Registration concepts for the just-in-time artefact correction by means of virtual computed tomography

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Abstract
This article deals with the enhancement of accuracy in CT by just-in-time correction of artefacts (beam hardening, scattered radiation) caused by the interaction of X-rays with matter. The so called EAR method needs for simulation a registration of the object. Therefore the article presents two different registration concepts.

Keywords: Computed tomography, beam hardening, artefact correction, registration, simulation

1. Introduction

In non-destructive testing, computed tomography (CT) is increasingly used for dimensional measurement tasks such as the industrial inspection of work pieces. Besides the determination of the measurement uncertainty, the improvement of the image quality is subject of current research, in order to establish CT as a measuring device.

The Iterative Artefact Reduction (IAR) represents a reference-free method which generates a correction line. Nonlinearities are approximated by combining pre- and post-processing image processing steps. This method was already presented in 2003 on the the International Symposium on Computed Tomography and Image Processing for Industrial Radiology [1]. While the IAR uses the uncorrected volume to determine the required path lengths the X-rays propagate in the object, the method that is presented here, uses existing geometric data (CAD, STL) of the object. The path lengths are identified during the data acquisition by means of simulation from the recorded geometric data. Therefore the correction line is already available at the beginning of the reconstruction (just in time).

A sufficient accurateness of the registration proves to be the most difficult part of the method. The spatial position and orientation of the CAD model in the virtual CT has to be aligned with the real object on the rotary disk by translation and rotation. The well-established registration methods require a suitable starting position which is determined in a coarse first registration step. The second step includes the exact registration which is realized by means of a 2D/3D registration algorithm. This step is performed using 2D projection data. Alternatively a multi sensor concept is applied for exact 3D/3D registration. Beside the detector measurements, a scatter plot describes the surface obtained by an optical sensor.
This paper is outlined as follows: The next section describes the principle idea of the Iterative Artefact Reduction and the new method of the just in time correction. Sections 3 and 4 present the two registration concepts, whose results are compared in section 5. At the end of the article we give a short summary.

2. Principles of artefact correction

In computed tomography, artefacts are caused by non-linearities of the acquisition system [2]. An effective and widely-used correction method for such non-linearities in homogeneous objects is based on the linearisation technique.

The idea of the linearisation procedure is to transform a measured polyenergetic projection value to the corresponding monoenergetic ray sum. This method needs the correct path length of an X-ray beam through an object. In practice the correction line is often obtained experimentally from a radiography of homogeneous reference objects. These objects have known path lengths and material characteristics like the observed object. The Iterative Artefact Reduction (IAR) method replaces this time consuming calibration process by determining the required path lengths directly from the reconstructed volume of the object. The IAR method requires the projection (raw) data and currently works only for homogenous specimens. No knowledge of the energy source spectrum or material characteristics is required.

The just in time reduction (EAR) method replaces the tedious image processing steps of the IAR method by determining the required path length directly from nominal data of the object. One advantage of this approach will be the better length data when using the nominal data model (CAD) instead of a uncorrected volume with artefacts. At the end of the data acquisition process, the correction line is available (just in time) for the reconstruction. Therefore the most important advantage is the saving in time. In order to calculate the path lengths a virtual CT-tool is used. Therefore the spatial position of the CAD model in the virtual CT must be aligned with the real object on the rotary disk by translation and rotation. In the following sections two registration concepts are discussed.

3. 2D-3D registration

There can be found several promising 2D-3D registration algorithms. Common to them is the necessity of an initial pose that has to be in the neighbourhood of the optimal pose. Otherwise due to a lot of local extrema in the similarity function, their convergence to the right pose can not be guaranteed [3,4]. In most industrial applications, the initial position of the object on the rotary disc is unknown. The task of a first registration step is to find this initial pose without any further user interaction. Afterwards, a fine registration as mentioned above can be performed.

In this paper another approach is proposed. The transformation is split into rotation and translation and solved separately. The latter can be determined by the intersection of some barycentral lines. These are the lines that connect the source with the barycentre of the detector (see figure 1). In the case of parallel-beam-geometry the barycentre of the model is placed exactly on the lines. If cone-beam-geometry is used, the barycentre is approximately on the lines. As a consequence, several barycentral lines intersect in the barycentre of the model B_S. An angular range of about 120° seems to be enough to determine the translation with a sufficient accuracy. The second part of the coarse registration is the determination of the rotation. If the rotation is expressed by the three Euler angles, three free parameters are left. These parameters are determined by an intensity based empirical approach. For this purpose, the similarities between the reference and simulated images on an equidistant grid of rotations are evaluated. The optimal measure for this task seems to be Normalised Cross Correlation as shown in [5].

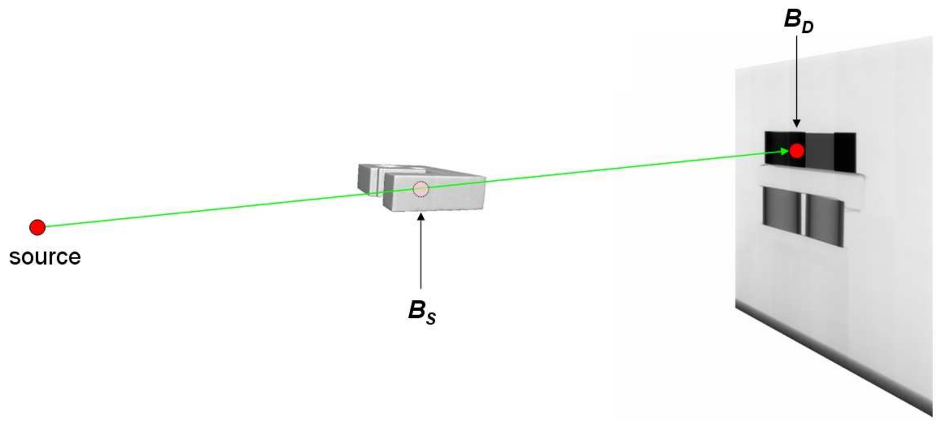


Figure 1. The barycentral line connects the source with the barycentre of the detector B_D. with respect to the measured intensities. The barycentre B_S of the object lies approximately on this line.

The next step is the exact alignment of the specimen. A lot of literature can be found concerning this topic, mostly in medical context. Following the procedure published by Penney [4], the registration algorithm is based on the production of simulated length projections. The wanted pose has a maximal similarity to the reference image. For optimisation tasks, Normalised Mutual Information seems to be the most promising similarity measure, as it exposes good convergence behaviour [4,5]. The numerical optimisation is multiresolutional, i.e. the optimisation starts with a coarse resolution and refines up to the original resolution. By this approach, the computational costs will be reduced a lot.

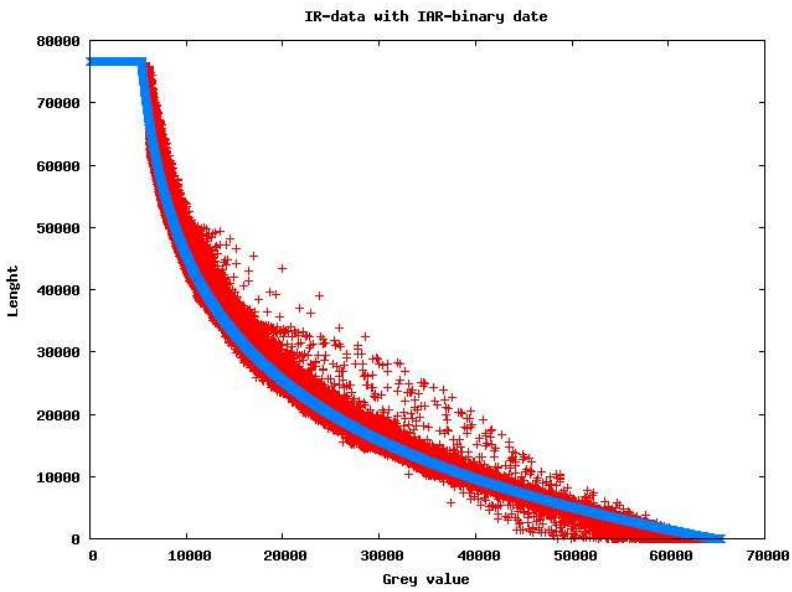


Figure 2. IR-point cloud with path lengths from IAR-binary volume.

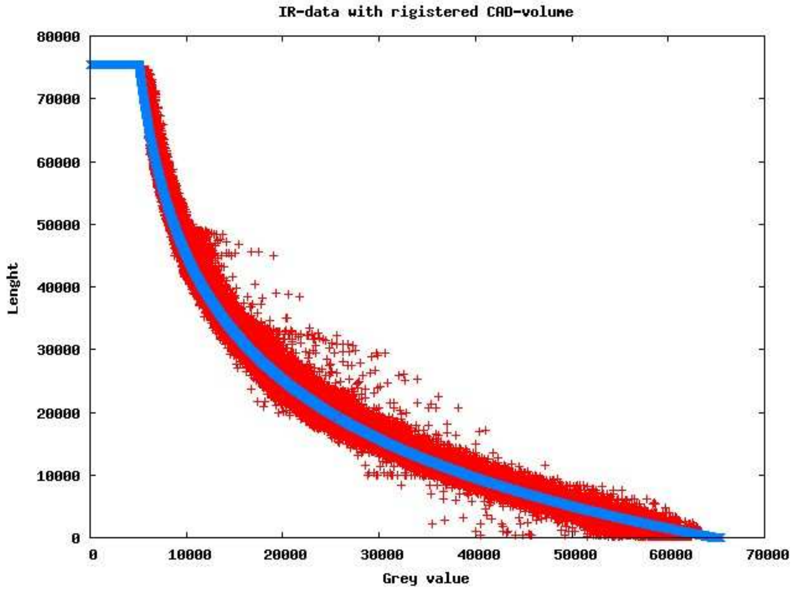


Figure 3. IR-point cloud with path lengths from 2D-3D registered CAD model.

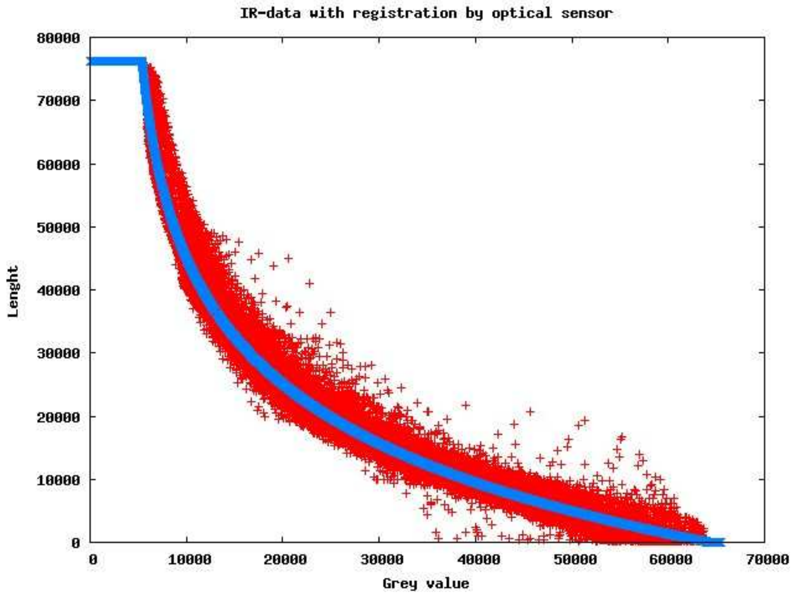
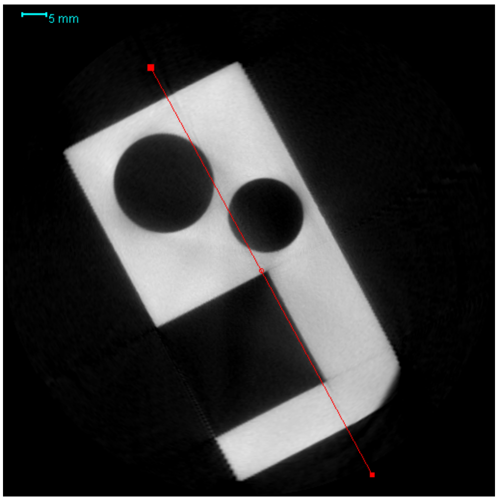


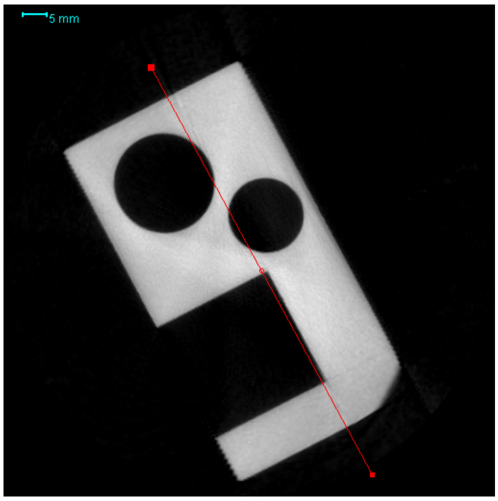
Figure 4. IR-point cloud with path lengths from 3D-3D registered CAD model.

4. 3D-3D registration

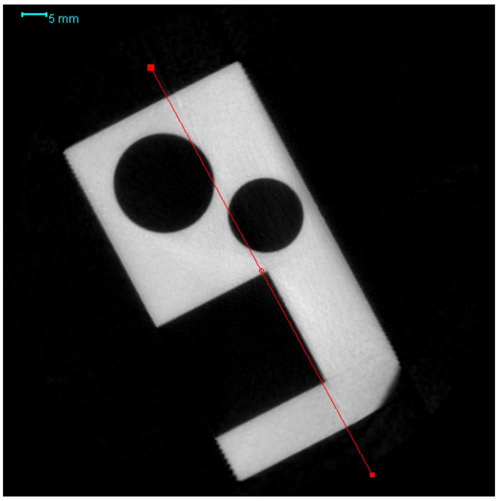
The multisensor Tomolibri combines a high-resolution CT-system with an optical sensor developed by the Fraunhofer IOF. The optical sensor is based on fringe projections and delivers 3D coordinates of the visible surface with an accuracy of less than 10 µm. Within a common research project, the Fraunhofer IPA has developed a feature-based registration algorithm which is able to align the 3D data of the optical sensor with the CAD-model [6]. This is performed by choosing corresponding geometric elements from both data sets manually. Afterwards, a coordinate transformation is calculated to align these elements. Because of dealing with the same dimensionality the problem is less ill posed. Hence it is expected that this approach decreases the registration error.



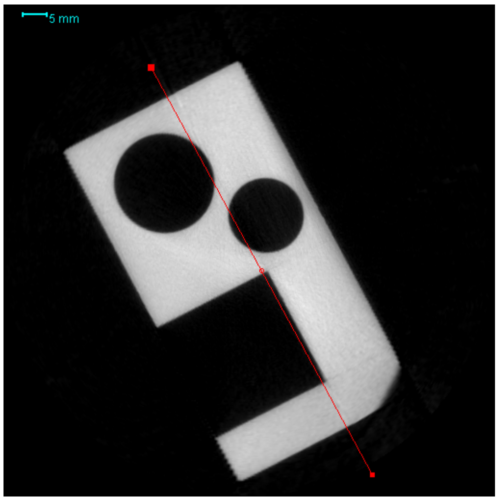
5a. Without correction



5b. With IAR correction



5c. With 2D-3D-EAR correction



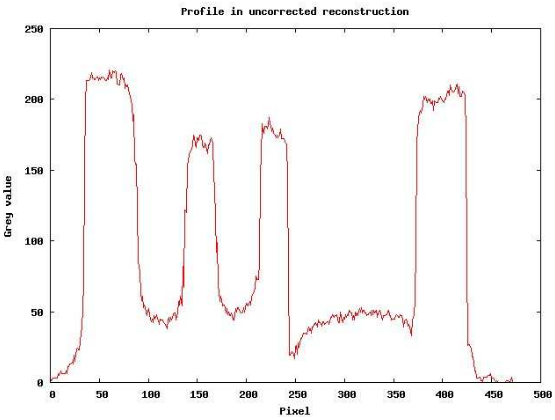
5d. With 3D-3D-EAR correction

Figure 5. Comparison of three different artefact correction methods with an uncorrected slice of a aluminum test phantom (top left). At top right, the traditional Iterative Artefact Reduction (IAR), at bottom left, the proposed corrections with the 2D-3D-EAR respectively the 3D-3D-EAR (bottom right). Figure 6 shows the profiles along the red lines.

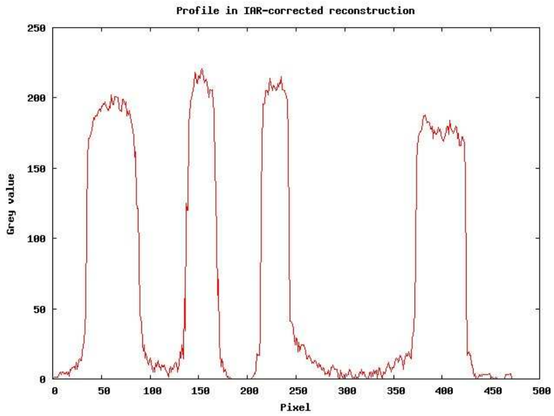
5. Results

Plotting detected intensities *I* against object path lengths *R* yields an *IR*-point cloud. Noise and other effects cause IR-points, whose path length does not match to the corresponding intensity and broaden the point cloud, see figure 2. A registration error broadens the point cloud additionally. Therefore the point cloud is an criterion for the quality of the registration process. The figures 2 – 4 show the point clouds and the fitted correction lines, generated with the IAR respectively with a 2D-3D and 3D-3D registered CAD-model. There is not much of a difference between the three point

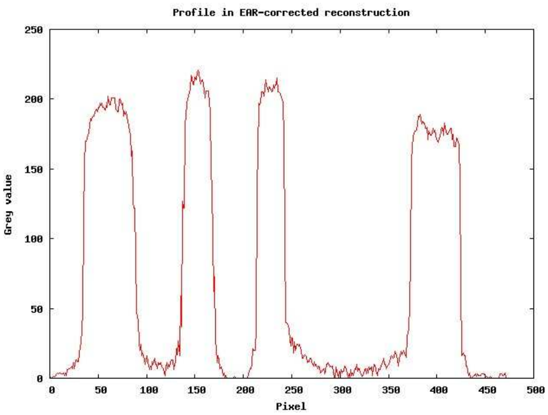
clouds. But in particular there are no accumulations of outliers. This indicates that in both registration concepts the registration error is smaller.
Figure 5 compares the results of the correction methods. The just in time corrected reconstructions are nearly the same as the more time consuming IAR corrected volume independent from the used registration concept. This fact is even more visible in the line profiles in figure 6.



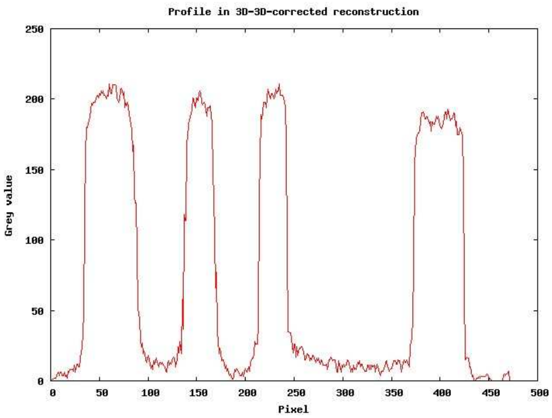
6a. Without correction



6b. With IAR correction



6c. With 2D-3D-EAR correction



6d. With 3D-3D-EAR correction

Figure 6. Profiles along the red lines in the cross sections of figure 5. The difference between the corrected profiles is negligible.

6. Conclusions

This paper introduces a further development of the Iterative Artefact Reduction (IAR) method. The just in time artefact reduction method (EAR) applies a priori knowledge of the object in order to accelerate the calculation of the correction line. The EAR-method needs a registration of the object. Therefore two registration concepts have been successful proved.

Acknowledgements

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