Reducing Computed Tomography Reconstruction and Beam Hardening Artifacts by Data Fusion

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Abstract
Reconstruction and beam hardening artifacts can limit the quality of computed tomography (CT) data sets and cause problems for later steps which process these data sets. This paper presents an approach to combine additional X-ray images during CT reconstruction in order to reduce artifacts and to improve the accuracy of data extracted from the CT in subsequent processing steps. In order to achieve this, a modified version of filtered back projection is used. However, this technique can also be applied to other reconstruction algorithms like the maximum likelihood expectation maximization (MLEM). This approach has been investigated with both synthetic voxel data and physical X-ray computed tomography data.

Keywords: CT, artifact reduction, data fusion, multi-angle radiography

1. Introduction

The evaluation of computed tomography (CT) data sets for technical objects is significantly influenced by metal artifacts, which cause streaks in the reconstructed data sets and distort structures in the vicinity of metallic objects [1]. Artifacts introduced by beam hardening and reconstruction algorithm are the most common and significant ones however, physical effects like scattered radiation, Poisson noise, motion, projection noise, photon starvation and edge effects also contribute to their generation [2]. Since these artifacts generally result in a loss of information, a variety of algorithms have been developed for their reduction.

The algorithms known from literature can be distinguished into two categories [3], iterative reconstruction methods [4–6] and projection completion methods [7–9]. In general, iterative reconstruction methods offer a higher image quality than projection completion methods [1] but they are computation intensive. This is due to the fact that the correction of metal affected parts is done by repetitive forward- and back-projections until the artifacts are reduced significantly. On the other hand, projection completion methods require only certain defined number of forward- and back-projections per correction and therefore the computational effort required by them is substantially less. However, the disadvantage of projection completion methods is that only non-metallic objects are corrected. The contours of metallic objects are assumed to be correct and therefore not considered by the method for artifact reduction.

Recently a new approach for the reduction of metal artifacts was presented in [10], which is based on a comparison of reconstructed and tilted CT data sets. For comparison, the reconstructed data sets in different orientations were rotated to be aligned to each other and the intensity values of corresponding grid cells were averaged. This led to a reduction of streaking artifacts, that have a unique direction. In this paper, we present a different way for the reconstruction of X-ray computed tomography data sets obtained at different orientations. During reconstruction, the object is back-projected into a grid. Rather than rotating reconstructed objects in different orientation for alignment, the grid is rotated corresponding to the object orientation before reconstruction. An advantage of the proposed way of handling the different orientations for the fused voxel data set as part of the method is, that the reconstructed object from both scans orientations are inherently aligned due to an initial appropriate rotation of the grid before...
reconstruction of the object. This makes the data fusion step simple, free from alignment of the object and reduces the number of interpolation steps from two to one. As the interpolation steps, in general, are sources of quality degradation of voxel data sets and add to the computation time, the proposed method not only improves the quality of the reconstructed data but also reduces computation time.

The paper is organized as follows. Section 2 outlines the steps involved in artifact reduction by data fusion, explaining the orientations in which the object are scanned, the reconstruction method used and the fusion of data from multiple scans. In Section 3, the method is investigated experimentally with both synthetic voxel data as well as physical X-ray computed tomography data and the results of artifact reduction are discussed. Finally, the paper is concluded in Section 4.

2. Artifact Reduction by Data Fusion

The object to be examined is scanned twice in the CT scanner at two orthogonal orientations. The projection data from both the scans are reconstructed with the filtered back-projection algorithm. However, in the second case, the reconstruction is done in such a manner that the 3D reconstructed object model has the same orientation as that of the 3D reconstructed object model from the first scan. In the final stage, the data from both reconstructed 3D models is fused selectively in order to reduce artifacts.

2.1 Two scans in Orthogonal Orientation

The orientation of a 3D object, in this method, is represented using quaternions which, as compared to Euler angles, are much simpler to handle and prevent the possibility of gimbal lock [11]. A quaternion \( q \) encodes the object orientation into four numbers \((a, b, c, d)\) out of which \(a\) is the real part and \((b, c, d)\) are the imaginary parts. It is given by:

\[
q = a + ib + jc + kd
\]  
(1)

where,

\[
i^2 = j^2 = k^2 = ijk = -1.
\]  
(2)

A conversion from axis angle representation comprising of an axis vector \((ax + by + cz)\) and angle \(\theta\) into quaternion representation is done as follows:

\[
q = \cos \left(\frac{\theta}{2}\right) + ia \sin \left(\frac{\theta}{2}\right) + jb \sin \left(\frac{\theta}{2}\right) + kc \sin \left(\frac{\theta}{2}\right).
\]  
(3)

The base orientation of an object representing no rotation is given by the quaternion \(q = 1\). In this paper two orthogonal orientations are used, i.e. one orientation with no rotation \(q_1 = 1\) and one orientation in which the object is rotated along the z-axis \((0, 0, 1)\) by 90°. This orientation is represented by the quaternion:

\[
q_2 = \cos(45^\circ) + k \sin(45^\circ) = \frac{1}{\sqrt{2}} + k \frac{1}{\sqrt{2}}.
\]  
(4)

CT scans of the object \(O\) are performed in these two orthogonal orientations \(q_1\) and \(q_2\), as shown in Fig. 1 and two sets of projection images are obtained \(P(O_{q_1})\) and \(P(O_{q_2})\). The corresponding projection images are associated with the quaternion data about the orientation in which the object was scanned. This is used in the reconstruction step in Section 2.2.
Figure 1: Two CT scans with object orientation $q_1$ (left image) and $q_2$ (right image).

2.2 Reconstruction Method

The Projection sets $P(O_{q_1})$ and $P(O_{q_2})$ are reconstructed with a modified version of filtered back-projection presented by Feldkamp et al. [12]. The modification is that the grid into which the object is reconstructed, is rotated according to the object orientation before the back-projection is done.

For the projection set $P(O_{q_1})$, the grid into which filtered back-projection is done is not rotated and is represented by the base grid $G_1$. For the projection set $P(O_{q_2})$ the grid is rotated before performing the filtered back-projection equivalent to the orientation of $q_2$. A rotation ($q$) of $G_1$ into a new grid system can simply be done by pre-multiplication of any coordinate of the grid with the rotation quaternion($q$) and post-multiplication with the conjugate of the same quaternion ($q^*$):

$$G_2(0, x_2, y_2, z_2) = q_2 \times G_1(0, x_1, y_1, z_1) \times q_2^*.$$  \hspace{1cm} (5)

The first set of projection data is reconstructed into grid $G_1$ to have the 3D voxel set $vol_1$ and the second set of projection data is reconstructed into the rotated grid $G_2$ to have the 3D voxel set $vol_2$:

$$vol_1 = R_{G_1} \{ P(O_{q_1}) \}$$ \hspace{1cm} (6)

$$vol_2 = R_{G_2} \{ P(O_{q_2}) \}$$ \hspace{1cm} (7)

where $R_{G_x}$ represents the reconstruction step into grid $x$.

The novel property of this method is that the two resultant volumes $vol_1$ and $vol_2$ are inherently aligned and the only difference between the values of each corresponding voxel in the two volumes are artifacts. This is the primary difference from the method published in [10] which presents a similar approach for metal artifact reduction but the main difference from our approach is the number of interpolation steps involved. Each interpolation step adds error to the actual intensity of the voxel data set. In the method presented in [10], CT scans of an object are done in different orientations and reconstructed back by filtered back-projection, which involves an interpolation step, and then the reconstructed models are rotated back to a common grid to be aligned which adds another interpolation step. In our method the grid is rotated before the reconstruction and the output volumes are inherently aligned to each other. Thus, only one interpolation step is involved concerning the filtered back-projection step.
2.3 Data Fusion

The $vol_1$ and $vol_2$ reconstructed in the previous section are inherently aligned i.e. the voxel data in both the volume corresponding to some $(x, y, z)$ will represent the same area of the object. Any difference between corresponding voxel data in both the volume sets are artifacts. Thus,

$$vol_1(x, y, z) \approx vol_2(x, y, z)$$  \hspace{1cm} (8)

and

$$vol_1(x, y, z) - vol_2(x, y, z) = \Delta vol.$$ \hspace{1cm} (9)

where, $\Delta vol$ represents the artifacts. The metal artifact streaks in both the reconstructed volume set $vol_1$ and $vol_2$ are not at similar positions because of the different orientations in which the objects were scanned. The orthogonal orientation chosen in our method minimizes the possibility of overlapping metal artifact streaks from the same object in $vol_1$ and $vol_2$.

Depending on whether the artifacts streaks are of high or low intensities a simple minimum or maximum algorithm is chosen for fusion respectively. Therefore, each voxel in the fused volume $vol_f$ gets the minimum or maximum intensity among the two corresponding voxel from $vol_1$ and $vol_2$ subject to which kind of artifacts are present. For bright streak artifacts:

$$vol_f(x, y, z) = \min \{vol_1(x, y, z), vol_2(x, y, z)\}.$$ \hspace{1cm} (10)

and for dark streak artifacts:

$$vol_f(x, y, z) = \max \{vol_1(x, y, z), vol_2(x, y, z)\}.$$ \hspace{1cm} (11)

3. Experimental Results

For evaluation of the method presented in the previous section a 2.5 cm $\times$ 2.5 cm printed circuit board (PCB) is used as a test structure (Fig. 2). The PCB used is a multi-layered board with 6 metal layers. Conventional 3D reconstructed data sets from CT scan of such PCB generally have a lot of streak like artifacts due to the long metal tracks and vias which hinders the accurate detection of the track dimensions or faults present. Therefore, it was considered to be a suitable test structure for evaluation of artifact reduction techniques. The method has been investigated with both synthetic CT data and physical X-ray computed tomography data.

![Figure 2: PCB used as the test structure for verifying the artifact reduction technique.](image-url)
3.1 Experimental Results based on Synthetic Data

Initial verification of this method was done with the synthetic 3D data of the PCB. The software used was programmed with reconstruction tool kit (RTK) [13] commonly used in the CT domain. The synthetic 3D data of the PCB were extracted from the gerber files used to manufacture the PCB and converted into suitable format for processing by the software. The grid coordinates were chosen in such a way that the PCB was parallel to the Z-plane of the grid. This synthetic object data set is referred to as $O^s$.

First a forward projection was done on the synthetic data set with quaternion orientation $q_1 = 1$ (i.e. no rotation) to get the projection images $P(O^s_{q_1})$, these were then reconstructed into an base grid $G_1$ by filtered back-projection to have a volume $vol_1^s$. A slice along the Z-plane of $vol_1^s$ is shown in left part of Fig. 3. It can be observed that the artifacts of the metal tracks in the PCB are in horizontal direction. In the next step $O^s$ is rotated along Z-axis by $90^\circ$, represented by quaternion $q_2$ given in Equation 4, to get $O^s_{q_2}$. A second forward projection was done on $O^s_{q_2}$ to get $P(O^s_{q_2})$. Before reconstruction of this projection images, the grid $G_2$ into which the back-

![Figure 3: Horizontal artifacts (left image) and vertical artifacts (right image) of metal structures in synthetic 3D data scanned in two orthogonal orientations.](image)

![Figure 4: Reduced artifacts after data fusion with synthetic data set.](image)
projection is done, is constructed by rotating $G_1$ by $q_2$ using Equation 5. Due to this rotation, the reconstructed volume $vol^*_2$ is inherently aligned with $vol^*_1$. A slice along the Z-plane of $vol^*_2$ is shown in right part of Fig. 3. However, in $vol^*_2$ the position and direction in which the artifact streaks appears are completely different. They are in vertical direction in $vol^*_2$ as opposed to horizontal direction in $vol^*_1$. Since the artifacts are in form of bright streaks, the volumes $vol^*_1$ and $vol^*_2$ are then fused with the minima algorithm as explained in Equation 10. A slice along the Z-plane of the resultant volume $vol^*_f$ is shown in Fig. 4. It is observed that the artifacts in the $vol^*_f$ are significantly reduced as compared to $vol^*_1$ or $vol^*_2$.

3.2 Experimental Results based on Physical X-ray Images

The method was also investigated with raw data from X-ray CT. The 6-layered PCB was scanned in two orthogonal orientation with X-ray generated from tube voltage of 185 kV and tube current of 200 mA. The projection image resolution was $992 \times 992$ with the magnification factor of 10.9467. For both the scans the projections were taken from 800 angles and the resultant voxel size is $35 \mu m \times 35 \mu m \times 35 \mu m$.

In the first scan the PCB was placed in the CT scanner in such a way that it was parallel to the flat panel detector, representing the orientation $q_1$ in Section 2.2 and projections were captured to get $P(O_{q_1})$. In the second scan the PCB was rotated 90° along the axis perpendicular to the flat panel detector and containing the X-ray source, representing the orientation $q_2$ in Equation 4. The projection set obtained refers to $P(O_{q_2})$. $P(O_{q_1})$ was reconstructed with filtered back-projection with base grid $G_1$ to obtain $vol_1$ while $P(O_{q_2})$ was reconstructed with filtered back-projection with rotated grid $G_2$ obtained by rotating $G_1$ by $q_2$ to get $vol_2$. Corresponding slices along the Z-plane of both $vol_1$ and $vol_2$ are shown in Fig. 5. It can be seen that they represent the same layer in the PCB and hence $vol_1$ and $vol_2$ are inherently aligned. Comparable to the synthetic data presented in Fig. 3, the position and direction of the streak artifacts in Fig. 5 do not overlap due to the orthogonal orientation in which the PCB was scanned. Since the artifacts are darker streaks, both the volumes $vol_1$ and $vol_2$ are fused with a maxima algorithm as explained in Equation 11, and a slice along the Z-plane of the fused volume $vol_f$ is shown in Fig. 6.

![Figure 5: Horizontal artifacts (left image) and vertical artifacts (right image) of metal structures in reconstructed data from physical X-ray CT scans.](image-url)
can be observed that the artifacts are significantly reduced in $\text{vol}_f$. There are minor areas in $\text{vol}_f$ where the artifacts are still present (middle left and middle top region of Fig. 6). These are due to the practical limitation of manually rotating the PCB in the CT scanner exactly by 90° in the second scan. However, this practical limitation does not hinder the scope of this method as long as the exact orientation after rotation is known. In this paper the exact orientation $q_2$ of the second scan was adjusted manually by visual inspection of reconstructed value so that $\text{vol}_1$ and $\text{vol}_2$ are aligned as accurately as possible. There are also correlation-based techniques [14] which can be used for the automatic calculation of rotation of an object.

4. Conclusion

In this paper, an artifact reduction technique for computed tomography by fusion of data from two CT scans of an object in orthogonal orientations has been presented. The method is based on the fact that the direction and position of the streak artifacts are correlated to the rotation axis of the associated computed tomography scan. Thus two or more computed tomography scans of an object with different orientations with respect to the rotation axis enable the identification of the artifact component such that they can be reduced in a computed tomography data set.

Experimental results based on synthetic data as well as physical X-ray computed tomography data have been provided. In both the cases it was found that the fused voxel data set had significantly less artifacts. An advantage of the proposed way of handling the different orientations for the fused voxel data set as part of the method is, that the reconstructed object from both scans orientations are inherently aligned due to an initial appropriate rotation of the grid before reconstruction of the object. This makes the data fusion step simple, free from alignment of the object and reduces the number of interpolation steps from two to one. As the interpolation steps, in general, are sources of quality degradation of voxel data sets and add to the computation time, the proposed method not only improves the quality of the reconstructed data but also reduces computation time.
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