F3-D: Computationally Efficient Simulations Segmentation and Image Reconstruction for CT X-ray Based EDS Systems Screening

Abstract—Despite recent technological advances, reliable detection of explosives in luggage and IEDs remains a challenging problem. For explosives detection in checked luggage, X-ray computed tomography (CT) is a widely-adapted sensing modality. CT X-ray based explosive detection algorithms are comprised of image reconstruction, segmentation and classification steps where first, three-dimensional X-ray attenuation images are formed. Next, the content of the images are decomposed into homogenous connected regions. Finally, the connected components are identified. Typically the image formation and segmentation are computationally the most intensive steps of the Explosive Detection System (EDS) image processing chain. This research aims to develop computationally efficient simultaneous image reconstruction and segmentation algorithms. In particular, we develop 1) analytic forward models for conebeam X-ray CT that can incorporate realistic system parameters, arbitrary imaging geometries and X-ray propagation models; 2) computationally efficient inversion algorithms for such models based on microlocal analysis; 3) computationally efficient simultaneous image reconstruction and segmentation algorithms; 4) computationally efficient filtered-backprojection algorithms that can take into account non-stationary noise; 5) computationally efficient filtered-backprojection type image reconstruction method with sparsity constraints. The outcomes of this research have implications, not only in X-ray CT based EDS, but also other applications involving synthetic aperture radar and sonar, as well as X-ray CT medical imaging.

I. PARTICIPANTS

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II. PROJECT OVERVIEW AND SIGNIFICANCE

For explosives detection in checked luggage, X-ray computed tomography (CT) is a widely-adapted sensing modality. X-ray CT based Explosive Detection Systems (EDS) algorithms are comprised of three keys steps: Image formation, segmentation and classification. Accurate and computationally efficient image formation and segmentation are essential for the overall performance of EDS algorithms.
Virtually all X-ray CT systems use filtered-backprojection type algorithms for image formation due to the availability of fast-backprojection algorithms. This research aims to combine image formation and segmentation into a single, computationally efficient step within a generalized filtered-backprojection framework.

The cone-beam transform, which is used to model X-ray projection data for a spiral source trajectory, as well as a wide range of other transforms involved in tomographic imaging, are Fourier Integral Operators (FIOs) [4-5]. Microlocal analysis is an abstract theory of FIOs, high frequency approximations and associated singularities. It provides mathematical techniques to invert FIOs in a generalized filtered-backprojection framework. This project uses microlocal techniques to combine image formation and segmentation into a single step to design computationally efficient and accurate image formation and segmentation. In particular, we 1) reformulated the cone-beam transform in its native geometry as an FIO; 2) developed a new inversion method based on microlocal analysis; 3) showed simultaneous segmentation and image reconstruction based on differential filtering and backprojection and applied the new method to X-ray CT image formation and synthetic aperture imaging; 4) developed a filtered-backprojection type image reconstruction method to suppress non-stationary noise; 5) developed an iterative backprojection-reprojection approach for image reconstruction.

Our microlocal analysis-based algorithms are expected to improve the throughput rate and accuracy of the current state-of-the-art EDS algorithms by combining image reconstruction and segmentation into a single, more efficient step. In the process, we also develop methods and algorithms that are applicable to all other imaging modalities where FIOs arise [3], [6].

At the end of this effort, we envision system level changes in explosives detection systems to accommodate generalized filtered-backprojection algorithms. We anticipate that these changes will have a direct effect on saving the lives of civilians and military personnel.

III. RESEARCH AND EDUCATION ACTIVITY

A. State-of-the-Art and Technical Approach

Despite seemingly different sensing modalities, detection of explosives in checked luggage using X-ray CT and automatic target recognition algorithms using SAR [2] share the same mathematical foundations and algorithmic architecture, and suffer from similar shortcomings. In both modalities, a number of projections of the object (scene) to be scanned are collected and an image is reconstructed using the geometric integral transforms. Next, the reconstructed image is passed to an automated pattern recognition algorithm to detect and classify distinct entities in the object (scene) with the hope of being able to identify explosives or military/civilian targets. Both approaches suffer from a high false-positive rate and are constrained with the throughput rate (number of baggage or square miles of area scanned per unit time). Existing X-ray CT-based and SAR-based technologies utilize data acquisition and image reconstruction algorithms designed and optimized for medical applications without taking into account the subsequent segmentation and classification steps needed for explosive recognition. Furthermore, the forward model for X-ray CT imaging upon which the classical filtered-backprojection algorithms are developed is a mathematically idealized representation of the X-ray imaging process. This model cannot accommodate system and imaging related parameters, such as finite system bandwidth and dose modulations, into the image reconstruction process. As such, an inversion provides less accurate and lower resolution images than those reconstruction algorithms that are based on more accurate X-ray measurement models [7]. However, the algorithms based on more accurate models are also computationally intense which makes their implementation in X-ray CT systems impractical. Similarly, segmentation algorithms that can be coupled with image reconstruction based on accurate models also suffer from high computational complexity as compared to fast-backprojection based algorithms. Therefore, a practical problem for X-ray CT image reconstruction, as well as for simultaneous segmentation and image
reconstruction, is to develop image reconstruction, segmentation and classification algorithms based on accurate forward models with the computational complexity of fast-backprojection algorithms. Our research fundamentally addresses these problems.

B. Major Contributions

2009-2010

- **New parametrization of the cone beam transform that can take into account system parameters and arbitrary imaging geometries** - In [1], we presented a new parameterization of the cone beam transform with arbitrary source trajectory and arbitrary detector orientation and showed that it is an FIO. We also presented a microlocal analysis based alternative filtered-backprojection type inversion algorithm for the cone beam transforms with spiral trajectory. This was recognized with a “Best Poster” award at the SPIE Medical Imaging Conference. Starting from the approach in [1], we developed a representation of the conebeam transform in its ‘native geometry,’ in the form of an FIO for arbitrary imaging geometries. This new representation indexes measurements in terms of the detector row and column number and has the ability to incorporate system related parameters in the amplitude of the FIO. These system-related-parameters can be bow-tie filter, detector dimensions, detector response function, dose modulations etc. There are two important consequence of the new conebeam transform representation which we describe below.

2011

- **Inversion of the new transform** – The new model, (applicable in arbitrary imaging geometries with realistic modeling of system-and-imaging-related-parameters) which is in the form of an FIO, can be inverted with another FIO using microlocal technique. The inversion formula is a generalized filtered backprojection type and can be implemented with the computational complexity of fast-backprojection algorithms using the fast FIO computation algorithm that has been recently developed by Candes and Demanet [8]. The new representation of the cone-beam transform and its inversion are documented in a provisional patent filed in March 2011 [9].

- **Incorporating segmentation into inversion** – A realistic modeling of X-ray imaging process and system in the form of an FIO also allows development of computationally efficient simultaneous segmentation, classification and image reconstruction algorithms by designing suitable differential filtering operators to be included into the generalized filtered-backprojection formula. We described such suitably designed adaptive filters in [10].

- We also developed an iterative backprojection-reprojection algorithm to invert FIOs that arise in X-ray CT and synthetic aperture imagery that can incorporate non-Gaussian object (or scene) and additive noise statistics. Non-Gaussian object (scene) statistics include edge-preserving prior models, such as the Lp-type generalized Gaussian and sparse signal models. The method approximates each iteration of an iterative minimization problem as an FIO which can be implemented using fast FIO computation algorithms [8]. We described our preliminary results in [11]. The new method which can be viewed as an iterative generalized filtered-backprojection formula, outperforms one step filtered-backprojection algorithms whenever robustness and sparsity are sought. Additionally, it is computationally efficient (of the same order as fast-backprojection) as compared to approaches described in [7].

2012

- **Extension of the new cone-beam transform to arbitrary detector plane orientation and surface topography** – We extended the FIO model described above to arbitrary detector plane orientation and arbitrary detector surface topography. This is presented in [12] and [13].

- We extended the simultaneous reconstruction and segmentation method described above to include classification.
2013

- **Extension of the new cone-beam transform and its inversion to a statistical setting** – We extended the microlocal reconstruction described above to a statistical setting where we developed a generalized filtered-backprojection type reconstruction that uses the noise, clutter and object statistics into the reconstruction formula [14]-[15].

- **Extension to the use of CATSIM granted** – Our research group obtained an exclusive license to GE’s proprietary X-ray CT simulation software platform called CATSIM. This software tool allows us to simulate realistic X-ray CT measurements based on system-related parameters as well as realistic X-ray propagation models. We performed extensive simulation experiments to test the following: 1) cone-beam X-ray CT image reconstruction using different trajectories, including circular, helix, saddle and helix-like trajectories and 3D forbild phantoms. These new trajectories are added to CATSIM. 2) We implemented and tested the direct reconstruction and segmentation algorithm using helical trajectory with noise.

### IV. FUTURE PLANS

Summer and Fall 2013 will be devoted to complete and submit the following journal papers.

1. Z. Li and B. Yazici, “FBP-type image reconstruction methods for arbitrarily rotated detector plane and detector surface orientation.”
2. H. C. Yanik, Z. Li and B. Yazici, “FBP-type computationally efficient simultaneous image reconstruction, segmentation and classification.”
3. Z. Li and B. Yazici, “Cone beam inversion in the presence of non-stationary noise.”

- Extending the collaboration with GE Global Research researchers to obtain real phantom data and X-ray CT images and to seek joint proposal opportunities.

### V. RELEVANCE AND TRANSITION

The project has strong relevance to ALERT goals as image reconstruction, segmentation and classification are essential parts of the X-ray CT based EDS image processing chain. Current commercial systems address each of these steps independently using generic algorithms. This project aims to couple these steps to improve the efficiency of the EDS image processing chain in terms of accuracy and computational complexity. While image reconstruction, segmentation and classification can be easily formulated as a one-step optimization problem using discrete forward models to improve accuracy, the main disadvantage of this approach is its high computational complexity that will prevent its implementation in practical systems. The project aims to combine these steps to improve accuracy while keeping the computational cost at the level of the fast-backprojection algorithms.

### VI. LEVERAGING OF RESOURCES

Continued discussions with colleagues at Analogic Inc., GE Research, and AFRL to build and expand upon the ALERT effort. Currently, ALERT is leveraging Yazici’s NSF and AFOSR projects. Yazici has also developed research collaborations with Dr. Bruno De Man and Dr. Jed Pack of GE Research; obtained an exclusive license to CATSIM, a proprietary software platform for X-ray CT simulations and is looking forward to joint proposal opportunities with colleagues at GE Research.
VII. PROJECT DOCUMENTATION AND DELIVERABLES

A. Other Publications

Two PhD thesis – Only Z. Li is funded by the project, but H. Yanik’s thesis is directly related to the ALERT project.

2. Z. Li, "FBP-type image reconstruction algorithms for x-ray computerized tomography," RPI PhD thesis.

B. Software Products

1. FBP-type image reconstruction algorithms for X-ray CT and SAR.

VIII. REFERENCES