



HAL
open science

Adapted acquisition trajectory and iterative reconstruction for few-views CT inspection

Marius Costin, Caroline Vienne

► **To cite this version:**

Marius Costin, Caroline Vienne. Adapted acquisition trajectory and iterative reconstruction for few-views CT inspection. 8th Conference on Industrial Computed Tomography (iCT 2018), Feb 2019, Wels, Austria. 21917 (8 p.). hal-04558342

HAL Id: hal-04558342

<https://hal.science/hal-04558342>

Submitted on 24 Apr 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Adapted acquisition trajectory and iterative reconstruction for few-views CT inspection

Caroline Vienne¹, Marius Costin¹

¹CEA, LIST, Département Imagerie et Simulation pour le Contrôle, F-91191 Gif-sur-Yvette, France, e-mail: caroline.vienne@cea.fr

Abstract

One of the major stakes of industrial Computed Tomography (CT) is the reduction of acquisition time in order to allow its use directly in production lines. With the introduction of robotic systems, which are capable of taking each piece from the production conveyor and to manipulate them inside an X-ray beam or to directly move the X-ray equipment around the object, new opportunities arise. Especially, the inspection trajectory is no more limited to one acquisition plane and when combined with an adequate algorithm, a satisfactory CT reconstruction can be obtained from few X-ray projections.

Such 3D trajectory makes the classical analytic reconstruction algorithms inappropriate and requires the use of 3D iterative reconstruction algorithms. In this work, we focus on two iterative algorithms, the well-known Simultaneous Algebraic Reconstruction Technique (SART) and the Discrete Algebraic Reconstruction Technique (DART), which integrates prior knowledge on the object, to perform 3D reconstructions from a limited data set. The performances of both algorithms on complex trajectories are evaluated in simulation environment using the CIVA software from CEA List and real acquisitions on non standard trajectories are performed with the robotic platform and reconstruction results with SART and DART algorithms are presented and compared.

Keywords: Robotized inspection, Iterative algorithms, sparse trajectory

1 Introduction

Among the various non-destructive testing (NDT) methods, X-ray computed tomography (CT) is a powerful tool to characterize and localize inner flaws and to verify the geometric conformity of an object. The number of industrial applications of CT is large and rapidly increasing with typical areas of use in the aerospace, automotive and transport industry. To support this growth of CT in the industrial field, robotized systems are being developed. They allow an increased flexibility with regards to the object and its environment but also bring new constraints such as a limited workspace. In this context, a robotic platform is being installed at CEA List to better understand and solve specific challenges linked to the robotization of the CT process [1]. The considered system integrates two high accuracy robots controlled with a master-slave strategy that move respectively the X-ray generator and detector.

In this work we are more particularly interested with the most obvious limitation brought by robotics manipulation, which is the impossibility to perform a standard circular trajectory. To deal with this limitation, various methods adapted to limited-angle trajectories have been proposed. The first achievement was the half-scan fan-beam, which corresponds to 180 degrees plus the opening angle of the fan. A weighting function to handle redundant data in case of a half-scan fan-beam reconstruction was introduced [2]. Later, 2D and 3D reconstruction methods with fan-beam and cone-beam projections, respectively, on less than a short scan were developed [3]. However, the performance of these algorithms is limited to a certain degree depending on the scanning angle range. This is due to the analytical nature of the algorithm and which is known to be more affected by missing data compared to its iterative counterpart. Specifically, the limitations of the algorithm could be viewed when the scanning angle is less than the short-scan range. In this case, it is not possible to reconstruct the whole object and only a region in the object can be reconstructed correctly. On the other hand, regularized iterative algorithms can perform much better with limited-angle data [4].

In this work, we focus on two iterative algorithms, the well-known Simultaneous Algebraic Reconstruction Technique [5] (SART) and the Discrete Algebraic Reconstruction Technique [6] (DART), which integrates prior knowledge on the object, to perform 3D reconstructions from a limited data set. The performances of both algorithms on complex trajectories are evaluated in simulation environment using the CIVA [7-8] software from CEA List and additional reconstruction results on real data acquired with the robotic platform are presented.



2 X-ray robotized inspection

2.1 Robotic X-ray CT setup

The X-ray equipment consists in a Viscom 225 kV microfocus tube with a tungsten target and a Perkin Elmer flat panel detector with 1024 x 1024 pixels of size of 200 μm . Two robots of KUKA's HA "High Accuracy" series are used to manipulate the X-ray source and detector. Robots are chosen so as to be compatible with these RX elements weight and to ensure good performances in terms of stability and repeatability. The complete robotic system is shown in Figure 1. It is installed inside a protected room of 4 m width and 6 m long, which allows the inspection of large components.

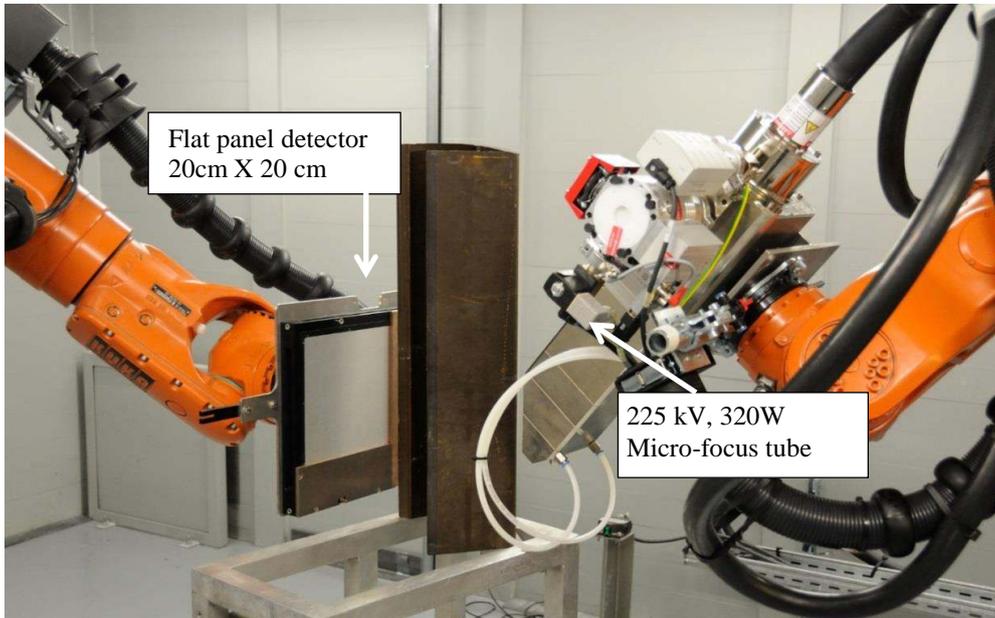


Figure 1. The robotic X-ray inspection platform installed at CEA List.

2.2 Identified challenges

Among the new challenges brought by the robotized tomography, we focus here more particularly on the limited access viewpoint imposed by the setup. To deal with this limitation, we highly rely on combination of robotics and CT simulation. CSR robotics software [9] is used to validate the accessibility of the trajectory and determine the maximum angular range we can expect (see Figure 2).

When a new trajectory is loaded, its accessibility by each robot is tested and a feedback is given to the user by colouring reachable points in green and non-reachable ones in red. Evaluation performed with the installed setup allows a maximum angular range of about 160°. The CIVA software is then used to simulate X-ray projections corresponding to such a trajectory and assess the capability of the reconstruction algorithm.



Figure 2: Model of the source robot (left) and the detector robot (centre) in CSR software and example of the visualization of the accessible trajectory (right).

3 Iterative reconstruction algorithms

For our application case, a sufficient amount of statistical information is available. Thus, among iterative algorithms we choose algebraic ones. In particular, we consider two regularized algebraic methods that minimize the Total Variation (TV) of the image. TV minimization [10] is a regularization term that enforces smoothness in the reconstructed image to account for unrealistic variations between neighbouring. This regularization tends to smooth out noise while preserving image edges. In addition, both algorithms integrate fast iterative shrinkage-thresholding algorithm (FISTA) technique to speed up the convergence speed [11].

3.1 SART-FISTA-TV algorithm

The Algebraic Reconstruction Technique (ART) was the first algorithm to be used in CT scanners [5]. It is a pure iterative algorithm without any modeling based on Kaczmarz method to solve the linear system $\mathbf{P} = \mathbf{A} \cdot \mathbf{f}$, where \mathbf{P} represents the projection data, \mathbf{A} refers to the projection system model and \mathbf{f} defines the voxel values in the object. The update of the value of each voxel of the reconstructed volume through ART algorithm is written as follows:

$$\mathbf{f}_j^{k+1} = \mathbf{f}_j^k + \lambda \frac{\sum_{p_i \in P_\theta} \frac{p_i - \sum_{n=1}^N a_{in} \mathbf{f}_n^k}{\sum_{n=1}^N a_{in}} a_{ij}}{\sum_{p_i \in P_\theta} a_{ij}},$$

where p_i represents a single pixel in the projection data P_θ acquired at the view angle θ , a_{ij} is an element in the matrix \mathbf{A} and k is the iteration index.

The SART update is then combined with a TV regularization and FISTA acceleration step, which is written as:

$$\mathbf{f}^{k+1} = \mathbf{f}^k + \frac{t^k - 1}{t^{k+1}} (\mathbf{f}^k + \mathbf{f}^{k-1}), \quad \text{with } t^{k+1} = \frac{1 + \sqrt{1 + 4(t^k)^2}}{2} \text{ and } t^0 = 1.$$

The combination of these regularization and acceleration steps brings a real improvement in the reconstruction, as can be seen in the simulation validation presented in Figure 3. For this validation, we consider a multi-disk object that includes square and circular holes as well as square and circular inclusions. A semi-helical trajectory is simulated with an angular range of 150° . The reconstruction is performed first with the SART algorithm and then with the SART-FISTA-TV one. A horizontal and vertical slice of the reconstructed volume is displayed with a 1D numerical comparison along the red line. In this limited-angle configuration, SART-FISTA-TV algorithm improves greatly the result compared with SART approach. The orthogonal slices in the reconstructed volume appear to be accurate and there are no streak artefacts caused by the limited number of projections.

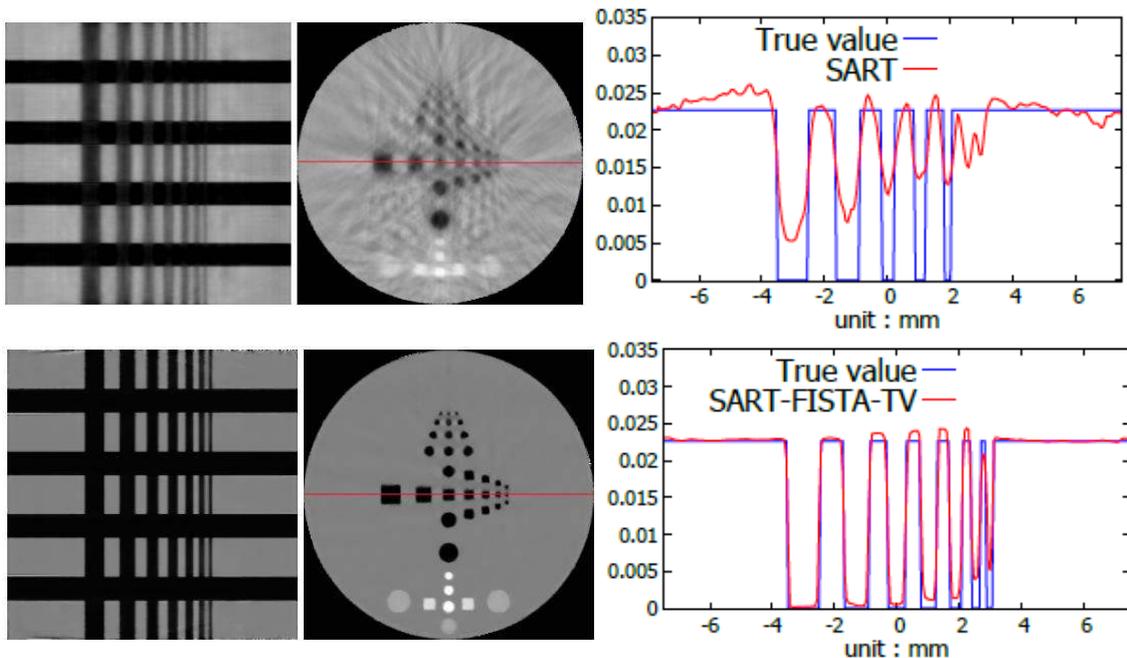


Figure 3: Comparison of SART (top) and SART-FISTA-TV reconstructions from an acquisition trajectory limited to 150° .

3.2 DART-FISTA-TV algorithm

When inspecting industrial objects, the different materials (aluminum, steel, plastic...) of the scanned object are often known in advance and thus an approximate value of the corresponding gray levels in the reconstruction could be defined. An iterative algorithm named DART has been developed [4] which can incorporate such prior knowledge of gray levels for each composition and can be applied if the object consists of five or less different materials. It is a regularized algebraic method that can produce accurate reconstruction results under extremely limited data conditions. Starting from an initial conventional algebraic reconstruction method like, a threshold operation is applied to obtain a segmented image that only has the pre-determined gray levels. A region U that contains the boundary region of the segmented image and other randomly added pixels is then defined. The pixels that do not belong to U are considered as fixed and are assigned their threshold values, whereas algebraic iterations on the non-fixed pixels belonging to U are performed again to refine the uncertain boundaries of the segmented image. By fixing the value of the pixels not belonging to region U , the number of unknowns in the system of linear equations is reduced and therefore the system becomes better determined. Finally, a Gaussian smoothing filter is applied before the iteration is repeated. The Gaussian filter is a way to reduce the fluctuations over the boundary pixels and to deal with noise.

We propose here to replace the Gaussian smoothing step by TV minimization combined with FISTA acceleration. The overall algorithm scheme is presented in Figure 4.

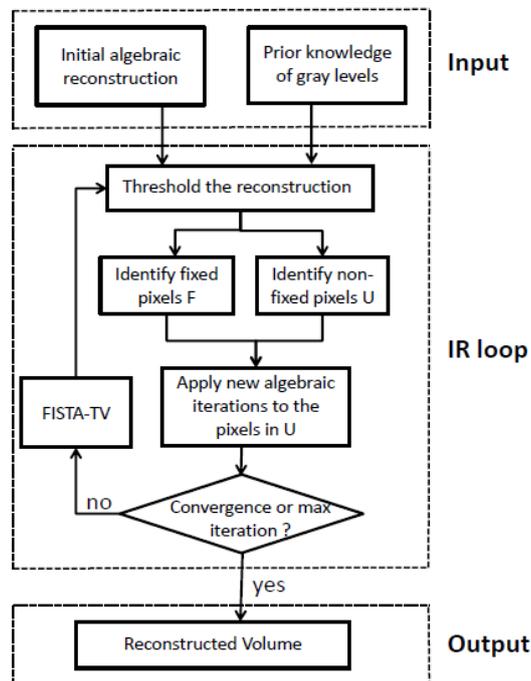


Figure 4: Principle of the DART-FISTA-TV algorithm

For numerical validation of DART-FISTA-TV, we show in Figure 5 reconstruction results from the same acquisition used for the validation of SART-FISTA-TV algorithm. Visually, DART-FISTA-TV appears to provide improved image reconstruction over SART-FISTA-TV and gives a more accurate reconstruction as we can see from the 1D numerical comparison between the real values and the reconstructed ones plotted along the red line.

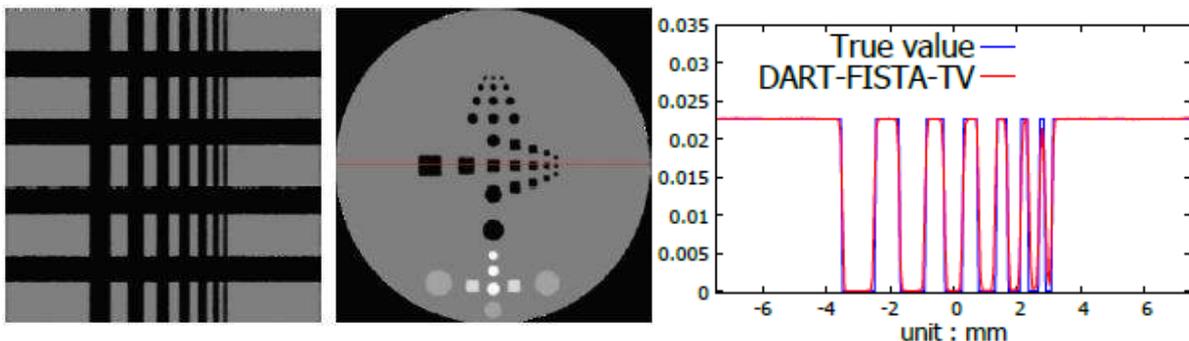


Figure 5: Reconstruction results with DART-FISTA-TV algorithm

4 Reconstruction on non-standard trajectories

By moving the X-ray source and detector with the robots, the acquisition trajectory is no longer constrained to a unique plane and so-called ‘non-standard’ trajectories can be realized. To keep a constant magnification, acquisition points are distributed on a sphere surface (see Figure 6). Each source point (in blue) is described by its spherical coordinates (ρ , θ , φ) and a partial spherical trajectory can be defined by fixing a limited angular range for the parameters θ and φ .

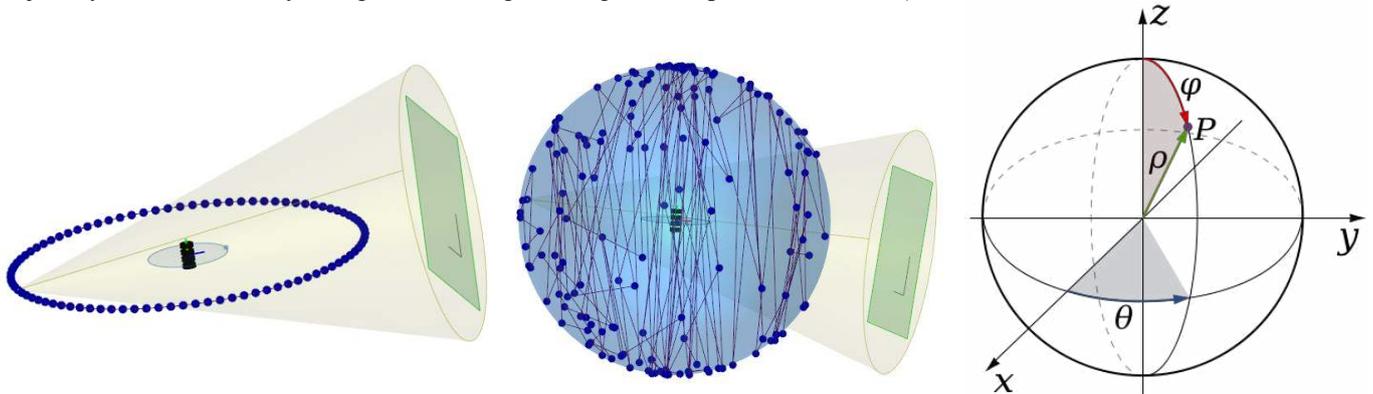


Figure 6: Classical circular trajectory (left) and “non-standard” spherical one (centre) simulated in CIVA environment. The source position in 3D space is described by its spherical coordinates (right).

In order to take into account the limitation of the robot workspaces, we consider angular-limited trajectory. More particularly, we compare the following three configurations:

- $\theta = 140^\circ$, $\varphi = 0^\circ$, 160 projections randomly distributed
- $\theta = 100^\circ$, $\varphi = 0^\circ$, 160 projections randomly distributed
- $\theta = 100^\circ$, $\varphi = 40^\circ$, 160 projections randomly distributed

The 3D view of the CIVA simulation scene, including the multi-disk phantom and the source trajectory (blue points), and the reconstruction results from SART algorithm are given in Figure 7. For each reconstruction two orthogonal slices are displayed. These few configurations give a first qualitative assessment of the impact of angular range in the reconstruction quality. A small angle out of the circular plane ($\varphi=40^\circ$) improves significantly the reconstruction of the object horizontal edges.

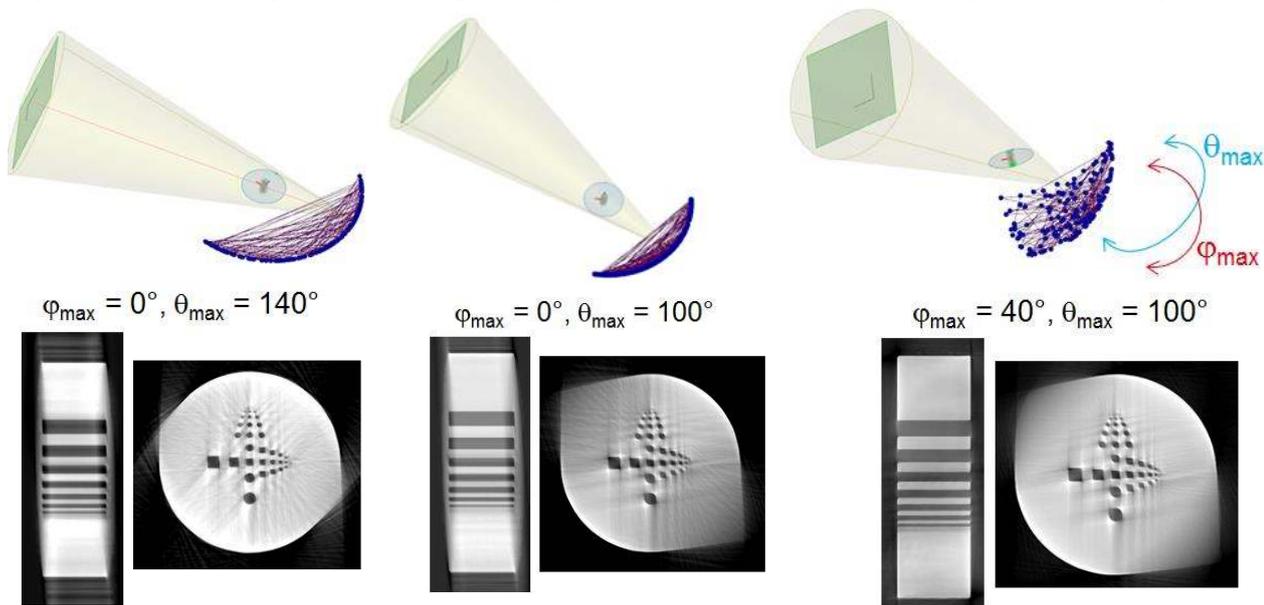


Figure 7: Visual comparison of three acquisition configurations reachable by the robotic system.

In the last configuration, we also perform the reconstruction with the DART algorithm and compare in Figure 8 the results obtained with the reconstruction of the SART algorithm. Intensity profiles are plotted along two directions and clearly show the improvement brought by the DART algorithm, especially along the diagonal of the reconstructed image. The information missing because of the limited angle of the trajectory affects significantly the quality of the reconstruction by SART and introduces a strong blur on the object edges. On the contrary, DART strategy allows a better definition of the object contours (see intensity profiles on Figure 8).

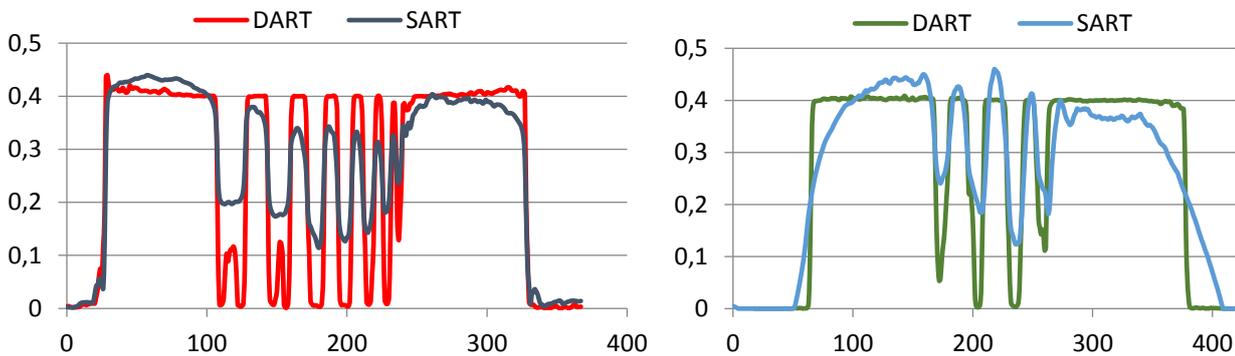
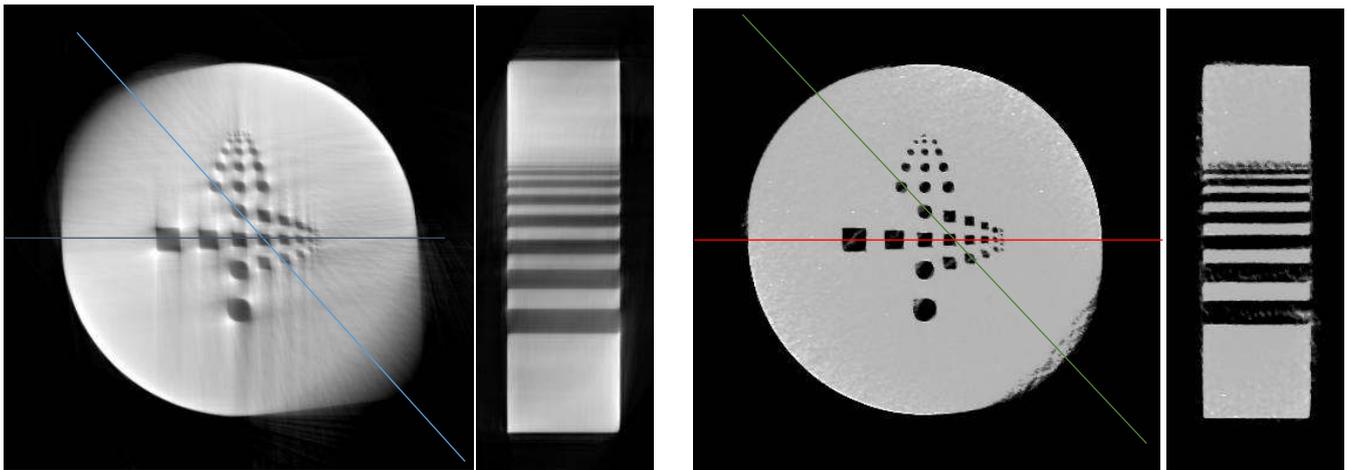


Figure 8: Comparison of CT reconstruction obtained with DART and SART algorithms from 160 projections acquired on a very limited angle trajectory.

5 Reconstruction on real data

An experimental acquisition on an incomplete trajectory limited to 150° is performed with the robotic system. The distances source-object and source-detector are 20 cm and 60 cm, respectively. During this inspection the two robots move while the object remains fixed (see Figure 9). The X-ray tube voltage is set to 150 kV and the current to $500 \mu\text{A}$. The considered object is an additive manufactured lattice structure in aluminum of size $8 \times 8 \times 8 \text{ cm}^3$. A sparse set of 30 projections is acquired along a circular trajectory limited to 150° .

The reconstruction is performed respectively with the SART-FISTA-TV and DART-FISTA-TV algorithms and the results are presented in Figure 10. A 3D view of the reconstructed volume and three orthogonal slices are shown. Visually, DART ensures a good reconstruction of the lattice structure from only 30 projections with sharp contours compared to SART reconstruction. However, in this case the support of the structure is not well reconstructed because of the beam hardening effect that modifies the values of the attenuation coefficient and should be corrected before applying DART strategy.

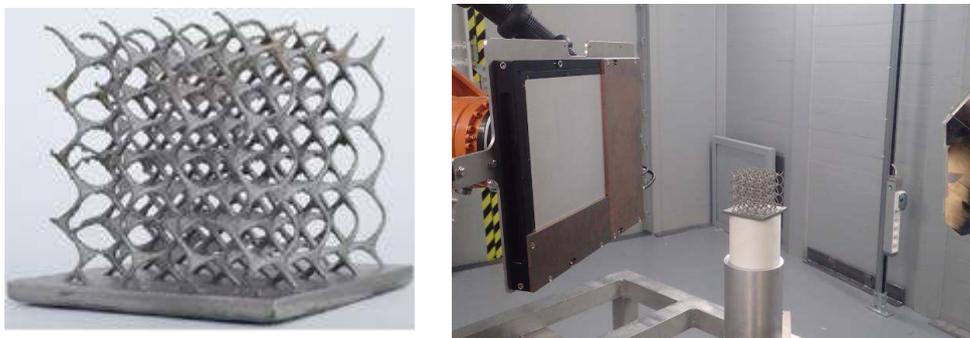


Figure 9: Lattice structure considered for the CT inspection (left) and view of the acquisition setup (right)

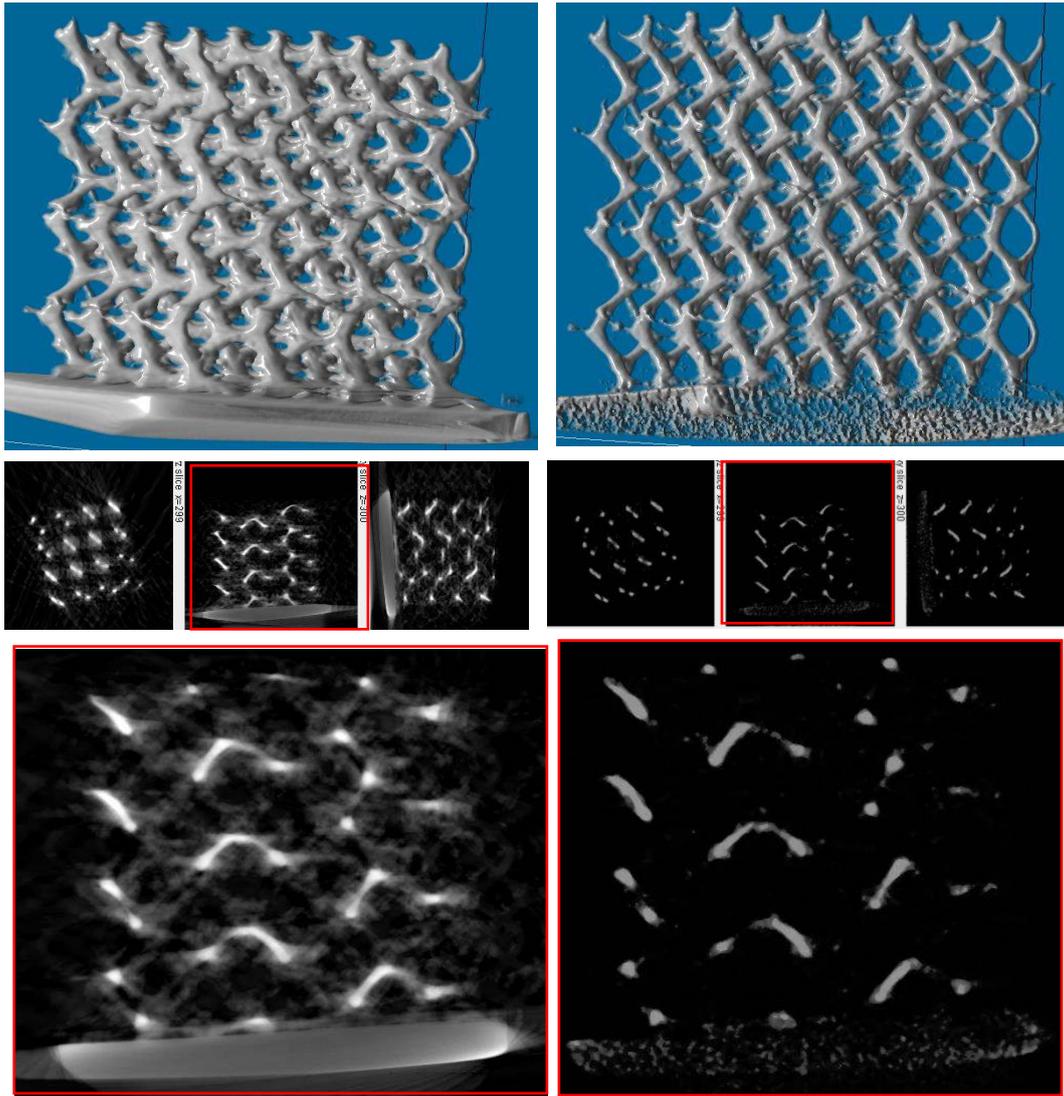


Figure 10: CT reconstructions of the lattice structure from 30 projections using SART (left column) and DART (right column) algorithms.

6 Conclusions

We presented in this work two regularized algebraic algorithms called SART-FISTA-TV and DART-FISTA-TV able to handle robotic CT trajectories. Compared to SART, it was shown that these two algorithms improve the image quality significantly when the scanning angle is relatively small and less than the half-scan range. We showed by numerical simulations that these algorithms are capable of reconstructing relevant 3D information from partial 2D and 3D trajectories. As expected, these algorithms work well with very few projections and no streak-like CB artefacts appear in the reconstruction.

References

- [1] H. Banjak, M. Costin, C. Vienne and V. Kaftandjian. "X-ray Computed Tomography Reconstruction on Non-Standard Trajectories for Robotized Inspection", 19th World Conference on Non-Destructive Testing 2016, Munich, Germany, 2016.
- [2] D. Parker, "Optimal short scan convolution reconstruction for fan-beam CT" *Med. Phys.*, pp. 9:254-257, 1982.
- [3] H. Kudo, F. Noo, M. Defrise and R. Clackdoyle, "New super-short-scan algorithms for fan-beam and cone-beam reconstruction", *IEEE Nuclear Science Symposium Conference Record*, vol. 2, pp. 902-906, 2002.
- [4] H. Banjak, M. Costin, C. Vienne, R. Guillaumet and V. Kaftandjian, "Iterative CT reconstruction on limited angle trajectories applied to robotic inspection", *QNDE*, Atlanta, United States, 2016.
- [5] R. Gordon, R. Bender et G. T. Herman, "Algebraic reconstruction techniques (ART) for three-dimensional electron microscopy and X-ray photography", *Journal of theoretical Biology*, vol. 29, No 13, pp. 471-481, 1970.
- [6] K. J. Batenburg and J. Sijbers, "DART: a practical reconstruction algorithm for discrete tomography". *IEEE Trans. on Image Processing*, vol. 20, No 9, pp. 2542-2553, 2011.
- [7] M. Costin, D. Tisseur, C. Vienne, R. Guillaumet, H. Banjak, N. Bhatia and R. Fernandez, "CIVA CT, an advanced simulation platform for NDT," in 6th Conference on Industrial Computed Tomography, Wels, Austria, 2016.

- [8] CIVA, "<http://www-civa.cea.fr>," [Online].
- [9] CSR, "<http://www.acel.co.uk/cimstation-robotics/>," [Online].
- [10] E. Y. Sidky, C. Kao, and X. Pan. "Accurate image reconstruction from few-views and limited-angle data in divergent-beam CT". In: *Journal of X-ray Science and Technology* 14.2, pp. 119–139, 2006.
- [11] A. Beck and M. Teboulle. "A fast iterative shrinkage-thresholding algorithm for linear inverse problems". In: *SIAM journal on imaging sciences* 2.1, pp. 183–202, 2009.