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Detection and positioning of radioactive sources using a four-detector response algorithm

Michael J. Willis*, Steven E. Skutnik, Howard L. Hall

Department of Nuclear Engineering, The University of Tennessee Knoxville, United States

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ABSTRACT

A method for detecting and identifying radioactive gamma-ray sources along with determining a directional bearing is described. This method is based upon comparing the relative intensities of four detectors placed side by side in a four-quadrant formation, allowing for the system to take advantage of shadowing in the occluded array of detectors. Based on this shielding principle, a fuzzy logic algorithm is used to analyze the gross count response of each individual detector with respect to the other three. The result of this algorithm is a numerical result that can be converted to a directional bearing in a 360° x–y plane.

1. Introduction

With the increasing availability of nuclear materials worldwide, there is a growing need for more sophisticated techniques to detect and locate illicit radioactive materials in real-world scenarios. Traditional detection techniques consist of various types of stationary portal monitors and portable radiation detection devices that are capable of determining the presence of radioactive sources in the vicinity of the detection unit. These devices are used across the world to safeguard borders and detect illicit materials at various key locations. Assorted systems implementing these devices are used both in the form of vehicle portals [1,2] (at major commercial portals such as seaports and land border crossings) and pedestrian portal monitors located at facilities where radioactive materials are employed such as hospitals, airports, and other high-traffic locations [3]. There are also numerous types of handheld and vehicle mounted detection devices that are used in survey and search techniques [4]. Each of these types of monitors is capable of detecting a radiation signature within a certain distance, but none produce a directional bearing of the source relative to the measurement location. A method that is more mobile and cost-effective than current detection systems and is capable of providing relative direction information for detected sources would facilitate a more timely response to a potential radiological threat. This work presents an approach that facilitates mobile deployment capability in a cost-effective manner based on existing commercial off-the-shelf technology while also providing directional bearing information of the source.

In this study, four 2 in. × 2 in. × 4 in. NaI(Tl) detectors and a Pixie-4 channel data acquisition (DAQ) from XIA LLC [5] were used to acquire the gamma spectroscopy data used to demonstrate the proposed radioactive source bearing algorithm. Comparative studies have shown that NaI(Tl) detectors represent a reasonable compromise between cost and performance for a system such as this one. This is mainly due to their sufficient resolution and ability to collect a gamma ray spectrum that can be used in analysis for manual or automatic isotope identification [6]. The detectors are placed in a quadrant formation to allow for occlusion of the source by the individual detectors. The premise of the shadowing effect in the four-detector algorithm relies on the attenuation of the radiation particles through a detector volume.

Similar studies have used a detector occlusion approach to show how detector responses differ based on the orientation of the detector system to the source [7,8]. Another approach uses an external shield to help determine the direction of the source within 11.1° from the actual angle. However, this requires upwards of four 3-min measurements at each location to determine the direction of the source [9]. The advantage of the approach proposed in this paper is that it requires only one short measurement to determine the location of all tested sources within 10.35° from the actual angle. Another benefit of this approach is that it is capable of determining the bearing of the source using a source count rate 1000 times less than tested in previous studies [8]. The system relies on the detectors that are closer to a radiation source shielding those that are farther away, creating a “shadow” effect.

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* Corresponding author.

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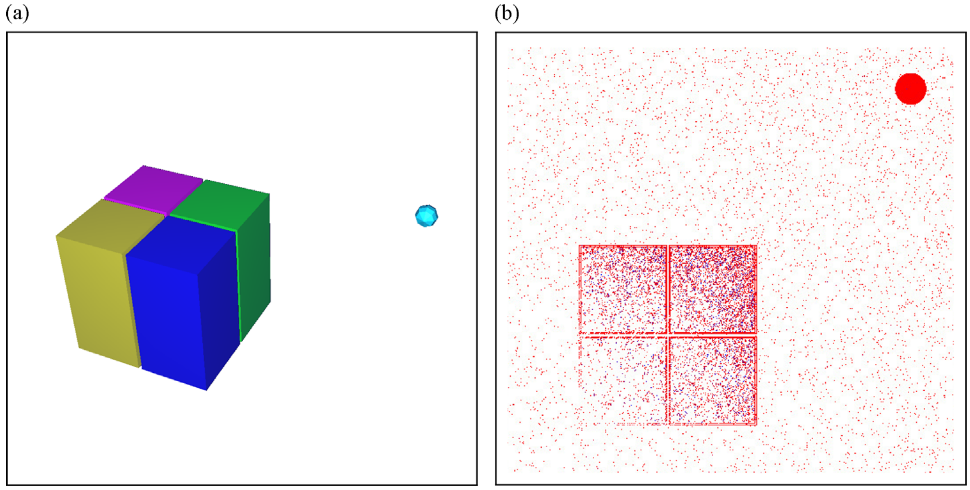

Fig. 1. Visualization of detector “shadowing” effect for individual particles. (a) 3D view of detectors and source. (b) VisEd particle tracker view of detectors and source.

A model created by Monte Carlo N-Particle (MCNP) transport code [10] provides a visual example of this shadow effect, as shown in Fig. 1.

By positioning multiple detectors together as an occluded array, the detectors in the system shadow the neighboring detectors depending on the source location. Taking advantage of this shadowing effect, a source position can be determined based on the relative measured signal intensity in the detector array; detectors that are closer to the radiation source see a comparatively more intense response compared to those further away. Additional shielding can also be added between the detectors to increase the attenuation of particles and promote the occlusion of the further detectors. Each location around the detectors in an x–y plane has a distinct intensity response profile for the four detectors that can be used to determine the relative directional bearing of the source.

Although the idea of occlusion has been used to determine source location as noted before, the application of fuzzy logic for analysis is a novel approach. In order to develop a system that can easily interpret the relative source position based upon the measured intensities, a fuzzy logic algorithm was constructed. This algorithm converts relative measured intensities into fuzzy membership functions (i.e., “low”, “medium”, or “high” intensities) and then interprets the combination of the four individual responses to give the position of the source relative to the detector array.

To test this algorithm, an MCNP model of the four-detector array was created to simulate relative detector responses for different source positions, which were then used as input parameters for the fuzzy logic position algorithm. Results were obtained from bench-top measurements using the Pixie-4 DAQ with the NaI(Tl) four-detector array and the MCNP model then were used to validate the accuracy of predicted positions from the fuzzy logic system.

2. Fuzzy logic

To develop the fuzzy logic algorithm, the MATLAB Fuzzy Logic toolbox was used. A more detailed description of the fuzzy logic methodology can be found in other literature [11,12], therefore only a brief overview will be provided in the following sections.

2.1. Fuzzy logic overview

Fuzzy logic is an approach used for problem solving that does not require value specific inputs, but is able to produce a very approximate result. The system requires an input or a set of inputs, tests the input against a set of pre-assigned rules, and generates an output that best fits the corresponding data.

2.1.1. Fuzzy rule sets

The first step is to design the set of fuzzy conditionals which define how the system responds. A system can be composed of an arbitrary number of fuzzy conditional statements; more fuzzy conditionals can be used to produce a more precise evaluation of the relative source position. A fuzzy system uses what is known as IF–THEN rules [13]. By creating simple “IF” policies that produce “THEN” results, a set of simple rules can be created that produce a fuzzy number relative to the directional bearing of the source. An example set of rules can easily be demonstrated in [13]

IF X1 is *small* **AND** X2 is *small*, **THEN** Y is *small* (1)

IF X1 is *large* **AND** X2 is *small*, **THEN** Y is *large* (2)

2.1.2. Fuzzy membership functions

A principal component to the fuzzy approach is the use of membership functions. These functions serve to create numerical values for input values that are descriptive words used in rule sets. If the above example were used as an example fuzzy set of rules, a numeric value would be assigned to the words “small” and “large”. A reasonable scale that might be assigned would be from 0 to 10, where small $=0$ and large $=10$. Membership functions would allow for an input that may not be equal to exactly 0 or 10. In cases like this, fuzzy systems can use the input data to achieve results that are close to those expected with definitive inputs of 0 or 10.

2.1.3. Mamdani-type fuzzy logic

In most fuzzy logic structures there exists multiple rules that are combined and compared to create a thorough rule set for evaluating a system's inputs. To assess multiple results from different rules, a system must have a logical methodology in estimating a combined result. A common type of fuzzy system that is capable of doing this is one that uses the Mamdani-type fuzzy logic approach [11,14]. In this type of method, the following four steps are used:

1. *Evaluate the antecedent for each rule*: This step involves the input values becoming “fuzzy”.
2. *Obtain each rule's conclusion*: A conclusion is formed for each rule based upon the fuzzy input.
3. *Aggregate conclusions*: The results from all rules are combined.