Modifications of Iterative Reconstruction Algorithms for the Reduction of Artefacts in High Resolution X-Ray Computed Tomography

Loes Brabant[1], Manuel Dierick[1], Elin Pauwels[1],Yoni De Witte[1] and Luc Van Hoorebeke[1]

[1]UGCT-Department of Physics and Astronomy, Faculty of Sciences, Ghent University, Proeftuinstraat 86, 9000 Ghent, Belgium [email: Loes.Brabant@UGent.be]

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ABSTRACT

X-ray Computed Tomography is a non destructive technique which allows for the visualization of the internal structure of complex objects. Most commonly, algorithms based on filtered backprojection are used for reconstruction of the projection data obtained with CT. However, the reconstruction can also be done using iterative reconstructions methods. These algorithms have shown promising results regarding the improvement of the image quality. An additional advantage is that these flexible algorithms can be modified in order to incorporate prior knowledge about the sample during the reconstruction, which allows for the reduction of artefacts. In this paper some of these advantages will be discussed and illustrated: the incorporation of an initial solution, the reduction of metal artefacts and the reduction of beam hardening artefacts.

1. INTRODUCTION

With high resolution X-ray Computed Tomography (CT) the internal structure of complex objects can be visualised in a non destructive way. The resulting data can be analysed in order to obtain quantitative information of the sample. For optimal accuracy of the analysis it is important to start from reconstructions with high image quality and as few artefacts as possible. At the Centre for X-ray Tomography of the Ghent University (UGCT) the differences in currently available reconstruction algorithms and possible methods to improve these algorithms are investigated.

Although reconstruction is most commonly done with the algorithm of Feldkamp, David and Kress (FDK, Feldkamp *et. al* 1984) there are alternative approaches, such as iterative reconstruction algorithms, which have shown promising results for the improvement of image quality. The main reason why these algorithms are not used is because, in comparison with filtered backprojection, they result in longer reconstruction times. However, this can be compensated by using an efficient implementation on a graphical processing unit**.**

Iterative reconstruction methods have better noise handling. They can provide improved results in case the projection data is limited to a certain angular range (limited angle tomography) or when the total number of available projections is limited (De Witte 2010)**.** Additionally they can reduce artefacts which often occur in high resolution CT (De Witte 2010), such as cone beam artefacts, metal artefacts and beam hardening (Hsieh et al 2000)**.** An important advantage of iterative reconstruction methods is that they can be implemented in a flexible way, which allows for the possibility to include prior knowledge about the X-ray beam or the sample in the reconstruction algorithms. This can, for example, be used to reduce metal artefacts, for example in De Man *et al.* 2000, or to incorporate physical processes which can be modelled, such as beam hardening like in Brabant *et al.* 2012, in the reconstruction process. When a sample needs to be scanned twice, before and after it has undergone a relatively small change, the first scan can be used as input for the reconstruction of the second scan, which drastically reduces the number of required projections for the second scan. There exist approaches that enforce similarity with a previously collected dataset, such as the PICCS algorithm (Chen *et al.* 2008).

In this paper the basic principles of iterative algorithms will be explained and some of the previously mentioned advantages will be discussed and illustrated: the incorporation of an initial solution, the reduction of metal artefacts and the reduction of beam hardening artefacts.

2. BASIC PRINICIPLES OF ITERATIVE RECONSTRUCTION METHODS

All iterative reconstruction methods start from an initial solution; usually this is an empty volume. This intermediate solution is forward projected to construct a *calculated* projection. The difference between this calculated and the measured projection is determined and backprojected using a weighted average. Subsequently it is added to the intermediate reconstructed volume; this is the update step of the algorithm.

There exist two main classes of iterative reconstruction methods: algebraic or statistical methods. The most important difference between these methods is that algebraic methods use integrated attenuation values in the update step, while statistical methods use the expected number of photons. In case of poor statistical information statistical methods can yield better results, however in high resolution CT the available statistical information is usually efficient so algebraic methods can be used. For the Simultaneous Algebraic Reconstruction Technique (SART), which is most often used at UGCT, the update process of a volume of *N* cubic voxels is given by (Andersen and Kak 1984):

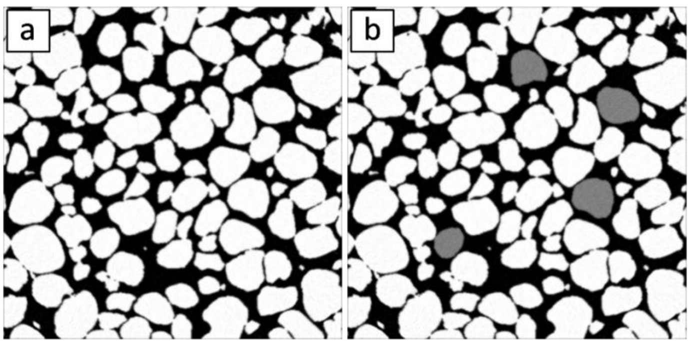
$$\mu_j^{(k+1)} = \mu_j^k + \lambda \frac{\sum_{r_i \epsilon P_\phi} \left(\frac{r_i - \sum_{n=0}^{N} w_{in} \mu_n^k}{\sum_{n=0}^{N} w_{in}} \right) w_{ij}}{\sum_{r_i \epsilon P_\phi} w_{ij}}. \quad (1)$$

Here, μ_j^k is the linear attenuation coefficient of voxel j after the k-th iteration, λ is a relaxation parameter, r_i is the total measured attenuation along ray *i* and P_ϕ is the projection with projection angle ϕ. w_{ij} represents the weights, which determine how much every grid point contributes to the total sum of the ray.

3. THE INCORPORATION OF AN INITIAL SOLUTION

Sometimes one wants to investigate the effects of a certain modification of a sample with CT. For example when one wants to investigate if a sample absorbs water or another fluid. In this case, two scans of the same sample are needed, one before the modification and one after the modification. If the introduced modifications are not too extensive, it is possible to reduce the number of required projections for the second scan when iterative methods are used for reconstruction. Indeed, iterative algorithms start from an initial solution, so the reconstruction of the first scan can be used as input for the second scan.

This principle is illustrated with simulations of a phantom in figure 1. For this simulation, the projections of a virtual phantom of sample sand, of which a slice is shown in figure 1a, were simulated with the in house developed *Projection Simulator* (De Witte 2010)**.** This volume was reconstructed with 512 projections and 1 iteration. Subsequently, the gray values of four of the grains changed (figure b) and again the projections of this second sample were simulated. The same slice for this sample is shown in figure 1b. Figure 1c, shows the same slice, reconstructed with 20 iterations and only 16 projections using the reconstruction of the first sample as initial solution. The four coloured grains can clearly be identified. Figure 1d shows the same reconstruction, but this time no initial solution was used. In this figure, none of the grains can be identified.



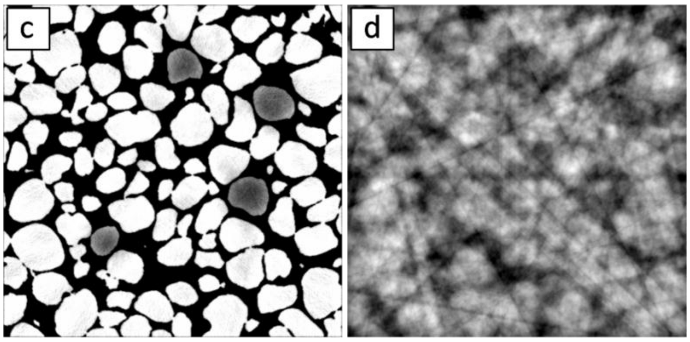


Figure 1: *Slice in a virtual phantom of sand. In the first sample, all grains are white (a), in the second sample four grains were coloured (b). The second sample was reconstructed with only 16 projections, with the reconstruction of the first sample as initial solution (c) and without an initial solution (d)*

4. METAL ARTEFACT REDUCTION

When metals are present in a sample which is scanned with laboratory based high resolution CT, streak artefacts can occur in the reconstructed image(s). If the reconstructions are done with iterative methods, these artefacts can be reduced by modifying the algorithm. A possible way to do this is to implement a condition which ensures that only the detector pixels with an attenuation below a certain threshold *T* are backprojected, unless the difference with the forward projected attenuation is very small. The last condition is added to ensure that a large number of voxels with a relatively small attenuation value which lie along one ray and result in a ray sum which is larger than the selected threshold are still updated. The result is illustrated for a slice of a scanned toy sample in figure 2.

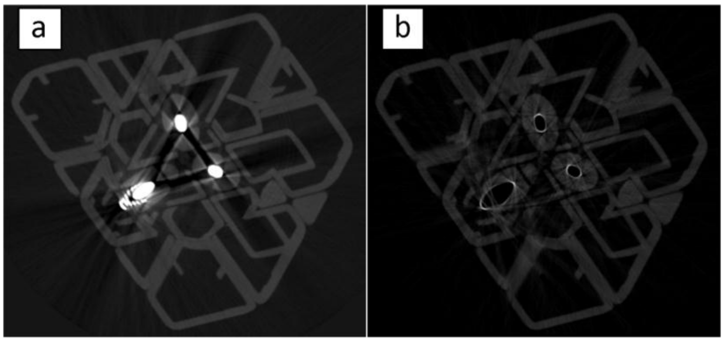


Figure 2: *Reconstructed cross-section of a scanned toy containing metal with SART, without (a) and with (b) metal artefact reduction with T = 1* $\boldsymbol{cm^{-1}}$.

5. BEAM HARDENING

The X-ray spectrum for laboratory based high resolution X-ray tomography is polychromatic, and X-rays with a low energy are more attenuated when propagating through a sample than X-rays with a high energy (hardening of the beam). Most reconstruction algorithms do not take this polychromaticity into account, which results in artefacts such as cupping. It is possible to model this beam hardening and incorporate it in the forward projector of the SART algorithm, the update step in equation (1) then becomes (Brabant *et al.* 2012):

$$\mu_j^{(k+1)} = \mu_j^k + \lambda \frac{\sum_{r_i \epsilon P_\phi} \left(\frac{r_i - \sum_{n=0}^{N} w_{in} \left(\frac{\mu_n^k}{\left(1 + \alpha \sum_{i=0}^{(n-1)} \mu_i^k\right)^\beta} \right)}{\sum_{n=0}^{N} w_{in}} \right) w_{ij}}{\sum_{r_i \epsilon P_\phi} w_{ij}}, \quad (2)$$

with $\alpha \in [0, 1]$ the strength of the correction and $\beta \in [2.5, 3.5]$ the energy dependency. The complete derivation of this equation can be found in Brabant *et al.* 2012. Figure 3 illustrates the effect of this beam hardening correction on a scanned aluminium sphere.

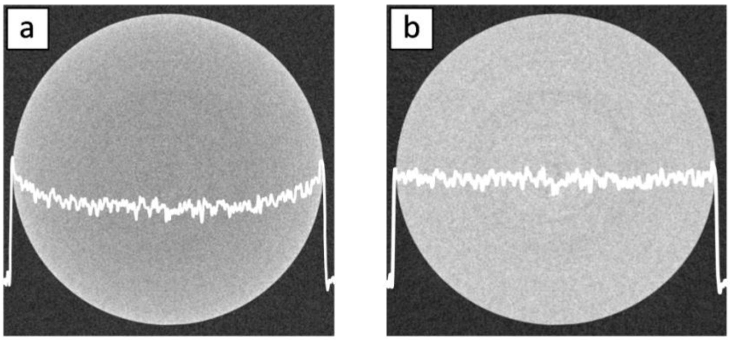


Figure 3: *Reconstructed cross-section of a scanned aluminium sphere with SART, without (a) and with (b) beam hardening correction performed with equation (2), with $\boldsymbol{\alpha}$ = 0.003 and $\boldsymbol{\beta}$ = 3.0. A line profile along the diameter of the sphere is shown in white.*

6. CONCLUSIONS

Iterative reconstructions algorithms are a useful alternative for reconstruction algorithms based on filtered backprojection. These algorithms can be adapted so prior knowledge about the sample or the beam can be incorporated, which allows for the reduction of artefacts or the required number of projections. We have illustrated the advantages of these methods, with the incorporation of an initial solution, the reduction of metal artefacts and the reduction of beam hardening artefacts.

7. ACKNOWLEDGEMENTS

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