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Scan and reconstruction of helical cone-beam industrial CT for big workpiece

Xiaobing ZOU [1, 2], Li ZENG [1, 3]
1 ICT Research Center, Key Laboratory of Optoelectronic Technology and System of the Education Ministry of China, Chongqing University, Chongqing 400044, China
2 College of Optoelectronic Engineerning, Chongqing University, China
3 College of Mathematics and Physics, Chongqing University, China
Phone: +86 2386394834;E-mail:xiaobingzou@163.com, Lizeng@cta.cq.cn

Abstract

In 3D cone-beam Industrial Computed Tomography (ICT), in addition to the case which the inspected workpiece is longer than the detector, it is common that the diameter of the detected workpiece is bigger than the width of the detector. The helical trajectory can solve the problem of long object scan, not the problem of big object scan. In this paper, a scan mode and reconstruction method is discussed, which trajectory is translation and dually helical. It does not only inspect the large and long object but also has fewer redundant projections. Firstly, the gantry is horizontally translated before scan, one part of the detected workpiece can be covered by ray-beam, and projections of the first spiral scan are acquired. Then, the gantry is horizontally translated along opposite direction before the second scan, another part of the detected workpiece can be covered by ray-beam, and projections of the second helical locus are acquired. The 3D image is reconstructed according to modified helical FDK algorithm. When reconstructing, projections don't need to be rebinned. The scan mode presented by this paper is easily implemented and efficiency is also high. The results of computer simulation validate the FOV(Field Of View) radius via this method can be improved to about two times compared with the traditionally helical cone-beam CT.

Keywords: Industrial CT, translation, dual helix, modified helical FDK algorithm

1. Introduction

Compared with 2D CT, 3D CT has much shorter scan time because it can make use of the rays more efficiently, and has more resolution. Helical cone-beam CT has been developed for more rapid and volumetric scanning with higher axial image resolution than that of planar locus. So the helical trajectory and reconstruction algorithm have attracted increased attention, and is gradually being used in medical diagnosis and engineering. Algorithms for helical cone-beam CT reconstruction are classified into the approximate and the exact algorithms. While exact algorithms can produce high quality images, they require large amount of computation [1-2]. Compared with exact algorithms, approximate algorithms can provide a feasible compromise

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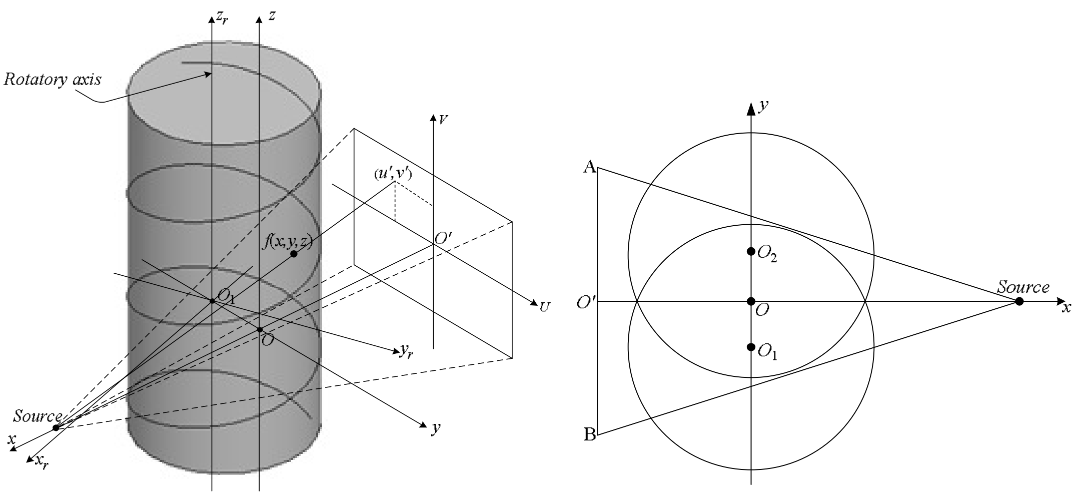
between the image quality and computational efficiency [3-4], thus, have been popularly adopted.

In some applications of industrial CT, except workpiece is longer than the detector, the case which the diameter of the workpiece is bigger than the width of the detector is often happened. In order to inspect the large object, the classical 2nd generation scan approach is still used. The scan speed of the 2nd generation scan is very slow, and the projection data is very redundant. In order to improve this scanning strategy, Fu Jian *et al*. proposed bias scan [5-6], half scan [7-9], and translated scan [10-11]. These scan modes are hardly implemented or acquire incomplete projections, and the projections are rebinned into parallel beam, which induce interpolation error. Li liang *et al*. presented BPF reconstruction for reduced detector [12]. The scan loci is similar to the trajectory proposed by Fu Jian *et al*., and BPF algorithm based on PI lines is used when reconstruction. We proposed a scan mode of native angle cone-beam CT in Ref. [13]. This scan mode can theoretically inspect workpiece of arbitrary diameter, and projections are not rebinned. But along with increase of translated times, image has more artifacts. Furthermore, all scan loci mentioned above are planar. To inspect long and big workpiece, we research a helical scan locus with large FOV and reconstruction method. This scan locus only needs workpiece to translate tow times and dually helical reconstruction algorithm modified helical FDK algorithm is used. Therefore it is easily implemented, high efficient, and has less artifacts.

2 Scan Mode and Modified Helical FDK Algorithm

2.1 Scan mode



(a) (b)

Figure 1 Proposed scan mode. (a) The first scan, (b) Planform of two scans.

Figure 1 demonstrates the principle of presented scan mode which inspects large objects by use of small detector, where Figure 1(b) denotes the planform on center plane, O_1 and O_2 is the position of gantry center of two translations, O' is projection point of center ray on the detector, O denotes midpoint of line segment O_1O_2. Before the first scan, the workpiece translates to O_1 which translated direction is parallel to line segment AB. With the workpiece rotating and translating, we achieve the first helical scan. Then the workpiece translates to O_2 which direction is opposite to the first translation direction. We can achieve the second helical scan. At each helical scan, workpiece isn't completely covered by X-ray at each rotatory angle. But through two helical scan, workpiece can be completely covered at each rotatory angle.

2.2 Modified helical FDK Algorithm

In standard helical FDK algorithm, the center ray pass trough rotatory axis [3-4]. For dually helical scan presented by this paper, the center ray doesn't intersect with rotatory axis (see Figure 1). So we must modify the standard algorithm for reconstructing the field of view. We assume a three-dimension attenuation function *f*(*x*, *y*, *z*,), which support is a cylinder of radius *r*. $O-xyz$ denotes global coordinate system, $O'-UV$ is detector coordinate system. At angular position β, the coordinate of point (x,y,z) in coordinate system $o-x_r y_r z_r$ (see Figure 1) is given by

$$\begin{pmatrix} x_r \\ y_r \\ z_r \end{pmatrix} = \left(\begin{pmatrix} x \\ y \\ z \end{pmatrix} - \begin{pmatrix} 0 \\ y_d \\ 0 \end{pmatrix} \right) \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ -z_0 + \dfrac{h}{2\pi}\beta \end{pmatrix}, \tag{1}$$

where $(0, y_d, 0)^T$ denotes the coordinates of gantry center in global coordinate system, h is helical pitch of spiral locus, (x_0, y_0, z_0) the start position of scan.

The X-ray source is located at a distance *R* from the origin, where *R*>*r*. Detector plane faces the source at a distance *D*. Let (u', v') be the coordinate of the projection of (x,y,z) on the detector, where u' refers to the line of the detector and v' to the column. Position of the X-ray source point is given by $(R,0,0)^T$, where T denotes transpose. u', v' is given by

$$u' = \frac{D}{R - x_r}\left(y_r + y_d\right), \quad v' = \frac{D}{R - x_r} z_r \tag{2}$$

Let $p(\beta, u', v')$ denote the cone-beam projection at angular position β. Derived from standard helical FDK algorithm proposed by Wang [3] and Kudo [4], the modified helical FDK algorithm is given by

$$f(x,y,z) = \frac{1}{2}\int_{\beta_S}^{\beta_E} \frac{1}{U^2} \tilde{p}(\beta, u', v') d\beta \tag{3}$$

where

$$U = \frac{R - x\cos\beta + y\sin\beta}{R}, \tag{4}$$

$$\beta_s = 2\pi \frac{z - z_0}{h} - \pi, \quad \beta_E = 2\pi \frac{z - z_0}{h} + \pi \tag{5}$$

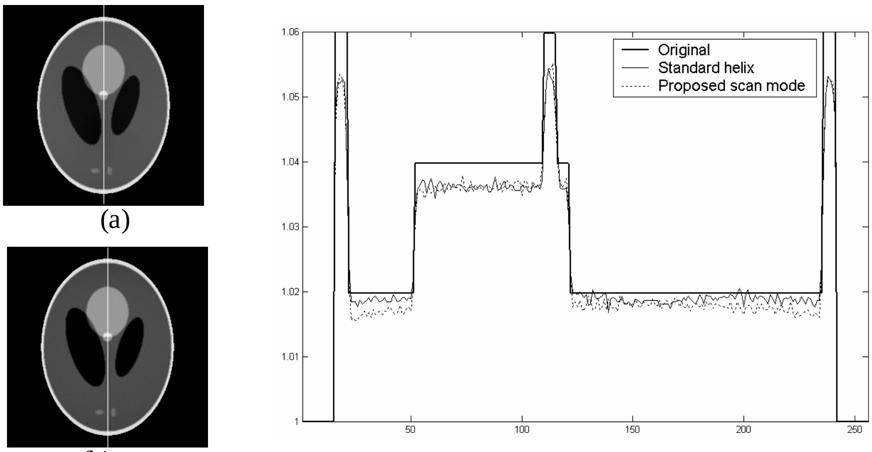
$$\tilde{p}(\beta, u', v') = \left[\frac{1}{\sqrt{D^2 + u'^2 + v'^2}} p(\beta, u', v') \right] * g(u'), \tag{6}$$

$g(u)$ stands for ramp filter, $*$ denotes the convolution operator.

The formula (4) is empirical, not proved theoretically.

3 Simulation

We use Shepp_Logan phantom to evaluate the performance of the proposed scan mode and algorithm. Parameters of the simulation are set to R =1400mm, D = 1500mm, h = 66.25mm, r=75mm, projection number per rotation N=720, length of workpiece l=150mm, number of image pixels 256×256×256. The simulated performance of the proposed scan mode is compared with standard helical scan with large detector. Parameters of small detector, which are used in proposed scan mode, are $w \times h$=100×75mm^2, number of detector cells for each row N_R = 170, number of detector cells for each column N_C=256. Parameters of big detector, which are used in standard helical scan, are $w \times h$=162×75mm^2, number of detector cells for each row N_R = 274, number of detector cells for each column N_C=256.



(a) (b) (c)

Figure 2 Slice at position z=-0.25. (a) Image reconstructed by using standard helix with large detector, (b) Image reconstructed by using proposed scan mode with small detector, (c) Profile on the line in left image.

Table 1 Evaluation of standard helix and proposed scan mode

	MSE	PNSR
Standard helix	188.458457	25.378647
Proposed scan mode	217.063030	24.764945

Figure 2 illustrates the reconstruction images and profile. Each image is with a display window [1.0, 1.06]. Table 1 denotes the evaluation reconstructed by standard helix and proposed scan mode, where MSE is mean square error, PSNR is peak signal to noise ratio.

The results represented Figure 2 and Table 1 show that image quality reconstructed by proposed scan mode with small detector is similar to that of the standard helical scan with large detector.

When the size of detector are equal with standard helix and proposed scan mode, for example, parameter are detector size $w \times h$=100×75mm^2, source-center R=1400mm and source-detector D=1500mm, the FOV radius of standard helix is 46.64mm, where the FOV radius of proposed scan mode is 90.27mm, which is about tow times as standard helix.

4 Conclusion

For inspecting large workpiece, we proposed a dually helical scan with workpiece translated two times. As a result, the proposed scan mode can enlarge inspection field, and is efficient on computation. Furthermore, projections are not rebinned. The performance of the proposed scan mode and reconstructed method are evaluated with Shepp_Logan phantom in comparison with the standard helical scan and standard helical FDK algorithm. The simulation invalidates the image qualify reconstructed by using proposed scan mode with small detector is similar to that reconstructed by using standard helix with large detector, and the FOV of proposed scan mode is improved about two time.

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