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A REVIEW OF RECONSTRUCTION METHODS FOR LIMITED ANGLE X-RAY TOMOGRAPHY IN NONDESTRUCTIVE EVALUATION APPLICATIONS

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ABSTRACT

In past 50 years, X-ray computed tomography (CT) has been developed to a relatively mature non-destructive evaluation (NDE) technology widely used in both medical diagnostics and industrial inspections. Historically, major improvements in tomography technologies were developed in medical CT, then adopted by communities for industrial applications. Nowadays, security inspection CT needs fast and composition distinctive technologies, and NDE requires more on high resolution and high penetration capabilities. Both pursue different objectives comparing with medical CT's major challenge: fast, low-dose and contrast improving images. Limited angle CT scan and laminography are common scenarios in NDE CT applications requires different reconstruction methods. In this paper, the authors reviewed the existing reconstruction methods in three categories, and compare them in different NDT applications limited view projections.

Keywords: X-ray, Tomography, Reconstruction algorithm, Limited angle, Nondestructive Evaluation, Laminography

1. INTRODUCTION

After half-century development, X-ray computed tomography (CT) plays a more and more important role in both medical and industrial applications. In NDE community, this technology serves as a powerful benchmark tool to characterize internal volumetric flaws and defects, regardless of surface conditions and sample materials. This innovation of this technology is pushing forward by researchers from different areas. The evolution of X-ray source and detectors improve the special resolution and contrasts for the images. Moore's law from semiconductor industry reduces the reconstruction time from hours to seconds and makes in-line CT possible. However, the reconstruction methods did not have revolutionary improvement in the past few decades.

CT reconstruction method is key process converting a series of 2D radiographic images into 3D CT images. Its mathematical foundation were researched even before CT technology is invented. Radon transform and its inversion were introduced by Johann Radon in 1917 serves as a classic theoretical bases for CT[1]. Tuy found the necessary and sufficient condition for a perfect CT reconstruction 1983[2]. The most successful reconstruction algorithm in practice is an analytical reconstruction method, called FDK algorithm designed by Feldkamp et al in 1984 [3]. Nowadays, it is still the reconstruction algorithm for most commercial CT systems due to its computing efficiency and universal suitability[4]. Iterative reconstruction (IR) methods have their advantage in some specific situations, especially when Tuy criteria is not satisfied. The major obstacle for commercialization is intense computing power requirements and lack of universal applicability.

2. DIFFERENT APPLICATION NEEDS

Most innovations in CT were accomplished for medical application purposes, because medical CT is the largest market. Some of them were directly adopted for industrial application. In recent years, there is higher demands for industrial CT in security inspections and nondestructive testing. This market differentiate requirements from the medical CT needs.

The top requirement for medical CT is fast imaging with better contrast and minimize the radiation exposure dose for patients. Some iterative algorithm are designed for reconstructing high-quality images from noisy projection data and sparse angle scans with less radiation dose exposure. Industrial CTs handle engineering parts, and put dose requirement at much lower priority. Instead, NDE engineers prefers higher spatial resolution, higher power for penetration capability and sometimes. Sometimes, limited by inspection objects sizes and geometry, only limited projection angles are accessible.

Rapidly growing markets in industrial CT motivate the researchers to spend more resources to industrial CT specific requirements distinguished from medical CT. Some iterative reconstruction methods may be promising solutions.

3. DIFFERENT LIMITED VIEW SCENARIOS

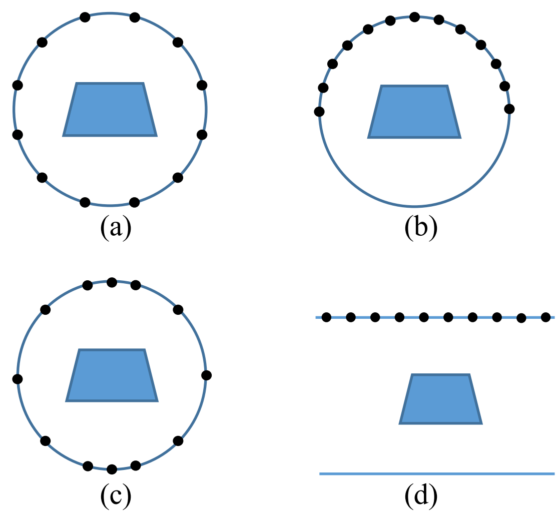

FIGURE 1: LIMITED ANGLE SCENARIOS (a) Sparse angle sampling (b) Missing angle sampling (c) Non-Uniform angle Sampling (d) Laminography

Figure 1 provided a collections of scenarios of limited angle (or limited view, or incomplete projection angle) CT. The black dots are the positions of X-ray source focal spots, and the detector is placed directly opposite to the source across the objects. The projections are also called samplings since each X-ray projection is a sampling in the projection space. (a) is commonly researched in medical applications since sparse angle scan can reduce exposure time and dose. However, (b), (c) and (d) are not usual, because it is not necessary for human body as object. [5] However, in NDE application, limited accessibility may force missing angle sampling as (b), and sometimes the scan trajectory may be optimized to (c) depend on object aspect ratio and region of interest. (d) laminography is a special case for missing angle sampling from mathematical point of view. Instead of rotational motion of regular tomography, laminography use translitional motion of source and detector, and is frequently used in NDE application, due to limited space accessibility around the object.[6]

These scenarios does not meet Tuy's sampling criteria, and 3D images cannot be perfectly reconstructed. From the literature, there are two concepts to deal with the missing angle/view projection data. One is to fill in missing sinograms by interpolation or forward/inverse quasi-Radon transform iterations. The other solve the reconstruction with iterative methods with additional constrains, such as *a prior* and known boundary conditions.

4. RECONSTRUCTION METHOD CATEGORIES

CT reconstruction methods are inverse modeling the X-ray projection transform. they solves an inversion problem to find the unknown solution of 3D images from known projection data. Most methods simplify the problems into linear systems and can be solved explicitly or implicitly.

After data acquisition, the projection data domain consists of the raw data from X-ray projection. Traditional analytical methods reconstruct the unknown image domain explicitly from inverse transform, with different combinations and orders of the tools including filters, back projection, Fourier and inverse Fourier transforms, etc.

The forward project transform is described as (1) with projection data from measurement g, and projection operator $\mathcal{P}$ and unknown 3D image f.

$$g = \mathcal{P}\{f\} \tag{1}$$

Analytical reconstruction methods are trying to explicitly inverse the projection transform with one-shot process, not includes iterations. The inverse operator $\mathcal{P}^{-1}$ in equation (2) is constituted of different sequences of orders of the tools including filters, back projection, Fourier transform, etc, based on simplifying the models.

$$f = \mathcal{P}^{-1}\{g\} \tag{2}$$

In contrast, Iterative reconstruction methods simplify the whole problem to a linear system (3), and solve it implicitly staring with a guess or a hint of f

$$\mathcal{P} f = g \tag{3}$$

Optimization theory can be used to find a solution for f with e.g. least square method with $\lambda R(f)$ regularization from some *a priori* knowledge.

$$f_* = arg\,\min_f(\|\mathcal{P} f - g\|_2^2 + \lambda R(f)) \tag{4}$$

Sometimes it is an under-determined or ill-posed problem, and with proper relaxation parameter and convergence criteria, each iteration move one step forward to a optimal solution, and finally converge. Usually inside each iteration, there is a forward projection and a backprojection of residual errors to update the solution[7]. This is why iterative reconstruction methods are hundreds to thousands times more computing intensive comparing to analytical reconstructions. Some iterative reconstructions purely rely on iterations and updates from algebraic calculation. Some implementations of iterative reconstruction use some physics or statistics models, even additional *a prior* knowledge to introduce more reasonable constraints for better convergence to accurate results. We put these IR methods in to a separate category as model based reconstruction methods in Table 1 comparing three different categories of reconstruction methods.[8, 9, 10] Obviously, Simpler models are easier to solve, but may introduce more error, and have less tolerance to noisy data and missing angle projections.

Now most iterative reconstruction algorithms are still in a theoretical research phase, and researchers focus on reconstruction stability, convergence criteria, and how to optimize parameters, and they majorly use synthetical simulation cases rather than experimental data[11, 12]. There are very few iterative reconstruction methods are used in practice or commercialized. The major obstacles of using iterative reconstructions are computational cost and lack of generalized IR methods with universal applicability. In the full paper, we will have detailed discussion about various reconstruction methods in Table 1 .

TABLE 1: Comparison of Three categories of reconstruction methods

	Analytical Reconstruction Methods	**Pure Algebraic Iterative Reconstruction Methods**	**Model based Iterative Reconstruction Methods**
Methods	FBP, FDK, Direct Inversion, BPF, etc	ART, SART, SIRT, MART, OS-SART, TVM, etc	ML-EM, OS-EM, MBIR, PSIG, etc
Speed	Fast	Medium	Slow
Data sampling tolerance	Need sufficient projections	Need low noise, and little missing angles	Promising with high noise, and limited angle data
Advantages	One iteration and done Fast and convenient	Iteratively improve but no new models added	Incorporate physical and statistical models, and *a prior* knowledges
Disadvantages	Not suitable for limited angle	Limited improvement sacrificing speed	Many parameters to tune up No universal criteria

5. SUMMARY

These paper reviews the CT reconstruction methods for NDE applications, especially for limited angle projection data. The pros and cons are summaries for different reconstruction method. As an interdisciplinary research area, different medical physicists, signal processing scientists, and NDE engineers use different terms for the same concept, this review paper also try to put together a nomenclature for iterative reconstruction methods to reduce the communication confusion.

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