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Three-dimensional localization of low activity gamma-ray sources in real-time scenarios

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ABSTRACT

Radioactive source localization plays an important role in tracking radiation threats in homeland security tasks. Its real-time application requires computationally efficient and reasonably accurate algorithms even with limited data to support detection with minimum uncertainty. This paper describes a statistic-based grid-refinement method for backtracing the position of a gamma-ray source in a three-dimensional domain in real-time. The developed algorithm used measurements from various known detector positions to localize the source. This algorithm is based on an inverse-square relationship between source intensity at a detector and the distance from the source to the detector. The domain discretization was developed and implemented in MATLAB. The algorithm was tested and verified from simulation results of an ideal case of a point source in non-attenuating medium. Subsequently, an experimental validation of the algorithm was performed to determine the suitability of deploying this scheme in real-time scenarios. Using the measurements from five known detector positions and for a measurement time of 3 min, the source position was estimated with an accuracy of approximately 53 cm. The accuracy improved and stabilized to approximately 25 cm for higher measurement times. It was concluded that the error in source localization was primarily due to detection uncertainties. In verification and experimental validation of the algorithm, the distance between ^{137}Cs source and any detector position was between 0.84 m and 1.77 m. The results were also compared with the least squares method. Since the discretization algorithm was validated with a weak source, it is expected that it can localize the source of higher activity in real-time. It is believed that for the same physical placement of source and detectors, a source of approximate activity 0.61–0.92 mCi can be localized in real-time with 1 s of measurement time and same accuracy. The accuracy and computational efficiency of the developed scheme make this algorithm a suitable candidate for its deployment in real-time localization of radioactive sources.

1. Introduction

The detection and identification of radioactive material is an important aspect of both nuclear safeguard and material protection. One of the key aspects in nuclear material surveillance is the identification and localization of the radioactive sources in real-time. Computational schemes are continually developed to facilitate such surveillance. The algorithm used to track the radiation source should be computationally efficient to facilitate early detection in near real-time, without sacrificing accuracy.

In previous studies, the geometric difference triangulation method was used to locate radiation sources [1]. The measurements collected from three sensors were used to estimate the source location and its strength. Howse et al. [2] discussed recursive and the moving horizon non-linear least squares estimation algorithms for the real-time estimation of a moving source. This work incorporated the use of four gamma-ray detectors located at four different positions of the monitoring area. The algorithm developed was used to track the location of the moving source within that region. The results were presented for a ^{137}Cs source moving along a predetermined path. For efficient collection of data, the approximate measurement time was 3 min at each point the source was stopped.

RadTrack, developed at Argonne National Laboratory, uses a combination of a set of radiation detectors and a video camera to track a radioactive source [3]. It utilizes a map of probability density function to localize the radiation source. The results were presented for both a 1 mCi ^{60}Co source and a relatively weak (100 μCi) ^{137}Cs source. For the 100 μCi source, the method of temporal linking reduced the mean error in estimation to approximately 0.9 m.

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Chin et al. [4] have addressed the problem in localization of low-level radioactive sources under realistic noise and measurement errors. For the performance evaluation of their iterative pruning (ITP) fusion algorithm, the results were reported for a ^{137}Cs source of extremely low activity of 0.911 μCi. The simulation results compare the localization error for different source strengths and sensor densities. For a 400 μCi source and sensor density of approximately 1 per 1100 m^2 area, the algorithm localized the source within 32.5 m. Circles of Apollonius could also be used in source localization [5]. This study discussed a key problem—i.e., ambiguity (non-uniqueness)—in the position estimates and how an additional detector distinguishes the actual source position. The analysis considered an ideal scenario with no statistical fluctuations.

A particle filter algorithm was proposed by Rao et al. [6] to detect radioactive sources. The outputs of this algorithm demonstrates the benefits of networked configuration over the non-networked and pair configurations of the counters. In this work, results were presented for a notional border monitoring scenario with twelve 2 in. × 2 in. NaI detectors. Another class of localization algorithms that has been explored extensively in the literature utilizes a Difference of Time-of-Arrival (DTOA) method [7–9]. Linear algebraic approach for localization using DTOA method is addressed in [9,10]. Some other works that are relevant to the work presented in this paper are discussed in [11–13].

This paper introduces a new, simpler, and faster approach to predict the source position in a three-dimensional domain. The algorithm is also proposed for use in real-time backtracing applications. The suitability of this algorithm for real-time applications required it to be fast and accurate even with limited data.

2. Source position prediction methodology

Radiation intensity $I(x_i, y_i, z_i)$ at a particular position (x_i, y_i, z_i), due to a localized radiation source, in a non-attenuating medium, is inversely proportional to the square of its distance from the source:

$$I(x_i, y_i, z_i) \propto \frac{S(x, y, z)}{r_i^2} \quad (1)$$

where r_i is the distance from the i^{th} position to a radiation source of strength S at position (x, y, z).

The generalization of Eq. 1 for various detector positions is

$$I_1 r_1^2 = I_2 r_2^2 = \ldots = I_i r_i^2 = S * K \quad (2)$$

where K is a constant of proportionality, I_i is the intensity at the i^{th} position and r_i is the distance from this position to the source (see Fig. 1).

Gunatilaka et al. [12] explained a general case for estimation of a source position in a two-dimensional domain. In a real-world situation where the source may be placed above the ground, i.e. where the discrimination in z-direction becomes important, backtracing in three-dimensional space will give a better insight of the source positioning. The localization of radioactive source becomes more rigorous in this scenario. The equation of any sphere centered at a detector position (x_1, y_1, z_1) and passing through the source position (x, y, z) is given by

$$(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2 = r_1^2 \quad (3)$$

where r_1 is the radius of the sphere. In general, the equation of any sphere with radius r_i centered at the detector position (x_i, y_i, z_i) and passing through the source position (x, y, z) is

$$(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2 = r_i^2, \text{for all } i = 1, 2, 3, 4 \quad (4)$$

If it is assumed that there is no attenuating medium in the line of sight of the detector, and the intensity at a position perfectly follows the inverse-square relationship, then

$$r_i^2 = \left(\frac{I_1}{I_i}\right) r_1^2 \equiv k_{1i} r_1^2, \text{ where}$$

$$k_{1i} = \left(\frac{I_1}{I_i}\right) \quad (5)$$

Combining Eq. 4 and Eq. 5, creates

$$(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2 = k_{1i} r_1^2, \text{ for all } i = 1, 2, 3, 4 \quad (6)$$

Four unknowns $(x, y, z, \text{and } r_1)$ are represented by Eq. 6. Thus, a minimum of four detector positions are required to determine these unknowns. Note that k_{1i} is evaluated by the intensities at the first and the i^{th} detector positions. The set of four equations represented by Eq. 6 (for $i = 1, 2, 3, 4$) are non-linear and can be solved for four unknowns if all the detector positions (x_i, y_i, z_i) and the constants k_{1i} are known. The quadratic nature of the problem forces it to have two solutions—one of which is the real source position. This ambiguity is similar to one presented in [5] and can be avoided by incorporating one more detector position. The solution that best satisfies the fifth detector equation (for $i = 5$ in Eq. 6) is deemed the predicted source position. Therefore, information of intensities at no fewer than five different detector positions is essential for localization through the proposed algorithm.

The approach to localization utilizes a domain discretization scheme. This scheme works by adaptively meshing the source domain into a finite number of discrete cells (see Figs. 1 and 2) and utilizing statistic-based successive refinements for convergence. For the convergence criterion, the standard deviation σ of the $I_i r_i^2$ values is minimized. Theoretically—with no statistical variation and detection uncertainties—centroids of cells near the actual source position should better satisfy the inverse-square relationship. At the actual source position, $I_i r_i^2$ is constant which implies

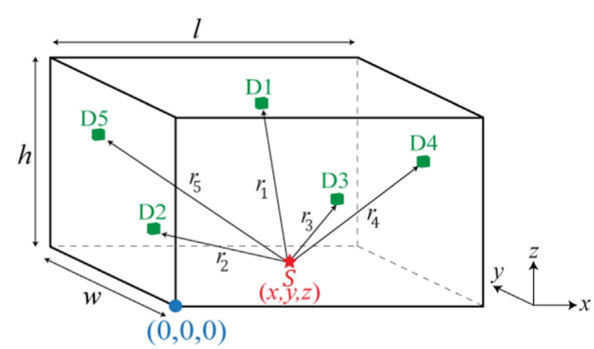

Fig. 1. A representation of the domain in which the source is backtraced ($n = 5$).

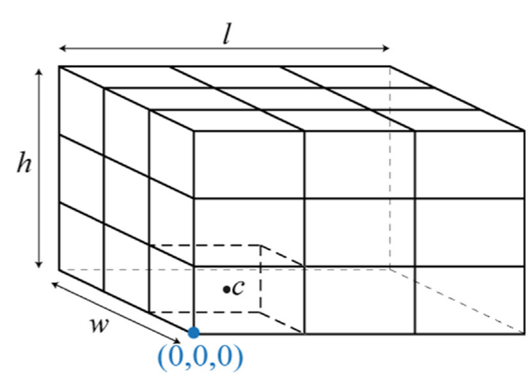

Fig. 2. Domain discretization: the centroid of the discrete cell is represented by c ($N = 3$).