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Real-time neutron source localization and identification with a hand-held, volumetrically-sensitive, moderating-type neutron spectrometer

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ABSTRACT

Measuring source-dependent properties of free neutrons over a large neutron energy range, with hand-portable instrumentation, continues to push the frontier of neutron detection instrumentation design and analysis techniques. Building on prior work – C.B. Hoshor, et al., A portable and wide energy range semiconductor-based neutron spectrometer, Nucl. Instrum. Methods Phys. Res. A 803 (2015) 68–81 – which focused on demonstrating one-dimensional-based energy-dependent neutron measurement and analysis with a new class of solid-state moderating-type spectrometer, this work introduces two "core" algorithmic methodologies that expand the analysis of neutron thermalization measurements to three spatial dimensions to determine the location and identity of neutron radiation sources in real time. Two extensions of these core methodologies are then proposed to further improve both the accuracy and reliability of source location and identity determinations with this new class of hand-held instrumentation. In 432 preliminary simulation tests, these method extensions are shown to decrease the average source location error by 64% and provide correct identity determinations in all test cases.

1. Introduction

1.1. Background and motivation

Hand-held instruments that passively detect, locate, and identify unknown sources of neutron radiation – either bare or obscured (i.e. shielded) by neutron moderating and/or absorbing material(s) – in real time, are important to nuclear non-proliferation applications. This application space requires real-time energy-sensitive measurement of free neutrons, ranging from thermal energies (~25 meV) to the top end of the evaporation spectrum (~20 MeV). To this end, the first representatives of a new class of solid-state moderating-type neutron spectrometer [1] have been iteratively designed to improve on multi-sphere- [2,3] and long-counter-based [4] moderating-type neutron spectrometers (see [1,5], and references therein, for information on prior art and history of development). Improvements include reduced instrument mass, greater detection efficiency than the present art, and real-time analysis of energy-sensitive neutron thermalization measurements in three spatial dimensions. It is the unique, energy-sensitive, three-dimensional neutron thermalization information afforded by this new class of instruments (introduced in [1]), coupled with the analysis techniques discussed herein, that is novel, and will be the primary focus of this work.

1.2. The 6C hand-held solid-state neutron spectrometer

Although the general methodologies introduced in this work could be applied to a wide variety of similar instrument designs, the discussion herein will primarily focus on the research team's most successful instrument to date, the 6C (6-inch Cylindrical) moderating-type neutron

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spectrometer. This section will provide a brief description of the 6C neutron spectrometer and the unique neutron thermalization information afforded by the instrument.

The active portion of the 6C neutron spectrometer, as shown in Fig. 1.1(C), consists of 8 neutron detector daughter boards evenly-spaced (axially) within a cylindrical volume (diameter = 6″, length = 12″) of high density polyethylene (HDPE) moderator. Each of the 8 detector daughter boards (Fig. 1.1(A)) is composed of a 4×4 square array of 2.0-cm × 2.0-cm microstructured neutron detectors (MSNDs). The MSND-based boards, developed and manufactured by Radiation Detection Technologies (RDT), are comprised of Si diodes, etched to form trenches and backfilled with ^{6}LiF powder; the MSND variant used in this work has an empirical thermal neutron detection efficiency of $\eta_{\mathrm{th}} \approx 22\%$ (the MSND detection mechanism has been described in detail previously [6]).

The fundamental novelty of the 6C spectrometer's design is that the internal array of 128 thin (≈525 μm), semiconductor-based, thermal neutron detectors (MSNDs) provides high neutron detection efficiency and volumetric resolution of the average neutron thermalization along three coordinate axes within the moderator–detector assembly, with minimal displacement of the moderating medium. The primary goal of this work is to introduce novel algorithmic methodologies that utilize this highly-efficient, statistically-predictable, three-dimensional neutron thermalization information (see Fig. 1.2) to determine the relative location and the identity of neutron radiation sources in real time. Sections 2 and 3 of this paper will introduce and discuss the "core" methods (currently implemented in the 6C spectrometer software) for determining the relative location and the identity of neutron sources. Sections 4 and 5 will then explore extensions of – and potential improvements to – these core methodologies.

2. Neutron response vectorization (NRV) method for determining neutron source location

2.1. NRV method description

The simulations represented in Fig. 1.2 illustrate the statistically-predictable dependence of the 6C spectrometer response (i.e., MSND detection intensities as a function of location within the moderating medium) with respect to the relative angular position of a neutron source of interest in the horizontal plane. Utilizing this dependence, the currently implemented algorithm for determining the location of a neutron source (relative to the 6C spectrometer) employs a 3-dimensional vector-summing method called the neutron response vectorization (NRV) method (note: the discussion in this section will be in terms of the common coordinate system defined in Figs. 1.2(A) and 2.1(A) unless otherwise specified). In the first step of this method, each neutron detector in the instrument is assigned a vector, $\boldsymbol{r}_l$, describing its physical location relative to the midpoint of the moderating medium's central axis (Fig. 2.1(B)),

$$\boldsymbol{r}_l = \begin{bmatrix} x_l \\ y_l \\ z_l \end{bmatrix}, \quad \text{for } l = 1, \dots, Q, \tag{2.1}$$

where Q is the total number of detectors in the system (for the 6C spectrometer, $Q = 128$). Next, geometric corrections are made to account for instrument asymmetries. By way of example, in the case of the 6C spectrometer, since the internal MSND arrays form a rectangular-prism-shaped grid within the moderator volume (as shown in Fig. 1.2), the currently-implemented NRV algorithm for this instrument employs a vector of Cartesian geometric expansion coefficients, $\Lambda = [\lambda_x, \lambda_y, \lambda_z]^T$, to multiplicatively transform the position vectors, $\boldsymbol{r}_l = [x_l, y_l, z_l]$, from their original rectangular prism orientation, to an expanded cubic form (Fig. 2.1(C)). This transformation is given by

$$\boldsymbol{c}_l \equiv r_l \circ \Lambda = \begin{bmatrix} \boldsymbol{x_l \cdot \lambda_x} \\ \boldsymbol{y_l \cdot \lambda_y} \\ \boldsymbol{z_l \cdot \lambda_z} \end{bmatrix}, \quad \text{where} \tag{2.2}$$

$$\lambda_x = 1, \qquad \lambda_y = \frac{\max(x_l) - \min(x_l)}{\max(y_l) - \min(y_l)}, \quad \text{and} \quad \lambda_z = \frac{\max(x_l) - \min(x_l)}{\max(z_l) - \min(z_l)},$$

(the operator "∘" represents the Hadamard product, i.e., element-wise multiplication). These cubic-oriented position vectors are then normalized to form spherically-oriented unit vectors (Fig. 2.1(D)),

$$\boldsymbol{u}_l \equiv \frac{\boldsymbol{c}_l}{|\boldsymbol{c}_l|} = \frac{\boldsymbol{r}_l \circ \Lambda}{|\boldsymbol{r}_l \circ \Lambda|} = \frac{1}{\sqrt{(x_l \cdot \lambda_x)^2 + (y_l \cdot \lambda_y)^2 + (z_l \cdot \lambda_z)^2}} \cdot \begin{bmatrix} x_l \cdot \lambda_x \\ y_l \cdot \lambda_y \\ z_l \cdot \lambda_z \end{bmatrix}. \tag{2.3}$$

Since these vectors are oriented spherically, they possess the highest degree of rotational symmetry achievable for the discrete system (i.e., Q discrete unit vectors, $\boldsymbol{u}_l$, $l = 1, \dots, Q$). With geometric asymmetries aptly accounted for and each position vector normalized, the number of neutron counts registered by each detector, N_l, is then multiplied by its associated unit vector, $\boldsymbol{u}_l$, yielding a set of detector response vectors (Fig. 2.1(E))

$$\begin{aligned} \boldsymbol{d}_l &\equiv N_l \cdot \boldsymbol{u}_l = N_l \cdot \frac{\boldsymbol{r}_l \circ \Lambda}{|\boldsymbol{r}_l \circ \Lambda|} \\ &= \frac{N_l}{\sqrt{(x_l \cdot \lambda_x)^2 + (y_l \cdot \lambda_y)^2 + (z_l \cdot \lambda_z)^2}} \cdot \begin{bmatrix} x_l \cdot \lambda_x \\ y_l \cdot \lambda_y \\ z_l \cdot \lambda_z \end{bmatrix}. \end{aligned} \tag{2.4}$$

All Q detector response vectors are then summed, resulting in a single resultant vector (Fig. 2.1(F)),

$$\begin{aligned} \boldsymbol{v}^{(R)} &\equiv \sum_{l=1}^{Q} \boldsymbol{d}_l = \sum_{l=1}^{Q} N_l \cdot \frac{\boldsymbol{r}_l \circ \Lambda}{|\boldsymbol{r}_l \circ \Lambda|} \\ &= \sum_{l=1}^{Q} \frac{N_l}{\sqrt{(x_l \cdot \lambda_x)^2 + (y_l \cdot \lambda_y)^2 + (z_l \cdot \lambda_z)^2}} \cdot \begin{bmatrix} x_l \cdot \lambda_x \\ y_l \cdot \lambda_y \\ z_l \cdot \lambda_z \end{bmatrix}. \end{aligned} \tag{2.5}$$

Since this equation is expressed in terms of each detector's physical position, r_l (predetermined/constant), and number of counts registered, N_l (measured/variable), with geometric expansion coefficients, Λ (predetermined/constant) as defined in Eq. (2.2), this resultant vector can be calculated from Eq. (2.5), alone, as the measured data accumulates (i.e., in real time). The direction of the resultant vector, $\boldsymbol{v}^{(R)}$, indicates the region of the instrument with the highest average detection intensity, and its magnitude is proportional to the degree of spatial localization (or dispersion) of this high intensity region. It is important to note here that both the direction and magnitude of $\boldsymbol{v}^{(R)}$ are altered, to some degree, with the introduction of any geometric asymmetry corrections, and this must be carefully considered in light of an instrument's design. However, in the case of the 6C spectrometer, the correction step described in Eq. (2.2) has been shown to improve the accuracy of this method – in comparison to skipping this step – regardless of source-to-spectrometer relative angular orientation, and has thus been incorporated into the core NRV methodology described here, by way of example. This vector, $\boldsymbol{v}^{(R)}$, is then normalized to produce a resultant unit vector, $\boldsymbol{u}^{(R)}$, in the expected direction of the neutron source of interest (Fig. 2.1(G)),

$$\boldsymbol{u}^{(R)} \equiv \frac{\boldsymbol{v}^{(R)}}{|\boldsymbol{v}^{(R)}|} = \frac{1}{\sqrt{\left(v_x^{(R)}\right)^2 + \left(v_y^{(R)}\right)^2 + \left(v_z^{(R)}\right)^2}} \cdot \begin{bmatrix} v_x^{(R)} \\ v_y^{(R)} \\ v_z^{(R)} \end{bmatrix}. \tag{2.6}$$

Fig. 2.1(B)–(D), provides a step-by-step visualization of the six major steps of the NRV method. For the example shown in Fig. 2.1, the NRV method was applied to a simulated 6C spectrometer response to a bare ^{252}Cf point source 2 m from what will be defined here as the moderating cylinder's circular "front face", located at $x = -12.6$ cm in Figs. 1.2(A) and 2.1(A) (i.e., the leftmost circular face in Fig. 1.1(B)–(D)). Notes: (1) Figs. 1.2(A) and 2.1(A) depict same simulated response data, (2) the ^{252}Cf energy spectrum used in this simulation is a "measured" spectrum