented into a bench-top DPC-CBCT system that uses a hospital-grade x-ray tube for the first time. The major challenge is that the x-rays from a hospital-grade tube with a source grating is only partially coherent and the coherence length is not as large as that of a synchrotron radiation, which may result in low fringe contrast and degraded image quality in the retrieved DPC image. By optimizing grating quality and system alignment, our system was able to produce good fringe contrast in the interferogram and DPC images using the moiré pattern-based phase retrieval approach. This work is a preliminary study of dynamic DPC-CBCT imaging using a hospital-grade x-ray tube.

The next section describes the principle of the moiré pattern-based phase retrieval approach and the experiment setup. Section 3 demonstrates how this approach works using an acrylic ball phantom and quantitatively compares the results of DPC-CBCT reconstruction to that using the phase-stepping method using a cylinder phantom. Section 4 concludes this research.

2. MATERIALS AND METHODS

2.1 Idea of moiré pattern-based phase retrieval approach

The moiré pattern of an interferogram, which has a spatial frequency f_0 , is distorted with the presence of an object in the optical beam as a result of phase change. The degree of distortion is determined by the differentiated phase shift by the object. Assume in a two-dimensional detector system the pattern is parallel to the x-axis, then the interferogram can be expanded to the first order as [6]:

$$I(x, y) = a_0(x, y) + c(x, y) \exp(2\pi i f_0 y) + c^*(x, y) \exp(-2\pi i f_0 y) \quad (1)$$

where

$$c(x, y) = \frac{1}{2} b(x, y) \exp\left(2\pi i \frac{nz_T}{d} \phi_x(x, y)\right) \quad (2)$$

nz_T is the n th Talbot distance, d is the period of the self image formed at the Talbot distance and $\phi_x(x, y)$ is the differentiated phase shift (the first derivative along x-axis) introduced by the object, which is the target DPC image. Equation (1) can be Fourier transformed along y-axis (perpendicular to the moiré pattern) as:

$$I_F(x, f) = A(x, f) + C(x, f - f_0) + C^*(x, f + f_0) \quad (3)$$

Therefore, the object information $\phi_x(x, y)$ is encoded at frequency $\pm f_0$ in the spectrum. The Fourier transform of any line along the y-axis looks like Fig. 1(a). If either of the two peaks at $\pm f_0$ is shifted to the zero frequency as shown in Fig. 1(b), the differentiated phase $\phi_x(x, y)$ can be directly computed from the inverse Fourier transform of the shifted peak using Equation (2).

One concern in implementing this approach to our DPC-CBCT system is that while moiré pattern appears, the system is actually misaligned with a lower fringe contrast, which may result in lower contrast, higher noise and worse phase wrapping in the resulting DPC image than the phase stepping approach in which the system should be well aligned.

2.2 Bench-top differential phase-contrast cone beam CT system using a hospital-grade x-ray tube

A bench-top differential phase-contrast cone beam CT system has been designed and built in our laboratory for this study. The x-ray generating system consists of a hospital-grade x-ray tube (Varian Rad-70D, Varian X-ray Products, Salt Lake City, UT) and a high-frequency x-ray generator (SHF1635MAMMO-480VAC, Sedecal USA, Arlington Heights, IL). The camera system includes a CMOS detector (RadEye HR (High Resolution) detector, Radicon Imaging Corp, Santa Clara, CA) and a frame grabber (PXD 1000, Imagenation, Beaverton, OR). An interface board together with software control, was developed to control the timing of x-ray shot and image acquisition. The phantom is mounted and rotated on a tomography sample stage (B4836TS Stage, Velmex Inc. Bloomfield, NY).

Gratings were fabricated at Cornell NanoScale Facility with an effective area of 60mm x 60mm on 4-inch <110> silicon wafers. Gratings and system are optimized for an effective x-ray energy of 24 keV (wavelength of 0.518 Å). Grating periods are 30.7 μm, 8.0 μm and 4.6 μm respectively for the source grating, phase grating and analyzer grating. The duty cycle is 50% for both phase grating and analyzer grating. Source grating opening width is 18 μm, and the distance between source grating to phase grating is 118 cm, which produces a

coherence length of 3.4 μm in the horizontal direction. The first fractional Talbot distance (17.72cm) is used in the setup.

Gratings are mounted on customized grating mounts that allow six degrees of freedom (three degrees of rotation and three degrees of translation) for fine alignment (U400-AC3K Precision Center Mirror Mounts, SP Optical Post, VPH No Slip Optical Post Holder, 460A-XY Quick-Mount Linear Stage and 37 Tilt and Rotation Platform, Newport Research, Irvine, CA). A motorized high precision linear stage (VP-25XA, Newport Research, Irvine, CA) is used to shift one of the gratings to generate phase shift with a step accuracy up to 0.1 micron.

All the components (except the high-frequency x-ray generator) are fastened on top of an optical table (SmartTable® ST-UT-48-8 Optical Table (4 ft x 8 ft x 8 in) with I-2000-428 isolating supports (4 legs, 28" high), Newport Research, Irvine, CA), and an ACMP air compressor supplies air flow to float the table top for vibration isolation. A picture of the system is shown in Figure 1 and detailed system parameters are listed in Table 1.

2.3 Experiment design

For a slightly misaligned system, the moiré pattern can be curved, non-parallel or parallel in any direction. To obtain a parallel pattern in the horizontal direction, the grating system was firstly well aligned to produce maximized pattern period (larger than the detector dimension) and maximized fringe contrast. Then while keeping the surface planes of the phase grating and analyzer grating parallel, the phase grating was rotated by a small angle (~ 1.5 degree) to generate the desired moiré pattern. Given that the detector pitch is 22.5 μm and several pixels are needed to display one period of the fringe pattern, a spatial resolution of $\sim 1\text{--}2$ lp/mm is expected for the retrieved DPC image.

Then the phantom was mounted on the rotation stage to produce a distorted moiré pattern at each view angle. The Fourier transform-based approach described in Section 2.1 was used to retrieve the DPC image for each moiré pattern. As the gratings themselves are not uniform, a background moiré pattern image was acquired and the background DPC image was retrieved, which was then subtracted from the DPC images from all view angles to correct the background uniformity. DPC-CBCT Reconstruction was finally performed using the Hilbert filter-based filtered backprojection (FBP) algorithm. The result was compared to that of the phase-stepping approach with eight steps. The exposure of one interferogram (moiré pattern image) is equivalent to the total of eight steps that generate the same DPC image.

An acrylic ball of 4mm in diameter and a cylinder phantom of 25.4mm in diameter were scanned using the bench-top DPC-CBCT system where at each view angle, only one interferogram was acquired to compute the DPC image. 60 DPC images were acquired for DPC-CBCT reconstruction of the acrylic ball while 120 DPC images were used for the cylinder phantom. The x-ray tube was operated at 40kVp and the exposure is 96mR per DPC image for the acrylic ball and 192 mR per DPC image for the cylinder phantom.

3. RESULTS

Figure 2 demonstrates the procedure how to retrieve a DPC image from a distorted moiré pattern for the acrylic ball. Figure 2 (a) and (b) show moiré patterns with different spatial frequency, namely 1.1 lp/mm and 2.2 lp/mm, which generate the first order component at different location in the Fourier domain. The upper peak is then shifted to the zero frequency in the middle, and the DPC image is calculated from its inverse. In comparison, eight step images are required to retrieve a DPC image as shown in figure 2 (c). Visually the DPC images retrieved using moiré pattern-based approach are comparable to that from the phase stepping approach, although the later one shows clearer edges, better contrast and lower noise.

Figure 3 shows typical DPC-CBCT reconstruction in both axial and sagittal slices of the acrylic ball. Despite lower background uniformity, the axial views reconstruction from moiré pattern-based DPC images with both spatial frequency look very similar to that using phase-stepping approach. In the sagittal view, however, both moiré pattern-based reconstructions show distorted edges and the image with the spatial frequency of 1.1 lp/mm is the worst, which is the result that the image resolution is limited by the carrying fringe frequency of the moiré pattern.

Figure 4 shows the reconstructed axial slices and sagittal slices of the cylinder phantom, which comprises four inserts (polycarbonate, polyimide, polystyrene and polytetrafluoroethylene) immersed in water background. Although the moiré pattern-based approach shows less uniformity, higher noise and less contrast, the reconstructions are visually comparable in both axial and sagittal slices. The background uniformity, noise level and contrast of the four inserts are measured and compared to that of the phase stepping approach. To be more illustrative, the measurements are normalized to the water background, as shown in Table 2. Compared to the phase stepping approach, the moiré pattern-based approach produces a 20% less object contrast.

4. CONCLUSION AND DISCUSSION

We have successfully implemented the moiré pattern-based phase retrieval approach in a bench-top DPC-CBCT system with a hospital-grade x-ray tube. Phantom studies indicate that the final reconstruction image quality using the new method is close to that of the phase stepping approach in terms of contrast and noise level. The longitudinal resolution of the reconstruction using 1.1 lp/mm is lower than that of 2.2 lp/mm as can be seen that the edge of the acrylic ball is deformed for 1.1 lp/mm in the sagittal view. As indicated in Figure 4 and Table 1, Object contrast manifested using the new approach is comparable to that of the phase-stepping approach. A centered dark area is observed in both sagittal slices, which might be caused by defect in the gratings. There is large room to further improve the image quality by improving grating quality, experiment alignment and data processing. The preliminary results of this research solved the problem of fast data acquisition for phase retrieval, and potentially it can be combined with the method proposed in reference [5] for dynamic DPC-CBCT imaging. To facilitate future research, the detector will be replaced

with a faster detector and other system components will be modified to perform continuous rotation and acquisition functions.

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References

1. Momose A, Kawamoto S, Koyama I, Hamaishi Y, Takai K, Suzuki Y. Demonstration of x-ray Talbot interferometry. *Jpn J Appl Phys.* 2003; 42:L866–L868.
2. Weitkamp T, Diaz A, David C, Pfeiffer F, Stampanoni M, Cloetens P, Ziegler E. X-ray phase imaging with a grating interferometer. *Opt Express.* 2005; 13(16):6296–6304. [PubMed: 19498642]
3. Pfeiffer F, Weitkamp T, Bunk O, David C. Phase retrieval and differential phase-contrast imaging with low-brilliance x-ray sources. *Nature Physics.* 2006; 2:258–261.
4. Qi Z, Zambelli J, Bevins N, Chen G. Quantitative imaging of electron density and effective atomic number using phase contrast CT. *Phys Med Biol.* 2010; 55:2669–2677. [PubMed: 20400806]
5. Yu Y, Ning R, Cai W. Performance evaluation of a differential phase-contrast cone-beam CT (DPC-CBCT) system for soft tissue imaging. *Proc SPIE.* 2011; 7961:79614X.
6. Takeda M, Ina H, Kobayashi S. Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry. *J Opt Soc Am.* 1982; 72(1):156–160.
7. Momose A, Yashiro W, Maikusa H, Takeda Y. High-speed x-ray phase imaging and x-ray phase tomography with Talbot interferometer and white synchrotron radiation. *Opt Express.* 2009; 17(15):12540–12545. [PubMed: 19654656]
8. Momose A, Yashiro W, Harasse S, Kuwabara H, Kawabata K. Four-dimensional x-ray phase tomography with Talbot interferometer and white synchrotron light. *Proc SPIE.* 2010; 7804:780405.
9. Momose A, Yashiro W, Harasse S, Kuwabara H. Four-dimensional x-ray phase tomography with Talbot interferometry and white synchrotron radiation: dynamic observation of a living worm. *Opt Express.* 2011; 19(9):8423–8432. [PubMed: 21643093]
10. Cai W, Zhao B, Conover D, Liu J, Ning R. Dynamic cone beam CT angiography of carotid and cerebral arteries using canine model. *Med Phys.* 2012; 39(1):543–553. [PubMed: 22225324]

Figure 1.

Principle of the moiré pattern-based phase retrieval approach. (a) shows the Fourier transform of one line along the y-axis in the interferogram, where the object information is encoded at the carrying frequency. If this information is shifted by f_0 as in (b), the object information can be extracted from the inversion Fourier transform of (b).

Figure 1.
Overview of the bench-top differential phase-contrast cone beam CT system using a hospital-grade x-ray tube.

Figure 2.

Illustration of the moiré pattern-based phase retrieval approach using an acrylic ball phantom (diameter=4mm). The spatial frequency of moiré pattern is 1.1 lp/mm for row (A) and 2.2 lp/mm for row (B). Row (C) shows the DPC image retrieved using eight phase steps for comparison.

Source of DPC images	Moiré pattern 1.1 lp/mm	Moiré pattern 2.2 lp/mm	Phase stepping
Axial
Sagittal

Figure 3.

Typical reconstruction slices using DPC images retrieved from moiré pattern of 1.1 lp/mm and 2.2 lp/mm. The reconstruction from phase stepping approach is shown in the last column for comparison.

Figure 4. Typical reconstruction slices of a cylinder phantom. (a) and (c) use DPC images retrieved from moiré pattern of 1.1 lp/mm. For comparison, (b) and (d) use DPC images retrieved from phase stepping approach.

Table 1

Major parameters of the DPC-CBCT system

Focal spot size	0.3 mm
Detector pixel size	22.5 μm for 1x1 rebin 45.0 μm for 2.2 rebin
Source-to-phase-grating distance	118 cm
Phase-to-analyzer-grating distance	17.72 cm
Object-to-detector distance	25.4 mm
Field of view	32 mm $\times$ 24 mm
Cone angle	$< 2^\circ$
Tube peak voltage	25–49.5 kVp
Tube current	16–200 mA
Exposure time per exposure	320 ms
Projection number	60 for acrylic ball 120 for cylinder phantom
Recon voxel size	(36.8 μm) ³
Phase grating period	8.0 micron
Analyzer grating period	4.6 micron
Source grating period	30.7 micron

Table 2

Comparison of moiré pattern-based reconstruction and phase stepping-based reconstruction. Measurements are taken in axial slices, and are normalized with respect to water.

	Background Uniformity	Background Noise Level	Contrast PI	Contrast PC	Contrast PTFE	Contrast PS
Moiré pattern-based reconstruction	23.9%	12.1%	+73.5%	+8.5%	35.3%	0.0%
Phase stepping-based reconstruction	14.8%	7.2%	+92.7%	+12.0%	41.6%	0.0%