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Cooperative data fusion of transmission and surface scan for improving limited-angle computed tomography reconstruction

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ABSTRACT

Limited-angle computed tomography allows faster inspection during production, but the reconstruction from limited-angle transmission data is an underdetermined problem which cannot be solved without any prior knowledge of the sample. In this paper, surface data from an optical scan is selected as prior information due to its high accuracy and availability. To incorporate this information, we have developed a new cooperative data fusion model in the compressed sensing framework. The model has been applied to numerical and experimental data and solved with a tailored algorithm. We demonstrate the benefit of the data fusion model and prove the robustness of the algorithm. The results from this study indicate that the data fusion process combines features resolved by both modalities and gives a significant increase in image quality. These improvements enable metrological measurements that are impossible with data acquired with any single modality.

1. Introduction

Computed tomography (CT) is an indirect imaging method to extract cross-sectional information of a specimen. In an x-ray transmission CT, a volume representing the attenuation coefficients is reconstructed from a series of projection images, which allows resolving material compositions of the sample under investigation and performing metrological measurements. After acquiring full angle non-truncated data along a circular trajectory using a cone beam x-ray source and a flat panel detector, the attenuation coefficients of the sample in the trajectory plan can be accurately reconstructed by filtered backprojection (FBP) [1,2] up to the sampling frequency while the attenuation coefficients in the rest of the reconstruction volume can be estimated by the Feldkamp–Davis–Kress (FDK) [3] algorithm.

In many applications, a full angle scan is prohibited by the shape of the sample or the limited scanning time. The reconstruction from a partial angular range scan is referred to as limited-angle tomography. Due to the missing data, the reconstruction problem becomes underdetermined. Without prior knowledge, conventional methods fail to reconstruct the sample correctly [4].

Previous research has shown promising results by adding cooperative prior data, i.e. complementary data acquired with a different modality, such as low resolution CT scan [5] or CAD. However, using a CT image as prior data requires a repeated measurement while CAD of the sample is not always provided. Surface scanning data, on the other hand, can be acquired comparably easily with an optical scanner giving it a unique advantage in availability. Surface scanning refers to optical systems that measure objects through visible light and generate dense 3D polygonal meshes. Conventionally, the optical data is used as the image support during a reconstruction [6,7]. The key requirement of conventional algorithms is a perfect, water-tight mesh surface representation and these approaches do not consider other objects in the field of view, which may lead to an over estimation of the attenuation coefficients of the sample under investigation. However, defective mesh surfaces with holes are more common in practice. Limitations of optical scanning arise if real-world points cannot be clearly identified in stereoscopic imaging or as part of the projected fringe pattern and as a result, the mesh contains holes. In this paper, cooperative data from surface scanning is fused with the x-ray projections during CT reconstruction.

By exploring the sparseness property of the image and making certain assumptions on the nature of the image, the solution to the limited-angle problem can be improved significantly by using compressed sensing (CS) theory. However, this is still not sufficient to lead to a unique solution to the problem, because the system

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matrix used in the reconstruction contains null space. Cooperative data fusion of surface data and transmission data reduces the null space and further improves the reconstruction result. In this paper, we propose a new model to fuse incomplete optical surface data with CT data. The fusing process takes place in the form of an iterative CT reconstruction with prior information. Iterative reconstruction algorithms are able to incorporate noise models, complex geometry as well as more sophisticated physical models to construct a more accurate estimation of the image to be reconstructed. The optical data as prior information translates into a regularization term in this estimation.

This paper is structured as follows. In Section 2, we introduce the date fusion model to incorporate surface data with transmission CT data and utilize the alternative direction method of multiplier (ADMM) [8] to compute the model. In Section 3, the improvement from the data fusion is demonstrated with simulation results and experimental results. The impact of our new data fusion model and the conclusion of our study are summarized in Section 4.

2. Materials and methods

2.1. Model for CT imaging

The attenuation of a three dimensional object is defined as a bounded function compactly supported on a three dimensional space, $f: \Omega \mapsto \mathbb{R}^3$, where $\Omega \subset \mathbb{R}^3$ is the set of coordinates in the reconstruction region. The measurement of the object is performed by projecting the object onto a 2D plane from a series of known angles with respect to the object [9]. The measurement process can be represented as

$$P_\theta f(\mathbf{e}) = \int_0^{L(\mathbf{e})} f(S(\theta) + nl)\mathrm{d}l \tag{1}$$

where $S(\theta) \in \mathbb{R}^3$ is the source position with respect to the object, which depends on the angle of the measurement. $\mathbf{e}(u, v) \in \mathbb{R}^2$ is the coordinate of a detector pixel on a 2D flat panel detector, while n is the normalized vector pointing from $S(\theta)$ to $\mathbf{e}$. $L(\mathbf{e})$ denotes the distance from the source to the detector element. The function $P_\theta f$ is referred to as a projection from angle θ. The geometry is illustrated in Fig. 1.

In numerical representation, the reconstruction region is discretized into N_x voxels, where $N_x = n_1 n_2 n_3$ and n_1, n_2, n_3 are the number of voxels in x, y, z direction. The attenuation coefficients are represented as $\mathbf{x} \in \mathbb{R}^{N_x}$ with the ith element of $\mathbf{x}$ being x_i. The measurement process will be approximated by replacing the integration with a summation:

$$y_j^\theta = \sum_{i=1}^{N_x} A_{ij} x_i \tag{2}$$

where y_j^θ denotes the total attenuation along the ray from the source to the center of the $j^{th}(j = 1, \ldots, N_y)$ detector element, where N_y is the number of pixels on the detector. The intersecting length of this specific ray in the ith voxel is $\mathbf{A}_{ij}$. Placing all the attenuation values from one projection into one vector results in the representation of a forward projection:

$$\mathbf{y}^\theta = \mathbf{A}^\theta \mathbf{x} \tag{3}$$

where $\mathbf{A}^\theta \in \mathbb{R}^{N_x \times N_y}$ is the forward projection matrix and $\mathbf{y}^\theta \in \mathbb{R}^{N_y}$ is a single projection. During a conventional cone beam CT scan, the source rotates around the object at a fixed distance while maintaining the central ray being perpendicular to the axis of rotation. To simplify the notation of a limited-angle cone beam CT model, we assume that the scanning angle is symmetric about the position of 0°, i.e. the scanning angle range is $[-\theta, \theta]$, and the N_{proj} projections are uniformly distributed in the $[-\theta, \theta]$ interval. Thus, the limited-angle cone beam CT can be denoted as:

$$\mathbf{y}^\Phi = \mathbf{A}^\Phi \mathbf{x} + \eta \tag{4}$$

where $\mathbf{A}^\Phi \in \mathbb{R}^{N_{proj} \times N_x \times N_y}$ is the limited-angle cone beam CT system matrix. $\mathbf{y}^\Phi \in \mathbb{R}^{N_{proj} \times N_y}$ is the measurement result and η models the noise occurred during the acquisition. The scan angle interval is $[-\Phi, \Phi]$. With a circular trajectory configuration, assuming the cone angle is θ_c, $\Phi_{min} = \frac{\pi}{2} + \frac{\theta_c}{2}$ is necessary to achieve an exact and stable reconstruction of the central plane and a good estimation in the rest of the reconstruction region, if N_{proj} is sufficiently large [10]. Limited-angle CT addresses situations, where $\Phi < \Phi_{min}$. The system matrix of limited-angle CT is underdetermined which leads to non-unique solutions. To narrow down the possible solution set, prior information is required in the reconstruction. The assumption that the image is sparse under some transformation is particularly important for industrial applications, as most of the industrial parts consist of a limited number of piece-wise constant materials. Here, we formulate the reconstruction problem in the compressed sensing framework:

$$\mathbf{x} = \underset{\mathbf{x}}{\operatorname{argmin}} \, \|\psi(\mathbf{x})\|_1, \quad \text{s.t.} \quad \mathbf{A}^\Phi \mathbf{x} = \mathbf{y}^\Phi \tag{5}$$

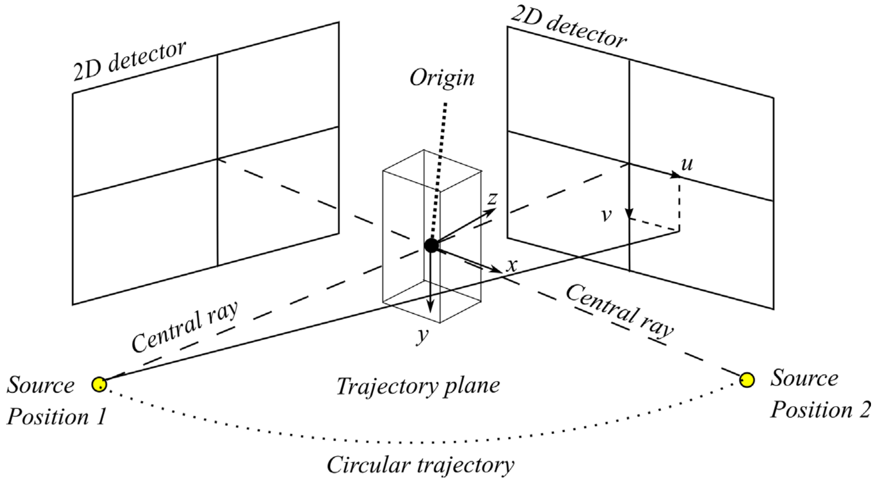

Fig. 1. Schematic of the CT setup. The scanning trajectory is either a full circle in the trajectory plane or part of a circle for limited-angle scanning. The source and the detector are aligned such that the central ray from the cone beam is perpendicular to the 2D detector plane through the geometry center of the 2D detector. The distance from the source to the origin and the distance from the source to the center of the detector are fixed during the scan.