R4-C.3: Advanced Cargo Screening

Abstract — A challenging problem in security is the screening of cargo. The greater size, density, and complexity of cargo makes CT-based sensing especially difficult. These problems are compounded when sensing geometry is limited. In this project, we aim to develop accurate physics-based models of X-ray cargo sensing and corresponding model-based image reconstruction methods for limited angle measurements based on compressed sensing for improved image quality.

I. PARTICIPANTS

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II. PROJECT OVERVIEW AND SIGNIFICANCE

A national security goal is the uniform screening of all cargo and checked baggage. Meeting this goal is challenging because of the volume of goods to be screened and the nature of screening required. This project aims to develop accurate physics-based models of cargo and checked baggage sensing, and to use these models to create methods for physics-based reconstruction. These methods will incorporate tools from compressed sensing and computational imaging to yield superior image quality from reduced measurement geometries and limited photon budgets that are typical for cargo applications. The methods developed will lead to more accurate and efficient screening of cargo and baggage, improving throughput, increasing detection, and reducing false alarm.

III. RESEARCH ACTIVITY

A. State-of-the-art and technical approach

Conventional methods for baggage and cargo screening consist of fully helical CT for smaller objects (checked baggage) or planar radiography or trace detection for larger cargo. Helical CT is complex and expensive and not practical for larger cargo. While planar radiography yields only limited information. In this project we aim to develop the tools necessary to create fully 3-dimensional property maps (i.e. reconstructions) from limited, potentially high-energy sensing modalities. One aspect of this work has focused on developing models and methods for non-rotational, limited angle tomography. A new aspect of this project that we have begun is focused on developing more efficient methods for nuclear resonance fluorescence (NRF) based screening of cargo. NRF is attractive because it provides direct information about material properties. But conventional NRF methods achieve localization through the combined use of source and sensor collimation, which is inefficient.

Nuclear resonance fluorescence achieves it effect by exciting nuclei through photon absorption. These ex-
cited states subsequently decay by the emission of (gamma-ray) photons in all direction [1]. Further, the energy distribution or spectrum of such emissions provides a signature of a material related to its chemical composition. Figure 1 shows such spectra obtained for three different materials [1]. The three materials can be identified by their unique spectra (see Fig. 1).

Figure 1: NRF Spectra for water, melamine, and a simulant explosive done by Passport Systems, Inc.

This material specific signature produced by NRF provides the potential to non-intrusively interrogate the composition of cargo. The interrogating photons are of high energy, in the range of 2-8 MeV and thus can penetrate thick and dense materials typically found in cargo applications. A cargo inspection system utilizing this idea is being developed by Passport Systems [2]. In this system, an electron beam of broad energy distribution and narrow focus illuminates a confined line of an object, as illustrated in Figure 2. Only the locations in the illuminated beam are excited, which then fluoresce in all directions isotropically. To achieve spatial localization along the illuminated line a set of collimated energy sensitive detectors are used. The intersection of the illumination line and the collimation opening localizes the measured response to a single spatial location. The energy sensitive detectors allow measurement of the material spectrum, which can be used to identify the material.

Figure 2: Diagram of a NRF system setup from Passport Systems, Inc.
Collimation based localization eliminates the need for image reconstruction, since the geometry of the problem localizes the spatial response. But the cost of this simple sensing scheme is that most of the emitted resonance photons are never measured. The relative photon efficiency of the approach can be seen to be limited to the fraction of the circle observed by the collimated solid aperture angle. The consequence is a significantly reduced signal to noise (SNR) and the need for longer integration times. This is coupled to the need to scan the illuminating beam through the entire volume, thus slowing the scanning operation.

In this project, we aim to develop models of nuclear resonance fluorescence (NRF) suitable for use in tomographic or coded aperture sensing and reconstruction methods. Our initial effort has focused on replacing the current collimation-based localization approach with a coded aperture approach. To this end, the collimators are replaced with a coded mask, as illustrated in Figure 3. In this way, more of the emissions from each illuminated voxel are captured and measured.

The coded mask, denoted by $m$, filters the spatially distributed emission data, $x$ through a linear convolutional process to create the measured signal $y$:

$$ y = m \ast x \quad (1) $$

Since the process is governed by counting statistics, the Poisson distribution applies. The overall SNR is then determined by the mean of the resulting measurements. In the coded mask case this mean can be higher, since more overall counts are obtained at each detector. The penalty that is paid is that the spatial material distribution is now coded in the measurements and cannot be simply observed at the detector output. Instead the equation (1) must now be inverted. This process is shown schematically in Figure 4. Note that the emissions at each energy or spectral level are independent and add linearly, therefore the problem decouples into independent problems at each energy. In what follows we focus on a single such energy.
We have begun initial experiments using mask-based coding to model and understand the potential benefits of such an approach. To this end we have studied a 1-dimensional profile recovery problem. The initial underlying true spatial distribution profile is shown in Figure 5 and is composed of two adjacent cosine pulses.

![Figure 5: Simulated 1D Phantom.](image)

For a coding mask we have initially used three small apertures. For this mask the overall signal magnitude of the data will be tripled relative to a fully collimated approach. Corresponding noisy, coded data for this case is shown in Figure 6 for an array of un-collimated detectors. As can be seen the original distribution is obscured by the coding process of the observation and must be inverted to obtain the desired pattern. In Figure 7 on the next page we show the original spatial distribution together with the resulting data inversion.

![Figure 6: Observed Data Corresponding to a Three Hole Mask.](image)
B. Major contributions

In the present project period, we researched the literature and started the process of developing the necessary physical models for NRF sensing. We have established a simulated model for generating data, along with some preliminary reconstruction algorithms. We have demonstrated a potentially viable sensing configuration.

C. Future plans

Future plans include the continuation of our effort to create NRF sensing models appropriate for data inversion and the creation of an associated accurate cargo sensing simulator for NRF based sensing in the MEV range, which can be used as a testbed for new coded aperture and tomographic sensing concepts. We will initially continue with our 1-dimensional simplified geometry and optimize the coding mask, studying resulting SNR, reconstruction quality, and ease of inversion. We will then extend these developments to 2D, initially exploring the use of 1D excitation and 2D sensing. We also aim to examine if full sheet excitation is possible, which would greatly increase throughput. Finally, we will examine the inclusion of integral, tomographic-like sensing configuration, which would allow simultaneous full volume measurements.

IV. RELEVANCE AND TRANSITION

A. Relevance of your research to the DHS enterprise

The development of new methods of fully three dimensional non-helical screening of checked baggage and cargo would provide increased security.

B. Anticipated end-user technology transfer

Dissemination through vendors such as Passport Systems or Astrophysics.
V. REFERENCES
