NDT&E International 84 (2016) 11–19

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Improvement of image characteristics in high-voltage computed tomography (CT) by applying a compressed-sensing (CS)-based image deblurring scheme

Kyuseok Kim, Hyosung Cho*, Uikyu Je, Chulkyu Park, Hyunwoo Lim, Guna Kim, Soyoung Park, Yeonok Park, Dongyeon Lee, Hunwoo Lee, Taeho Woo

Department of Radiation Convergence Engineering, iTOMO Group, Yonsei University, 1 Yonseidae-gil, Wonju, Gangwon-do 26493, Republic of Korea

ARTICLE INFO

Article history:
Received 15 April 2016
Received in revised form
21 July 2016
Accepted 22 July 2016
Available online 27 July 2016

Keywords:
High-voltage computed tomography (CT)
Compressed-sensing (CS)
Image deblurring

ABSTRACT

We have established a high-voltage computed tomography (CT) system with a 1–3 MV LINAC x-ray generator for industrial nondestructive testing. However, reconstructed CT images are typically blurred, limiting its image performance, mainly due to the finite focal spot size of the x-ray source, aspects inherent to detector such as the detector pixel size and the detector resolution, and the reconstruction procedure as well. Thus the recovery of the reconstructed CT images from their degraded version is essential for improving the image characteristics. In this work, we investigated the compressed-sensing (CS)-based deconvolution scheme for more accurate image deblurring in CT. We implemented the proposed image deblurring algorithm for CT and performed a systematic simulation and experiment to demonstrate its viability. Our results indicate that the proposed deblurring scheme appears to be effective for the blurring problems in CT and is applicable to improve its present image characteristics.

1. Introduction

Since Röntgen discovered x-rays in 1895, x-ray imaging techniques have continuously advanced from planar radiography to digital tomosynthesis (DTS), computed tomography (CT), and other modalities. They have been a powerful tool capable of inspecting internal structures of an examined object in a variety of applications of medicine, industry, material science, *etc.* Particularly, in CT, the first CT scanner was built for medical imaging by Hounsfield in 1972 and immediately introduced into clinical practice as the most important invention in radiological diagnosis since the discovery of x-rays. On the other hand, the first application of industrial CT is traced back to the first 1980s in the field of nondestructive testing (NDT) and its full-scale applications appeared in the later 1990s in many industrial applications such as electronics, automotive, aerospace, archeology, military, and so on [1].

Recently, as a continuation of our NDT R&D [2], we have established a high-voltage CT system especially to inspect large and highly-dense objects available in industry. As shown in Fig. 1, the system mainly consists of a 1–3 MV LINAC x-ray generator (focal spot size: 2 mm, HEXTRON3/1-500, Granpect Inc.), a flat-panel detector (pixel size: 200 µm, pixel dimension: 2048 × 2048, XRD1621, PerkinElmer Inc.), and a lathe for object's installation and rotation. However, reconstructed CT images are typically blurred, limiting its image performance, mainly due to the finite focal spot size of the x-ray source, aspects inherent to detector such as the detector pixel size and the detector resolution, and the reconstruction procedure as well. Thus the recovery of the reconstructed CT images from their degraded version is essential for improving the image characteristics. In this work, we investigated the compressed-sensing (CS)-based deconvolution scheme for more accurate image deblurring in CT. Here the CS is the state-of-the-art mathematical theory for solving the inverse problems, which exploits the sparsity of the image with substantially high accuracy [3,4]. In the following sections, we briefly describe the implementation of the proposed image deblurring scheme in CT and present our simulation and experimental results.

2. CS-based image deblurring scheme in CT

Most of the image deblurring methods are based on the standard image degradation model in which the observed (or *blurred*) image, $g(x,y)$, is formed by convolving the original (or *exact*) image, $f(x,y)$, by the shift-invariant point-spread function (PSF) of the system, $\mathrm{psf}(x,y)$, followed by adding white Gaussian noise, $n(x,y)$:

* Corresponding author.
E-mail address: hscho1@yonsei.ac.kr (H. Cho).

http://dx.doi.org/10.1016/j.ndteint.2016.07.003
0963-8695/

$$g(x, y) = f(x, y) \otimes \otimes \, \mathrm{psf}(x, y) + n(x, y), \tag{1}$$

where the operator $\otimes\otimes$ represents two-dimensional (2D) convolution. Because the convolution operation in spatial domain is mathematically equivalent to multiplication ($\times$) in frequency domain, the preceding model can be written in an equivalent frequency-domain representation:

$$G(u, v) = F(u, v) \times \mathrm{PSF}(u, v) + N(u, v), \tag{2}$$

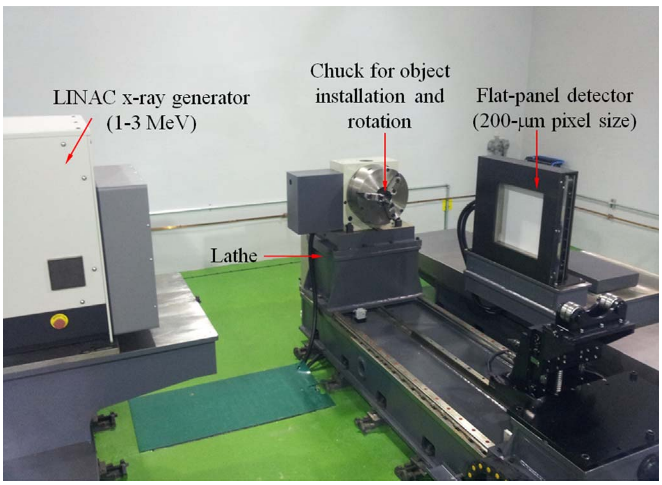

Fig. 1. The high-voltage CT system that we established in this work. The system mainly consists of a 1–3 MV LINAC x-ray generator (focal spot size: 2 mm, HEXTRON3/1-500, Granpect Inc.), a flat-panel detector (pixel size: 200 μm, pixel dimension: 2048 × 2048, XRD1621, PerkinElmer Inc.), and a lathe for object's installation and rotation.

where the terms in capital letters are the Fourier transforms of the corresponding terms in the convolution equation. Thus the degraded image can be restored by the deconvolution method, provided that PSF is known, as follows:

$$f(x, y) = \Im^{-1}\left[\frac{G(u, v) - N(u, v)}{\mathrm{PSF}(u, v)}\right], \tag{3}$$

where the term $\Im^{-1}$ represents the inverse Fourier transform. In planar radiography, PSF is the 2D intensity profile of the image obtained of a point object which describes the amount of blurring by the imaging system. In practice, a small hole having a diameter of about 10 μm in an otherwise radiopaque sheet of lead replaces the point object. However, in CT, PSF should reflect the effect of the reconstruction procedure on the image degradation process as well as the system's blurring effect for more accurate image deblurring. In this paper, we partitively referred the PSF reflecting the CT reconstruction procedure to PSF_{CT}. Numerous deconvolution methods have already been established in the literature,

Table 1
Test conditions used in the simulation and experiment.

Parameter	Dimension
Source-to-object distance (SOD)	2025 mm
Object-to-detector distance (ODD)	460 mm
Angle step ($\Delta\theta$)	0.75°
Voxel size and dimension	0.15 mm, 300 × 300 × 300 for simulation
	0.15 mm, 750 × 750 × 750 for experiment
Pixel size	0.2 mm
Test phantom	Pump casting, electric motor
CT reconstruction algorithm	FBP
Deblurring algorithm	CS

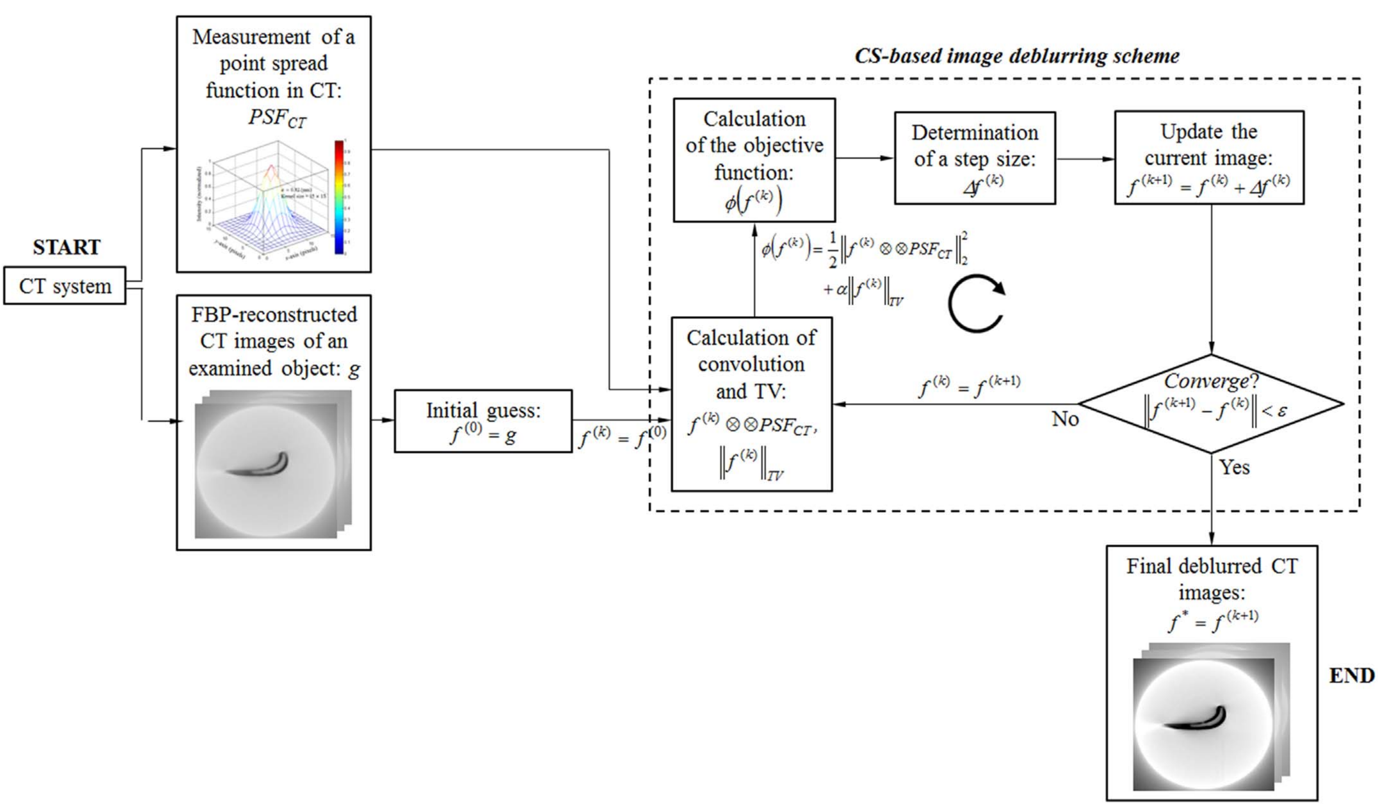

Fig. 2. The simplified flowchart of the proposed CS-based deconvolution scheme for image deblurring in CT. Here the FBP-reconstructed CT images of an examined object are deblurred iteratively through the proposed deconvolution scheme until the mismatch between the current image and the updated image converges to a specified tolerance ε.