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Fast-neutron, coded-aperture imager

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ABSTRACT

This work discusses a large-scale, coded-aperture imager for fast neutrons, building off a proof-of concept instrument developed at the U.S. Naval Research Laboratory (NRL). The Space Science Division at the NRL has a heritage of developing large-scale, mobile systems, using coded-aperture imaging, for long-range γ-ray detection and localization. The fast-neutron, coded-aperture imaging instrument, designed for a mobile unit (20 ft. ISO container), consists of a 32-element array of 15 cm × 15 cm × 15 cm liquid scintillation detectors (EJ-309) mounted behind a 12 × 12 pseudorandom coded aperture. The elements of the aperture are composed of 15 cm × 15 cm × 10 cm blocks of high-density polyethylene (HDPE). The arrangement of the aperture elements produces a shadow pattern on the detector array behind the mask. By measuring of the number of neutron counts per masked and unmasked detector, and with knowledge of the mask pattern, a source image can be deconvolved to obtain a 2-*d* location. The number of neutrons per detector was obtained by processing the fast signal from each PMT in flash digitizing electronics. Digital pulse shape discrimination (PSD) was performed to filter out the fast-neutron signal from the γ background. The prototype instrument was tested at an indoor facility at the NRL with a 1.8-μCi and 13-μCi 252Cf neutron/γ source at three standoff distances of 9, 15 and 26 m (maximum allowed in the facility) over a 15-min integration time. The imaging and detection capabilities of the instrument were tested by moving the source in half- and one-pixel increments across the image plane. We show a representative sample of the results obtained at one-pixel increments for a standoff distance of 9 m. The 1.8-μCi source was not detected at the 26-m standoff. In order to increase the sensitivity of the instrument, we reduced the fastneutron background by shielding the top, sides and back of the detector array with 10-cm-thick HDPE. This shielding configuration led to a reduction in the background by a factor of 1.7 and thus allowed for the detection and localization of the 1.8 μCi. The detection significance for each source at different standoff distances will be discussed.

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1. Introduction

The ability to detect and identify potentially illicit nuclear material is important for national security measures. To seek out the fast-neutron emission signature from nuclear material, one must have an instrument with neutron sensitivity in the less than 1.0 to several MeV energy range. Two critical components for detection are the amount of observation time and the distance at which a source can be detected. To serve these criteria, the most efficient method would be to have a large-effective-area instrument with sensitivity to fast neutrons and the ability to distinguish these neutrons from background γ rays. Aside from the system triggering when a threat is present, the ability to localize the source is paramount. Such an instrument is a large-scale, fast-neutron, coded-aperture imaging system based on organic scintillators for neutron/γ-ray detection and discrimination. Depending on the application, the instrument could operate either passively or in an active interrogation environment. Used in tandem with an active interrogator, the instrument would search for neutron emission from potential threat material. Specifically, a field-deployable instrument would be ideal for detecting and locating delayed neutron emission from nuclear material undergoing interrogation. In passive applications, with a well-understood background environment, the large effective area of the instrument can be utilized for threat detection. Previous work using organic scintillators for fast-neutron imaging and spectroscopy has been in the form of scatter cameras. The scatter camera – although demonstrated to operate successfully [1] – requires the incident neutron to undergo two successive scatters in multiple detection planes instead of a single scatter in one plane. Therefore, the inherent efficiency is reduced compared to similarly sized coded-aperture imagers, which typically have half of the detector array masked.

The work herein discusses a large-scale, coded-aperture imager for fast neutrons, building off a proof-of-concept prototype [2]

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developed at the U.S. Naval Research Laboratory (NRL). Work on fast-neutron coded-aperture imagers done by others can be found elsewhere [3,4]. The Space Science Division at NRL has a heritage in developing large-scale, mobile systems, using coded-aperture imaging, for long-range γ-ray detection of hazardous isotopes. The SuperMISTI (Mobile Imaging Stereoscopic and Threat Identification) system [5] (Figs. 1 and 2) was designed to fit in a standard 20 ft. (6.1 m) ISO shipping container, complete with a 6×13 array of 12.7 cm NaI(Tl) detectors situated behind a coded mask of 5-cm-thick lead elements; the array and mask are separated by the maximum distance allowed by the container. With the success of this past work for γ-ray coded-aperture imaging, we sought to design and investigate a comparably sized fast-neutron coded-aperture imaging array for a similar mobile system.

2. Coded-aperture imaging

The principle behind coded-aperture imaging involves modulating the radiation source flux by arranging a pattern of absorbing and transmitting elements. Depending on the stimuli to be detected, the masking material is chosen such that absorption or moderation for a given energy range is achieved. The coded-aperture imaging technique is an extension of the pinhole camera – the smaller the aperture, the better the camera resolution. Unless a source is extremely close or bright, the limiting flux allowed by the small aperture reduces the sensitivity of the camera. To exploit the resolution of the pinhole camera but increase the throughput flux, an array of pinholes are arranged in some known pattern – a coded aperture. The resulting flux through the coded aperture is an ensemble of overlapping shadow patterns detected by position-sensitive detectors, from which a source image can be decoded. More detailed discussion on coded-aperture imaging principles can be found elsewhere [6–8].

The method we employed to perform image reconstruction is shown graphically in Fig. 3 [9]. In this example, we show a 3×3 detector array and a 5×5 coded mask, where the number of hits shown for each detector constitutes the value registered over some integration time above a given threshold. For the coded mask, the 1 s represent open elements, and the 0 s represent closed elements. The upper right part of Fig. 3 shows the projection of the coded mask for detector hits in the upper left corner (represented by the 5×5 shaded region starting at the upper left) and the lower right corner (represented by the 5×5 shaded region starting at the lower right). The overlapping region (the central 3×3 array) shows where the hits from the detectors and the region of the coded mask that was sampled contribute to the fully coded field of view. Shown in the lower right of Fig. 3 is the full representation of the coded image for the registered hits from the 3×3 array of detectors. The outlined square represents the fully coded field of view. Outside this region is the partially coded field of view, which is where only a partial number of detectors contribute to the coded image.

The coded mask pattern was chosen to optimize the imaging capabilities of the instrument. Three common patterns that have been useful for imaging in past applications [10,11] were the uniformly redundant array (URA), the modified uniformly redundant array (MURA), and the pseudorandom pattern. For this work, we decided to investigate a 12×12 pseudorandom mask pattern. This mask has no discernible pattern (random), but the elements are arranged in a manner that yields optimal imaging performance (*pseudo*random) such that imaging artifacts were limited in the reconstructed image [9]. The pseudorandom mask pattern has high throughput with the criteria on the masking elements of 50% transparent (open) and 50% opaque (closed). Using Monte Carlo simulations, a set of mask patterns were randomly generated, and the pattern that yielded the best response to an on-axis point source was chosen. A secondary test was performed by folding a

Fig. 1. The SuperMISTI 20 ft. ISO container on a mobile trailer.

Fig. 2. A view from inside the container shows the γ-ray, coded-aperture imaging system. Upon entering, the left side of the container comprises the array of lead coded-mask elements (10 cm × 10 cm × 5 cm) mounted to the inner container wall. The opposite facing side of the container comprises the 6×13 array of 12.7 cm NaI(Tl) detectors. Adjacent to the detector array are the associated VME and NIM electronics and power supply.