Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2017 March ; 10132: . doi:10.1117/12.2255724.

Geometric Calibration Using Line Fiducials for Cone-Beam CT with General, Non-Circular Source-Detector Trajectories

M.W. Jacobson¹, M. Ketcha¹, A. Uneri¹, J. Goerres¹, T. De Silva¹, S. Reaungamornrat², S. Vogt³, G. Kleinszig³, and J. H. Siewerdsen¹

¹Department of Biomedical Engineering, Johns Hopkins University, Baltimore MD, 21205 USA

²Department of Computer Science, Johns Hopkins University, Baltimore MD, 21218 USA

³Siemens Healthineers XP Division, Erlangen, Germany

Abstract

Purpose—Traditional BB-based geometric calibration methods for cone-beam CT (CBCT) rely strongly on foreknowledge of the scan trajectory shape. This is a hindrance to the implementation of variable trajectory CBCT systems, normally requiring a dedicated calibration phantom or software algorithm for every scan orbit of interest. A more flexible method of calibration is proposed here that accommodates multiple orbit types — including strongly noncircular trajectories — with a single phantom and software routine.

Methods—The proposed method uses a calibration phantom consisting of multiple line-shaped wire segments. Geometric models relating the 3D line equations of the wires to the 2D line equations of their projections are used as the basis for system geometry estimation. This method was tested using a mobile C-arm CT system and comparisons were made to standard BB-based calibrations. Simulation studies were also conducted using a sinusoid-on-sphere orbit. Calibration performance was quantified in terms of Point Spread Function (PSF) width and back projection error. Visual image quality was assessed with respect to spatial resolution in trabecular bone in an anthropomorphic head phantom.

Results—The wire-based calibration method performed equal to or better than BB-based calibrations in all evaluated metrics. For the sinusoidal scans, the method provided reliable calibration, validating its application to non-circular trajectories. Furthermore, the ability to improve image quality using non-circular orbits in conjunction with this calibration method was demonstrated.

Conclusion—The proposed method has been shown feasible for conventional circular CBCT scans and offers a promising tool for non-circular scan orbits that can improve image quality, reduce dose, and extend field of view.

1. INTRODUCTION

Geometric calibration is the process of identifying a cone-beam CT (CBCT) system projection geometry, i.e., the relationship between 3D points and their 2D projected locations at various gantry positions. This relationship depends on system geometric parameters such as the Source-Detector Distance (SDD) and the orientation of the detector panel in each projection view. Most commonly, geometric calibration is performed by

scanning a known 3D configuration of radio-opaque spherical fiducials (e.g., [1–3]), such as the BB phantom in Fig. 1(a) by Cho et al. The system geometry may then be deduced by fitting parametric models of the projection geometry to the observed projected marker locations. In recent years, alternative “online” calibration methods have been proposed that can deduce geometry directly from a patient scan [4, 5]. However, these methods tend to be computationally intensive or to rely on specific assumptions about the orbit shape. Offline phantom-based calibration methods are still preferred, due to their minimal computational demands.

A problem with spherical marker phantoms, however, is that they are often customized to relatively restricted orbit shapes and ranges of gantry motion. Phantom and software customization is needed either to avoid or to contend with marker projection overlap of the kind shown in Fig. 1(a). When marker overlap occurs, accurate determination of their projected locations is compromised, potentially degrading calibration accuracy. Moreover, overlap makes it difficult to perform 3D-2D marker matching steps typically required by calibration algorithms. We propose an alternative calibration method based on a multi-wire line fiducial phantom as illustrated in Fig. 1(b). Line fiducials overcome the occlusion hazards of spherical fiducials, because their projections overlap very mildly as long as the wires are mutually non-coplanar in 3D. This makes the phantom amenable to a wider range of orbits and less sensitive to phantom positioning.

2. METHODS

2.1. Mathematical Preliminaries

In CBCT, the projection of a 3D coordinate to a 2D view coordinate is described by the equation $x=PX$. Here, X and x are 4×1 and 3×1 homogeneous coordinate vectors representing the 3D and 2D locations respectively. The matrix P is a 3×4 projection matrix, for that particular projection view, with the following 9 degree of freedom decomposition,

$$P=KR[I - C], \quad (1)$$

$$K=\begin{bmatrix} \text{SDD} & 0 & u_0 \\ 0 & \text{SDD} & v_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

In these equations, SDD is the Source-Detector distance, (u_0, v_0) are 2D image coordinates where the focal spot projects orthogonally onto the detector (the so-called piercing point), R is a 3×3 orthogonal matrix whose rows are the detector axes, and C is a 3×1 vector representing the 3D location of the focal spot.

A 3D line can be parametrized by two points on the line, represented by 4×1 homogeneous vectors $X=\begin{bmatrix} \tilde{X}^T, 1 \end{bmatrix}^T$ and $Y=\begin{bmatrix} \tilde{Y}^T, 1 \end{bmatrix}^T$. Under cone-beam projection, the 3D line maps to a 2D line whose equation $a_i u + b_i v + c_i = 0$ is compactly expressed as $I^T X = 0$. Here $I = [a_i, b_i,$

$c_i]^T$ and $x = [u, v, 1]^T$ are homogeneous vectors representing the 2D line itself and a point on the line, respectively. Since X and Y are points on the 3D line, they project to points satisfying the 2D line equation, leading to,

$$l^T P[X, Y] = 0 \quad (3)$$

Put another way, l is orthogonal to both PX and PY and is therefore given by their cross-product $l = PX \times PY$. Incorporating (1) then leads to the following explicit form for l ,

$$l = K^{-T} R \left(C \times (\tilde{X} - \tilde{Y}) + (\tilde{X} \times \tilde{Y}) \right) \quad (4)$$

where we have ignored irrelevant scale factors.

2.2. Geometric Calibration Method

In the method proposed, scans of a multi-wire phantom are acquired and sample points of their 2D line shadows are extracted. Equation (4) is then used as a basis for estimating, for each acquired view, the geometric entities K , R , and C . It is assumed that the 3D phantom geometry is known.

Fiducial Extraction—For each fixed wire, i , sample points x_{ij} lying on the 2D line shadow l_i are to be extracted. A binary map of the line shadows in each view is obtained by thresholding. Morphological operations are then applied to detect and remove intersection points of the line shadows from the binary map. Next, region growing is used to group high-attenuation pixels in the remaining sub-segments. Finally, a search is made to determine which sub-segments belong to the same wire. This is done by comparing the sub-segments pair-wise for proximity and collinearity.

Geometry Estimation—The geometry parameters in each fixed projection view are estimated by minimizing the following least squares cost function, motivated by equation (4),

$$f(\alpha, \theta, C) = \sum_{ij} \|x_{ij}^T K_\alpha^{-T} R_\theta \left(C \times (\tilde{X}_i - \tilde{Y}_i) + (\tilde{X}_i \times \tilde{Y}_i) \right)\|^2 \quad (5)$$

Here $\alpha = [\text{SDD}, u_0, v_0]^T$ is a parametrization of K , and θ is a 3×1 vector of Euler angles parametrizing R . The cost function reaches a value of zero, due to (4), when the samples x_{ij} lie on the line l_i exactly.

Determining Phantom Geometry—For each fixed wire, i , a pair of 3D points X_i, Y_i is needed to describe the wire's 3D pose and must be *a priori* known with high accuracy. In formal, high precision manufacturing, the phantom wire poses would normally be pre-specified as part of the fabrication process. In this work, however, we constructed the

phantom with approximately desired dimensions and then obtained more precise estimates of X_i , Y_i post-facto using a standard CBCT scan of the phantom on an already-calibrated system. Samples of the i -th wire's line projections were extracted from the scan as detailed above and a line fit to the samples was made to obtain an equation vector, l . This was done in each projection view. Equation (3) was then used to obtain an overdetermined set of linear equations in X and Y (two per view). By solving the system algebraically, estimates of X_i and Y_i were obtained.

2.3. Experimental Methods

Experiment #1: Application to a Circular Scan Orbit—The method was tested with circular scans made using the prototype C-arm CT system shown in Fig. 2. The system was calibrated using both an 8-wire phantom, and with a BB phantom. The phantoms were of the form and approximate dimensions shown in Fig. 1. The 3D wire poses in the multi-wire phantom were determined using a BB-calibrated scan with this system, as outlined in Section 2.2. Three data sets were acquired. The first was a scan of a set of 4 lead BBs mounted in Styrofoam, well-separated in the field of view both axially and off-axis. Centroid locations were calculated for each marker in each acquired view. Next, a slanted wire phantom (not the 8-wire calibration phantom) was scanned for the purpose of calculating Point Spread Functions (PSFs). Finally, a head phantom scan with natural temporal bone detail was acquired (93 kV, 120 mA, 333°/499 views).

The geometry under each calibration was then used to do the following post-analysis. The 4-BB phantom centroid data was used to calculate Back Projection Error (BPE) for all markers and views. The BPE measures the failure of rays back-projected from a marker's projection shadows to intersect. A best fit 3D intersection of the rays is first computed for each marker. Then, the distance of each ray from this intersection point gives the BPE for that marker and view. Volume reconstructions were made of the slanted wire and head phantoms using the FDK algorithm with 90% hamming filter cut-off and voxel size 0.3 mm. The PSF phantom was used to obtain Gaussian PSF fits at 12 locations in the phantom and their Full Widths at Half Maximum (FWHMs) were computed.

Experiment #2: Application to Non-Circular Orbit—Simulated scans of a head phantom and an 8-wire calibration phantom were generated in the sinusoid-on-sphere trajectory depicted in Fig. 3. The pixel pitch for the head scan simulation was 0.616 mm and half that for the wire phantom. The trajectory was derived from a 200°/498 view circular arc based on the Artis Zeego (Siemens Healthineers) robotic C-arm. A sinusoidal series of out-of-plane gantry tilts was then added, such that the peak-to-peak longitudinal variation in source position was 14 cm. Such an orbit was of interest for two reasons. First, improved image quality due to greater axial coverage is expected. Second, it would be challenging to calibrate this orbit with BB phantoms, since large out-of-plane excursions of the gantry increase occurrences of BB projection overlap.

The head phantom contained 2 stacks of Defrise phantom disk inserts imitating Teflon and polyethylene (see Fig. 6). The multi-wire calibration procedure was used to compute the geometry, and the head was then reconstructed with 200 iterations of the Penalized

Likelihood (PL) algorithm with voxel size 0.5 mm. Huber penalties were used with regularization parameters chosen to match (within 0.5 mm) the resolution of an FDK-reconstructed circular scan at the disk edge nearest the central axial plane. Resolution at the disk edges was quantified by fitting Gaussian error functions to the disk edge spread function. The derivative of this function gives a local Gaussian PSF whose FWHM was computed for each disk as a function of axial distance from the equatorial plane. BPE calculations were also made, similar to Experiment #1, but with simulated ground truth projections of 16 markers.

3. RESULTS AND BREAKTHROUGH WORK

Experiment #1: Application to a Circular Orbit

Results are summarized in Figs. 4 and 5. As seen in Fig. 4, the line-based calibration method out-performed calibration via the BB phantom in terms of BPE. Almost uniformly across all views, the worst of the 4 marker BPEs was better for the line phantom and sub-voxel in magnitude. Most of the BPE from the BB method was found to be longitudinal in direction. Since the slanted wires were longitudinally aligned, this higher error was not reflected in the in-plane PSF measurements. All 12 PSF samples were 0.65 ± 0.05 mm for both calibrations. However, the head reconstructions using the BB calibration show more prominent blur and streak artifacts (indicated in Fig. 5 by arrows), which may be associated with small errors in longitudinal calibration. In any case, the trabecular detail under the line phantom was at least as good as that obtained with the BB phantom.

Experiment #2: Application to Non-Circular Orbits

Results are summarized in Figs. 6 and 7. The calibrated reconstruction performed almost indistinguishably from ground truth, both visually (Fig 6) and quantitatively (Fig. 7). Similar to Experiment #1, BPE results (not shown) were sub-voxel (< 0.25 mm) across all views. Fig. 6 also compares imaging performance to the FDK-reconstructed circular orbit simulation. The FDK reconstruction used the ground truth geometry, so its inferior performance, as seen in the figure by a preponderance of edge blur and streak artifacts, is entirely attributed to the orbit itself and not to calibration error. This highlights the benefit of a noncircular orbit for certain imaging tasks.

4. CONCLUSIONS AND DISCUSSION

This work shows the successful implementation of a new geometric calibration method applicable to both conventional circular orbits and to non-conventional, non-circular orbits that challenge existing BB-based methods. Future work will include optimizing the line fiducial configuration and application to other non-circular scans.

Acknowledgments

This work was supported by NIH grant R01-EB-017226 and academic-industry collaboration with Siemens XP.

References

1. Daly MJ, et al. Geometric calibration of a mobile C-arm for intraoperative cone-beam CT. *Med Phys.* 2008; 35(5):2124–36. [PubMed: 18561688]
2. Cho Y, et al. Accurate technique for complete geometric calibration of cone-beam computed tomography systems. *Med Phys.* 2005; 32(4):968–83. [PubMed: 15895580]
3. Noo F, et al. Analytic method based on identification of ellipse parameters for scanner calibration in cone-beam tomography. *Phys Med Biol.* 2000; 45(11):3489–508. [PubMed: 11098919]
4. Ouadah S, et al. Self-calibration of cone-beam CT geometry using 3D–2D image registration. *Physics in Medicine and Biology.* 2016; 61(7):2613–2632. [PubMed: 26961687]
5. Wicklein J, et al. Image features for misalignment correction in medical flat-detector CT. *Med Phys.* 2012; 39(8):4918–31. [PubMed: 22894418]

Figure 1. Illustration of CBCT system geometry calibration phantoms, each with sample 2D projection views. (a) BB phantom as in Cho et al. with a pair of overlapping marker shadows marked by arrow. (b) The proposed wire fiducial phantom.

Figure 2.
Prototype C-arm for CBCT based on the Cios Alpha (Siemens Healthineers).

Figure 3.
Sinusoid-on-sphere orbit used for Experiment #2.

Figure 4. Experiment #1: Circular Orbits. The maximum marker BPE per view for each calibration method.

Figure 5.

Experiment #1: Circular orbits. (a) FDK head reconstruction based on BB phantom calibration. (b) FDK head reconstruction based on multi-wire phantom calibration.

Figure 6.
Experiment #2: Noncircular Orbits. Reconstructions of head phantom in both a circular and sinusoidal orbit.

Figure 7.

Experiment #2: Noncircular Orbits. Edge resolution at disk edges as a function of distance from the central axial plane for different orbits.