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Iterative geometric calibration in circular cone-beam computed tomography

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ABSTRACT

The reconstructed image may be distorted by geometry artifacts due to the presence of mechanical misalignments in circular cone-beam computed tomography (CT) system. To avoid geometry artifacts intervention, a novel geometric calibration method belonging to the iterative-type methods, which uses a dedicated calibration phantom to determine all geometry parameters, is presented in this paper. The phantom consists of two steel balls, and the trajectories of two ball centers are two circles in circular scan. Minimization of the errors between the predicted trajectories of ball center and the ideal circles is the principle in the proposed method. In summary, the proposed method consists of three parts. Firstly, an efficient description of geometry which reduces the number of geometry parameters from 7 to 4 is stated. Then, a nonlinear least square model depending on the 4 parameters is derived. At last, the Levenberg–Marquardt algorithm (LMA) is applied to solve the optimization problem. We implemented the proposed method and the classical analytic method presented by Noo et al. on real data in our laboratory cone-beam CT. The results indicated that our method could provide satisfactory reconstructed images as good as Noo's method.

1. Introduction

Neither the medical CT nor the industrial CT can be used into practice directly without geometric calibration, since the reconstructed images may be distorted severely by geometry artifacts [1]. The circular scan is adopted for most applications in industrial CT, and many available geometric calibration methods have been developed. All the methods can be divided into three groups: the analytic-type methods with calibration phantom, the iterative-type ones with calibration phantom and the self-calibration ones without any dedicated objects.

The geometry parameters can be obtained from explicit analytic formulas by use of the analytic-type methods [2–8]. The analytic-type methods have been used in industrial CT widely due to the computational efficiency and high precision. The most classical method of this group is Noo's method [2] which contains valuable insight into analytic methods. However, some geometry parameters are always ignored in this group, e.g., the rotated angle of flat detector along some row is assumed to be equivalent to zero in Noo's method.

The computational complexity of the second group is higher than the first group, but the complete set of parameters can be determined. Some of these calibration procedures [9] calculate the geometry parameters view by view, and just one projection with the precise knowledge of reference point on the phantom is acquired at each view angle. While other methods [10] need more than one projection on the full circular-scan, and only the distances among reference points are required. Although these methods are sensitive to initial values, the optimal results always can be reached because the measured geometry parameters are close to the true ones in practical CT system.

Recently, the self-calibration methods were developed based on iterative techniques [11–15], in which image entropy, sharpness, etc. were used to evaluate tomographic image quality. The main advantage of these methods is that the pre-calibration using dedicated phantom is not required any more. However, the computational costs of these methods are heavy due to the multiple time-consuming image reconstructions. In addition, one kind of image evaluation criterion, such as image entropy, may not be general for different applications.

Our method belonging to the iterative-type methods needs multiple projections of a dedicated calibration phantom sampled on the full circular-scan path. Some advantages of the analytic-type methods are introduced into the method. Firstly, a modified calibration phantom with only 2 steel balls was designed in our implementation. Secondly, just 4 geometry parameters need to be determined because of the introduction of intersection point between the flat detector and the line which passes through the focal spot of X-ray source and is orthogonal to the rotation axis.

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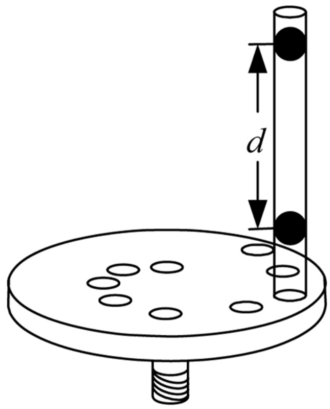

Fig. 1. The calibration phantom consists of a disk and a cylinder of Lucite in which two metallic balls are positioned. The distance between two ball centers is measured on the scale of micrometers when manufactured.

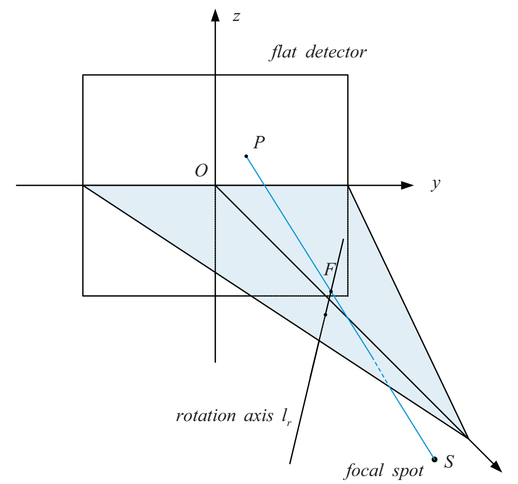

Fig. 2. Coordinate system definition.

In summary, our calibration procedure consists of four steps. The first step is detecting the centroid coordinates of projected ball. The second step is describing the efficient geometry which reduces 7 alignment parameters to 4. The third step is deriving a non-linear least square model depending on the above 4 geometry parameters. At last, the LMA is applied to solve the optimization problem.

The paper is organized as follows. After a brief description of the calibration phantom and definition of geometry in Section 2, the details of the proposed method are introduced in Section 3. Experiments on real data are given in Section 4, and conclusions are summarized in Section 5 at last.

2. Calibration phantom and definition of geometry

2.1. Calibration phantom

Rough suggested such a method that determined all geometry parameters from a series of projections of dedicated reference points [9]. Steel ball bearings called reference points are often used to constitute a calibration object to exhibit high contrast projection, e.g., PSD-2 calibration phantom contains 108 steel balls [16]. Generally, better calibration results can be achieved utilizing more reference points during calibration procedure but resulting in overlapping with neighboring balls on projection image or increasing computational complexity. In this framework, a phantom with only 2 steel balls was designed and manufactured which was motivated by Noo's work shown in Fig. 1.

A hollow cylinder in which two metallic balls are positioned is placed on a disk of Lucite. The diameter of disk is 150 mm, and the distance between two ball centers is a constant d. 8 holes are distributed on the disk spiral-shaped, so the rotation radii of phantom can be tuned aiming to assure both balls are visible on the projected image. Additionally, to assure one cylinder can be replaced by another under specific situations, a series of cylinders with the distance between two ball centers varying from 10 mm to 200 mm with 10 mm increments are manufactured.

Unless otherwise stated, the lowercase letters a and b represent the upper and lower balls respectively in the following discussion, e.g., coordinates $(0, y_i^a, z_i^a)$ and $(0, y_i^b, z_i^b)$ denote the centroid coordinates of upper and lower projected balls at the ith view angle.

2.2. Coordinate system definition and geometrical parameters

2.2.1. Coordinate system definition

A general micro-focus industrial cone-beam CT system consists of a micro-focus X-ray source, a stage with four degrees of freedom and a flat-panel detector, which are mounted on an optical bench. In the field of geometric calibration, the X-ray source is often regarded as a point source.

To describe the geometry of the cone-beam CT system, two coordinate systems referred as the 3D (three dimensional) object coordinate system and 2D (two dimensional) detector coordinate system were introduced in most reported publications [2,4]. In our work, only one right-handed Cartesian coordinates x–y–z is defined which is shown in Fig. 2. We choose the center of flat detector as the origin point. The axis perpendicular to the flat detector is defined as the x-axis; y-axis and z-axis are parallel to the horizontal and vertical direction of the flat detector, respectively. The line passing through the focal spot S which is orthogonal to the rotation axis intersects the flat detector at the point P. And then the source–object–distance (SOD) equals length of line segment SF and source–detector–distance (SDD) is equivalent to length of line segment SP. It is noted that SDD is not the shortest distance from the X-ray source to the flat-panel detector. In this coordinate system, the rotation axis may be inclined and have no intersection point with x-axis, and the focal spot may be apart from x-axis in respect that misalignments occurred in practice. As a consequence, these misalignments will lead to distorting reconstructed images. Artifact-free reconstructed images can be obtained only with the accurate knowledge of geometrical information.

2.2.2. Geometrical parameters

As already stated above, the set of parameters existed in such a circular cone-beam CT system are listed as follows:

(1) (x_s, y_s, z_s), the coordinates of the X-ray focal spot in the given system.
(2) $\vec{n}$, the unit direction vector of rotation axis l_y, without loss of generality $n = \left(n_1, n_2, \sqrt{1 - n_1^2 - n_2^2}\right)^T$.
(3) $(x_l, y_l, 0)$, the coordinates of intersection point between the rotation axis l_y and (x, y)-plane.

This leads to a total of 7 geometry parameters that need to be determined accurately. Intuitively, the geometry can be obtained