A New, Computationally Efficient FBP-type Image Formation and segmentation Method for Cone beam X-ray Computed Tomography

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Abstract

We introduce a new FBP-type image formation method applied to cone-beam projection data.

- We parameterize the cone-beam transform in its native geometry so that the resulting imaging equation is a Fourier Integral Operator (FIO).
- We developed a new and novel FBP-type image formation method.
- The FIO formulation and the associated inversion method have several advantages including computationally efficient implementation and ability to incorporate arbitrary imaging geometries and system related parameters as well as pattern recognition tasks for optimized identification of explosives.
- Numerical simulations show the superiority of the new image formation method as compared to the widely implemented Feldkamp algorithm.

Relevance

- X-ray CT based Explosive Detection Systems require reconstructed image to be segmented and analyzed to detect and identify explosives or other threats.
- Typically, the image reconstruction, segmentation and pattern analysis are performed independent of each other.
- Furthermore, segmentation and pattern analysis are computational bottlenecks.
- Our approach couples image reconstruction, segmentation and pattern recognition tasks to optimize detection and identification of explosives. Furthermore, it is computationally efficient.

Technical Approach

Cone-beam transform and geometry of a X-ray CT scanner

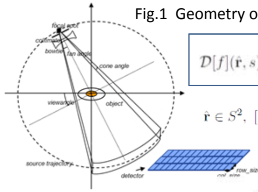


Fig.1 Geometry of an X-ray CT Scanner

$$\mathcal{D}[f](\hat{\mathbf{r}}, s) := \int_0^{\infty} f(\gamma(s) + t\hat{\mathbf{r}})dt$$

$$\hat{\mathbf{r}} \in S^2, \ [s_0, \ s_1] \subseteq \mathbb{R}.$$

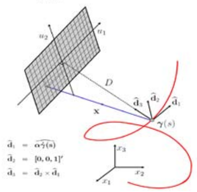


Fig.2 A local coordinate system for cone-beam projection on a planar detector. $\Upsilon(s)$ denotes the source trajectory [1], [2].

Cone beam transform as a Fourier Integral Operator(FIO)

$$d(\boldsymbol{u}, s) = \frac{1}{4\pi^2}\int e^{i\boldsymbol{\omega}\cdot(\boldsymbol{u}-\boldsymbol{\rho}(\mathbf{x},s))} A(\boldsymbol{\omega}, \mathbf{x}, s) f(\mathbf{x}) d\boldsymbol{\omega} d\mathbf{x}$$

where

$$\hat{\mathbf{r}}(\mathbf{x}, s) = \frac{(\mathbf{x}-\gamma(s))}{|(\mathbf{x}-\gamma(s))|}$$

$$\hat{\mathbf{d}}_1 = \widehat{\alpha\dot{\gamma}(\mathbf{s})} \qquad \rho_1(\mathbf{x}, s) = D\frac{(\mathbf{x}-\gamma(s))\cdot\hat{\mathbf{d}}_1}{(\mathbf{x}-\gamma(s))\cdot\hat{\mathbf{d}}_3}$$

$$\hat{\mathbf{d}}_2 = [0, 0, 1]' \qquad \rho_2(\mathbf{x}, s) = D\frac{(\mathbf{x}-\gamma(s))\cdot\hat{\mathbf{d}}_2}{(\mathbf{x}-\gamma(s))\cdot\hat{\mathbf{d}}_3}$$

$$\hat{\mathbf{d}}_3 = \hat{\mathbf{d}}_2 \times \hat{\mathbf{d}}_1 \qquad \boldsymbol{\rho}(\mathbf{x}, s) := [\rho_1(\mathbf{x}, s), \ \rho_2(\mathbf{x}, s)]$$

- Can accommodate arbitrary imaging geometries, such as arbitrary source trajectory or arbitrary detector surface

Reconstruction Formula

We form the image by means of a filtered-back-projection operator

$$I(\mathbf{z}) = \mathcal{K}[d](\mathbf{z}) := \int e^{-i\phi(\boldsymbol{\omega},\mathbf{z},\boldsymbol{u},s)} \mathcal{Q}(\boldsymbol{\omega}, \mathbf{z}, \boldsymbol{u}, s) d(\boldsymbol{u}, s) d\boldsymbol{\omega} d\boldsymbol{u} ds$$

where $\phi(\boldsymbol{\omega}, \mathbf{x}, \boldsymbol{u}, s) = \boldsymbol{\omega}\cdot(\boldsymbol{u} - \boldsymbol{\rho}(\mathbf{x}, s))$

and $\mathcal{Q}(\boldsymbol{\omega}, \mathbf{z}, \boldsymbol{u}, s)$ is the filter to be determined.

Reconstruction filter

- Filter is chosen so that the PSF of the image formation is approximately the Dirac-delta function

Segmentation filter

- Filter is chosen so that the PSF is approximately a linear combination of the Dirac-delta function and its Laplacian

By linearization and stationary phase approximation

$$I(\mathbf{z}) \approx \int e^{i(\mathbf{z}-\mathbf{x})\cdot\boldsymbol{\xi}} \left| \frac{\partial(\boldsymbol{\omega}, s)}{\partial\boldsymbol{\xi}} \right| \mathcal{Q}(\boldsymbol{\omega}, \mathbf{z}, \boldsymbol{u}, s) f(\mathbf{x}) d\boldsymbol{\xi} d\mathbf{x}$$

Deter. of the Jacobian that comes from a change of variables $\boldsymbol{\xi} = \nabla\boldsymbol{\omega}\cdot\boldsymbol{\rho}(\mathbf{x}, s)|_{\mathbf{x}=\mathbf{z}}$

- Reconstruction filter – helical scan

$$\mathcal{Q}(\boldsymbol{\omega}, \mathbf{z}, \boldsymbol{u}, s) = \left|\frac{\partial\boldsymbol{\xi}}{\partial(\boldsymbol{\omega}, s)}\right| = \frac{D}{C_3^2}\left|R\omega_1 + \frac{h}{2\pi}\omega_2\right|$$

- Segmentation filter

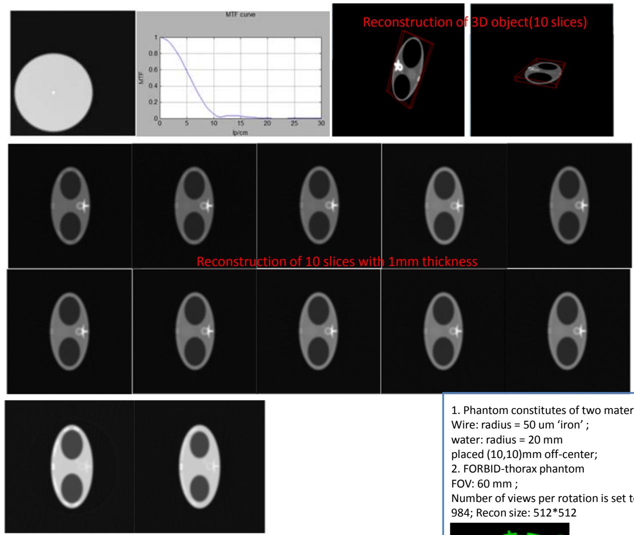
$$\mathcal{Q} = (1-\mu)|\omega| + \mu|\boldsymbol{\xi}|^n$$

μ and n are real numbers between 0 and 1

Advantages of the inversion method

- Applicable to arbitrary imaging geometries, can accommodate system related parameters, such as dose modulations, system bandwidth, bow-tie filter etc.
- Recovers the edges at the right location and orientation
- Can be coupled with segmentation and classification tasks.
- Analytic image formation and segmentation method that can be implemented efficiently using the fast FIO calculations [3].

Performance comparison



FDK(8mm away from center) New inversion Edge map and profile plot

1. Phantom constitutes of two materials:
Wire: radius = 50 um 'iron' ;
water: radius = 20 mm
placed (10,10)mm off-center;
2. FORBID-thorax phantom
FOV: 60 mm ;
Number of views per rotation is set to 984; Recon size: 512*512

3D FORBILD phantom

- The slices reconstructed by the new inversion method far away from the center slice look better than the widely implemented FDK's algorithm
- Edge map is obtained by applying the differential filter, and thresholding the negative pixel values

Accomplishments Through Current Year

1. Parametrized cone-beam transform in its native (detector) geometry. Showed that it is a FIO and developed a filtered-backprojection type inversion method for image reconstruction.
   - New representation of the cone-beam transform can accommodate system related parameters.
   - Implemented the method numerically and demonstrated its feasibility in a realistic phantom simulation
2. Coupled the new inversion method with the edge detection task for simultaneous segmentation and reconstruction of images directly from projection data

Future Work

- Incorporate system related parameters and constraints into the FIO representation and extend the inversion method.
- Incorporate classification task to image reconstruction.
- Test simultaneous edge detection, classification and reconstruction algorithm using real phantom data
- Document results in the form of journal papers and patent disclosures

Opportunities for Transition

- Our work provides a framework for computationally efficient simultaneous image formation, segmentation and pattern recognition optimized for explosive detection application.
- Strong interest by General Electric (GE) Global Research Center.
- GE provided an exclusive license for CatSIM, a highly proprietary state-of-the-art simulation toolbox for X-ray CT.
- Open to talk to all X-ray CT manufacturers

Patent Disclosures

Birsen Yazıcı and Zhengmin Li, "A filtered-back projection type image reconstruction method for cone beam X-ray Computed Tomography", Invention disclosure letter, filed March 2011, Case number: 1414, Rensselaer Polytechnic Institute.

Publications Acknowledging DHS Support

Zhengmin Li and Birsen Yazıcı, "A New and Novel FBP-type Image Reconstruction Method for Cone-beam X-ray Computed Tomography" in preparation.

H. Cagri Yanik, Z. Li, B. Yazıcı, "An FBP-type direct segmentation of Synthetic Aperture Radar images," to appear in SPIE Defense and Security Conference, April 2011.

Other References

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