Compressed-sensing (CS)-based Micro-DTS Reconstruction for Applications of Fast, Low-dose X-ray Imaging

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In this paper, we introduce limited-angle tomography in which the object being imaged is rotated around the center of an inclined X-ray beam, the so-called micro-DTS (digital tomosynthesis), with a few-view image reconstruction based on the compressed-sensing (CS) theory for applications of fast, low-dose X-ray imaging. We implemented an effective CS-based reconstruction algorithm for micro-DTS and performed systematic simulation works. The assessment of the image characteristics was performed by using several figures of merit such as the root-mean-square error (RMSE), the contrast-to-noise ratio (CNR), and the universal image-quality index (UQI) to compare the reconstructed images to the simulated phantoms. According to our results, compared to the FBP-based method, the CS-based reconstruction method substantially enhanced image accuracy against image artifacts from few-view and limited-angle projections. In the simulation, 41 projections were used for the half-tomographic angles of 30°, 45°, and 60°, giving UQI values of 0.92 ∼ 0.97, which seems promising for potential applications of fast, low-dose X-ray imaging.

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I. INTRODUCTION

Digital tomosynthesis (DTS) is a limited-angle tomographic technique that provides some of the tomographic benefits of computed tomography (CT) but at reduced dose and cost [1]. It also allows the geometry of the system to be open; thus the X-ray beam path is more favorable than it is in CT; sometimes, the CT gantry structure imposes limitations on its use due to the size or the geometrical complexity of the object to be imaged, which is frequently the case in industrial applications. While many efforts have been made to develop effective DTS algorithms particularly with an isocentric linear source trajectory in clinical and industrial implementations, a strong desire exists for the development of DTS algorithms with a circular source trajectory directly on a C-arm system. Pelc et al. recently revisited the circular source trajectory by mounting a flat-panel detector onto a mobile C-arm system [2,3]. On the other-hand, with recent advances in foundational mathematical theory, compressed-sensing (CS), the development of three-dimensional (3D) image reconstruction algorithms from few-view data has been in the spotlight as a promising approach for reducing the radiation dose and the imaging time. This approach has been shown to be capable of producing a very accurate reconstruction even under conditions such as few-view and limited-angle data [4–7]. Recently, reducing the imaging dose has become an issue of critical importance in the broader radiological community.

In this paper, we introduce for potential applications to fast and low-dose X-ray imaging, a DTS system, the so-called micro-DTS system, in which the object being imaged is rotated around the center of an inclined X-ray beam with a state-of-the-art image reconstruction based on the CS theory. The micro-DTS system is geometrically equivalent to the conventional DTS system with a circular source trajectory, which is suitable for anatomical imaging of small objects. We implemented an effective CS-based reconstruction algorithm for the micro-DTS system and performed systematic simulation works to evaluate the image characteristics in terms of several figures of merit.

II. MATERIAL AND METHOD

Figure 1 shows a schematic illustration of the micro-DTS geometry, which consists of an X-ray source, a flat-panel detector, and an X-ray transparent stage. The
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Fig. 1. (Color online) Schematic illustration of a micro-DTS geometry. Here, the X-ray source and the flat-panel detector are stationary, and the object being imaged is placed on an X-ray transparent stage and rotated 360° around the rotational axis between each exposure.

object being imaged is placed on the X-ray transparent stage and rotated through 360° around the rotational axis between each exposure, keeping the X-ray source and the detector stationary; in a conventional DTS geometry with a circular source trajectory, the source and the detector are rotated from vertical by the half-tomographic angle $\alpha$ and are locked in place. Here, $\alpha$ is defined as the angle between the central X-ray beam and the rotational axis and can be adjusted by using the position of the C-arm. The DTS typically generates 3D images with high spatial resolution in two dimensions and with limited resolution in the third by using conventional reconstruction methods; in the micro-DTS, plane of interests (POIs) perpendicular to the rotational axis (i.e., $x$-$y$ slices in Fig. 1) are reconstructed with an angularly-closed shape as CT images.

Conventional reconstruction algorithms for the DTS are based on the filtered-backprojection (FBP) method, as an analytical method, with an additional deblurring filter. However, this approach usually requires sufficient projections with low noise levels for image reconstruction of acceptable quality, which imposes severe restrictions on the radiation dose and the imaging time. In this work, instead, we considered a CS-based reconstruction algorithm as an optimization-based iterative reconstruction method. In this approach, an energy function $\phi(x)$, consisting of a fidelity term and a total-variation (TV)-norm regularization term, is minimized by calculating the gradient projection of $\phi(x)$, with the step size being determined by using an approximate Hessian matrix calculation at each iteration, with the Gradient-Projection-Barzilai-Borwein (GPBB) formulation [8]. This energy functional has the nice property of preserving straight and sharp edges in the image. The CS-based reconstruction is simply represented by the image vector $x^*$, which is the solution to the constrained convex optimization problem, described as follows:

$$
\begin{align*}
    x^* &= \text{argmin}_{x} \phi(x), \\
    \phi(x) &= \frac{1}{2} \|Ax - b\|^2_2 + \lambda \|x\|_{TV} \quad \text{s.t.} \quad x \geq 0, \\
    \|x\|_{TV} &= \sum_{j=1}^{N} |D_jx|_2.
\end{align*}
$$

Here, $x$ is the unknown image vector, $A$ is the system matrix, $b$ is the measured projection vector, $\lambda$ is the TV regularization parameter specifying the relative weighting between the fidelity term and the TV-norm regularization term, $\|x\|_{TV}$ is the discrete TV of $x$, $N$ is the number of voxels, and $D_j$ is the forward difference approximation to the gradient at voxel $j$. For comparison, we also implemented a reconstruction algorithm based on the conventional FBP method with an appropriate deblurring filter to control the incomplete frequency responses originating from limited-angle scanning. Detailed results on the FBP-based micro-DTS reconstruction will be presented separately.

The simulation conditions used in the study are listed in Table 1. For all simulations, 41 projections acquired at an angle step of about 8.85° through 360° were used for $\alpha = 30^\circ$, 45°, and 60°. A voxel format of $100 \times 100 \times 100$ was selected to save computational time. Figure 2 shows the two simulated phantoms used in the study: (a) the 3D Shepp-Logan phantom and (b) the 3D Zubal head phantom.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dimension</th>
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</thead>
<tbody>
<tr>
<td>Source-to-detector</td>
<td>1000 pixels</td>
</tr>
<tr>
<td>Distance (SDD)</td>
<td></td>
</tr>
<tr>
<td>Object-to-detector</td>
<td>500 pixels</td>
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<tr>
<td>Distance (ODD)</td>
<td></td>
</tr>
<tr>
<td>Half-tomographic angle ((\alpha))</td>
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<tr>
<td>Number of projections</td>
<td>41</td>
</tr>
<tr>
<td>Reconstruction algorithm</td>
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<tr>
<td>Voxel format</td>
<td>100 $\times$ 100 $\times$ 100</td>
</tr>
<tr>
<td>Test phantoms</td>
<td>3D Shepp-Logan, 3D Zubal head</td>
</tr>
</tbody>
</table>

Fig. 2. (Color online) Two simulated phantoms used in the study: (a) the 3D Shepp-Logan phantom and (b) the 3D Zubal head phantom.