Nuclear Instruments and Methods in Physics Research A 784 (2015) 417–422

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

X-ray and neutron interrogation of air cargo for mobile applications

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ARTICLE INFO

Available online 1 January 2015

Keywords:
X-ray
Neutron
Radiography
Security
Mobile system
Dual-energy

ABSTRACT

A system for scanning break-bulk cargo for mobile applications is presented. This combines a 140 kV multi-view, multi-energy X-ray system with 2.5 MeV neutrons. The system uses dual energy X-ray radiography with neutron radiography. The X-ray and neutron systems were designed to be collocated in a mobile environment. Various materials were interrogated with the intent of distinguishing threat materials such as explosives from similar benign materials. In particular, the identification of threats and bengins with nearly identical effective atomic numbers has been demonstrated.

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1. Introduction

Checkpoint security at ports, borders, airports, and key facilities is a critical priority for many governments. Security measures are aimed at a broad range of possible threats, however invasive or time-consuming security efforts can disrupt the flow of traffic at these checkpoints. Potential security systems would ideally have fast scan times with high detection rates and low false alarms, be sensitive to a broad range of threats, and be easy and straightforward to operate. Currently dual energy X-ray radiography is the standard at most checkpoints, and these systems can be scaled to meet various needs, such as small carryon baggage up to entire shipping containers [1–5]. These systems excel at finding items with a distinctive shape or approximate composition through dual energy radiography (e.g. plastic vs. metal), however conclusively identifying explosives and other critical threats and distinguishing them from benign materials are far more challenging [6].

The efficacy of security measures is almost always strengthened through multi-sensor fusion, that is, the concurrent use of multiple orthogonal technologies to interrogate a suspected bag or parcel. To that end, neutron radiography and detection are excellent analogs to X-ray radiography [7–11]. X-ray interactions with matter are mostly dependent on the density of the material and its effective atomic number. Neutrons, however, interact in different ways, being more dependent on the nuclear structure of the various atoms and their isotopes. The correlation between neutron and X-ray attentuation for various materials is quite weak, which means that they are excellent orthogonal technologies. In addition, this orthogonality allows for conclusive material identification of drugs and explosives, provided the detection resolution of the X-ray and neutron systems are high enough.

Dual energy radiography exploits the fact that multiple X-ray spectra impingent on an object will interact in ways that are dependent on the composition of the object. By comparing attenuation coefficients and analyzing this ratio relative to calibration materials, one can find the effective atomic number for an unknown material. Dual energy X-ray radiography is not often used to its full capabilities in commercial systems however. Most are used only to classify effective atomic number (Z) based on ranges, e.g. “organic” for low Z values, “inorganic” for mid-range Z values, and “metal” for higher Z values. Despite the broad classification, one can design a system with much higher Z resolution. When combined with an orthogonal technology, it increases the resolution of the entire system.

In this work we sought to exploit dual energy radiography as much as possible, and to combine it with a rugged and easy-to-use neutron system. This work focuses on establishing the overall viability of the XNT concept and integrating improvements in the effective atomic number determination. We have developed enhanced dual-energy techniques to improve the standard atomic number determination, and have combined our X-ray system with a neutron interrogation system. We have validated the technique with experimental data and provided results to show its effectiveness in detecting threat compounds and distinguishing them from benign compounds.

2. System concept and design

Dual energy radiography works by measuring attenuation coefficients of different X-ray spectra for an unknown material and comparing that signal with attenuation coefficients of known materials [1,2,4]. The transmission of a given spectrum of radiation through a material can be given by the equation

$$I = I_0 e^{-\mu x} \tag{1}$$

where I is the detector signal, I_0 is the initial X-ray signal (typically measured with an air scan), μ is the attenuation coefficient, and x is the length of material traversed by the X-ray beam in a line between the source and the detector. By probing different areas of the X-ray spectrum, e.g. with two different detectors, Eq. (1) can be

http://dx.doi.org/10.1016/j.nima.2014.12.032
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rewritten as

$$I_H = I_{0_H} e^{-\mu_H x}$$
$$I_L = I_{0_L} e^{-\mu_L x}. \quad (2)$$

Here I_H is the signal from the higher energy detector, I_L is the signal from the lower energy detector, I_{0_H} is the air signal from the higher energy detector, and I_{0_L} is the air signal from the lower energy detector. This can be solved to yield the ratio:

$$\frac{\mu_H}{\mu_L} = \frac{\ln \frac{I_H}{I_{0_H}}}{\ln \frac{I_L}{I_{0_L}}}. \quad (3)$$

Notice that these ratios are only dependent on the signals at the detector and not on the thickness of the object, which is an unknown. If a mixture or compound is present, the effective atomic number can be expressed at our X-ray energies according to the formula [12]

$$Z_{eff} = \left[\sum_i f_i \cdot Z_{eff_i}^{2.94} \right]^{1/2.94}, \quad (4)$$

and its measured Z_{eff} can be found by comparing its properties with calibrated materials.

Neutrons are also governed by a form of the Beer–Lambert law similar to Eq. (1) given by [7]

$$\Phi = \Phi_0 e^{-\lambda_N x}, \quad (5)$$

where λ_N is the linear neutron coefficient of the material. The material identification properties of the neutron attenuation lie in the mass attenuation coefficient of the neutron data which can be expressed as

$$\Phi = \Phi_0 e^{-\zeta_N \rho x}, \quad (6)$$

where ζ_N is the neutron mass attenuation coefficient and ρx is the areal density of the material. Now ζ_N can be expressed as

$$\zeta_N = \frac{N_A}{A}\sigma = \frac{1}{\rho x}\ln\frac{\Phi_0}{\Phi}. \quad (7)$$

Here the quantity N_A/A is the average molecular weight of the material. This quantity can be obtained by dividing the logarithm of the measured neutron attenuation by the areal density as shown on the right. X-rays can determine this areal density by using a calibration procedure similar to the dual-energy calibration described above [8]. The same photoelectric effect causes deviations from the true areal density that is dependent on the atomic number of the material.

Fig. 1 shows the XNT concept system. The system concept used a 1 m × 1 m tunnel, a 2.5 MeV D–D neutron generator, and a 170 kV X-ray tube. Cargo passes through the system at a belt speed of 20 cm/s, with a minimal radiation exclusion zone appropriate for an airport environment. For our experiments we used a 140 kV X-ray tube, a 3 MV accelerator to create neutrons at 2.5 MeV, and a 1 m × 1 m tunnel. Discrepancies were due to availability of sources. We used a microstructure neutron detector utilizing a hydrogenous radiator [13]. This detector used recoil protons generated in the radiator and accelerated them through an electric field to an electron detector. The X-ray detectors were commercial off-the-shelf detectors. They used a low-energy front detector composed of gadolinium oxysulfide, a copper filter, and a rear detector composed of CsI(Tl).

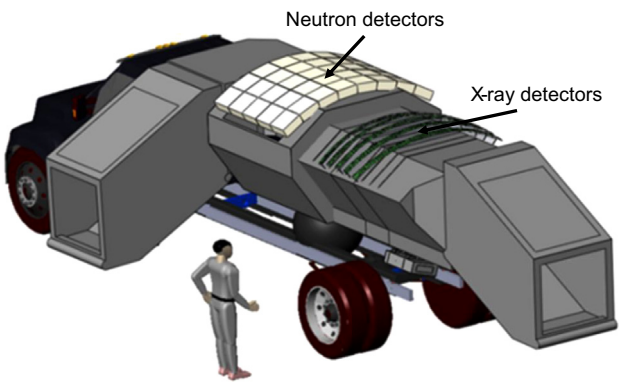

Fig. 1. A design concept for a mobile system with X-ray and neutron radiography. Both the neutron and X-ray sources shoot from the bottom up in this configuration.

The neutron beam we generated for radiography was a cone beam with a 48° angle field of regard, and a 30° angle field of view. An X-ray beam covering the same range of angles was also used. This angle geometry was chosen to provide both adequate flux in the neutron system, and also to have adequate separation of the views on the X-ray side to eliminate as much collinear data as possible. The 30° field of view was chosen to provide enough coverage to adequately image all the targets of interest. We approximated the solid angle geometry of the neutron detectors by using five linear arrays of X-ray detectors with 12° of spacing between them. We used a radial geometry in the detector plane by placing nine discrete linear subarrays in a circular arc for each detector plane. This radial geometry approximated the neutron beam geometry the best and was much cheaper than a corresponding flat panel detector. Matched views were crucial due to the neutron attenuation being dependent on areal density information provided from the X-ray views. The five views were physically composed of three detector arrays at 0°, 12°, and 24°, with the additional two views being obtained by scanning the cargo backwards. The X-ray geometry can be seen in Fig. 2.

3. Improved effective atomic number resolution

In current commercial systems, Z_{eff} determination is usually performed on each pixel in the image separately. Image processing algorithms such as smoothing or blending create a uniform-looking image. These commercial algorithms allow an operator to distinguish typically three material classes: “organic,” “inorganic,” and “metal.” These classes are simply different Z_{eff} ranges, given approximately by [6]

Organic: $1 < Z < 11$.

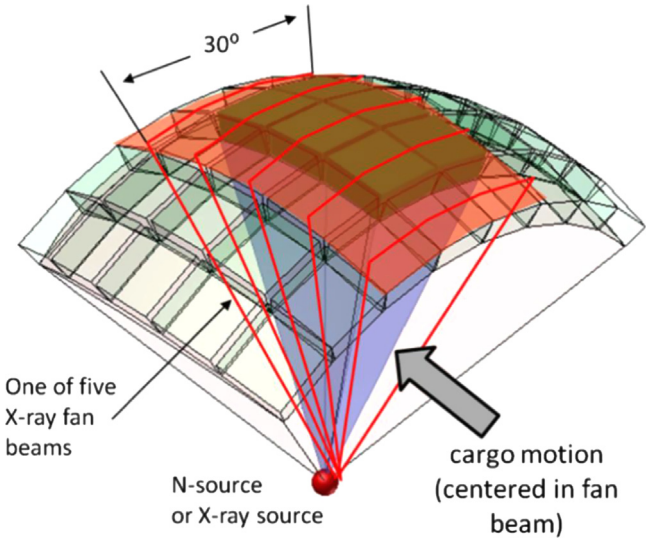

Fig. 2. Sparse linear arrays for X-rays (red) match the neutron field of view (blue). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

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