Evaluation of neutron techniques for illicit substance detection

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Abstract
We are studying inspection systems based on the use of fast neutrons for detecting illicit substances such as explosives and drugs in luggage and cargo containers. Fast-neutron techniques can determine the quantities of light elements such as carbon, nitrogen, and oxygen in a volume element. Illicit substances containing these elements are characterized by distinctive elemental densities or density ratios. We discuss modeling and tomographic reconstruction studies for fast-neutron transmission spectroscopy.

1. Introduction

Nuclear techniques using fast neutrons are being examined for detection of illicit substances, such as explosives and drugs, in luggage and cargo containers. Fast-neutron techniques are attractive because they can determine the quantities of many of the light elements of interest, such as carbon, nitrogen, and oxygen. We are currently analyzing two system concepts: fast-neutron transmission spectroscopy (FNTS) and pulsed fast-neutron analysis (PFNA) [1]. In this paper we discuss only FNTS as applied to the detection of explosives in luggage.

FNTS is based on the fact that many of the light elements of interest have significant features in their cross sections that allow identification of the elemental constituents from the measured transmission ratio. The technique was first examined by Overley [2] to determine compositions of bulk organic materials. In this technique an accelerator is used to produce nanosecond pulsed beams of protons or deuterons that strike a target and produce a pulsed beam of neutrons with a continuum of energies. The material to be interrogated is placed in the flight path between the target and detector and time-of-flight techniques are used to measure a transmission ratio as a function of neutron energy. This ratio is unfolded to yield the projected area densities of the various elements. In this paper we investigate the capability of the FNTS technique to detect a block of RDX explosive using three to five low-resolution area projections.

2. Monte Carlo modeling

The Monte Carlo transport code MCNP [3] has been used to simulate neutron transmission through single materials, combinations of materials, and simple phantoms. Transmission spectra are unfolded to determine the elemental projected densities, which are then provided as input to the tomographic reconstruction routines discussed below in Sections 3 and 4.

The phantom used in this study is shown in Fig. 1. It consists of an 8 cm square of RDX explosive (C,H,N,O,, $\rho = 1.83 \text{ g/cm}^3$), an 8 cm square of nylon (C,H,,NO,, $\rho = 1.1 \text{ g/cm}^3$), an 8 cm diameter circle of ethanol (C,H,OH, $\rho = 0.789 \text{ g/cm}^3$), and a uniform background of silk (C,H,,N,O,, $\rho = 0.3 \text{ g/cm}^3$) placed inside a 40 cm square. An 8 cm cube of RDX corresponds to approximately 1 kg of explosive. If the slice used in this reconstruction is assumed to be 2 cm thick, then the RDX object has a mass of 230 g. If the elements from the other objects were converted into RDX explosive, approximately 900 g of explosive could be formed.

The calculational model assumes a white neutron source (the zero-degree neutron energy spectrum from the $^9\text{Be}(d,n)$ reaction at $E_d = 5 \text{ MeV}$) illuminating the object being interrogated with a collimated, parallel neutron beam which is 2 cm by 2 cm in cross section. This source has a high neutron yield in the range 1–4 MeV, which contains many resolved resonances for the light elements. The source-detector distance was 5 m, with source and detector timing widths of 2 ns. The number of source neutrons used corresponds to irradiation for 1 s at an average deuteron current of 2.4 $\mu$A [4]. Analog particle transport was used (i.e., no variance reduction) so that each neutron from the source represents one neutron from a real source. This results in counting statistics that have the same magnitude.
3-OBJECTS

Density

g/cm³

1.830
1.647
1.464
1.281
1.098
0.915
0.732
0.549
0.366
0.183
0.000

Fig. 1. Phantom used in these calculations. The pixel resolution in this picture is 0.5 cm. The resolution used in the reconstruction and MCNP calculations was 2.0 cm.

and variation across energy phase space as would be seen in an actual experimental or test geometry. Use of the appropriate errors is important in evaluating analysis and decision-making algorithms that use the unfolded projection data.

The transmission data are analyzed in the time domain using standard nuclear techniques [5] adapted to the method of effective variance [6]. The details of the algorithm are contained in Refs. [7,8]. A sample transmission spectrum for a projection ray which passes through the RDX and nylon squares is shown in Fig. 2. The results of unfolding this spectrum are given in Table 1.

3. Tomography and explosive detection

The experimental data measured by FNTS will consist of one-dimensional projection profiles of the areal density of the elements H, C, N, and O at one or more projection angles. The data from these projection profiles may be used directly or may undergo additional processing (e.g., tomographic reconstruction) before being input to an explosive detection algorithm.

The problem with the use of a single projection in explosive detection occurs because the projection data consists of an integral along the line-of-sight of the projection. Thus elements at different positions along this line-of-sight can overlap with the explosive and obscure the explosive signature when present, or combine with other elements to indicate the presence of explosives when no explosive is present. A single projection may be used as an initial screening to eliminate some luggage, however. For example, if insufficient nitrogen is detected in the projec-

Table 1

Areal densities for a projection ray which passes through the RDX and nylon squares of the three-body phantom shown in Fig. 1. Exact refers to the areal density calculated using the actual elemental densities. Unfolded refers to the areal density calculated from the MCNP transmission data.

<table>
<thead>
<tr>
<th>Element</th>
<th>Exact[10^{24}\text{atoms/cm}^2]</th>
<th>Unfolded[10^{24}\text{atoms/cm}^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1.707</td>
<td>1.034 ± 0.111</td>
</tr>
<tr>
<td>C</td>
<td>0.470</td>
<td>0.507 ± 0.055</td>
</tr>
<tr>
<td>N</td>
<td>0.355</td>
<td>0.339 ± 0.102</td>
</tr>
<tr>
<td>O</td>
<td>0.425</td>
<td>0.440 ± 0.035</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>−0.0365 ± 0.0863</td>
</tr>
<tr>
<td>Al</td>
<td>0</td>
<td>0.0025 ± 0.0818</td>
</tr>
<tr>
<td>Si</td>
<td>0</td>
<td>0.0203 ± 0.0447</td>
</tr>
<tr>
<td>Cl</td>
<td>0</td>
<td>−0.0311 ± 0.1206</td>
</tr>
<tr>
<td>Fe</td>
<td>0</td>
<td>−0.0165 ± 0.0969</td>
</tr>
<tr>
<td>Cu</td>
<td>0</td>
<td>0.0249 ± 0.0858</td>
</tr>
</tbody>
</table>

Fig. 2. MCNP calculated neutron transmission ratio as a function of energy for a projection ray which passes through the RDX and nylon squares in the phantom of Fig. 1. The variation in transmission is due to variations in the elemental cross sections of H, C, N, and O comprising the RDX and nylon squares, and the silk background.
4. Few-view reconstruction

We have used the tomographic reconstruction techniques contained in the Donner library [9,10] to study the phantom of Fig. 1. For reconstructions using a small number of projections, the algebraic reconstruction technique provided the best reconstruction. In particular, we have looked at conjugate gradient, maximum likelihood, and maximum entropy techniques. In general all three techniques produced a reasonable reconstruction of the phantom. For simplicity, we choose to use the maximum likelihood method with 25 iterations.

Fig. 3 shows a reconstruction of the nitrogen density distribution for three and five projection angles starting at 0° (horizontal projection) and uniformly distributed between 0 and 180°. The results show that the five-angle reconstruction provides a better image of the square and of its surroundings.

Fig. 4. Reconstruction of the nitrogen density distribution using the MCNP calculated projection data.

Some parameters that impact on explosive detection are (1) the number of projection angles, (2) the pixel resolution, (3) the shape and size of the explosive, (4) the position, shape, and type of obscuring material, (5) the reconstruction algorithm, (6) the accuracy with which the elemental projection densities can be obtained, and (7) the parameters used to detect explosive. The emphasis in this paper is on the number of projections required to detect a relatively large block of RDX sampled with relatively poor pixel resolution using realistic uncertainties in the elemental areal densities.
the actual nitrogen density. The three-angle reconstruction is not that inferior, however, and could provide a sufficiently accurate reconstruction of the nitrogen density distribution to be used successfully by various explosive qualifiers.

5. Reconstruction with MCNP data

The results shown in Fig. 3 use projection data calculated directly from the phantom density distribution. In practice, the projection data will have uncertainties from the statistics of the projection process and from the unfolding of the density distributions from the measured neutron spectra.

We have used MCNP and the unfolding process (Section 2) to calculate the projections for three and five angles. The results are shown in Fig. 4 for the nitrogen density distribution. A side-by-side comparison shows that reconstructed results from the MCNP simulations compare favorably to those using the exact projections with no errors. Both the general shape and densities are reasonably reproduced.

6. An explosive detection algorithm

The purpose of the tomographic reconstruction is to spatially separate objects within the phantom to avoid confusing the explosive qualifier when it is applied to each pixel in testing for the presence or absence of explosives. The best explosive qualifier is one that is sensitive to explosives and relatively insensitive to other materials or combination of materials. Note that combinations of materials can arise from packing, pixel resolution, reconstruction error, or statistical uncertainty in the unfolding process.

In this paper we use an explosive qualifier that converts the H, C, N, and O elemental densities at each pixel into an equivalent explosive density. Thus the higher the density the more likely that the pixel contains an explosive.

The top half of Fig. 5 shows the result of applying this qualifier to the MCNP data for the case of three projections. Even for this small number of projections, and even though the exact shape is not very well resolved, the explosive is clearly visible. The bottom half of Fig. 5 shows the results if only pixels with explosive densities greater than 0.5, 1.0 and 1.5 g/cm³ are displayed. The 0.5 threshold overestimates the explosive area, while the 1.5 threshold underestimates it. For this case a density of 1.0 g/cm³ provides a good compromise between detection and false alarms.

7. Summary

The results of this work show that for the phantom used in these calculations, it is relatively easy to identify the square block of nitrogen-based explosive using three projection angles, 2 cm resolution, and reasonable uncertainty in the unfolded projection densities. Thus the FNTS technique appears to be a very promising method for explosive detection.

The next steps in this study involve looking at phantoms consisting of rectangular blocks of explosives in configurations with other types of objects and phantoms containing thin slabs of explosive. It is expected that the thin slab cases will impose more stringent requirements on the number of projections and on the pixel resolution. We also intend to explore other explosive qualifiers.
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References

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