Metal artifact reduction by fusion of CT scans from different positions using the unfiltered backprojection

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Abstract

Metal objects or metal parts in an object are still a major problem of X-ray computed tomography (CT) because of so called metal artifacts. We propose a new method – a multipositional data fusion – for automatically fusing multiple CT volumes from different positions to reduce these metal artifacts. After scanning a specimen several times at different positions and reconstruction of every scan (e.g. by the filtered backprojection), we also perform an unfiltered backprojection. Based on the assumption that metal artifacts occur the most wherever X-rays are attenuated a lot, the unfiltered backprojection is used to autonomously estimate the likelihood of metal artifacts in every voxel of every scan. The different volumes are registered and then fused by weighted sum preferring the voxels with low values in the unfiltered backprojection results.

In our tests on real objects, our method fully automatically created optimized volumes with significantly less metal artifacts. The multipositional data fusion was compared to the commercially multi spectra fusion of Werth Messtechnik GmbH and outperformed it in one of the use cases.

Keywords: computed tomography, metal artifact reduction, multipositional, data fusion, unfiltered backprojection

1 Introduction

After being used for medical purposes for almost 50 years, CT has also become an important tool for dimensional measuring on industrial parts. Nevertheless, a lot of industrial use cases that involve metal are still very challenging for industrial CT. Due to physical effects like beam hardening, scatter and high absorption, achieving good image quality and reliable measurements is sometimes very difficult when scanning metal objects. Especially multi-material specimens with high density differences are not suitable for the common workflow. There are several methods that address these problems by reducing metal artifacts – e.g. dual energy CT or algorithmic approaches (see chapter 2) – but wherever X-rays are attenuated too much and therefore the corresponding projections just do not contain enough information, these methods often cannot correct metal artifacts sufficiently.

We propose a new method for metal artifact reduction based on the fact that metal artifacts are very dependent on the positioning of the scanned object (see [1]). If an object is turned and scanned in a different position, the metal artifacts will appear at different locations of the volume model (e.g. see figure 1).

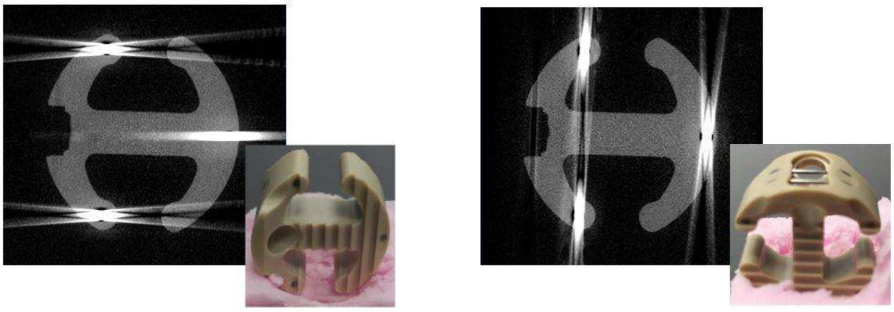

Figure 1: Two registered CT scans of an intervertebral disc implant – scanned from different positions – with typical metal artifacts and two photos that show the different positioning of the implants during the scans

As already proposed by several researchers [2-4], multiple scans from different views can be fused to create one improved volume model. The idea of our method is that it is better to only use correct data and ignore the flawed data with metal artifacts whenever possible. Hence, our method builds on the existing CT data fusion approaches by estimating the local influence of metal artifacts. Using the unfiltered backprojection as a simple heuristic, local weights are created that are used in the fusion process so that the influence of areas with higher probability of metal artifacts is minimized while areas with lesser probability of metal artifacts determine most of the result.

In our tests on simulations as well as real objects this method creates volumes with significantly less metal artifacts and a much higher image quality. Using this method, we could also measure object features that were not reasonably measureable before.

Additionaly, the multipositional data fusion was compared to the multi spectra fusion of Werth Messtechnik GmbH (see [5-7]). This paper presents two use cases: In one of them the multpositional data fusion was better; in the other one the multi spectra fusion was better.

2 State of the art

There are a lot of different approaches to decrease the influence of metal artifacts (especially scatter, beam hardening and noise). First of all, if possible, using the right filter and increasing the exposure time and energy might already be sufficient, but this requires a strong Xray-source which is expensive and thus is often not available.
There are a lot of purely algorithmic approaches. Some of them alter the projections [8-17], some adjust the iterative reconstruction process in order to align the process more with the real world process [18-25] and others correct the reconstructed volumes (e.g. [26]). These algorithmic approaches can be very effective and suit a lot of use cases, however, in many use cases purely algorithmic approaches are not sufficient.
Lastly, there are techniques that use multiple scans in order to achieve more information about the specimen. Most prominently, dual energy or multi spectra methods use two (or more) scans with different energy spectra (see [27-29]). Based on the measured differences in the scans, an optimized volume is calculated. Although these methods often increase noise, most of the time they decrease metal artifacts a lot and deliver great results. Despite the amount of mentioned impactful metal artifact reduction methods, problems remain. Wherever X-rays are attenuated almost completely, the scanning process does not gather enough information for an effective reconstruction. For this case, there is another type of approach which needs multiple scans: The idea of fusing scans from different scanning positions (see [30-32]) which is the basis of this paper.

3 Method

3.1 The unfiltered backprojection as a heuristic

The physical effects of beam hardening, scatter and noise as well as a low signal are the main reasons for metal artifacts. All of these effects are most strongly pronounced wherever X-rays are attenuated very much (e.g. in metal objects or between metal objects in multi-material objects). Therefore, in order to automatically estimate the influence of metal artifacts in a voxel of a scan, we propose to compute how much all of the X-rays passing through this voxel have been attenuated. This sum of attenuations can be calculated very easily by an unfiltered backprojection reconstruction (a Radon transform) which is the basis for the well-known filtered backprojection reconstruction algorithm (see [33]). For the parallel beam case the backprojection reconstruction for projections p_γ from angles γ for a voxel µ at position $(x;\ y)$ is given by (see [34], p. 175):

$$\mu(x,y) = \int_0^\pi (x\cos\gamma + y\sin\gamma)\, d\gamma$$

In all of our examples we found a great correlation (e.g. see Figure 2) between metal artifacts and the unfiltered backprojection: Wherever the unfiltered backprojection has high values the influence of metal artifacts was high too. In order to visualize the difference of the unfiltered backprojection we subtracted two unfiltered backprojection reconstructions in Figure 2. Regions that are bright in the difference image are more strongly disturbed by metal in the first scan while regions that are dark in the difference image are more strongly disturbed by metal in the second scan.

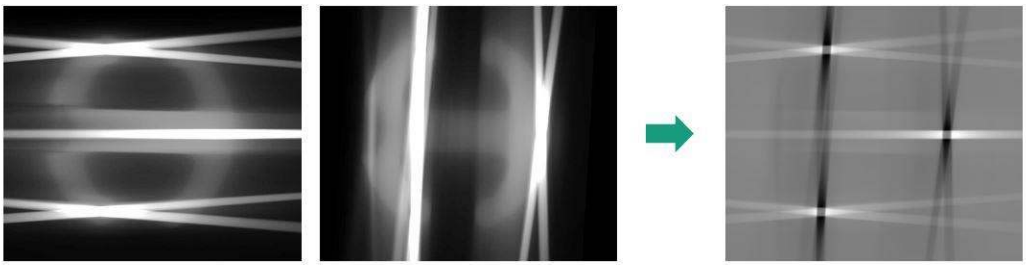

Figure 2: The registered unfiltered backprojection reconstructions of the scans from Figure 1 (left images) as well as the difference of both to visualize the different estimation of influence of metal artifacts (right image)

3.2 The multipositional data fusion

Workflow

To create a CT-volume with less metal artifacts, we propose the following workflow: First of all, we scan the specimen multiple times in different positions with the same parameters and under the same conditions. (The different positions are very crucial, so thinking about the positions that should complement each other optimally is important.)
Then we reconstruct the scans by an arbitrary reconstruction method and, additionally, we perform an unfiltered backprojection for every scan. In order to fuse the different volumes, we register the reconstructed volumes on one of the volumes and transform the backprojections equivalently, so that they are orientated equally. Lastly, based on the results of the backprojections, weights are calculated for the fusion and used in a weighted sum to get a fused volume.

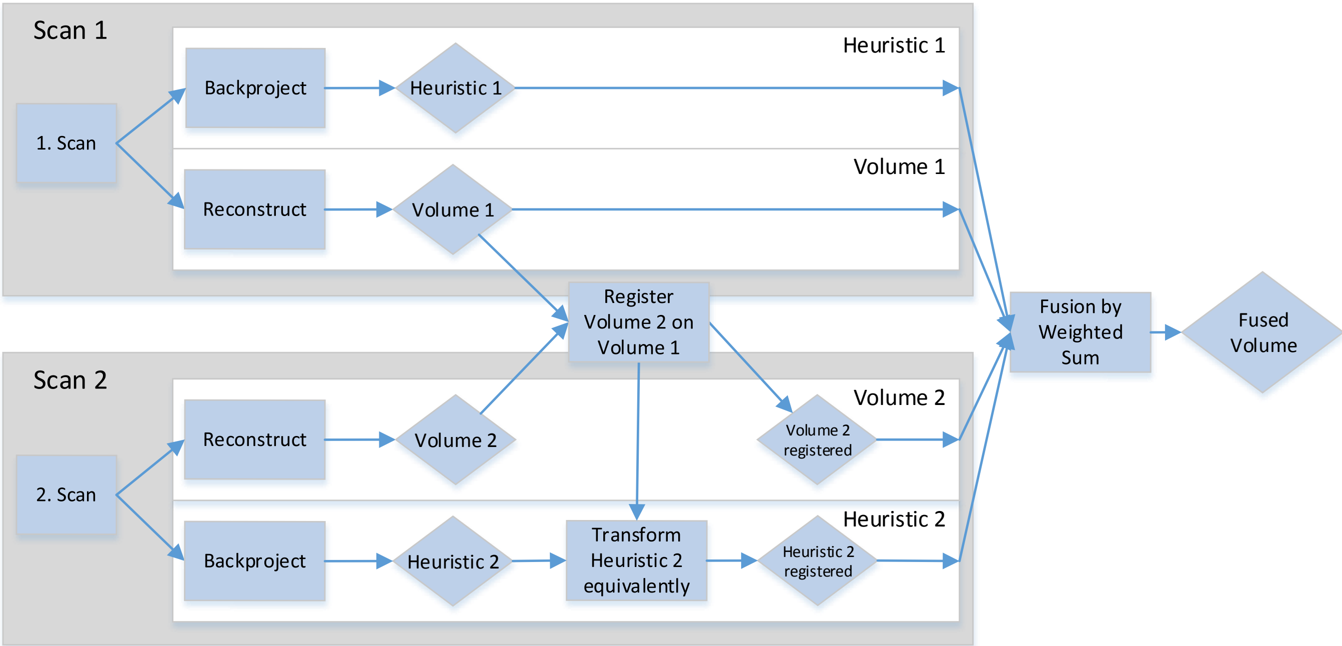

Figure 3: Workflow of the multi-positional data fusion of two scans using the unfiltered backprojection as heuristic

Definitions

Some variables are needed to explain our method in detail. Therefore, let

- $i \in \mathbb{N}$ be the parameter that indexes every single scan,
- $X_i \in \mathbb{R}^{d_1 \times d_2 \times d_3}$ be the voxelized volume model according to scan i reconstructed by the filtered backprojection method with $d_1, d_2, d_3 \in \mathbb{N}$ as the dimensions of the volume,
- $W_i \in \mathbb{R}^{d_1 \times d_2 \times d_3}$ equivalently be the voxelized volume model according to scan i reconstructed by the unfiltered backprojection method,
- $x_{i,j} \in \mathbb{R}$ be a single voxel of volume X_i, $j \in [1, d_1 \cdot d_2 \cdot d_3]$,
- $w_{i,j} \in \mathbb{R}$ be a single voxel of volume W_i.

Reconstruction and backprojection

We use a filtered backprojection method of Fraunhofer EZRT with a shepp-logan filter for the reconstruction and just omit the filter in order to get the unfiltered backprojection. For n scans we therefore get n reconstructed volume models X_i of the objects from the filtered backprojection and n volumes W_i from the unfiltered backprojection that we use for weights in the fusion later.

Voxel-based registration

Due to a lot of artifacts in our tests, locating the surface often was a difficult task that needed human interaction. Therefore we decided not to use a registration method that needs the surface of the scanned object. Instead we use a voxelbased registration method from the Elastix open source tool box [35], based on the Insight Segmentation and Registration Toolkit (ITK) that was adjusted to our use case with the help of the Fraunhofer IZFP. In order not to just find a local optimum, we provide a good initial position for the volume that has to be registered and then move the volume until the normalized correlation was minimized. After registering the reconstructed volumes, we rotate and shift the unfiltered backprojections in the same way we moved the reconstructed volumes. The registration results in transformed volumes $\tilde{X}_i$ and $\widetilde{W}_i$.

Multi-positional data fusion by weighted sum

To create an optimized volume X^*, we use a weighted sum for every single voxel $x_j{}^* \in X^*$, $j \in [1, d_1 \cdot d_2 \cdot d_3]$. Therefore, we have to calculate weights voxelwise first. Because high values of the unfiltered backprojection indicate metal artifacts, we form the quotient to get preliminary weights $\tilde{\omega}_j = {}^1\!/_{w_j}$ for every single voxel $w_{i,j}$. The weights should add up to 1, so the preliminary weights are divided by the sum of all preliminary weights in order to get the first real weights:

$$\omega_{i,j} = \tilde{\omega}_{i,j} \Big(\sum_j \tilde{\omega}_{i,j} \Big)^{-1}$$

Furthermore, in order to regulate how much lower values in the unfiltered backprojection will be preferred, we introduce the parameter $\tau \geq 1$ and adjust the formula for the weights:

$$\omega_{i,j} = \widetilde{\omega}_{i,j}\left(\sum_{j} \widetilde{\omega}_{i,j}{}^{\tau}\right)^{-1}$$

Finally, the scans can be fused by calculating the weighted sum for every voxel $x_j{}^*$:

$$x_j{}^* = \sum_{i}^{n} \omega_{i,j}\ x_{i,j}$$

4 Experiments and results

The necessary effort of performing at least two single scans is of course a great disadvantage. Hence, the method is uneconomical and therefore not reasonable for some use cases. But – as multi spectra CT is a widely used method – performing two scans is acceptable if the additional benefit is great enough. Therefore, besides using our method, we used a multi spectra fusion method of Werth Messtechnik GmbH for comparison. We present two use cases: The first use case (an intervertebral disc) highlights the benefits of our multipositional data fusion, while the second use case (an electrical socket) shows the advantages of using two energy spectra.

All of the following experiments were performed on a Werth TomoScope HV 500 with a detector resolution of 992×992 and pixel size of 400µm. A greater resolution would have been possible, but was not necessary to show the artifacts and the impact of the examined methods. The contrast in the pictures is adjusted so that the plastic is clearly visible, in order to highlight the metal artifacts.

4.1 Example 1: Intervertebral disc

As a first example, we present an intervertebral disc implant from the company Medtronic Sofamor Danek Deggendorf GmbH (see Figure 4) made of plastic (PEEK) and tantalum bars. We scanned it with the following parameters (see Figure 4, Table 1 and 2).

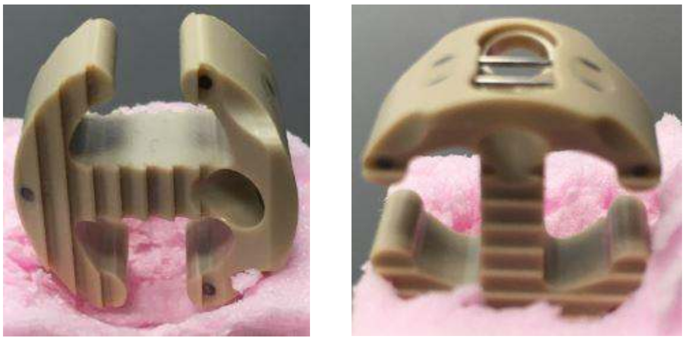

Figure 4: Two photos of the intervertebral disc in different scanning positions (left: Position 1 for Scan 1 and 3, right: Position 2 for Scan 2).

	All Scans
voxel size	25.16 µm
magnification	15.7136
projection number	495
prefilter	no filter

Table 1: General parameters of example 1.

	Scan 1	Scan 2	Scan 3
position (see Figure 4)	1	2	1
voltage	220 kV	220 kV	120 kV
current	115 µA	115 µA	210 µA
exposure time	1s	1s	0.285s

Table 2: Further parameters of example 1.

Due to the high atomic number of tantalum (73), metal artifacts – streaks and cupping – make it impossible to measure the surface of the plastic in the single scans. After using the presented multipositional data fusion with the algorithmic parameter $\tau = 3$, great improvements are visible: Although the results of our method are not optimal yet, most of the streaks and the cupping vanish (see Figure 5). The plastic surface of the intervertebral disc is visually intact and could be measured. In contrast to our method, performing the Werth multi spectra fusion did not improve the image quality at all (see Figure 6). We suppose that the difference of the multi spectra scans – although scanned with 120 kV and 220 kV – due to the high density of tantalum was not great enough.

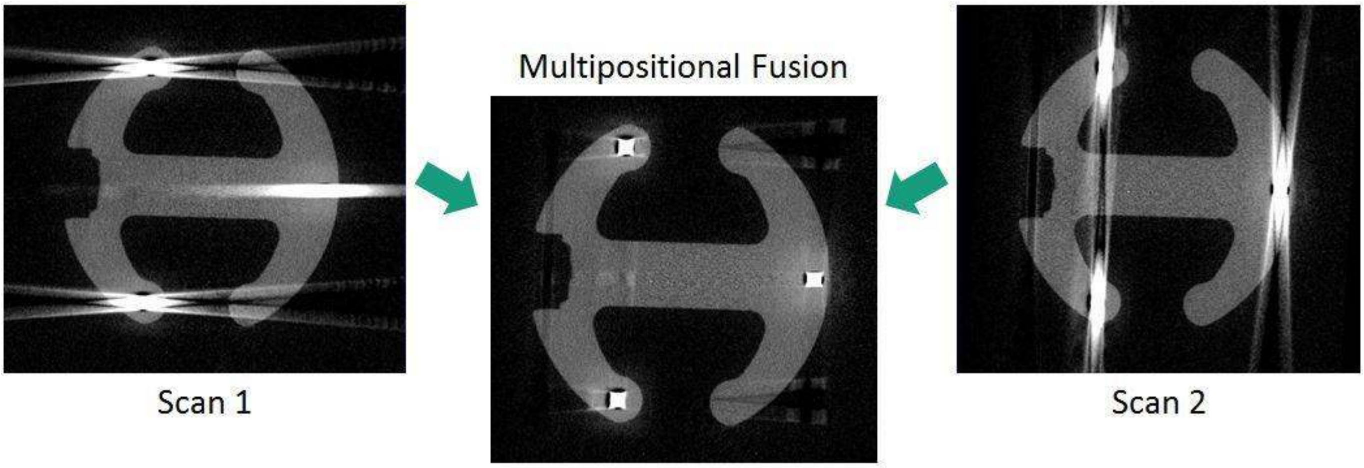

Figure 5: Two registered CT-scans of an intervertebral disc implant from different positions (top images, left: Scan 1, right: Scan 2) and the fusion created by our multipositional data fusion (bottom image, middle).

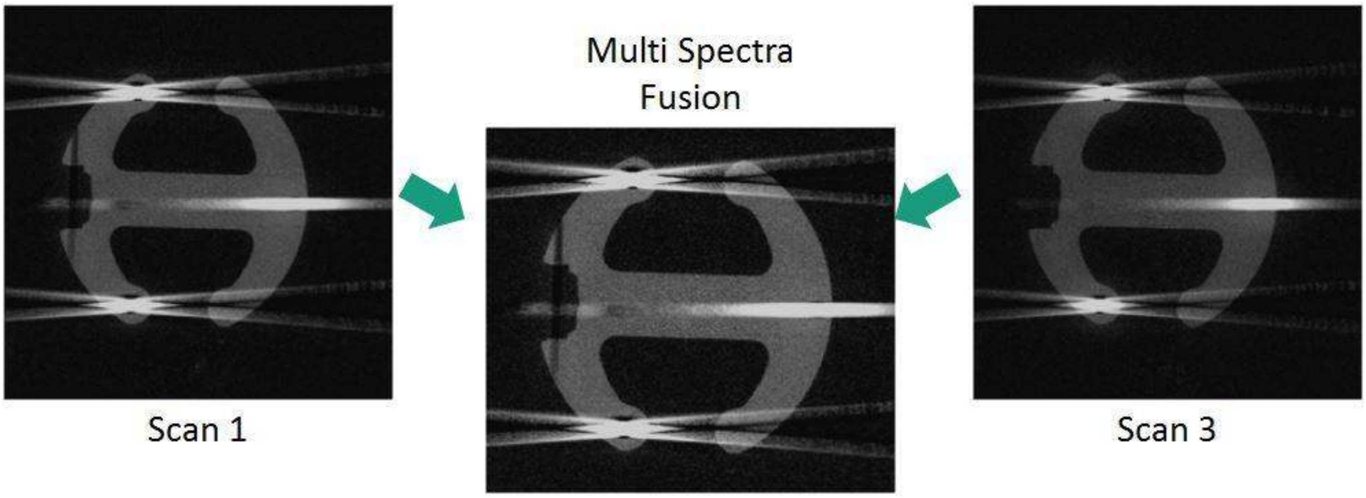

Figure 6: Two CT-scans of an intervertebral disc implant with different energies (top images, left: Scan 1, right: Scan 3) reconstructed by the filtered backprojection of Werth and the fusion created by the Werth multi spectra fusion (bottom image, middle).

4.2 Example 2: Electrical socket

As a second example, we present an electrical socket from the Berker GmbH & Co. KG (see figure 7) made of several different plastic and metal materials (including steel and an alloy of copper and zinc). We scanned it with the following parameters (see Figure 7, Table 3 and 4).

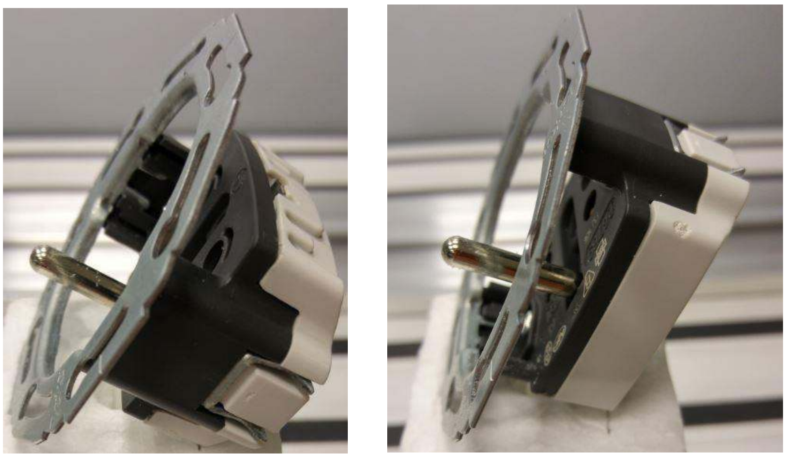

Figure 7: Two photos of the electrical socket in different scanning positions (left: Position 1 for Scan 1 and 3, right: Position 2 for Scan 2)

	All Scans
voxel size	99.83 µm
magnification	3.96052
projection number	695
prefilter	no filter

Table 3: General parameters of example 2.

	Scan 1	Scan 2	Scan 3
position (see Figure 4)	220 kV	220 kV	150 kV
voltage	90 µA	90 µA	90 µA
current	0.5s	0.5s	0.5s
exposure time	220 kV	220 kV	150 kV

Table 4: Further parameters of example2.

Due to the very complex composition of plastic and metal parts, increasing the image quality of the electrical socket is a very difficult task. Therefore, after using the presented multipositional data fusion with the algorithmic parameter τ=5, the image quality improves, but a lot of artifacts remain (see figure 8). There are some regions where the multipositional data fusion outperforms the Werth multi spectra fusion, but, in general, the spectra fusion approach resulted in a truer image with fewer artifacts (see Figure 9). In contrast to the use case before, the differences of the low and the high enery scans was great enough and therefore the multi spectra fusion could use the bonus information. Instead, due to the mass of artifacts in all directions, some regions of the multipositional scans suffered in both scans. Hence, the multipositional fusion could not increase the image quality in these regions.

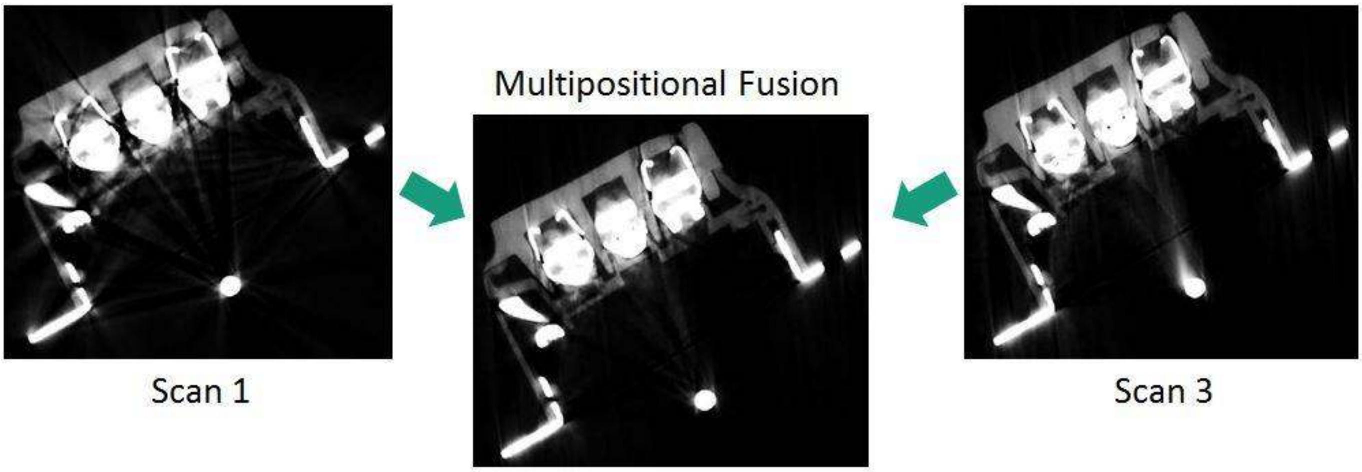

Figure 8: Two registered CT-scans of an electrical socket from different positions (top images, left: Scan 1, right: Scan 2) and the fusion created by our multipositional data fusion (bottom image, middle)

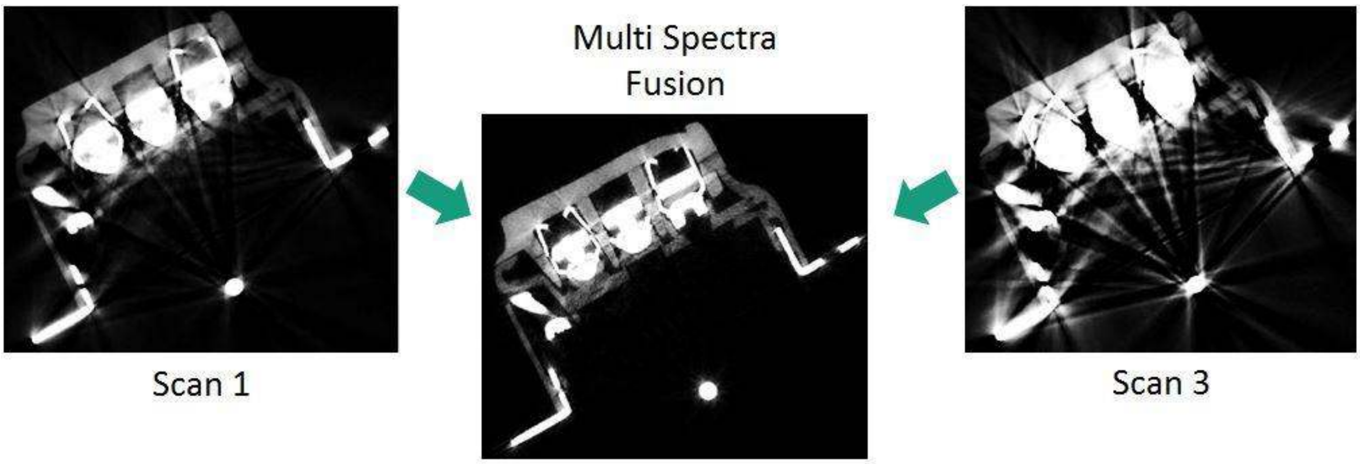

Figure 9: Two CT-scans of an electrical socket with different energies (top images, left: Scan 1, right: Scan 3) reconstructed by the filtered backprojection of Werth and the fusion created by the Werth mutli spectra fusion (bottom image, middle)

5 Conclusions

We presented a method for fusing two CT-scans performed with two different scanning positions. We showed that the method can decrease artifacts and even can outperform multi spectra fusions on some use cases. Our experiments indicate that our method shines when there are regions in the object that absorb almost all passing X-rays. While mutli spectra approaches need a high energy scan with sufficienctly good image quality, our presented approach is able to handle two scans with severe artifacts as long these artifacts are differently located. Therefore, the presented method increases the range of application whenever the available CT-system can not scan with sufficient energy for a standard CT-scan of a metal specimen.

Hence, there are probably a lot of use cases for the multipositional data fusion and we expect a lot of practical application and a large benefit, even though the method has to be refined a lot. Most notably, we asume that more advanced – probably use case specific – heurstics are needed to make the most of the idea of multipostional data fusion. Furthermore, multipositional and multi spectra approaches could be combined, in order to achieve the best results.

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References

[1] R. Schmitt, C. Niggemann, Einfluss der Bauteilorientierung auf die Messunsicherheit bei dimensionellen Computertomografie Messungen, Werkzeugmaschinenlabor, W. d. R., 2010.

[2] R. Alvarez, A. Macovski, Energy-selective reconstructions in X-ray computerized tomography, Physics in medicine and biology 21, Vol 5, p. 733–744, 1976.

[3] C. Heinzl, J. Kastner, E. Gröller, Surface extraction from multi-material components for metrology using dual energy CT, IEEE transactions on visualization and computer graphics 13, Vol 6, 2007.

[4] V. Rebuffel, Dinten, Dual-energy X-ray imaging: benefits and limits, Insight-non-destructive testing and condition monitoring 49, Vol 10, p. 589–594, 2007.

[5] S. Faby, S. Kuchenbecker, S. Sawall, D. Simons, H.-P. Schlemmer, M. Lell, M. Kachelrieß, Performance of today's dual energy CT and future multi energy CT in virtual non-contrast imaging and in iodine quantification: A simulation study. In: Medical physics 42 (7), S. 4349–4366, 2015.

[6] S. Kuchenbecker, S. Faby, S. Sawall, M. Lell, M. Kachelrieß2015): Dual energy CT: How well can pseudo-monochromatic imaging reduce metal artifacts? In: Medical physics 42 (2), S. 1023–1036, 2015.

[7] D. Simons; M. Kachelrieß, H. Schlemmer, Recent developments of dual-energy CT in oncology. In: European radiology 24 (4), S. 930–939, 2014.

[8] X. Chen, F. Verhaegen, D. Laurendeau, S. A. Enger, L. Beaulieu, An algorithm for efficient metal artifact reductions in permanent seed implants, Medical physics 38, Vol 1, 2011.

[9] T. Heußer, M. Brehm, L. Ritschl, S. Sawall, M. Kachelrieß, Prior-based artifact correction (PBAC) in computed tomography, Medical physics 41, Vol 2, 2014.

[10] R. Joemai, Bruin, W. de Paul, Veldkamp, J. H. Wouter, J. Geleijns, Metal artifact reduction for CT: Development, implementation, and clinical comparison of a generic and a scanner-specific technique, Medical physics 39, Vol 2, p. 1125–1132, 2012.

[11] W.A. Kalender, R. Hebel, J. Ebersberger, Reduction of CT artifacts caused by metallic implants, Radiology 164, Vol 2, DOI: 10.1148/radiology.164.2.3602406, p. 576-577, 1987.

[12] S. Karimi, P. Cosman, C. Wald, H. Martz, Segmentation of artifacts and anatomy in CT metal artifact reduction, Medical physics 39, Vol 10, p. 5857–5868, 2012.

[13] G. Liugang, S. Hongfei, N. Xinye, F. Mingming, C. Zheng, L. Tao, Metal artifact reduction through MVCBCT and kVCT in radiotherapy, Scientific Reports 6, 2016.

[14] E. Meyer, R. Raupach, M. Lell, B. Schmidt, M. Kachelrieß, Normalized metal artifact reduction (NMAR) in computed tomography, Medical physics 37, Vol 10, p. 5482–5493, 2010.

[15] E. Meyer, R. Raupach, M. Lell, B. Schmidt, M. Kachelrieß, Frequency split metal artifact reduction (FSMAR) in computed tomography, Medical physics 39, Vol 4, p. 1904–1916, 2012.

[16] D. Prell, Y. Kyriakou, M. Beister, W. A. Kalender, A novel forward projection-based metal artifact reduction method for flat-detector computed tomography, Physics in medicine and biology 54, Vol 21, p. 6575, 2009.

[17] Q. Wang, L. Li, L. Zhang, Z. Chen, K. Kang, A novel metal artifact reducing method for cone-beam CT based on three approximately orthogonal projections, Physics in medicine and biology 58, Vol 1, p. 1, 2012.

[18] P. Bannas, Y. Li, Motosugi, Utaroh, K. Li, M. Lubner, G. Chen, P. J. Pickhardt, Prior image constrained compressed sensing metal artifact reduction (piccs-mar): 2d and 3d image quality improvement with hip prostheses at ct colonography, European radiology 26, Vol 7, p. 2039–2046, 2016.

[19] L. Brabant, E. Pauwels, M. Dierick, D. van Loo, M. A. Boone, L. van Hoorebeke, A novel beam hardening correction method requiring no prior knowledge, incorporated in an iterative reconstruction algorithm, NDT & E International 51, DOI: 10.1016/j.ndteint.2012.07.002, p. 68-73, 2012.

[20] B. de Man, J. Nuyts, P. Dupont, G. Marchal, P. Suetens, An iterative maximum-likelihood polychromatic algorithm for CT, IEEE transactions on medical imaging 20, Vol 10, DOI: 10.1109/42.959297, p. 999–1008, 2001.

[21] B. Man, J. Nuyts, P. Dupont, G. Marchal, P. Suetens, Reduction of metal streak artifacts in x-ray computed tomography using a transmission maximum a posteriori algorithm, IEEE transactions on nuclear science 47, Vol 3, p. 977–981, 2000.

[22] J. Nuyts, B. Man, J. A. Fessler, W. Zbijewski, F. J. Beekman, Modelling the physics in the iterative reconstruction for transmission computed tomography, Physics in medicine and biology 58, Vol 12, DOI: 10.1088/0031-9155/58/12/R63, p. 63-96, 2013.

[23] G. van Gompel, K. van Slambrouck, M. Defrise, K. J. Batenburg, J. Mey, J. Sijbers, J. Nuyts, Iterative correction of beam hardening artifacts in CT, Medical physics 38, Vol S1, 2011.

[24] K. van Slambrouck, J. Nuyts, Metal artifact reduction in computed tomography using local models in an image block-iterative scheme, Medical physics 39, Vol 11, p. 7080–7093, 2012.

[25] H. Zhang, L. Wang, L. Li, A. Cai, G. Hu, B. Yan, Iterative metal artifact reduction for x-ray computed tomography using unmatched projector/backprojector pairs, Medical physics 43, Vol 6, p. 3019–3033, 2016.

[26] J. Maier, C. Leinweber, S. Sawall, H. Stoschus, F. Ballach, T. Müller et al., Simulation-Based Metal Artifact Reduction for Computed Tomography of Multi-Material Components, 2016.

[27] R. Alvarez, A. Macovski, Energy-selective reconstructions in X-ray computerized tomography, Physics in medicine and biology 21, Vol 5, p. 733–744, 1976.

[28] C. Heinzl, J. Kastner, E. Gröller, Surface extraction from multi-material components for metrology using dual energy CT, IEEE transactions on visualization and computer graphics 13, Vol 6, 2007.

[29] V. Rebuffel, J.-M. Dinten, Dual-energy X-ray imaging: benefits and limits. In: Insight-non-destructive testing and condition monitoring 49, Vol 10, p. 589–594, 2007.

[30] C. Heinzl, M. Reiter, M. Allerstorfer, J. Kastner, E. Groller (Hg.), Artefaktreduktion mittels Dual Viewing für Röntgencomputertomographie von Multimaterialbauteilen, DGZFP-Jahrestagung 2010, 2010.

[31] H. Ballhausen, M. Reiner, U. Ganswindt, C. Belka, M. Söhn, Post-processing sets of tilted CT volumes as a method for metal artifact reduction, Radiation Oncology 9, Vol 1, p. 114, 2014.

[32] J. Guhathakurta, S. Kiess, J. Hillebrand, J. Denecke, I. Effenberger, S. Simon, Reducing Computed Tomography Reconstruction and Beam Hardening Artifacts by Data Fusion, Digital Industrial Radiology and Computed Tomography, 2015.

[33] L. A. Feldkamp, L. C. Davis, J. W. Kress, Practical cone-beam algorithm, J. Opt. Soc. Am. A 6, Vol 1, p. 612-619, 1984.

[34] T. Buzug, Computed Tomography, Springer, p. 175, 2008.

[35] S. Klein, M. Staring, K. Murphy, M. A. Viergever, J. P. W. Pluim, Elastix: a toolbox for intensity-based medical image registration, IEEE transactions on medical imaging 29, Vol 1, p. 196–205, 2010.