Simulation-Based Metal Artifact Reduction for Computed Tomography of Multi-Material Components

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Abstract

Computed tomography (CT) reconstructions of objects containing metal are often corrupted by metal artifacts such as beam hardening, x-ray scatter, off-focal radiation, or partial volume artifacts. These effects lead to the introduction of dark streaks in the reconstructed volumes, which may prevent a correct metrological assessment of the object. Our goal is to correct these artifacts by calculating a correction that compensates for the contribution of artifacts in the acquired measurement data. To do this, we use computer simulations of the CT measurement process. Two simulations are carried out, based on an appropriate model of the object. The model could be an initial reconstruction or a CAD model. One simulation considers all physical effects that cause metal artifacts using dedicated analytic methods as well as Monte Carlo-based models. The other one represents an “ideal” CT measurement without any artifacts. Thus, the difference gives an estimate of the contribution of the metal artifacts and is used to correct the measured data. The performance of the proposed method is evaluated for simulated and measured data for multi-material objects. This approach allows for the reconstruction of volumes that are nearly free of artifacts and thus clearly outperforms the currently known metal artifact reduction algorithms.

Keywords: Computed Tomography, Metal Artifact Reduction, Multi-Material Components

1 Introduction

In recent years CT has been increasingly used in metrology since it provides a high measurement point density, requires comparably short measurement times, and allows the non-destructive assessment of internal features. However, the investigation of objects containing metal is still challenging as the reconstructed volumes are often corrupted by severe metal artifacts. There are several effects that lead to the formation of these artifacts. Beam hardening, x-ray scatter, off-focal radiation, and partial volume artifacts may be the most prominent ones. Although the appearance of these effects is not only restricted to metallic components they are referred to as metal artifacts since the high density and the high atomic number of metals increases the impact of these effects.

Various approaches to reduce metal artifacts have been proposed. In principle, they can be divided into two classes: so called “sinogram inpainting” techniques that remove the contribution of the metal from the acquired projection data using different interpolation schemes [1 - 5], and iterative methods that are able to incorporate dedicated physical models of the interaction between x-rays and the material within the reconstruction process [6 - 10]. Sinogram-based methods do not require much computer processing, but they introduce new artifacts due to an inappropriate replacement of missing data. Iterative methods are usually more accurate, but have the drawback that they require long processing times. Therefore, we propose a comparably fast approach that uses similar models as iterative methods to derive a correction term which contains the contribution of artifacts to the acquired measurement data. In general, the proposed approach is not restricted to multi-material components and can also handle other artifacts such as cone-beam artifacts. However, this work focusses on its application to metal artifact reduction (MAR).
2 Material and Methods

2.1 Simulation-Based Artifact Correction

The projection data $p$ of any CT measurement can be described as the sum of two terms: An ideal data term $p_{\text{ideal}}$ that is the x-ray transform of the measured component, and an artifact term $p_{\text{art}}$ that contains the difference between the x-ray transform and the measured data:

$$ p = p_{\text{ideal}} + p_{\text{art}} = X f_{\text{ideal}} + (p - X f_{\text{ideal}}). \tag{1} $$

Here $f_{\text{ideal}}$ represents the three-dimensional distribution of the attenuation coefficient and $X$ the x-ray transform operator. Applying the inverse x-ray transform operator $X^{-1}$ to equation (1), the problem can also be formulated in the image space:

$$ X^{-1} p = X^{-1} p_{\text{ideal}} + X^{-1} p_{\text{art}} = f_{\text{ideal}} + f_{\text{art}}. \tag{2} $$

Obviously, if the artifact term deviates from zero, artifacts are introduced to the reconstructed volume. Considering multi-material components, this deviation mainly results from beam hardening caused by the presence of metal, x-rays that are scattered into the metal trace, additional contributions of off-focal radiation, and nonlinear partial volume artifacts.

The proposed approach uses simulations of the CT measurement that model these effects to derive an estimate of the artifact term $f_{\text{art}} \approx f_{\text{art,est}} = X^{-1} [p_{\text{sim}} - p_{\text{sim,ideal}}]$ which is used subsequently to derive an estimate of the ideal reconstruction $f_{\text{ideal,est}}$:

$$ f_{\text{ideal,est}} = X^{-1} p - f_{\text{art,est}} \tag{3} $$

In a first step, an initial reconstruction $f$ of the measured data is performed and segmented to derive a prior model for the metal $f_{\text{metal}}$:

$$ f_{\text{metal}} = T f. \tag{4} $$

Here $T$ represents the segmentation operator which is, for our purpose, a marching cubes algorithm. Subsequently, this segmentation is used as the initial basis for the simulation of projection data $p_{\text{sim}}$. Beam hardening is simulated by a polychromatic forward projection based on a modification of the semi-empirical tube spectrum $w(E)$ of Tucker et al. [11], and on tabulated values of the attenuation coefficient of the object $\mu_o$, the prefilter $\mu_p$, and the x-ray detector $\mu_d$, as well as the corresponding intersection length $L$. The contribution of off-focal radiation is simulated by convolving the simulated polychromatic intensities with an off-focal kernel $G_{\text{off}}$ that is determined by a calibration measurement. Nonlinear partial volume artifacts are reproduced by an appropriate subsampling of the simulated intensities. The contribution of scattered x-rays $I_s$ is calculated using a hybrid approach that uses a Monte-Carlo scatter simulation with a reduced number of photons to determine the free parameters of an analytic scatter convolution algorithm [12]. Thus, the simulated projection data are calculated as follows:

$$ p_{\text{sim}} = -\ln(I_s + G_{\text{off}} \ast \int dE E w(E) e^{-\mu_o L_O} e^{-\mu_p L_P} (1 - e^{-\mu_d L_d})). \tag{5} $$

Finally, ideal projection data $p_{\text{sim,ideal}}$ are simulated using a monochromatic forward projection of a reference energy $E_0$, which is chosen to be centroid value of the assumed x-ray spectrum:
\[ p_{\text{sim.ideal}} = -\ln(E_0 \ e^{-\mu_{0}l_0}) \] (6)

According to equation (3) the difference between the real and the ideal simulation can be used to correct the measurement data for metal artifacts.

### 2.2 Data Acquisition

The measurements were conducted on a Werth TomoScope\textsuperscript{®} 200 that is equipped with a commercial micro-focus x-ray tube and an energy integrating flat detector. A total number of 800 projections were acquired over 360 degrees. The tube voltage was set to 225 kV and the tube current to 170 \( \mu \)A. Furthermore, a 1.2 mm Sn prefilter was used during image acquisition in order to harden the x-ray tube spectrum.

### 2.3 Simulation Study

A quantitative evaluation of the proposed approach was performed using simulated data. Therefore, a CAD-model of a multi-material component was designed (figure 1). The materials of the multi-material component were set to PMMA and copper. Projection data were simulated according to equation (5). The geometrical as well as the physical parameters of the simulation were set to the ones of the measurement (section 2.2). The polychromatic x-ray spectrum \( w(E) \) was simulated using the semi-empirical tube spectrum model from Tucker et al. Scattered x-rays were simulated using a Monte-Carlo scatter simulation, and off-focal radiation was simulated by convolving the simulated data with a Gaussian function in intensity domain. In addition, an ideal reference simulation, which assumes a point-shaped, monochromatic x-ray source and no x-ray scattering, was performed. Thus, the performance of the proposed correction approach can be evaluated by a comparison to the ideal reference.

### 3 Results

The proposed approach was applied to simulated data as well as to measured data of a Werth TomoScope\textsuperscript{®} 200. The results of the proposed approach were compared to reference algorithms, namely normalized metal artifact reduction (NMAR) \[2\] and iterative reconstruction with total variation regularization \[6\]. Normalized metal artifact reduction is an inpainting-based approach that tries to determine the metal trace within the acquired projection data and to replace it using a sophisticated interpolation scheme. The iterative reconstruction optimizes the raw data fidelity in an iterative matter while incorporating prior knowledge in terms of the assumption that the reconstructed image is piecewise homogeneous.

#### 3.1 Simulated Data

The simulated projection data were generated as described in section 2.3. The simulated projections were reconstructed using the analytic Feldkamp-David-Kress reconstruction algorithm \[13\]. Subsequently, the reconstruction was segmented into three classes: Metal, plastic and air. Since the metal artifacts mainly propagate into the plastic part of the component, the segmented plastic shows similar artifacts as the reconstruction while the metal can be segmented accurately. Thus, only the segmented metal was used as basis for the simulation of beam hardening, off-focal radiation, and partial volume effects. Only the Monte-Carlo scatter simulation was based on both the segmented metal and the segmented plastic.
Since all physical parameters are known for the simulated data, exactly the same parameters can be used for the artifact simulation. Reconstruction of the simulation-based artifact correction as well as reconstructions using the reference algorithms are shown in figure 2. While the normalized metal artifact reduction and the iterative reconstruction is not able to remove the streak artifacts from the reconstructions, the proposed simulation-based artifact correction leads to images that are nearly free of artifacts. A comparison to the monochromatic reference simulation shows that there are only minor deviations in the region of the metal. The simulation study also demonstrates, that the correction of beam hardening, off-focal radiation, and partial volume artifacts, does not require a model of the plastic part but can be performed using only the metal part.


### 3.2 Measurement data

The simulation study demonstrated that the proposed approach can potentially remove most of the metal artifacts if the physical parameters of the CT acquisition are known. However, in case of measurement data, the simulation-based artifact correction uses the methods described in section 2.1 to approximate unknown parameters such as the x-ray tube spectrum or the spatial distribution of scattered x-rays. The measurements were acquired as described in section 2.2. The correction steps are performed as described in section 3.1. Figure 3 shows the correction results of the simulation-based artifact correction as well as the results of the reference algorithms. Similar to the simulation study (section 3.1), the normalized metal artifact reduction and the iterative reconstruction cannot satisfactorily remove the streak artifacts from the reconstruction. The simulation-based artifact correction, in contrast, provides images that are nearly free of artifacts.
Discussion and Conclusion

We presented a new method that uses CT simulations to correct for metal artifacts. It can be applied to any multi-material measurement that allows for the appropriate segmentation of the metal or comes with a CAD model. Very good correction results for both simulated and measured data were obtained that are almost free of artifacts. This approach is clearly superior to inpainting-based metal artifact reduction techniques (when the object contains a high proportion of metal) and iterative reconstruction algorithms that do not incorporate sophisticated models of the interaction between x-rays and matter within the reconstruction process.

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