F3-A1: Advanced Model-based Algorithms for X-ray Portal Screening

Abstract — We present novel analysis, modeling, and reconstruction methods for X-ray based portal screening. One part of this work continues development of a new tomographic screening configuration based on limited-angle linear tomography. In contrast to conventional methods, this new configuration aims to produce a tomographic, 3D reconstruction from time sequential 2D views of moving objects. Another thrust is focused on understanding and exploitation of multi-energy X-ray CT. Part of this multi-energy work aims at a first-principles understanding of the benefits and limitations of multi-energy sensing. We demonstrate results suggesting that the use of more than two energies can be beneficial for X-ray based discrimination tasks and further that the conventionally used Compton and photoelectric basis functions may not be optimal. Another part of the work focuses on improving existing dual-energy X-ray methods. We present application of learning based methods to the problem of discrimination of explosives from non-explosives through the optimization of multi-energy sensing.

I. PARTICIPANTS

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II. PROJECT OVERVIEW AND SIGNIFICANCE

X-ray based screening of material is widely used for its ability to look inside baggage and reveal potential explosive threats without the need for time consuming physical examination. Planar radiography is compact, fast, and inexpensive, but only provides a projected view of an object, with interior structure overlaid on itself. The use of tomography can provide a 3-dimensional representation of the interior of the objects through the use of larger, more expensive and time consuming scanners. Existing X-ray based tomographic methods can provide excellent structural information but are limited in their ability to discriminate different material properties.

In this project we address these existing limitations of current X-ray based screening systems. In one thrust we have been developing a motion based limited-angle linear tomography method for 3D baggage scanning that relies on existing compact screening hardware. The aim is to provide enhanced 3D image formation from existing small footprint hardware allowing for enhanced explosive screening. Another thrust is focused on multi-energy X-ray imaging. Traditional multi-energy X-ray tomography is limited to the use of 2 energies and material decompositions involving only the photoelectric and Compton basis functions. Our previous work suggests this is not sufficient to model complex scenes. In this period we began applying machine learning approaches to optimize the multi-energy sensing and discrimination process and maximize the information extracted from multi-energy CT measurements. Benefits of this work include a unified theory of multi-energy imaging and improved discrimination of explosive and non-explosive materials.
III. RESEARCH AND EDUCATION ACTIVITY

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

A1. Dual Energy Image Formation

The dual energy technique is designed for and frequently used in medical applications such as material characterization in tissues, cardiac and coronary imaging, and bone densitometry [7] as well as luggage screening [2]. The standard approach is to reconstruct the attenuation coefficient for two different energy levels using conventional filtered back projection (FBP) and map these reconstructions into density and atomic number images which provide unique information about material properties [2, 3]. However, the FBP method neglects the polychromatic nature of the X-ray source and the energy dependency of the X-ray interactions. As a result, the reconstructions suffer from streak artifacts in the presence of high atomic number (Z) materials such as metals [4]. Ying et al. [5] proposed a two-step polychromatic dual energy method, which first estimated the Radon transforms of Compton scatter and photoelectric effect images from dual energy projections via a non-linear constrained optimization process and then used FBP reconstruction to obtain the corresponding images. Their results show inaccuracies in low effective atomic number (Zeff) reconstructions mainly due to the fact that the measurement data is insensitive to the photoelectric effect which is insignificant for low Z materials. To the extent of our knowledge, the literature lacks CT methods for luggage screening that do not neglect the polychromatic nature of the source; are able to cope with the high variety of material types that can be found in a luggage; and are sufficiently accurate in terms of identifying explosives.

The conventional approach to tomographic imaging has historically been to acquire projection data using a single X-ray source spectrum with measurements that average the material attenuation across this range of illumination energies $E$. Density images formed by this approach correspond to the assumption that material attenuation $\mu$ is governed by an energy independent effective material density. In reality, different materials exhibit different attenuation dependences on X-ray energy $\mu(E)$. In the seminal work [8], a basis decomposition approach for multi-energy imaging was proposed, wherein the overall energy dependence of any material was represented as a weighted linear combination of a photoelectric component and a Compton scattering component, based on physical arguments:

$$\mu(x, y, E) = a_p(x, y)f_p(E) + a_c(x, y)f_c(E)$$

where $f_p(E)$ represents the photoelectric component and $f_c(E)$ represents the Compton scattering component. Given a low or high X-ray spectrum $S_{L,H}(E)$ each projection is an integral of the total attenuation for each angle over the X-ray energy range. Projections are functions of the measurement angle $\Theta$ and the position on $x'$ which is the tilted version of the x axis by $\Theta$:

$$P(\Theta, x') = \int S_{L,H}(E) \exp \left( -f_{K\alpha}(E)A_{I}(\Theta, x') - f_p(E)A_{p}(\Theta, x') \right) dE$$

In this formulation, $A_{I}(\Theta, x)$ and $A_{p}(\Theta, x)$ are the Radon transforms for the X-ray path of each measurement of Compton and photoelectric coefficients respectively (see Figure 1).

**Linear Tomography Work:**

Existing X-ray-based carry-on baggage screening systems are primarily line-scanner based, providing only one or two projection views of a bag. Since objects are overlaid and a limited viewpoint is obtained, threat discrimination is confounded. For example, a knife viewed end-on has a very small profile and may be missed. Thus, fully 3D reconstruction of carry-on baggage is desirable. Unfortunately,
carry-on scanners are constrained in size and cost. In response, we have proposed a novel linear motion
tomography configuration that exploits existing stationary hardware. The aim is to provide 3D tomographic
reconstructions without the need for complex helical scanning hardware.

Our configuration uses a 2D planar detector geometry together with stationary X-ray sources. As an object
is moved over the detector by a transport belt, projections are acquired. The motion of the object provides
projections at a variety of angles, as illustrated in Figure 2.

The range of projection angles is severely limited and the projections are incomplete, thus reconstruction is
extremely challenging. We are using our experience in advanced model-based iterative reconstruction meth-
ods to develop and apply model-based algorithms to this problem. This year we developed the necessary

mathematical model for a three-dimensional configuration of the type described. The scene at each time is a
translation of the scene at a reference time through the known linear motion. Each time a linear projection of
the translated scene is observed, so that at time  the observation is given by an equation of the form:

\[ y_k = PT_k x \]

where \( y_k \) is the projection at time \( k \), \( P \) is the linear projection operator, \( T_k \) is the known motion induced trans-
lation operator, and \( x \) is the scene at the reference time. The collected set of such observations provides the
overall observation model for this limited angle tomography problem:

\[ y = Hx \]

where \( y \) is the collection of observations and \( H \) is the aggregate projection operator. This year we have fo-
cused on a simple iterative solution of the set of linear equations, corresponding to ML estimation of the
unknown scene \( x \).

Previously, we developed a fast forward projector based on Siddon’s method and coupled this with a simple
pixel-based back-projector. The challenging geometry of the system led to the presence of artifacts, however.
In the current period we investigated more accurate ray-based back projectors and methods to accurately
approximate these back-projectors. These new methods improved reconstruction quality and still allow the
fast parallelization necessary for transition to practical use. In addition, we studied the benefits of improved
observation geometry in the sensor configuration. A cross-section of a reconstructed suitcase example is
shown in Figure 3.
Another challenge arises from the computational burden arising in the solution of the tomographic inverse problem. Iterative methods are used and exhibit slow convergence due to the poor conditioning of the problem. In response we have been developing a preconditioner for the problem which exploits its structure and aims to speed convergence, and thus reduce computation time as well as improve reconstruction quality (see Figure 4).

**Multienergy Work:**

In this work we have begun an examination of the fundamental benefits of energy diversity in X-ray imaging. X-ray measurements are related to the linear attenuation coefficient (LAC) of materials in the field of view. The LAC is a function of energy and is different for each material, as illustrated in Figure 5.

![Figure 3: Example linear tomographic reconstruction.](image)

![Figure 4: Illustration of effect of preconditioner on reconstruction speed and quality for a synthetic example.](image)

![Figure 5: Illustration of material dependence of LAC energy for Iodine, Calcium and Water. These differences allow the discrimination of different materials from multi-energy X-ray observations.](image)
The LAC of compounds is composed of a density weighted sum of the LACs of the component elements:

\[
\frac{\mu(E)}{\rho} = \sum_i w_i \frac{\mu_i(E)}{\rho}
\]

Thus the discriminative material information in X-ray measurements of objects is contained in their LAC curves as a function of energy. Given this critical link between the energy dependence of LAC and X-ray observation, we have embarked on a fundamental investigation of the behavior of these attenuation-energy curves. Current conventional dual-energy CT scanners use only two measurement energies and seek a corresponding two-dimensional material expansion in terms of the photoelectric and Compton basis energy curves. This fundamentally represents a material through a two-dimensional feature. In previous work we studied the properties of the LAC curves of a collection of materials which included 114 non-explosives (including teflon, nylon, honey) and 84 explosives (including TNT, HMX, ANFO) using the XCOM database of material properties. In the current period we expanded our dataset of Linear Attenuation Coefficient curves of materials, and currently have 124 explosives and 194 non-explosives. As part of the non-explosives class we have 12 biological materials such as soft tissue and bone. We compared the dimensionality of the LACs of the explosives with the LACs of the biological materials by calculating the singular value decomposition and examining the number of non-zero singular values. The resulting singular values are shown in Figure 6. It can be seen that for the biological materials the first two singular values are significantly larger than the remaining singular values. On the other hand, for the explosives class and for the entire compounds dataset there are more than two large singular values. This demonstrates that the dimensionality of the LAC curves is higher in the case of luggage scanning and motivates the use of more than two features/energies.

Another direction of this work has focused on adapting the selection of multi-energy features to the explosive detection task to increase detection performance. In particular, we developed a new learning-based feature selection approach we termed sequential linear discriminant analysis (SLDA) and demonstrated that it could improve discrimination performance. We have continued investigation methods for multi-energy feature selection in the present period. We applied different classification-aware methods and tested their performance both by the area under the ROC (AUC) and by classification accuracy. Figure 7 on the following page shows the AUC results, as well as the accuracy of both a linear and a non-linear classifier, as a function of feature dimension. It can be seen that SLDA provides the highest accuracy. In addition, it can be seen that when using a non-linear classifier, classification accuracy is increased as the dimension increases, as opposed to the linear classifier. This shows that the problem is not linearly separable and requires more complex detection rules.

![Figure 6: Singular values of the LACs. In blue- all the compounds in our dataset. In orange – the subset of explosives compounds. In green- the subset of biological compounds. The singular values indicate that the dimensionality of the LACs when considering explosives and other materials is higher than in medical applications. This motivates the use of more than two multi-energy features.](image-url)
B. Major Contributions

Our work to date is contributing to X-ray based explosive detection by:

1. Providing new configurations of sensing systems exploiting model-based reconstruction methods for 3D reconstruction. These configurations could allow for compact, cost-effective 3D sensing for portal based carry-on screening.

2. Providing extensions of existing image-based methods and new algorithms for existing systems providing the possibility of improved information extraction from these existing systems.

3. Providing a first principles understanding of the value of energy diversity in X-ray sensing.

4. Optimizing information extraction in multi-energy X-ray sensing.

IV. FUTURE PLANS

Linear tomography:

We will continue to optimize our tomographic models to reduce artifacts and improve quality. In addition we will reduce computation time through improved preconditioning of the resulting optimization problem. We will incorporate prior information into the reconstruction algorithm to improve quality. We will also explore the use of multi-core and GPU implementation of our algorithms for reduction in computation time. Finally, we will explore the possibility of explosive detection without reconstruction by developing and applying the tools for high-dimensional learning.

Multi-energy:

We plan to continue our examination of the fundamental properties and benefits of multi-energy diversity in X-ray sensing of materials. We will focus on the nature and optimality of the representational material subspace. In addition, we will work on iterative reconstruction of the multi-energy features from raw tomographic data and the inclusion of accurate models of tomographic data uncertainty into our formulation.

V. DOCUMENTATION

A. Publications

1. L. Eger, W. C. Karl, P. Ishwar, H. Pien, “Classification-aware dimensionality reduction methods for explosives detection using multi-energy X-ray computed tomography,” in Computational Imaging, C. A. Bou-


B. Technology Transfer

Graduate student Limor Eger is working at Analogic as a summer intern, summer 2012, implementing some of the research on inverse methods for tomography. In addition, Zach Sun has interacted with the company SureScan on the application of linear tomography.

C. Seminars, Workshops and Short Courses


VI. REFERENCES


