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Measurement of the X-ray computed tomography instrument geometry by minimization of reprojection errors—Implementation on experimental data☆

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ABSTRACT

A procedure for measuring the geometry of X-ray computed tomography (CT) instruments is applied to an experimental CT instrument. In this study, the geometrical measurement procedure is implemented with the CT^2 reference object, comprising steel spheres with known center positions in a local coordinate frame affixed to a cylindrical carbon fiber framework. The procedure can be implemented with other sphere-based reference objects, provided the sphere center coordinates are known. The effects of number of acquired projections and rotation mode (stepped or continuous) on the quality of measured geometrical parameters are studied. Finally, the output of the geometrical measurement procedure is used to inform the physical adjustment of the experimental CT instrument to its ideal alignment. The effectiveness of the measurement procedure to correctly determine the instrument geometry is demonstrated from dimensional measurements performed on a tomographically reconstructed validation object from radiographs acquired under initial (misaligned) and adjusted (aligned) instrument geometry.

1. Introduction

The geometry of an X-ray computed tomography (CT) instrument is defined by the relative positions and orientations of the three major components: X-ray source focal spot, sample rotation axis, and detector. Discrepancies between the geometry of the CT instrument with which radiographic projection images are acquired and the backprojection geometry in tomographic reconstruction from the images will contribute to inconsistencies between dimensional measurements performed on the reconstructed volume and the actual dimensions on the measured part(s) [1]. Consequently, these inconsistencies will result in errors of measurements performed on the volumetric data. The ability to measure the geometry of a real CT instrument and subsequent compensation of any detected misalignments is a critical step in improving the quality of reconstructed datasets and in reducing errors in CT measurements [2].

In this study, we apply a geometrical measurement procedure with a dedicated reference object to the TORATOM (Twinned ORthogonal Adjustable TOMograph, see Ref. [3]) experimental CT instrument at the Centre of Excellence Telč, Institute of Theoretical and Applied Mechanics, v.v.i, Czech Academy of Sciences (henceforth referred to by the abbreviation CET). The geometrical measurement procedure is based on the least squares estimation of a set of geometrical parameters in a CT ray-tracing model. The development of the reference object (named the Computed Tomography Calibration Tube—CT^2) is presented in Ref. [4], while the geometrical measurement procedure is introduced and applied to simulated data in Ref. [5]. It should be noted that the geometrical measurement procedure can be implemented with any other sphere-based reference object, provided the sphere center positions in a local coordinate frame are known, e.g. from measurement by CMM. Certain considerations in the practical implementation of this procedure, namely the number of acquired radiographic projection images and the modality with which the reference object is rotated (i.e. stepped or continuous), are investigated to provide an indication of robustness

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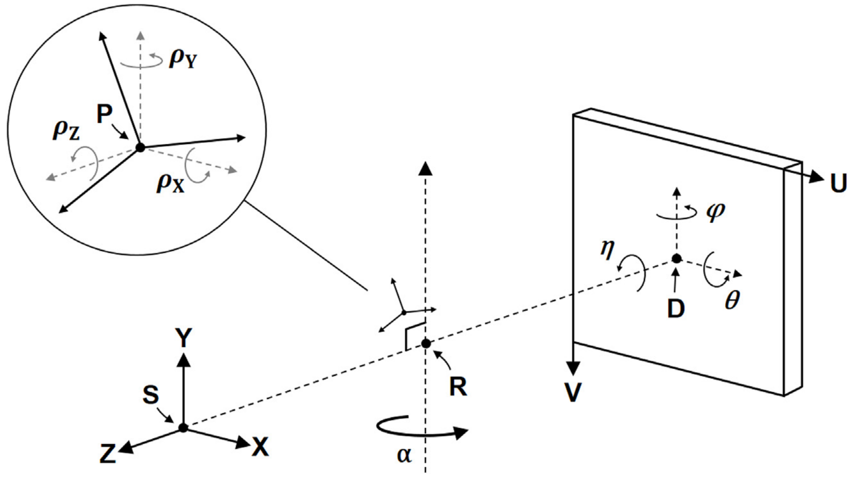

Fig. 1. Scheme for the parameterization of a typical cone-beam CT instrument and the position and orientation of a reference object within the global coordinate frame.

in the measurement of the instrument geometry.

The geometry of the experimental instrument aligned roughly with a standard TORATOM procedure (henceforth referred to as the 'initial' instrument geometry) is measured. Misalignments in the initial geometry are reduced by applying a series of physical adjustments to bring the instrument to its aligned state, which is defined in section 2. CT measurements of a separate validation object are performed under initial and adjusted geometries. Dimensional measurements from both reconstructed datasets are compared to determine the efficacy of the geometrical measurement procedure to correctly inform the physical adjustment of the instrument to its aligned state.

2. Cone-beam CT geometry

The geometry of a cone-beam CT instrument is defined by the relative position and orientation of X-ray source focal spot, axis of object rotation (AOR), and detector [1]. The following description of the coordinate convention is supplemented by the diagram in Fig. 1, which also includes the parameterization of the reference object position and orientation. Coordinate conventions in this study are chosen to correspond to previously used conventions [5]. A right-handed global Cartesian coordinate system is fixed on the X-ray source focal spot. The Y axis is parallel to the AOR, while the Z axis is coincident with the line from the source focal spot **S** that intersects the AOR orthogonally. The X axis subsequently follows the right-hand screw rule. In an aligned instrument, the detector rows are parallel to the global X axis, while the detector columns are parallel to the Y axis. The Z axis ideally intersects the detector at its geometrical center. The U and V axes of the detector coordinate frame correspond to the indexing axes for the detector column and rows, respectively.

The position of the AOR is given by $\mathbf{R} = (0,0, z_R)$, corresponding to the coordinate position of its intersection with the Z axis. The orientation of the AOR is given by the unit vector $\hat{\boldsymbol{r}} = (0,1,0)$. Rotation of the sample stage is parameterized by the angle α. The position of the detector center is parameterized by the point $\mathbf{D} = (x_D, y_D, z_D)$. Detector orientation is defined by three extrinsic rotations performed about local axes that are parallel to the axes of the coordinate system and whose origin is the detector center: tilt θ about the local X-axis, slant ϕ about the local Y-axis, and skew η about the local Z-axis. Rotations are applied in the following order: (1) η, (2) ϕ, and (3) θ.

When measuring the CT geometry, the position and orientation of the reference object must also be determined. Parameterization of the reference object in the CT geometry is given by the position of its local origin and the orientation of its local axes with respect to the global origin and coordinate axes, respectively, at the $\alpha = 0°$ position of the rotation stage. The position of the local origin in the global frame is given by the point $\mathbf{P} = (x_P, y_P, z_P)$ and the orientation of the local axes is given by three extrinsic rotations, performed sequentially in the order (1) ρ_Y, (2) ρ_Z, and (3) ρ_X. These parameters are considered nuisance parameters as they do not describe the CT geometry, yet are necessary for its measurement. The CT geometry can therefore be defined by 13 geometrical parameters: 7 instrument parameters and 6 reference object parameters, summarized in Table 1.

3. Reference object

The reference object presented in Ref. [4] is used in this experimental study and is briefly discussed here. It should be noted that the geometrical measurement procedure, which is described in more detail in Ref. [5], can be implemented with any sphere-based reference object. The CT^2 reference object consists of $M = 48$ high X-ray absorption spheres of 2.5 mm diameter fixed to a hollow, cylindrical carbon fiber support (Fig. 2). Carbon fiber is chosen as the support material due its relatively low X-ray absorption, providing high contrast in the radiographic imaging of the spheres for visual detection. The spheres are arranged in 10 circular trajectories at various heights along the central axis of the cylindrical support. An additional marking sphere is included in the top circular trajectory to break the symmetry and facilitate sphere identification in the radiographs. Sphere locations were chosen to reduce the number of overlaps in their cone-beam projections at the highest magnification position of the reference object while ensuring the full inclusion of all spheres in the detector field of view. The three-dimensional (x, y, z) coordinate position of each sphere center m was measured on a tactile CMM with a maximum permissible error (MPE) of 2 + L/300 µm, where L is the measured length in mm. The set of sphere center coordinates in the object's local frame $(x, y, z)_{m=1,2,\ldots,48}$ constitute the dimensional reference for measurement of the CT geometrical parameters.

Table 1
Geometrical parameters for CT instrument and reference object.

Component	Feature	Parameters
X-ray focal spot	Position	$\mathbf{S} = (0,0,0)$
AOR	Position	$\mathbf{R} = (0,0, z_R)$
AOR	Orientation	$\hat{\boldsymbol{r}} = (0,1,0)$
Detector	Position	$\mathbf{D} = (x_D, y_D, z_D)$
Detector	Orientation	(η, φ, θ)
Reference object	Position	$\mathbf{P} = (x_P, y_P, z_P)_{\alpha=0°}$
Reference object	Orientation	$(\rho_X, \rho_Y, \rho_Z)_{\alpha=0°}$