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Stochastic image reconstruction for a dual-particle imaging system

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ABSTRACT

Stochastic image reconstruction has been applied to a dual-particle imaging system being designed for nuclear safeguards applications. The dual-particle imager (DPI) is a combined Compton-scatter and neutron-scatter camera capable of producing separate neutron and photon images. The stochastic origin ensembles (SOE) method was investigated as an imaging method for the DPI because only a minimal estimation of system response is required to produce images with quality that is comparable to common maximum-likelihood methods. This work contains neutron and photon SOE image reconstructions for a ^{252}Cf point source, two mixed-oxide (MOX) fuel canisters representing point sources, and the MOX fuel canisters representing a distributed source. Simulation of the DPI using MCNPX-PoliMi is validated by comparison of simulated and measured results. Because image quality is dependent on the number of counts and iterations used, the relationship between these quantities is investigated.

1. Introduction

The principles of Compton-scatter photon imaging are well understood and have been applied to applications such as nuclear security and astrophysics. Compton-scatter cameras traditionally generate images by applying the Compton-scatter equation,

$$\cos\theta = 1 - \frac{m_e c^2 E_{d1}}{E_{d2}(E_{d1}+E_{d2})} \quad (1)$$

to calculate the angle, θ, from the scatter axis at which the photon originated. E_{d1} is the energy deposited by the photon in a scatter and E_{d2} is the energy remaining after the scatter. Each angle defines the surface of a cone that represents all possible origins of that event. To measure the required parameters for Eq. (1), a Compton camera typically consists of a scattering and absorbing medium. This may consist of separate detector arrays or can be accomplished with position sensitive detectors. Recorded counts are *correlated events* which correlate the two required interactions to calculate the scatter angle. A neutron-scatter camera defines cones in a similar fashion to the Compton camera but instead uses elastic scattering events in two different detectors [1,2]. The cones are projected onto a surface and their superposition produces an image of the source. This method, often referred to as simple backprojection, produces images with a large point-spread function partly due to the inclusion of the entire cone in the image. The image is also blurred because effects inherent to radiation measurements, and the construction of the imaging system, cause many cones to not overlap with the actual source location. These effects include detector energy and timing resolution as well as positional uncertainty of the particle interaction within an individual detector.

Statistical techniques for image reconstruction have improved image quality for Compton-scatter and neutron-scatter cameras compared to simple backprojection. One such method, maximum-likelihood expectation-maximization (MLEM) has been widely implemented [3–6]. Another technique, stochastic origin ensembles (SOE) has been proposed as an alternative to MLEM. It was shown that SOE image reconstruction provides comparable image quality to MLEM by Andreyev et al., and does so without requiring an extensive estimate of input parameters to describe system response [7]. The only inputs required for SOE image reconstruction are the backprojected cones and a single value describing the angular resolution of the system. This is significant because deriving or simulating system response is often computationally

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intensive. For a system that uses multiple detector configurations, depending on the application, using a large number of system response functions may not be feasible.

SOE has been applied to tomographic reconstruction as well as adapted to Compton-scatter cameras for medical imaging applications [8–10]. These studies presented the method for SOE image reconstruction and showed simulated results from Compton cameras meant for close-range imaging. However, in safeguards, large fixtures such as containers and pipes must be measured, which requires a longer source-to-detector distance than is typical in medical applications. Consequently, safeguards applications require a larger system to obtain reasonable detection efficiency.

Imaging both photons and neutrons is of great interest in these applications as it may provide a more robust detection of shielded SNM, that emits both neutrons and photons, when intervening material is present. A typical source for a safeguards measurement will provide a high photon count rate compared to the neutron count rate – typically by an order of magnitude or more [11]. However, photon background radiation will have a significant effect on image reconstruction. Safeguard measurements are typically performed in facilities containing other radioactive sources contributing a high rate of photon background radiation [11]. In comparison, neutron background rates are generally lower.

This paper investigates the application of SOE imaging to a dual-particle imaging system for safeguards applications at standoff distances of several meters. The dual-particle imaging system combines a traditional Compton-scatter camera with a neutron-scatter camera in a two-plane design [12,13]. We have chosen to investigate the feasibility of SOE image reconstruction because only a minimal definition of system response is required to produce images that may offer quality comparable to MLEM solutions.

2. Image-reconstruction method

The SOE algorithm for this study was implemented as a modified version of the method proposed by Andreyev et al. [7]. SOE reconstruction uses the Metropolis-Hastings algorithm which relies on Markov-Chain Monte Carlo sampling to produce an image. A full derivation of the SOE method is presented by Sitek for use in tomography [8]. A brief description of the method implemented in this study follows.

1) Let $\boldsymbol{N}$ represent the total number of events. A cone for each event is projected onto a pixelated sphere that is centered in between the front and back plane of the DPI and extends beyond the system. The intersection of the cone and sphere defines a region of possible source origins that is close in shape to a circle. Each projected cone is broadened by 8° both inside and outside of the intersection. This broadening accounts for resolution effects that shift projected cones away from the actual source location. The size chosen for the broadening of the projected cones is described in detail in Section 2.2.
2) The location for a single origin, $\boldsymbol{k}$, is randomly sampled as a pixel from each projected cone. The collection of origins is the starting image state $\boldsymbol{Y_0}$.
3) A new, potential image state, $\boldsymbol{Y_{s+1}}$, is created by randomly selecting a single origin, $\boldsymbol{k}$, from $\boldsymbol{Y_s}$, for a possible move to a new pixel. The new pixel is randomly sampled from those within the broadened projection of the cone. The number of origins located at the new pixel, in state $\boldsymbol{s+1}$ ($\boldsymbol{P_{k,s+1}}$), is compared to the number of origins located at the old pixel, in state $\boldsymbol{s}$ ($\boldsymbol{P_{k,s}}$).
4) The new location of $\boldsymbol{k}$ will be accepted or rejected based on an acceptance probability defined as

$$A(Y_s \rightarrow Y_{s+1}) = \min\left(1, \frac{P_{k,s+1}+1}{P_{k,s}}\right). \tag{2}$$

   If the new location of $\boldsymbol{k}$ is accepted, the current image state becomes $\boldsymbol{Y_{s+1}}$, otherwise the current image state remains as $\boldsymbol{Y_s}$. Based on the acceptance probability $\boldsymbol{A}$, if an origin is moved to a pixel with more origins, the current image state will be accepted. The addition of one to $\boldsymbol{P_{k,s+1}}$, in Eq. (2), represents the possible movement of origin $\boldsymbol{k}$. If the number of origins at the new location is lower, the acceptance probability is the ratio of the number of origins at the new location to the number of origins at the old location. The acceptance probability is designed such that origins are preferentially moved to pixels with more origins, which represent a higher probability of being the source location.
5) A single iteration of the algorithm is defined as the repetition of steps (3) and (4) $\boldsymbol{N}$ times. The algorithm is then performed for a number of iterations until the image reaches a quasi-stationary state. An investigation of the required number of iterations is presented in Section 3.3.

The main difference between our implementation of SOE and the method proposed by Andreyev et al. is the representation of space from which each origin is sampled. Because the DPI was optimized for sources at standoff distances, three-dimensional imaging is not feasible. For this reason, our implementation of SOE sampled each origin from the circular projection of each cone onto a sphere. Two methods for the projection of cones onto a sphere are used for different applications. For far-field imaging, the apex of each cone is located at the system center. The system center is defined as the middle point of the gap between the front and back planes. In this case, the radius of the sphere is irrelevant because any radius will provide the same result. For near-field imaging, the apex of each cone is centered in the front-plane detector that recorded the initial scattering event. An approximate distance to the source must be known, and used for the sphere radius.

2.1. Resolution recovery

To achieve better convergence of the event origins, we used a modified version of a method proposed by Andreyev et al. for resolution recovery [14]. Each projected cone was broadened by a fixed amount to account for the effects of energy, time, and spatial uncertainty. A study was conducted to determine the optimum broadening for projected cones using measured and simulated results.

2.1.1. Measurement and simulation of DPI resolution

The DPI, shown in Fig. 1, was constructed as follows: A front plane consisted of a 4 × 4-square grid of EJ-309 liquid scintillators that were 5.1 cm thick and had a diameter of 7.6 cm with detectors spaced at 15 cm intervals (measured from detector centers). A back plane contained EJ-309 liquid scintillators and NaI(Tl) scintillators in a 4 × 4-checkerboard pattern. Both types of back-plane detectors had a thickness of 7.6 cm and a diameter of 7.6 cm and were spaced at 25 cm intervals. The planes were separated by 30 cm [12,15].

The DPI was simulated with the Monte Carlo code MCNPX-PoliMi and post-processor MPPost [16,17]. To accurately model the full system resolution, which defines the accuracy of recorded counts, it was imperative that the energy resolution and neutron light output response for the EJ-309 liquid scintillators were well