Metal Artifact Reduction for Multi-Material Objects
Bärbel Kratz1#, Frank Herold1, Malte Kurfiß1, Thorsten M. Buzug2
1YXLON International GmbH, Essener Bogen 15, 22419 Hamburg, Germany, e-mail: baerbel.kratz@hbg.yxlon.com, frank.herold@hbg.yxlon.com, malte.kurfiss@hbg.yxlon.com
2Institute of Medical Engineering, University of Lübeck, Ratzeburger Allee 160, 23562 Lübeck, Germany, e-mail: buzug@imt.uni-luebeck.de
#all algorithms have been implemented at the Institute of Medical Engineering, University of Lübeck

Abstract
In computed tomography metal objects introduce inconsistencies during the data acquisition. Reconstructing this raw data leads to an image including artificial stripes as well as shadows between multiple metal objects. To enhance the resulting image quality the influence of metal objects could be reduced before reconstruction. One possibility of metal artifact reduction is the new computation of the metal-influenced raw data. Here, different interpolation methods in different dimensions are regarded. It is shown, that the inclusion of more dimensional information results in an enhanced image quality.

Keywords: Computed Tomography, Metal Artifacts, Artifact Reduction, Fourier Transform, Interpolation, Image Quality

1 Introduction
In the beginning of computed tomography (CT) in non-destructive testing, there has been a broad range of application with a single material apart air in the scanned volume. Light alloys like aluminum or plastic parts are ideal sample for CT scans with low impact of artifact caused by extreme absorbing regions in the scan. The more CT became a standard tool in laboratories the more complex the tasks became. Nowadays there are many applications with not only one material but multiple materials, often with a huge difference in absorption. Examples are aluminum casting with steel liners or injection molded plastic with metal connectors. In the first example the steel liners are often hard to penetrate with the X-ray energy used for the aluminum resulting in strong metal artifacts, blurring the area around the liners. For injection molded connectors the task is even harder. Not only is the difference in absorption higher but also the demand for accuracy in the data. Both examples have in common that often a reason for the CT scan is inspecting the interface between the lighter materials to the denser one, which is strongly influenced by metal artifacts. In addition to these relatively simple examples with advancement in technology and production processes the objects are more and more complex leading to a wide range of materials like in medical application and therefore also calling for solutions originally developed for medical use.

CT for medical applications has been confronted with the challenge of a wide density range and therefore attenuation coefficients from its very beginning. Most challenging for the CT are very dense materials, e.g. metal, in combination with soft tissue. The large range of contrast and the strong absorption of the X-rays inside the metal lead to artifacts, overlaying the feature in the surrounding material. Dental fillings out of gold are one example, which lead to strong metal artifacts reducing the detectability of important information for further diagnoses.

CT-imaging became a main technique for industrial non-destructive testing. The CT information can be mapped one-to-one to the test part directly, which has also a three dimensional extent. In comparison, radiographic images consist of an overlay of all density information along the beam direction. Therefore, the real position of density variances in space can be only depicted with a CT
scan correctly. The fields of application are ranging from highly specialized tasks in CT inline inspection to universal X-ray systems, metrology and high-resolution CT, for example in microelectronics [1,2]. In any field the acquired CT data will help either to speed up the inspection process e.g. for initial prototyping or to reduce the number of rejects for safety-critical parts, where simple radiography will lead to ambiguous results.

The reconstruction process itself consists of an acquisition of several digital X-ray images from different viewing angles, so called projections, followed by the mathematical computation of corresponding slices. The state-of-the-art reconstruction algorithm, the filtered backprojection (FBP, [3]), needs projections which are acquired from equally spaced segments of a circle perpendicular to the rotation axis of the test part. However, artifacts may occur during image reconstruction because of the incompleteness of the physical model taken as a basis. Especially metal objects in low density materials like plastic lead to artifacts overlaying the whole reconstructed CT-data. They are shaped as stripes as well as shadows between multiple metal objects and reduce the image quality. One reason for these artifacts is the insufficient penetration of the material that will lead to shadowing or partial volume effects and sampling errors. Increasing the voltage and using metal filters cutting the X-ray spectrum will lead to better penetration but on the other side to a loss of contrast. Therefore, the plastic may not be visible anymore. A better collimation of the single X-ray beam will also reduce metal artifacts, but will limit the variability of the scanner geometry. Moreover the scan time may be increased because the collimation will decrease the spatial resolution of a single projection, i.e. more projections are required.

It is possible to improve the image quality by using metal artifact reduction (MAR) strategies. In the last three decades many different approaches have been presented as potential solutions for this problem. Regarding the application field of medical CT-data most of the approaches are based on the substitution of the metal-influenced projection data with surrogate values before image reconstruction, e.g. using one-dimensional interpolation [4,5] or flat-panel based interpolation [6]. The success of all restoration methods depends on the continuation of structures into the recomputed area. Hence, all given information should be included into the recomputation (in [7] this is shown for medical data). In this work, a first proof of concept is given that the inclusion of more dimensional information leads to higher image quality for NDT data. This validation is done using the MAR-methods, which have been presented in [4] and [7] for medical CT-applications.

2 Materials

The raw data used in this paper is given by \( p(\mathbf{r}) \) with the coordinate vector \( \mathbf{r} = (\gamma, \xi, \zeta) \). It is a stack of two dimensional fan-beam acquisitions with the angle \( \gamma \), the detector position \( \xi \) and the axial position \( \zeta \) of the acquisition. However, all approaches are applicable on cone-beam or spiral data as well. The data has been acquired with a Siemens Somatom Definition AS+ scanner at 140 kV and 11 mA. The scanner geometry is fan-beam with a curved detector. Different objects have been regarded for a general evaluation. In the following, two electrical isolators consisting of plastic and metallic parts are used exemplarily (see Figure 1).
Figure 1: Two electrical isolators with metal inlays: side view (a) and top view (b) from isolator 1 and side view from isolator 2 (c).

3 Methods

3.1 Metal Segmentation

In this paper, two approaches for metal artifact reduction (MAR) methods are regarded. Both are based on the recomputation of the metal influenced projection values before image reconstruction. Hence, this strategy needs a separation of metal influenced projection values which can be realized using threshold segmentation in a preliminary reconstructed volume. A forward projection of a metal-only volume results in a raw data with entries at the positions $r_i$ of metal influenced projection values. Using this information, these values can be removed from projection data space. Based on the remaining non-influenced projection data at the positions $r_i$, different interpolation methods are applicable for the recomputation of the missing data. These new values will hopefully lead to a reduced artifact influence inside the final CT reconstruction.

3.2 Fourier-based Metal Artifact Reduction

In general, the reduction of metal artifacts by recomputed projection values is highly depending on the ability to continue existing structure information into the new values correctly. Since the structure information of the data is implicit given in the corresponding Fourier coefficients this behavior can be realized using a Fourier-based interpolation method. Another advantage of this approach is the possibility to use higher dimensional Fourier transforms for interpolation, e.g. a three dimensional CT data can be handled at once. Introducing structural information of the second or third data dimension potentially leads to more precise interpolation results. Compared to other approaches the dimensional handling, e.g. a neighborhood definition, is inherently given for the Fourier-based approach.

In order to interpolate the missing values $r_i$, the projections $p(r_i)$ are expanded into a Fourier sum

$$p(r_i) := \sum_{\kappa=0}^{\left|\mathbf{R}'\right|-1} \hat{p}(\mathbf{k}_\kappa) e^{2\pi i \mathbf{k}^T r_i}, \quad \forall r_i \in \mathbf{R}' ,$$

with the set of supporting points $\mathbf{R}'$ and the set of desired positions $\mathbf{R}$. The Fourier coefficients $\hat{p}(\mathbf{k}_\kappa)$ are searched at the equispaced frequencies $\mathbf{k}_\kappa$, where this vector has the same dimension as the non equispaced coordinates $r_i$.

Interpolation problem (1) can be turned into matrix vector notation $\mathbf{p} = \mathbf{F}\hat{\mathbf{p}}$ with the vectors

$$\mathbf{p} := (p(r_i))_{i=0}^{\left|\mathbf{R}'\right|-1}, \quad \hat{\mathbf{p}} := (\hat{p}(\mathbf{k}_\kappa))_{\kappa=0}^{\left|\mathbf{R}'\right|-1}$$

(2)
and the non equispaced Fourier matrix

\[ \mathbf{F} := \left( e^{2\pi i \mathbf{r}^\top \mathbf{r}} \right)_{\mathbf{r},\mathbf{r}' = 0} \]  

(3)

In practice, the inversion of equation (1) is not directly solvable using standard algorithms as the Fast Fourier transform (FFT). This algorithm is limited to equispaced supporting points, which is not fulfilled after removing the metal-influenced projection values in raw data space. For the non equispaced Fourier matrix \( \mathbf{F} \) no simple inversion exists. Alternatively, in [8] a fast Fourier algorithm has been presented which can be used for arbitrary distributed supporting points. The so-called Non Equispaced Fast Fourier Transform (NFFT) is available as open source C-library [9].

For the application of metal artifact reduction, the linear system of equations \( \mathbf{p} = \mathbf{Fp} \) is underdetermined, since the number of desired values is higher than the number of unaffected projection values. With this precondition \( \mathbf{R}' \prec \mathbf{R} \) the system can be solved by the following minimization problem [10]

\[ \sum_{\kappa=0}^{[R'-1]} \left( \hat{\mathbf{p}}_\kappa \right)^2 \mathbf{w}_\kappa \rightarrow \min \quad \text{subject to} \quad \mathbf{p} = \mathbf{Fp} \]  

(4)

The damping factors \( \mathbf{w}_\kappa \) can be used to incorporate further knowledge into the decay of the Fourier coefficients. Since a smooth solution for this equation is favored, the behavior of the coefficients will conform to the behavior of the damping values. The minimization problem in equation (4) is equivalent to solving the damped normal equation of second kind

\[ \mathbf{FWFW}^\top y = \mathbf{p}, \quad \hat{\mathbf{p}} = \mathbf{WFW}^\top y \quad \text{with} \quad \mathbf{W} = \text{diag}(\mathbf{w}_\kappa)_{\kappa=0}^{[R'-1]} \]  

(6)

To approximate the coefficients \( \hat{\mathbf{p}} \) equation (2) can be solved iteratively by a variant of the conjugated gradient method, the conjugated gradient normal equation (CGNE), which is adapted to the structure of the damped normal equation of second kind in equation (6) (more details are given for example in [8] and [11]).

In each CGNE-iteration all matrix vector multiplications with the non equispaced matrices \( \mathbf{F} \) and \( \mathbf{F}^\top \) can be performed efficiently using the NFFT-library. Finally, after the computation of the equispaced coefficients the missing values \( \mathbf{p}(\mathbf{r}_i) \) can be computed by applying an ordinary FFT.

### 3.3 Comparison Method

In the field of metal artifact reduction many authors perform a comparison with their new algorithms and well-known approaches. One of the first proposed MAR-approaches is easy to implement and therefore often used for comparison. It is based on a one dimensional linear spline interpolation [4]. After removing the metal influenced projection values the spline interpolation is performed for each single angular view and each single detector row of a three dimensional raw data set. The linear interpolation is used in the next section as comparison method.

Concerning equation (4), there are multiple possibilities for a damping definition. Here, a combination of the NFFT-interpolation with the results of the polynomial comparison method is regarded. Based on such a preliminary result, the damping in equation (4) could regulate the NFFT-computation to a potentially better solution than the initial interpolation result.

---

294
4 Results and Conclusion

In this section, MAR-results are presented for the two isolators shown in Figure 1. In general, the application of a three dimensional NFFT-interpolation yields a comparable or better image quality than a one or two dimensional NFFT-interpolation. Hence, only the three dimensional results are regarded to reduce the amount of Figures in this paper. The one dimensional linear interpolation method is shown as well to enable a direct comparison with this well-known MAR-method.

In addition to a visual comparison of the resulting images, a numerical evaluation is possible. In the following the reference-free evaluation technique is used which has been presented in [12]. The method projects the reconstructed image of a MAR-result forward into projection data space. The resulting data set can then be compared directly with the original projection data. Image artifacts are expected to be represented by differences to the original data set. Therefore, the measured projection data set can be interpreted as inherently given reference and it becomes possible to use a distance measurement, e.g. a relative error computation (here named by REL\textsuperscript{FP}).

Figure 2 shows detailed views of one representative slice in raw data space for isolator 1 (see Figure 1 (a-b)). Two regions in the metal influenced traces are marked for a further comparison. The original data set (Figure 2 (a)) shows structured values at both positions. The one dimensional linear interpolation (Figure 2 (b)) was not able to approximate this behavior; the structures are lost at both positions. However, the three dimensional NFFT-result (Figure 2 (c)) preserved the structural behavior at the positions.

![Figure 2: Detailed view in raw data space for the isolator 1 (see Figure 1 (a-b)): original (a), result of the one dimensional linear interpolation (b) and the result of the three dimensional NFFT interpolation (c). At the two marked positions original structures are visible (a), which are lost after the one dimensional approach (b) but preserved using the three dimensional method (c).](image)

The corresponding image reconstructions are shown in Figure 3. Regarding the first marked position both methods lead to a successful reduction of the metal artifacts. While in the original image (Figure 3 (a)) artifacts appear around the metal part, these streaks are removed in the linear interpolation result (Figure 3 (b)) as well as in the NFFT-interpolation result (Figure 3 (c)). However, regarding the edge at the second marked position, in the polynomial result this area is overlaid by new artifacts and the original edge is completely destructed. In contrast, in the NFFT-result the edge has been preserved correctly.

After this first visual impression, the corresponding numerical errors REL\textsuperscript{FP} are given in Table 1. The error of the original metal image is defined as 100 %. Both interpolation methods are able to reduce this initial error. While the one dimensional linear interpolation leads to a small error reduction, the three dimensional NFFT yields an obviously better reduction of the image error. These errors confirm the visual impression of a higher image quality for the NFFT-approach.

<table>
<thead>
<tr>
<th></th>
<th>Original: Fig. 3 (a)</th>
<th>Pol. result: Fig. 3 (b)</th>
<th>NFFT result: Fig. 3 (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error in %</td>
<td>100</td>
<td>96</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 1: Error computation for the MAR-results (shown in Figure 3) of isolator 1 using the REL\textsuperscript{FP} metric [12].
Figure 3: Detailed view of the original data for isolator 1 (see Figure 1 (a-b)) after image reconstruction: original (a), result of the one dimensional linear interpolation (b) and the result of the three dimensional NFFT interpolation (c). Regarding the first marked position the original image (a) shows artifacts caused by metal. They can be removed with both MAR-methods. Position 2 marks an edge which is destroyed using the one dimensional approach (b) but preserved using the three dimensional method (c).

In Figure 4 detailed views in raw data space are depicted for isolator 2 (see Figure 1 (c)). This data set represents an interpolation problem with high complexity. One of the metal traces lies at the intersection of the object and background (lower part of the detailed views). Hence, the interpolated values are highly influenced by the projection values of the background in the close neighborhood. These influences become visible as dark lines inside the new values of the linear interpolation (Figure 4 (b)) and as a blurred edge in the NFFT-result. Besides, three positions are marked in all views. While in the original data set (Figure 4 (a)) structures are visible, these characteristics are lost after the one dimensional linear interpolation (Figure 4 (b)) completely. The three dimensional NFFT-result (Figure 4 (c)) is still able to approximate most of these structural behaviors.

Figure 4: Detailed view in raw data space for the isolator 2 (see Figure 1 (c)): original (a), result of the one dimensional linear interpolation (b) and the result of the three dimensional NFFT interpolation (c). At the three marked positions original structures are visible (a), which are lost after the one dimensional approach (b) but approximated using the three dimensional method (c).

Regarding the corresponding image reconstructions, shown in Figure 5, three positions are marked for further explanations. At the first and third positions the original image (Figure 5 (a)) shows image artifacts caused by metal objects. The one dimension linear interpolation (Figure 5 (b)) and the NFFT-interpolation (Figure 5 (c)) are both able to remove the artifacts. Furthermore, the second position marks an example for the above mentioned complexity of this data set. While in the original image an object edge is clearly visible, this information is lost after the one dimensional interpolation. In the result of the three dimensional approach this edge is still visible. This behavior is visible at multiple positions at the intersection between object and background. The loss of structures at the linear interpolation has been visible already in the raw data space. Instead, the NFFT is able to approximate new values based on three dimensional structure information, which preserves most of the object edges.
Figure 5: Detailed view of the original data for the isolator 2 (see Figure 1 (c)) after image reconstruction: original (a), result of the one dimensional linear interpolation (b) and the result of the three dimensional NFFT interpolation (c). Position 1 and 3 show in the original image (a) artifacts caused by metal. They can be removed with both MAR-methods. Position 2 marks an edge which is destroyed using the one dimensional approach (b) but preserved using the three dimensional method (c).

Finally, the corresponding image errors are shown in Table 2. The error reduction is not as obvious as for the first example. However, the NFFT-approach is again able to reach a better error reduction.

<table>
<thead>
<tr>
<th></th>
<th>Original: Fig. 5 (a)</th>
<th>Pol. result: Fig. 5 (b)</th>
<th>NFFT result: Fig. 5 (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error in %</td>
<td>100</td>
<td>87</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 2: Error computation for the MAR-results (shown in Figure 5) of isolator 2 using the RELFP metric [12].

5 Conclusion
The results presented in the previous section lead to the conclusion that a higher dimensional interpolation for MAR-application results in promising enhancement of the image quality for NDT-applications. Regarding different materials, the raw data of a CT scan becomes more structured. This information should be involved during a recomputation step for metal artifact reduction. With more accurate new values the corresponding reconstructed image involves a reduced number of artifacts as well. The Fourier-based approach leads to satisfying results. Metal artifacts can be removed and original object edges are preserved. Approaches which are limited to one dimension should be avoided in general, because they destroy important image information.

References