R4-C.1: Advanced Multispectral Computed Tomography (CT) Algorithms

I. PARTICIPANTS

<table>
<thead>
<tr>
<th>Faculty/Staff</th>
<th>Name</th>
<th>Title</th>
<th>Institution</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clem Karl</td>
<td>PI</td>
<td>BU</td>
<td><a href="mailto:wckarl@bu.edu">wckarl@bu.edu</a></td>
</tr>
<tr>
<td></td>
<td>David Castañón</td>
<td>Professor</td>
<td>BU</td>
<td><a href="mailto:dac@bu.edu">dac@bu.edu</a></td>
</tr>
<tr>
<td></td>
<td>Limor Martin</td>
<td>Post-Doc</td>
<td>BU</td>
<td><a href="mailto:limor@bu.edu">limor@bu.edu</a></td>
</tr>
</tbody>
</table>

II. PROJECT DESCRIPTION

A. Overview and Significance

Explosives represent a continuing threat to aviation security [1-4]. Dual-energy X-ray computed tomography (DECT) attempts to use the additional energy-dependent material information obtained by making multiple energy-selective measurements of attenuation. DECT methods estimate a small number of material-specific parameters at each image location and use them for material discrimination. A pair of commonly used parameters are the photoelectric and Compton coefficients, which are derived from a physics-based X-ray attenuation model. Conventional DECT methods are mostly targeted at medical applications, which have fewer artifacts. In the security application, many different materials may be scanned in various degrees of clutter and metal objects are common. In this application, image noise and metal artifacts are more severe and can lead to less reliable estimates of the photoelectric and Compton coefficients. In this project, we developed a new structure-preserving dual-energy inversion method (SPDE) for the formation of enhanced photoelectric and Compton coefficient images. This framework greatly reduces the noise and artifacts present in photoelectric and Compton images compared to conventional DECT results. The improved images can lead to more accurate subsequent material and object identification, resulting in fewer false alarms, greater security and reduced passenger inconvenience.

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

Several DECT techniques have been suggested since the 1970s [6-8]. They are mostly targeted at medical applications and do not deal with the image artifact mitigation necessary for security applications [11-14]. In contrast to existing work, this project developed a new structure-preserving dual-energy inversion method (SPDE) for the formation of enhanced photoelectric and Compton coefficient images for security needs. We form the images as the solution of an optimization problem which explicitly models the physical tomographic projection process. Metal induced streaking is reduced by appropriately down-weighting unreliable data. A boundary-preserving prior based on [9] is incorporated to improve object localization. In particular, we estimate a mutual boundary-field along with the photoelectric and Compton images. The boundary field provides accurate object localization and allows smoothing inside the objects.
The observed normalized log-sinogram data in DECT sensing follows the non-linear Beer-Lambert law [5-7]:

\[
I_s(\ell) = -\ln \left( \frac{\int w_s(E)e^{\int \mu(x, E)dx}dE}{\int w_s(E)dE} \right)
\]

where \(w_s(E)\) is the spectral weighting used in the measurement, \(\mu(x, E)\) is the linear attenuation coefficient (LAC) of the material at spatial location \(X\) and energy \(E\) and \(I_s(\ell)\) is the measurement along ray-path \(\ell\) for spectral weighting \(S\). Examples of LAC curves and spectral weighting functions are shown in Figure 1.

![Figure 1: Left: the linear attenuation coefficient (LAC) curves of a few example materials. Right: examples of spectral weighting functions \(w_s(E)\) (normalized to unit sum).](image)

The characteristics of the material at spatial location \(x\) are captured through the energy dependent function \(\mu(x, E)\). Typically, this function is approximated as a linear combination of a few basis functions [9]. A common choice of basis functions in DECT are the photoelectric and Compton functions. The LAC representation in the photo-Compton model is given by:

\[
\mu(x, E) = a_p(x) f_p(E) + a_c(x) f_c(E)
\]

where \(f_p(E)\) and \(f_c(E)\) are the photoelectric and Compton energy-dependent basis functions, and \(a_p(x)\) and \(a_c(x)\) are the corresponding material-dependent coefficients at each spatial location \(x\). The photoelectric and Compton basis functions and photoelectric and Compton coefficient pairs for a few example materials are shown in Figure 2 on the next page. The goal is to separate materials on the basis of their coefficient values.
In many DECT methods, the goal is to reconstruct the coefficient images \( a_p(x) \) and \( a_c(x) \), given the dual-energy measurements \( I_1(\ell) \) and \( I_2(\ell) \). Since the problem is nonlinear and high-dimensional, a well-known solution approach is to separate it into two decoupled sub-problems. In the first sub-problem, a nonlinear set of equations is solved for the basis coefficient sinograms \( A_p(\ell) \) and \( A_c(\ell) \) defined as

\[
A_p(\ell) = \int a_p(x) \, dx \quad \text{and} \quad A_c(\ell) = \int a_c(x) \, dx .
\]

The second sub-problem is tomographic reconstruction of the basis coefficient images \( a_p(x) \) and \( a_c(x) \), from these sinograms. This reconstruction step is usually accomplished by applying filtered back projection (FBP) to each sinogram individually and as such mutual structure information is not used.

Our focus in this work is on improving the solution of the second sub-problem in DECT; i.e., reconstruction of the basis coefficient images from the sinograms. This problem is related to the field of multi-sensor image fusion. Each basis coefficient sinogram may be regarded as observations obtained from a different measurement channel/modality. In our SPDE method, we utilize the mutual structure information and reconstruct the coefficient images jointly. In this way, object localization may be improved in both images. An illustration contrasting the similarities and differences between the typical DECT and the proposed approaches are shown in Figure 3 on the next page.

Figure 2: Top: The photoelectric and Compton basis functions. Bottom: A scatter plot of the photoelectric and Compton coefficients of a few example materials.
The general formulation of SPDE in vector form is given by the following:

\[
\min_{(a_p \geq 0, \alpha \geq 0, \lambda)} \left\| A_p - Ta_p \right\|_{W_z}^2 + \left\| A_c - Ta_c \right\|_{W_z}^2 + \lambda_1 \left\| Da_p \right\|_{W_{ps}}^2 + \lambda_2 \left\| Da_c \right\|_{W_{cs}}^2 + \lambda_3 \left\| a_p \right\|_2^2 + \lambda_4 \left\| a_c \right\|_2^2 + \lambda_5 \left\| Ds \right\|_2^2 + \lambda_6 \left\| s \right\|_2^2
\]

where \( S \) is a common fused boundary field, \( T \) is the tomographic operator, \( D \) is the derivative operator, \( W_z \) is a data weighting matrix, \( W_{ps} \) and \( W_{cs} \) are weighting matrices derived from \( s \), and \( \lambda_i \) are non-negative regularization parameters.

Three effects are explicitly captured in the formulation above. First, the scanner tomographic model \( T \), capturing the geometry of the data acquisition, is used. Inclusion of this model for allows the use of non-conventional scanning geometries, as has been suggested recently for non-rotational or limited angle X-ray scanners, and links the measured sinograms to the property images. Second, explicit use is made of a mutual object boundary-field \( S \) to mitigate and limit the propagation of artifacts as well as fuse information from both scans, thereby improving object delineation and suppressing streaks. Third, the sinogram data are weighted through \( W_z \) to reduce the effect of unreliable, low count rays caused by metal. The presence of explicit prior knowledge about artifact effects is important to improve the quality of the final images.
C. Major Contributions

The new SPDE framework generates a unified, joint estimate of the coefficient images where object boundary information from both scans are combined to provide explicit preservation of region values and boundaries. In particular, the more robust Compton image information helps stabilize the more noise sensitive photoelectric image. We have implemented a 2D version of this framework and demonstrated preliminary results in reducing the artifacts in dual-energy photoelectric and Compton imagery on two representative slices. In particular, we have reduced metal artifacts and object splitting and improved material property uniformity. Figure 4 shows results obtained from 95kVp and 130kVp data obtained from the Imatron C300 CT scanner under Task Order 3 (TO3). The top row shows the results of conventional reconstructions of the photoelectric and Compton coefficients. The presence of metal causes severe streaking in the photoelectric image and shading and intensity variation in homogeneous regions of the Compton image. Such light and dark streaking can lead to object splitting in subsequent segmentation and labeling tasks of an ATR, compromising threat identification. In contrast, the bottom row shows our new SPDE method. The reduction of streaking artifacts is readily apparent, as is the improved uniformity of homogeneous object regions.

![Figure 4: Two example slices from the Imatron data set for TO3. Top: conventional FBP-based photoelectric and Compton reconstructions based on decoupled processing. Severe streaking and shading due to metal are evident. Bottom: New SPDE reconstructions. Reduction of streaking and improved uniformity of object regions demonstrated.](image)

In Figure 5 on the next page, we show the corresponding improvement in the percent of pixel SNR relative to the conventional FBP approach. Improvements of 100-300% can be seen.
A key important goal is to reduce the spread of material property values, which will produce improved classification outcomes. To this end, we plotted the photoelectric value versus the Compton value for three labeled materials to examine the impact of the new method on feature spread. Figure 6 shows scatter or cloud plots of the photoelectric mean versus Compton mean for different object materials. These points illustrate the potential for improvement in material separability possible with the new method. With SPDE, the material clusters become tighter relative to the conventional approach. Thus, SPDE shows promise for more accurate and reliable material classification results.

Figure 5: Improvement in mean SNR of the new SPDE reconstructions relative to the conventional FBP approach as a percentage. Improvements of 100-400 percent are achieved.

Figure 6: Cloud (scatter) plots of object photoelectric mean versus Compton mean following methodology in TO3. Each point corresponds to one object and ellipsoids correspond to 1-sigma line. Each color corresponds to single material. Tighter clustering of points means less variability of measured material properties and better ability to separate material. Left: Results with the conventional DECT method. Right: Results with SPDE. It can be seen that while there is still significant variability, the spread of the three material groups has been reduced in the case of SPDE, which has the potential for more accurate material classification.
D. **Milestones**

The project, as originally envisioned, has reached the following major milestones:

1. Theoretical formulation of a novel joint reconstruction framework for artifact mitigation in dual energy CT;
2. Initial 2-D simulations to validate concept and refine formulation
3. Extension of formulation to real 2-D data from TO3; and
4. Initial validation on real 2-D scanner projection data.

E. **Future Plans**

Our future plan during Year 3 is to merge the artifact mitigation developments under R4-C.1 and the robust reconstruction and recognition work under R4-B.4 and focus them on a new direction in advanced X-ray based checkpoint screening. In particular, this new direction would aim to address current limitations identified, for example, in TSA RFI HSTS04-15-RFI-CT7999 together with the requirements for the next generation checkpoint. These goals include enhanced screening with lower false alarms, higher throughput and automated target identification. In addition, these goals need to be met with limited scanner footprint, weight and cost. To accomplish this, scanners will need to create 3D images from limited numbers of views and utilize novel, non-rotational geometries. We propose to incorporate the lessons learned from our previous projects to develop new algorithms for highly limited view tomographic reconstruction, artifact suppression and unified learning-based object identification based on compressed sensing and coded-aperture methods coupled with powerful optimization solver approaches, such as ADMM. One aspect of this work will exploit and adapt our previous work on non-conventional, limited geometry synthetic aperture radar reconstruction to these challenging security problems. We will focus on reducing the number of projection views needed for satisfactory reconstruction quality through the use of sparsity and compressed sensing methodologies. Another aspect of this work will focus on integrating classification and reconstruction in a unified process. Yet another aspect of this work will focus on development of robust material models from training data.

III. **EDUCATION AND WORKFORCE DEVELOPMENT ACTIVITY**

A. **Course, Seminar or Workshop Development**

Special session of ICIP 2015 on Computational Imaging is being developed.

Graduate course on image formation called “Image reconstruction and restoration” was conducted with 15 enrolled students.

B. **Other outcomes that relate to educational improvement or workforce development**

BU PhD student Limor Martin graduated and became a postdoctoral associate working on this project. She now works for Applied Materials Inc., in Rehovot, Israel.

IV. **RELEVANCE AND TRANSITION**

A. **Relevance of Research to the DHS Enterprise**

This project is of relevance to the DHS enterprise because it is developing methods to mitigate image artifacts in X-ray based baggage sensing, serves to optimize information extraction from raw data and provides tools to improve response to new threats. These approaches can reduce the number of false alarms, which in turn
can reduce the need for OSARP and manual inspection. These concerns will grow as the use of multi-spectral X-ray scanning increases at the checkpoint.

B. Potential for Transition

Demonstration of improved performance of dual-energy CT systems.

C. Transition Pathway

The novel methods developed in this effort are being disseminated to vendors through workshops and through prior student engagement in summer internships. The research was applied to TO3 validation data for proof of concept. In addition, as a result of the presentation of this work at the twelfth Advanced Development for Security Applications workshop (ADSA12), TSL/S&T personnel (C. Love, R. Krauss, R. Klueg) expressed interest in collaborating with us to see how these methods would perform on laboratory material samples.

D. User Connections

- Christina Love, Transportation Security Administration
- Ronald Krauss, Department of Homeland Security
- Robert Kleug, Department of Homeland Security

V. PROJECT DOCUMENTATION

A. New and Existing Courses Developed and Student Enrollment

<table>
<thead>
<tr>
<th>New or Existing</th>
<th>Course/Module/ Degree/Cert.</th>
<th>Title</th>
<th>Description</th>
<th>Student Enrollment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Course</td>
<td>Image reconstruction and restoration</td>
<td>Graduate course on image formation</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

VI. REFERENCES


This page intentionally left blank.