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Technical Notes

3D reconstruction based on compressed-sensing (CS)-based framework by using a dental panoramic detector

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A B S T R A C T

In this work, we propose a practical method that can combine the two functionalities of dental panoramic and cone-beam CT (CBCT) features in one by using a single panoramic detector. We implemented a CS-based reconstruction algorithm for the proposed method and performed a systematic simulation to demonstrate its viability for 3D dental X-ray imaging. We successfully reconstructed volumetric images of considerably high accuracy by using a panoramic detector having an active area of 198.4 mm × 6.4 mm and evaluated the reconstruction quality as a function of the pitch (p) and the angle step ($\Delta\theta$). Our simulation results indicate that the CS-based reconstruction almost completely recovered the phantom structures, as in CBCT, for $p \leq 2.0$ and $\theta \leq 6°$, indicating that it seems very promising for accurate image reconstruction even for large-pitch and few-view data. We expect the proposed method to be applicable to developing a cost-effective, volumetric dental X-ray imaging system.

Introduction

Panoramic radiography, introduced in the late 1940s, made major progress in dentistry, providing dentists with a single comprehensive image of both the jaws and the maxillofacial structures [1,2]. Cone-beam computed tomography (CBCT), introduced in the mid-1990s, also created a revolution, facilitating the transition of dental X-ray imaging from 2D to 3D images of sub-millimeter resolution with faster scanning time and lower dose than in conventional medical CT by employing a large-area flat-panel detector [3]. In addition, recently, handy two (or three)-in-one dental imaging systems that combine the panoramic and the CBCT (or/and cephalometric) features in one device have been launched in the global market, equipped with one panoramic detector and one flat-panel detector together. However, market prices for the combined systems are still high mainly due to the detector cost, thus posing an obstacle for the more widespread use of these systems, especially, in local dental clinics.

In this work, we propose a practical method that can combine the two functionalities of dental panoramic and CBCT features in one by using a single panoramic detector. Here a linear-type panoramic detector is tilted by 90° from the orientation for panoramic imaging and rotates together with an X-ray tube around the rotational axis several times along a spiral (or zigzag) trajectory to cover the whole imaging volume during the projection data acquisition. Figure 1 shows the schematic illustrations of (a) a conventional dental CBCT geometry and (b) the proposed geometry. As indicated in Fig. 1(a), in the CBCT, there is a penalty for the large detector coverage because its exact reconstruction is not possible due to insufficient sampling of the imaging volume by the diverging X-ray beam. While the filtered-backprojection (FBP) algorithm has been widely used as an approximate method for the cone-beam image reconstruction, the resulting cone-beam artifacts increase with the imaging volume thickness [4]. Furthermore, the amount of scatter also increases with the detector size, reducing the image contrast. As a possible solution to the cone-beam related artifacts, a linear-type (*e.g.*, 198.4 mm × 6.4 mm in our case) detector can be scanned helically in the axial direction to provide sufficient volumetric sampling. Figure 2 shows the schematic illustrations of the proposed scan geometries for volumetric dental X-ray imaging by using a linear-type panoramic detector: (a) a spiral scan geometry and (b) a zigzag scan geometry. Here the zigzag scan is devised to eliminate the use of the slip-ring technology in the spiral scan which allows continuous multiple rotations but increases the system complexity [5]. The proposed approach to volumetric dental X-ray imaging, compared to the CBCT, leads to imaging benefits such as alleviating cone-beam artifacts and reducing scatters, as well as decreasing system cost. Another advantage of the proposed method would be increased image quality in general, implying that one can go lower in exposure to reach the same image quality as a CBCT,

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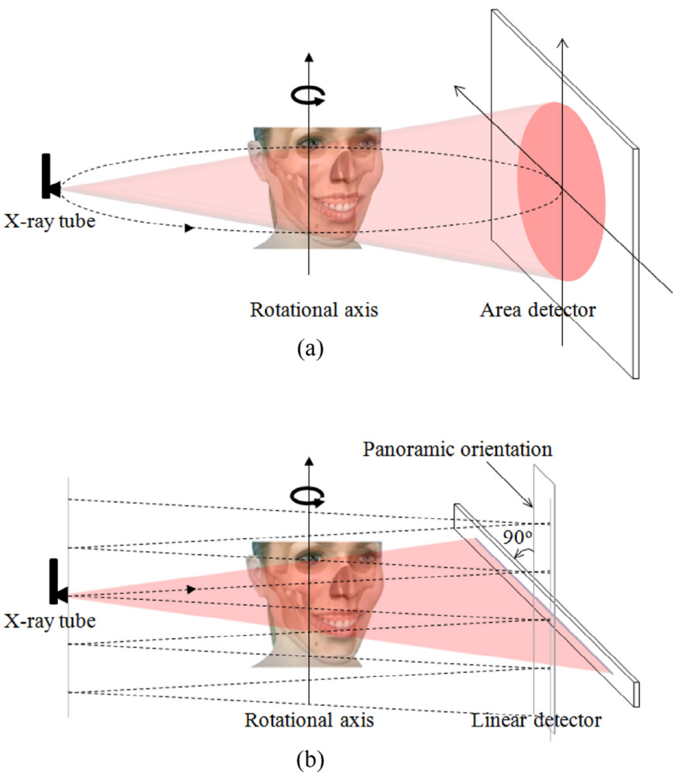

Figure 1. Schematic illustrations of (a) a conventional dental CBCT geometry and (b) the proposed geometry. In the proposed geometry, a linear-type panoramic detector is tilted by 90° from the orientation for panoramic imaging and rotates together with an X-ray tube around the rotational axis several times along a spiral (or zigzag) trajectory to cover the whole imaging volume during the projection data acquisition.

because for a given field-of-view (FOV) size and exposure settings, scatter will be reduced in the proposed geometry due to the use of a thin detector. We employed a compressed-sensing (CS)-based framework, rather than the common FBP-based framework, for more accurate image reconstruction. Here the CS is a state-of-the-art mathematical scheme for solving the inverse problems, which exploits the sparsity of the image with substantially high accuracy [6]. We implemented a CS-based algorithm for the proposed method and performed a systematic simulation to demonstrate its viability for 3D dental X-ray imaging. In the following sections, we briefly describe the implementation of the CS-based reconstruction algorithm for the proposed method and present the simulation results.

Materials and methods

The X-ray imaging procedure can be modeled approximately by a discrete linear system as follows:

$$\mathrm{A}x = b, \tag{1}$$

$$x = (x_1, x_2, \ldots, x_N)^{\mathrm{T}},$$
$$b = (b_1, b_2, \ldots, b_M)^{\mathrm{T}},$$
$$\mathrm{A} = \{a_{ij}\}, i = 1, 2, \ldots, M \text{ and } j = 1, 2, \ldots, N, \tag{2}$$

where x is the original image vector to be reconstructed, b is the measured projection vector, **A** is the system matrix, relating x and b, N is the number of voxels, M is the total number of sampling points in the projection vector, and the superscript $^{\mathrm{T}}$ is the transpose operator. In the CS framework, x is normally recovered as an optimal solution, x^*, for the convex optimization problem described in Eq. (3) by minimizing the following objective function, $f(x)$, assuming that most components of derivative images are negligibly small:

$$x^* = \underset{x \in Q}{\arg\min} f(x),$$
$$f(x) = \frac{1}{2}\|\mathrm{A}x - b\|_2^2 + \alpha \sum_{i=1}^{N} \|D_i x\|_2, \tag{3}$$

where Q is the set of feasible x, $1/2\|\mathrm{A}x-b\|_2^2$ is the fidelity term, $\sum_{i=1}^{N}\|D_i x\|_2$ is the sparsifying term, α is the parameter that balances the two terms and is chosen so that signal-to-noise ratio is maximized (*e.g.*, $\alpha = 0.1$ was used in the simulation), and D_i is the forward difference approximation to the gradient at voxel i. The convex optimization problem described in Eq. (3) can be solved approximately, but efficiently, by using the accelerated gradient-projection Barzilai–Borwein (GPBB) formulation [6]. Details on the mathematical descriptions of the CS reconstruction framework can be found in our previous paper [7].

Figure 3 shows the simplified flowchart of the CS-based reconstruction framework for the proposed method, and it is briefly described as follows. Firstly, the measured projections b^m are acquired from the imaging system. The initial guess $x^{(0)}$ is then assumed as the image reconstructed by simple backprojection (BP), followed by forward projection (FP) to obtain the computed projections b^c. By using the b^m, the b^c, and the current updated image $x^{(k)}$, the objective function $f(x)$ is computed to determine the step size $\Delta x^{(k)}$ for the next updated image $x^{(k+1)}$. The image x is successively updated until the mismatch between the current and the updated images converges to a specified tolerance ε. During the iterative procedure,

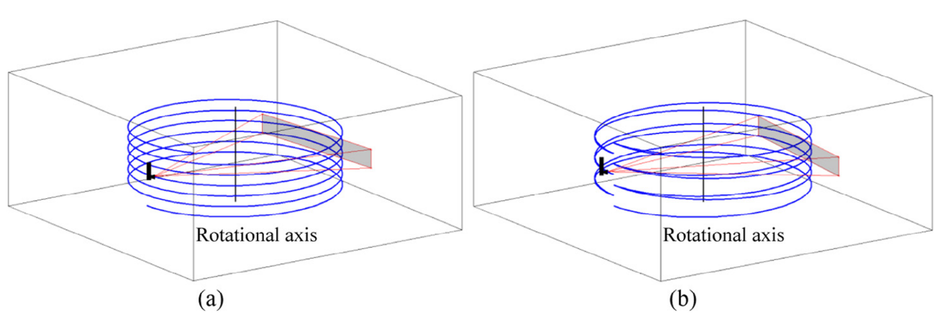

Figure 2. Schematic illustrations of the proposed scan geometries for volumetric dental X-ray imaging by using a linear-type panoramic detector: (a) a spiral scan geometry and (b) a zigzag scan geometry.

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