Fast Estimation of Optimal Specimen Placements in 3D X-ray Computed Tomography

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Abstract. 3D X-ray computed tomography (3DXCT) is increasingly used in industry as a method for quality control and nondestructive testing. More recently a further demanding application area was found in metrology. All these application areas share the need, that the highest possible accuracy and precision is required from every scanning result. In this context, the issue of errors and distortions introduced by artefacts is critical. Picking the optimal placement of a specimen on the rotary plate leads to a reduction of artefacts and an improvement of the overall quality in the resulting dataset. However, finding optimal and stable placements of complex specimens is tedious, time-consuming and therefore expensive.

In this work a tool for 3DXCT systems was developed, which estimates the optimal placement of a specimen using its 3D geometrical model prior to a real scan. This geometrical model is usually available either as a CAD model or obtained from a reference scan of a different modality. The proposed method allows the determination of potentially good or bad placements of the specimen on the rotary plate as well as the identification of regions of the specimen, where most of the artefacts are likely to appear. A specimen's placement is defined by its orientation on the rotary plate. Besides the penetration lengths of the X-rays through the specimen also the placement stability and the corresponding Radon space representation are considered in the analysis. The GPU-based ray casting is used to simulate the scanning procedure and to calculate the penetration lengths of the rays.

The Radon space analysis facilitates the identification of critical faces, which will be inaccurately represented in the XCT reconstruction data. In order to estimate the amount of data lost in Radon space every triangle of the 3D geometrical model is investigated. Additionally, a feature-selection functionality is provided, in order to constrain the analysis on critical features or areas of interest. The results are visually represented in 3D views, in order to depict areas, which are estimated to suffer the most from artefacts. Additionally results are visually presented by linked views, allowing visual analysis, comparison and exploration. A stability widget depicts the robustness of the placement with respect to parameter variations.

The results of applying the tool on a complex real world component are demonstrated in detail. The calculated optimal placement is tested versus the initial placement of the specimen. All evaluations are performed using commercially available software tools. In order to verify the optimality of the found placement, initial and optimal placements are tested using variance comparisons.

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1. Introduction and Motivation

3D X-ray computed tomography (3DXCT) is a powerful imaging technique to generate volumetric representations from a series of 2D X-ray penetration images. 3DXCT shows its main advantage in a comprehensive nondestructive characterization of specimens regarding internal and external structure as well as material characterization. Besides being increasingly employed in industry for nondestructive testing and quality control, a new and challenging field of 3DXCT is metrology, which has to fulfill the demands of today's standards in industrial quality control. Compared to conventional metrology, 3DXCT is still the only method to facilitate dimensional measurements also of the internal structure and of inaccessible parts of a component.

However, one of the most critical issues in the context of 3DXCT is the issue of artefacts [4], [5], artificial structures in the resulting dataset, which do not correspond to real structures of the specimen. Especially in the area of metrology, artefacts may hinder or even prevent reliable measurements. A reason for artefacts is found in the beam hardening effect. Beam hardening arises due to the fact, that the correlation between attenuation and penetration length is nonlinear in case of the polychromatic X-ray radiation sources as used in 3DXCT. Because of this nonlinearity, the higher energy parts of the spectrum tend to pass through matter while lower energy parts are absorbed. So the spectrum gets modified and contains mainly the higher energy portions: the X-ray spectrum gets hardened. Beam-hardening causes two types of artefacts we would like to address in this publication: cupping artefacts and bright or dark bands or streaks between dense objects in the image [2] (see Figure 1). The characteristics and strength of these artefact types are determined by the scanning parameters, geometry, material composition and placement of the specimen.

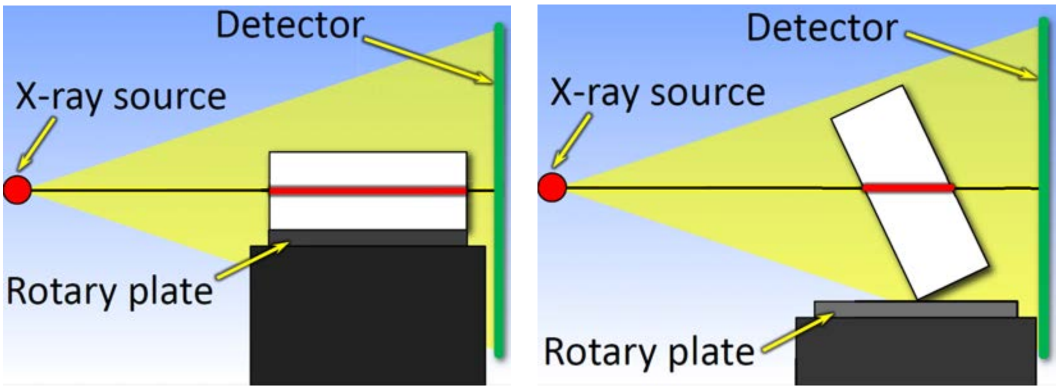

Figure 1. Demonstration of a good and a bad placement. The left placement shows high penetration lengths and faces parallel to the central beam, which are prone to generate severe artefacts. The enhanced placement allows reducing these artefacts to a minimum (right image) for improved scan quality.

In this work the main focus is put on a method to determine the optimal specimen orientation on the rotary table, in order to reduce artefacts before they arise [1]. To reach this goal the following aspects having a major influence on the reconstructed result were considered as basis for the developed algorithm:

1) Short penetration lengths through the specimen
2) Underrepresented surface data during scanning
3) Penetration lengths and lost surface data parameters have to be stable within a certain range (usually about 5 degrees)

The three presented analysis methods as well as the complete workflow are demonstrated using real world data and evaluated using commercial software tools. The performance of the method is indicated for the not optimized system implementation.

2. The Dreamcaster – A tool for fast estimation of optimal specimen placements in 3DXCT

To find an appropriate placement of a specimen for a 3DXCT scan is a tedious process requiring funded knowledge and long term experience of the operators. In case of elevated specimen complexity, finding the optimal placement is getting increasingly difficult and often impossible, even for domain specialists. However, the optimal specimen placement allows to constrain the amount of artefacts to a minimum and therefore to improve the overall scanning results for further data processing, e.g. for metrology applications.

To address the above mentioned issues, a visual analysis tool was developed in this work (see Figure 2). The Dreamcaster tool estimates the optimal orientation of a specimen on the rotary plate using the corresponding triangulated 3D geometrical model as input. The Dreamcaster tool was designed to provide a fast, simulation-based preview of an XCT-scan and to estimate the quality of the scan data at a certain specimen placement, employing general purpose GPU programming for acceleration of the computations. It includes a penetration length analysis, an evaluation of the placement stability and an investigation in Radon space. Using these analysis modes, the presented tool determines potentially suitable placements of a specimen. Furthermore it enables the domain experts to study the correspondence of the penetration lengths and the Radon space representation regarding artefacts and the scan quality. Each of the presented parameters is visualized in an individual placement map in an individual view. Using interactive linked views the different parameters are connected to find the overall optimum placement of the specimen (see Figure 6). In addition to these features the Dreamcaster tool identifies regions of the considered specimen, which are prone to cause the major portion of artefacts. Using marker widgets the analysis may be focused of specific features and areas of interest. Finally a stability widget was implemented, which allows to determine the robustness of a considered placement regarding slight positional changes.

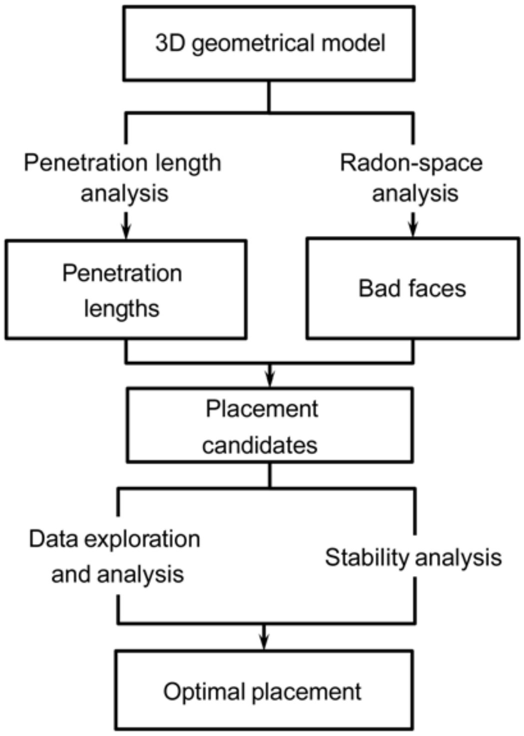

Figure 2. The Dreamcaster workflow. Using the 3D geometrical model of the specimen, the penetration length analysis and the Radon-space analysis are performed for each placement. Then placements with optimal parameters are evaluated regarding their quality using visual analysis. Additionally, the stability of the placements is evaluated using the stability widget.

1.1 Penetration length analysis:

The penetration-length analysis answers two important questions regarding the overall optimality of a placement (Figure 3): What is the maximal penetration length and what is the average penetration length? High penetration lengths are prone to cause beam-hardening artefacts. Therefore these parameters are very important to minimize. In this approach, maximum and average penetration length are calculated using ray casting for the characterization of a placement considering not only a single projection but a full scan.

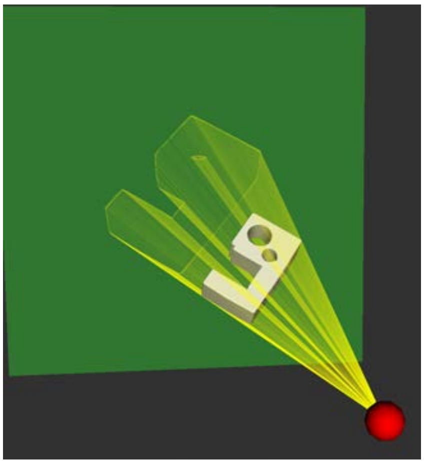

Figure 3. Visualization of penetration length analysis. Rays are indicated as semi-transparent yellow lines. The green plane represents the detector. The red sphere is the X-ray source.

1.2 Radon space analysis:

The 3D cone-beam scanning is an approximation of a sampling process, which samples the set of plane integrals from the 3D function representing the density distribution of the scanned object. In mathematics it is known as the Radon transform [7]. The Radon transform maps the density distribution function from 3D spatial domain to the 3D Radon space. Every point in this 3D Radon space is the plane integral of the function in 3D space. Reconstruction algorithms as the filtered back projection by Feldkamp et al. [3] approximate the inversion of the Radon transform, which maps the supporting plane of every face of a specimen in the spatial domain to a point in Radon space [7]. For a single projection in circular cone-beam scanning geometry, the Radon space representation yields the surface of a sphere, whose diameter is equal to the distance from the X-ray source to the rotation center. A full 360° scan yields a torus in Radon space, because as the rotary plate turns, the sphere in Radon space is rotated as well. The higher the number of projections, the better the Radon transform is sampled inside the torus.

However, the part of information in Radon space, which is not represented inside the torus, forms a shadow zone, in which the Tuy-Smith's sufficiency condition [9], [10] for a complete reconstruction does not hold. All faces perpendicular to the rotation axis (except those in the midplane) and all faces whose supporting planes do not intersect the circular trajectory of the source are in this shadow zone (Figure 4). In this respect these faces will cause back projection artefacts.

In the presented Radon-space analysis the faces of the specimen's triangular model are considered. For each face in the triangular model the corresponding Radon space representation of the face's supporting plane is calculated. The analysis aims at minimizing the surface area of the faces, whose representation is lying outside the torus in Radon space

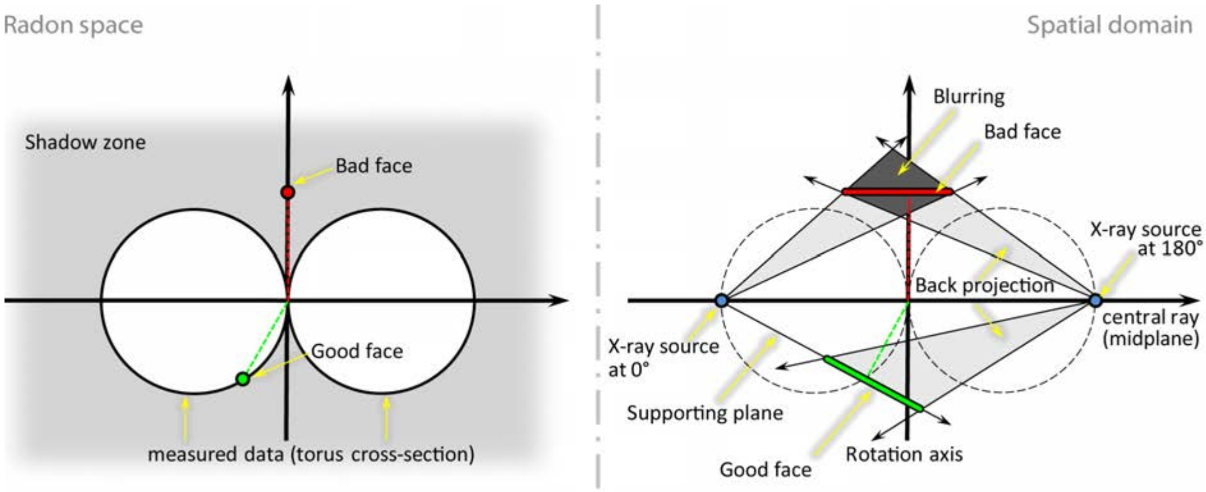

Figure 4. Radon space analysis. Examples of good and bad faces (red) are demonstrated in the cross-section of the Radon space (left) and the spatial domain (right). White circles in the Radon space correspond to the cross-section of the torus in Radon space of a full scan. The shadow zone is depicted in grey.

formed by a full scan. The placement with the minimal surface area of insufficiently represented faces is considered to be optimal. In the demonstration system these faces are marked in red.

1.3 Placement stability:

As for manual placements a typical placement error of 1-5 degrees may occur, the results of the penetration-length analysis and the Radon-space analysis should remain stable within this range. So the stability of a placement is evaluated in a custom stability widget, which allows a distinction between improvement and deterioration of the parameters along predefined directions, showing the direction in which parameters vary most (Figure 5). In each cell of the widget the considered parameter (e.g., maximum penetration length) is visualized. The axes correspond to the Euler angles α and β, which determine the placement of the specimen. α is defined as the angle between rotary plate and the Z axis of the specimen's coordinate system, β defines the rotation about the specimen's Z axis. The central cell represents the currently considered placement. Neighboring cells are obtained by stepwise changing the Euler angles. Using color coding the deviations for the selected parameter are shown: green corresponds to better placements, red to worse placements. The arrow tips indicate by grey level coding how strong a parameter changes in this direction.

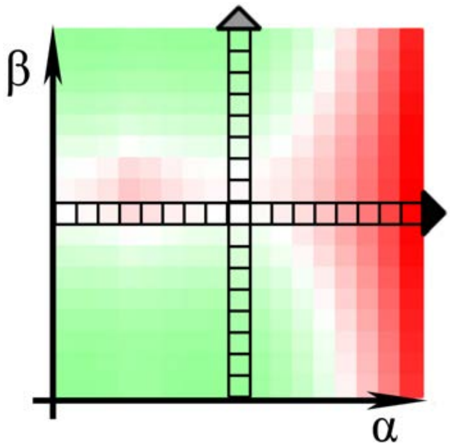

Figure 5. Stability widget. Central cell indicates the currently considered placement; for neighboring cells the placements are obtained by stepwise changing the Euler angles. Green indicates better placements, red worse placements. Arrow tips indicate the strength of a parameter change in this direction.

3. Implementation and Performance

The demonstration system of the Dreamcaster tool was implemented in Visual C++ using the visualization toolkit VTK [8] for visualization tasks and the CUDA toolkit [6] for acceleration of computations.

Depending on the surface model used the main performance limiting aspect is the ray casting step, which cannot be improved by conventional methods, e.g. early ray termination. Typical computation times are dependent on the number of placements to be evaluated and the number of projections to be evaluated per placement. In order to calculate the parameters average penetration length, maximal penetration length and underrepresented faces area percentage in Radon space, the calculation times are ranging between 2 seconds (12 triangles, 256*256 pixel per projection image, 1000 projections) and 70 seconds (200k triangles 256*256 pixel per projection image, 1000 projections) per placement on recent hardware (Nvidia Geforce 200 series, Intel Core i7). The demonstration system is not yet considered as optimized. However evaluations of a specimen placement may be achieved right before a scan in reasonable time.

4. Results and Evaluation

In order to identify the optimal placement of a specimen, either individual regions of interest are defined to focus the evaluation on or the evaluation is applied on the complete specimen.

The evaluation starts with the penetration-length analysis and the Radon-space analysis performed on a set of placements specified by the user. If any regions of interest are specified, the penetration-length analysis will consider only rays intersecting at least one of these regions. Similarly, the Radon-space analysis will consider only those triangles of the 3D geometrical model, which at are least partially inside one of the specified regions of interest. Increasing the amount of evaluated placements allows a refinement of the optimal placements. Typically 50 placements in each direction provide reliable results even for specimens with higher complexity. The system suggests possible placement candidates for the user to further consider by weighting the individual parameters according to the user's presets. Using the stability widget and the linked views functionality of the tool the users may pick the optimal and most stable placement for the subsequent real world 3DXCT scan.

Regarding the optimal placement it is recommended to pick a placement with the shortest possible values of the maximal and average penetration lengths. Consequently, the

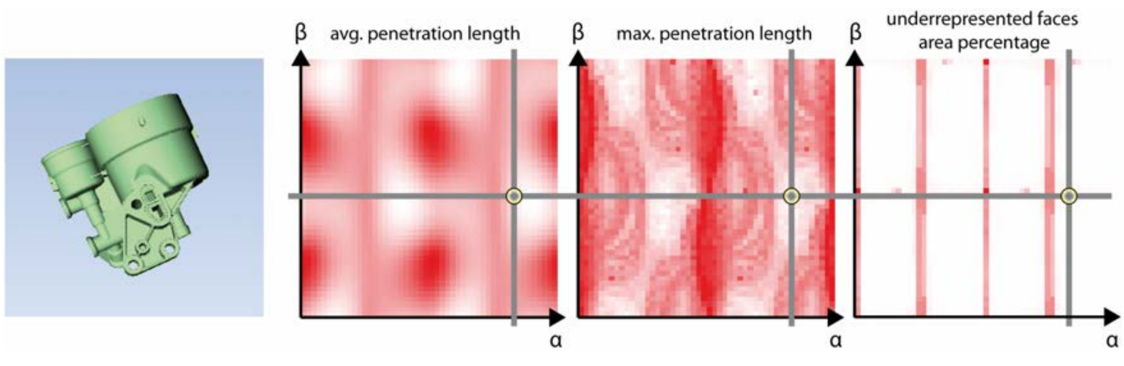

Figure 6. Linked view concept for placement maps. Each placement map (average penetration length, maximal penetration length and underrepresented faces area percentage) consists of 50*50 placements, achieved by stepwise changing the Euler angles α and β. The deviations between the placements are color-coded from white to red. White indicates no deviation, red high deviation. The grey cross hairs indicate the considered placement in each view. The optimal placement is found in areas with low deviations in all three placement maps.

surface area of the underrepresented faces has to be minimized. The optimal placement should remain stable at least within 1-5 degrees to avoid irregularities due to slight placement errors.

The proposed method was applied on an oil filter housing. This specimen is a complex, irregularly-shaped component with a high number of features of interest for dimensional measurement. The placement maps were calculated for 50*50 placements and 90 projections per placement. The results of this evaluation are seen in Figure 6. Red areas indicate high maximum and average penetration lengths. For the Radon space analysis red indicates a large percentage of underrepresented faces area in the considered surface model. The grey cross hairs in the linked views of placement maps indicate the considered placement in each map. The marked optimal placement is most stable regarding modifications of the Euler angle β, in which angular modifications of up to +/- 30° show a marginal influence on the results. Also in α modifications of up to +/- 10° only influence the scan result in a minor way. In this respect the optimal placement of the specimen is found.

In order to verify the optimality of the extracted placement, each placement is tested using variance comparisons of real XCT scans. The CAD model was used as reference for the extracted surface models to test. All surface models were extracted using the advanced surface determination tool of VGStudioMax. All variance comparisons were performed using Geomagic Qualify and best fit as alignment method. The results of this evaluation are depicted in Figure 7. Green areas indicate low deviations from the test model to the reference model, red areas strong positive and blue strong negative. In the grey areas no reliable variance comparison data could be extracted by Geomagic Qualify. These test points are considered to be out of range. In both evaluations corresponding critical areas are marked by black arrows. These test points are considered to be out of range. In both evaluations corresponding critical areas are marked by black arrows. These arrows further indicate those areas, in which the most improvements were achieved by using the optimal placement calculated in the tool.

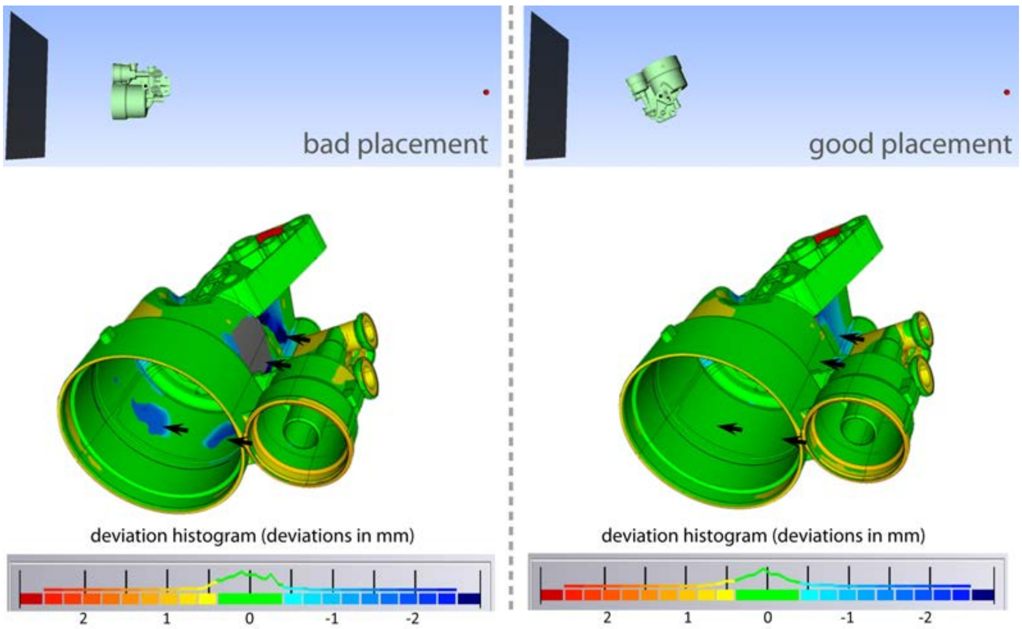

Figure 7. Variance comparisons, CADs vs. surface models of XCT data for bad placement and optimal placement as calculated by the Dreamcaster tool. The considered placements are indicated in the overview images above the variance comparisons (red dot: source, black plane: detector). Black arrows indicate the critical areas in the bad placement.

5. Conclusions and future work

In this work a visual analysis tool for evaluation of specimen placements was introduced. The presented approach uses the 3D geometrical model of a specimen as basis for all further calculations. Based on the geometry information a penetration-length calculation and a Radon-space analysis are performed. Furthermore using a novel widget the stability of a placement may be evaluated. The achieved results applying the tool on real world data is demonstrated on a complex oil filter housing. The combination and weighting of all evaluated parameters allows to clearly identify an optimal position even for a complex component.

For future work, the position of the specimen on the rotary plate could be considered in addition to the orientation. However, integrating this feature would strongly increase the computational complexity and was therefore neglected in this approach. Furthermore an automation of parameter weighting and additional discriminative parameters for the optimal placement could be envisaged.

6. Acknowledgements

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References

[1] Artem Amirkhanov, Christoph Heinzl, Michael Reiter, Meister Eduard Gröller, Visual Optimality and Stability Analysis of 3DCT Scan Positions, IEEE Transactions on Visualization and Computer Graphics, 16(6):Page 1477 -1487, October 2010.

[2] J. F. Barrett and K. Nicholas. Artifacts in CT: Recognition and avoidance. Radiographics ISSN 0271 5333, vol. 24(6):1679–91, 11 2004.

[3] L. A. Feldkamp, L. C. Davis, J. W. Kress. Practical cone-beam algorithm. J. Opt. Soc. Am. A, 1(6):612 619, June 1984.

[4] J. Hsieh. Computed Tomography: Principles, Design, Artifacts and Recent Advances. SPIE Press, 2 2003.

[5] S. Kasperl. Qualitätsverbesserungen durch referenzfreie Artefaktreduzierung und Oberflächennormierung in der industriellen 3DComputertomographie. PhD thesis, Technische Fakultät der Universität Erlangen Nürnberg, 2005.

[6] NVIDIA. CUDA Programming Guide 2.3, 2009.

[7] J. Radon. Üeber die Bestimmng von Funktionen durch Ihre Integralwerte längs gewisser Mannigfaltigkeiten. Berichte über die Verhandlungen der Sächsische Akademie der Wissenschaften, 1917.

[8] W. Schroeder, K. Martin, B. Lorensen, The Visualization Toolkit, Third Edition. Kitware Inc., 2007.

[9] B. D. Smith. Image reconstruction from cone-beam projections: necessary and sufficient conditions and reconstruction methods. IEEE Trans Med Imaging, 4(1):14–25, 1985.

[10] H. K. Tuy. An Inversion Formula for Cone-Beam Reconstruction. SIAM Journal on Applied Mathematics, 43(3):546–552, 1983.