An Acquisition Geometry-Independent Calibration Tool for Industrial Computed Tomography

Jonathan HESS*, Patrick KUEHNLEIN*, Steven OECKL*, Tobias SCHOEN*
*Fraunhofer IIS (Dr.-Mack-Str. 81, 90762 Fuerth)

Abstract. We present a method that allows calibration of an arbitrary acquisition system for x-ray computed tomography (CT) by using projection data. Calibration in this context is a completely vector based determination of the acquisition geometry parameters, especially detector misalignments. No external measurement devices are used. The system calibrates itself by using its own image-providing property.

Introduction

Misalignment in computed tomography systems can cause severe artefacts in reconstructions. Therefore it is necessary to calibrate every system setup. Several algorithms already exist, which try to identify all relevant parameters for circular acquisition geometries. For arbitrary geometries and individual system setups those procedures can hardly be applied. We present an approach which is independent from acquisition geometry and system setup.

State of the art

In the work of Noo et al. [1] a standard algorithm is introduced. The authors expect an ideal circular movement and the degrees of freedom of the detector are not entirely described. The detector plane has only up to two degrees of freedom (DOF). Karolczak et al. [2] add a single DOF, but we want to calibrate all three possible DOF. However a similar calibration phantom is being used.

Sun et al. [3] uses a different kind of calibration phantom, a quadratic disc, with added spheres in the corners. Ideally the spheres describe a square, detector misalignments result in distorted squares. One problem is the needed exact positioning of the phantom in the x-ray beam and some disregarded parameters.

A more recent article of Xu and Tsui [4] determines again only one DOF of the detector, although the other DOF may be nonzero. The presented method expects noise-free data input and the remaining system parameters beside the detector are not determined.

Another current method is defined by Wu et al. [5], who follow a similar optimization approach but have once again less parameter.

Principle

Every tomography system consists of an x-ray source, an x-ray detector and a manipulation system, capable of moving the components or the specimen. A test phantom is placed
inside the x-ray beam and several projections are acquired. Between these projections a random specimen displacement is performed. Only the relative movement has to be known and no specific trajectory has to be used. After the acquisition, position information of the phantom is extracted from the two dimensional projection data.

We use a vector based representation of the whole system, including possible movement and positioning of the components and the test phantom (figure 1).

Using the gathered data, a nonlinear optimization is done by using the Levenberg-Marquardt algorithm according to [6]. The resulting vector based representation of the x-ray system contains the actual positioning and orientation of the components. This information can then be used to adjust the system manually or virtually, by supplying the needed parameters to post processing tools (e.g. reconstruction algorithm).

Figure 1: Vector based representation of CT system

Geometry parameters

An arbitrary CT system consists of three independent components: a source, an object and a detector. The acquisition geometry, which forms the basis for each position, is parameterized by the set $\Omega$ and assumes an object which is represented by $M$ coordinates.

$$\Omega = \{o_t, \alpha_{tilt}, \alpha_{slant}, \alpha_{skew}, x_d, y_d, z_d, r_{c_d}, r_{x_d}, r_{y_d}, r_{z_d}, x_s, y_s, z_s, r_{c_s}, r_{x_s}, r_{y_s}, r_{z_s}, x_o, y_o, z_o, r_{c_o}, r_{x_o}, r_{y_o}, r_{z_o}, x_{sph,1}, ..., x_{sph,M}\}$$

The set of all possible parameter configurations is called $\tilde{\Omega}$. The task is to determine the best (optimal) solution $\tilde{\Omega}^* \in \tilde{\Omega}$. Hereby holds:

- $o_t$, vector to the detector midpoint
- $\alpha_{tilt}, \alpha_{slant}, \alpha_{skew}$ Euler angles of the misaligned detector
- $x_d, y_d, z_d$ translation basis of the detector
- $x_s, y_s, z_s$ translation basis of the source
- $x_o, y_o, z_o$ translation basis of the object
- $r_{c_d}, r_{x_d}, r_{y_d}, r_{z_d}$ Euler angle rotational basis and centre of rotation of the detector
- $r_{c_s}, r_{x_s}, r_{y_s}, r_{z_s}$ Euler angle rotational basis and centre of rotation of the source
- $r_{c_o}, r_{x_o}, r_{y_o}, r_{z_o}$ Euler angle rotational basis and centre of rotation of the object
- $x_{sph,1}, ..., x_{sph,M}$ initial geometry of the object, parameterized by $M$ coordinates
In most CT systems, some of these parameters are fixed. We define a subset of $\Omega$ for every acquisition system to be calibrated.

**Detector misalignment**

The detector misalignment can be separated into translational and rotational parameters. The rotation of the detector is parameterized by the so called Euler angles, as you can see in Figure 2. The three Euler angles tilt, slant and skew are the common terms in the corresponding literature and, thus, are used in this article.

![Figure 2: Euler angles of misaligned detector](image)

**Calibration phantom**

We have designed an individually, problem-shaped calibration object. It is quite similar to the one used by Smekal et al. [7] The calibration phantom is placed between x-ray-tube and detector and a certain number of previously defined projections are acquired.

In the context of this work a synthetic cylinder is used, whose curved surface is added by $M = 8$ spheres made of steel, see Figure 3. These spheres are arranged on a helical trajectory, in order to realize an object which is effective in all directions (i.e. width, height and depth). The cylinder is locally described, which means the distance $d_{k,l}$ of each sphere $k$ to each other sphere $l$ is known

$$
  d_{k,l} = \left\|x_{loc,k} - x_{loc,l}\right\|^2, \forall\{k,l\} \in \sigma(1, ..., M)
$$

whereas $\sigma(1, ..., M)$ describes all two element subsets of the M-set and $x_{loc,j}, 1 \leq j \leq M$ describes the midpoint of sphere $j$ in a local coordinate system. For the simulations and the real data test all spheres have a radius of 1mm, the cylinder of 5mm. In order to simplify the identification of the spheres in the image, one sphere is placed outside of the helical trajectory, namely in the middle of the cylinder.
Problem modelling

In relation to the parameter configuration $\Omega$ the residual function $e(\Omega) \in \mathbb{R}^{M \times N}$ is defined, which calculates the error between the theoretically exact pixel values

$$x_{t,m}(\Omega) = \begin{pmatrix} v_{t,m}(\Omega) \\ w_{t,m}(\Omega) \end{pmatrix}$$

and the measured pixel values

$$\hat{x}_{t,m} = \begin{pmatrix} \hat{v}_{t,m} \\ \hat{w}_{t,m} \end{pmatrix}$$

of the $M$ projected sphere midpoints. For all $1 \leq i \leq NM$ the residual function is defined by

$$e(\Omega)_i := \|x_{t,m}(\Omega) - \hat{x}_{t,m}\|^2,$$

$$m = i \mod M,$$

$$t = i \div M = \left\lfloor \frac{i}{M} \right\rfloor$$

The complete median quadratic error $E^2(\Omega) = \frac{1}{NM} \|e(\Omega)\|^2$ is therefor

$$E^2(\Omega) = \frac{1}{NM} \sum_{t \in N} \sum_{m \in M} \|x_{t,m}(\Omega) - \hat{x}_{t,m}\|^2$$

To find the best solution $\hat{\Omega}^*$ we minimize this function

$$\hat{\Omega}^* = \min_{\Omega \in \Omega} \min E^2 = \min_{\Omega \in \Omega} \frac{1}{NM} \sum_{t \in N} \sum_{m \in M} \|x_{t,m}(\Omega) - \hat{x}_{t,m}\|^2$$
Results

We used simulated data to verify the results of our algorithm. Scorpius XLab developed by Fraunhofer EZRT was used as simulation tool. [8] For comparison with existing algorithms, a circular movement was chosen as acquisition geometry. All simulations did not include noise to the image data and the overall error tolerance, i.e. the absolute difference of the results between two subsequent iterations, was set to $10^{-12}$. The optimization used the Levenberg-Marquardt algorithm. [6]

<table>
<thead>
<tr>
<th>Table 1. Simulated system setup</th>
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<td>focus detector distance</td>
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<td>focus object</td>
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<td>detector pixels</td>
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<td>detector slant</td>
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<td>detector shift</td>
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Projections were simulated with a slanted detector-plane (+26.57 degrees) and a shifted detector-midpoint (268.3 mm), see Table 1 for the full geometry description. We used a heavily misaligned system, the shift was about one fourth of the complete detector size and the slant angle was greater than 25 degrees. This was done intentionally to show the capabilities of this approach.

![Figure 4: Corrected reconstruction; shift corrected reconstruction; uncorrected reconstruction](image)

Figure 4 shows three different reconstructions, using all correction values (left), using only the shift correction (center) and using no correction at all (right).

The algorithm was also tested using a typical micro-CT system, the system setup parameters are shown in Table 2. A circular acquisition geometry was used to reconstruct the calibration phantom.

<table>
<thead>
<tr>
<th>Table 2. Real system setup</th>
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Figure 5 shows the reconstruction results without corrections, while we present in Figure 6 reconstruction with corrections. In order to visualize the real cylinder in a better way, the grey values in the image have been inverted. The low absorbing regions (white) close to the heavily absorbing spheres are the real bore holes to fit the spheres.

**Figure 5:** Visualization of reconstructed slices without any correction

**Figure 6:** Visualization of reconstructed slices using the determined correction values

**Summary**

We proposed a new acquisition geometry-independent calibration method for Computed Tomography. The results show the flexibility and reliability of this approach. We have a robust algorithm which even correctly works with heavily misaligned systems. Our approach combines the functionality of various current methods. Since we can handle arbitrary acquisition geometries, one single tool could be sufficient to calibrate different CT systems and it could be used in medical diagnostics as well as in industrial non-destructive testing.
References


