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Assessment of geometric misalignments in cone-beam CT using ball phantom trajectories

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1. Introduction

A computed tomography (CT) is one of the most widely used x-ray techniques in medical and non-destructive testing fields and the priority concern for CT imaging is to achieve the best image quality while minimizing absorbed dose. Beyond other system factors, accurate assessment of spatial relationships is crucial to improve image quality since the geometrical misalignment can result in severe artifacts that contaminate the tomographic image quality [1,2,3].

In this study, we propose two geometric calibration methods for the flat-panel detector (FPD)-based cone-beam CT systems. Both methods use a ball-bearing phantom to calculate geometric parameters such as three angular variables and vertical and parallel offsets for the detection plane, source-to-detector distance (SDD), and source-to-object distance (SOD). The first one utilizes radial pairs extracted from projection images acquired at specific four angles, while the other requires the complete elliptical trajectory of the ball bearings; thus requires a complete 2π scan. The performances of the proposed methods are quantitatively investigated by Monte Carlo (MC) simulations and experimental measurements.

2. Materials and Method

2.1 Definition of geometric parameters

The geometry of the CT system can be described as a combination of the stationary source and detector and the rotational object, as shown in Fig. 1. Then seven parameters to describe the geometric misalignment of source and detector can be defined as follows: three rotation angles of the detector plane (η, θ, ϕ) for each x-, y-, and z-axis, translations of the detector plane (u_0, v_0) for x- and y-directions, SDD, and SOD. The rotation angles θ and ϕ are defined as out-of-plane angles, while η is defined as an in-plane angle. (u_0, v_0) refers to the center of the detection plane.

2.2. Radial pair-based method

We first assume that two out-of-plane angles (θ, ϕ) are zero since they have a negligible effect on the resultant tomographic image quality [4]. Four checkpoints (A_1, A_2, A_3, A_4) are defined from the projection images of a ball-bearing phantom at each 90° of projection angle (i.e., 0°, 90°, 180°, 270°). Then the points (A_1, A_3) and (A_2, A_4) become radial pairs. Fig. 2(a)-(d) shows examples for projection images of ball bearings at each checkpoint.

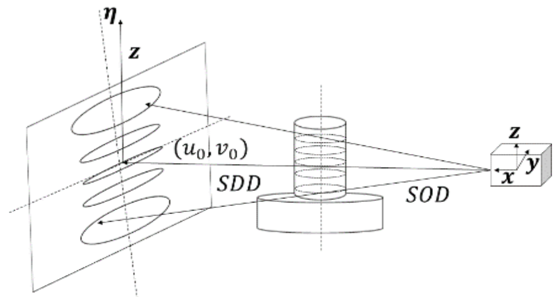

Fig. 1. A picture describing the cone-beam CT geometry.

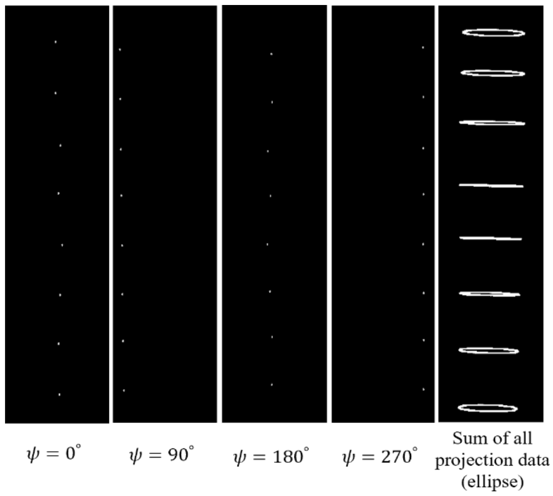

Fig. 2. (a)-(d) Projection images of ball bearings for each checkpoint and (e) a cumulative image of every projection data for a complete 2π scan.

In-plane angle η can be calculated by adopting the projection point of the center of trajectory. Four parameters (u_0, v_0, SDD, SOD) can be calculated based on the spatial ratio between each checkpoint and radial pairs.

2.3. Elliptical trajectory-based method

In contrast to the radial pair-based method, the elliptical trajectory-based calibration requires a complete 2π scan of the ball-bearing phantom. In a similar manner to the radial pair-based method, we first assume that θ is zero. The calculation of η is equivalent to the radial pair-based method and the remaining five parameters can be calculated from the elliptical trajectories of the ball bearings [5]. An example for extracted trajectories is shown in Fig. 2(e).

2.4 Evaluation

The evaluation of calibration methods is performed using MC simulations and experimental measurements. Both calibration methods are used to estimate the geometric misalignments and their estimates are compared with the ground truth values.

For the MC simulations, 30-kVp x-ray spectrum is emitted at each step angle of 1^o and the projection images for the eight iron ball bearings with a diameter of 0.1 mm are acquired by a 256 × 256-formatted ideal detector array with a pixel pitch of 0.1 mm. The ball bearings are equally spaced in a height-direction by 2 mm. SOD and SDD are 10 cm and 12 cm, respectively. Then artificial misalignments (u_0 = 10 pixels, v_0 = 10 pixels, and η = 2^o) are implemented to the MC geometry. Both methods are used to estimate these misalignments. The estimated geometric misalignments are compared with the ground truth values.

The experimental measurements are performed using a 30-kVp x-ray spectrum produced by a tungsten target x-ray tube (XTF5011, Oxford Instruments, Oxfordshire, UK) and a 1548 × 1032-formatted x-ray detector with a pixel pitch of 99 μm (Shad-o-Box 1548 HS, Teledyne Rad-icon Imaging Corp., Sunnyvale, CA). The phantom is composed of a plastic cylinder with a height of 110 mm and eight steel ball bearings with a diameter of 0.5 mm. The ball bearings are attached directly to the surface of the plastic cylinder with an interval of 10 mm. The SOD and SDD of the experiment system are 390 mm and 500 mm, respectively. The misalignments for the experimental system are set as follows: in-plane rotation of 1°, u- and v- directional translation of u_0 = 26 pixels and v_0 = 84 pixels.

3. Preliminary Results

3.1 Monte Carlo simulations

Tab. I: Comparison of estimated geometric misalignments for the MC simulations

Parameter	Ground truth	Radial pair	Elliptical trajectory
SOD [cm]	10	9.48	9.50
SDD [cm]	12	11.50	11.51
u_0 [pixels]	138	138.50	139.14
v_0 [pixels]	138	138.50	134.06
η [degrees]	2	1.94	1.94
ϕ [degrees]	0	N/A	-0.23

Tab. I compares the estimated geometric misalignments by two calibration methods with ground truth values. The radial pair-based method shows good accuracy in (u_0, v_0) with an error of less than 0.5% and shows about 5% errors for SOD and SDD. The elliptical

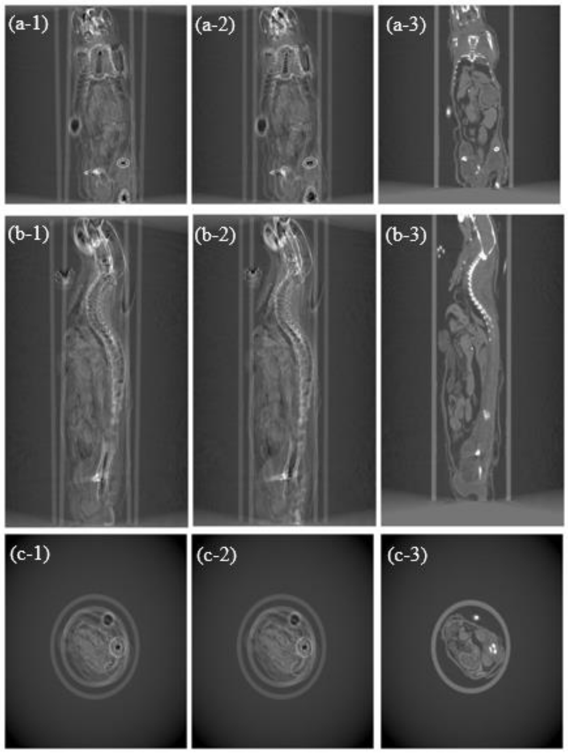

Fig. 3 Comparison of tomographic images for postmortem mouse. Rows from top to bottom respectively represent coronal, sagittal, and axial slices. Columns from left to right show images without any calibration, calibration of η, and complete calibration, respectively.

trajectory-based method shows a similar result for the SDD, SOD, and u_0 but shows poor accuracy for v_0. Both methods show similar results on η with errors of less than 3%.

3.2 Practical application

Fig. 3 compares the calibrated and uncalibrated tomographic images of a postmortem mouse. Estimated geometric information is applied in the image reconstruction process for calibrated images [6]. The effect of η is easily shown in the sagittal views and those of horizontal and vertical offsets can be found in axial views. Visual observation validates that the radial pair-based method provides proper calibration for a given CT system.

4. Conclusion

Two geometric calibration methods for FPD-based CBCT systems have been introduced. The radial pair-based method is computationally more efficient and showed good agreement with the ground truth. The elliptical trajectory-based method can estimate an additional out-of-plane rotation angle ϕ but shows slightly low accuracy for the calculation of translations. A detailed description of calibration methods including mathematical derivation of each parameter will be presented at the conference.

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