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A Feasibility Study of Using Hybrid Collimation for Nuclear Environment

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Abstract

This paper presents a feasibility of a gamma ray imager using combined electronic and mechanical collimation methods. This detector is based on the use of a multiple pinhole collimator, a position sensitive scintillation detector with Anger logic readout. A pixelated semiconductor detector, located between the collimator and the scintillation detector, is used as a scattering detector. For gamma rays scattered in the first detector and then stopped in the second detector, an image can also be built up based on the joint probability of their passing through the collimator and falling into a broadened conical surface, defined by the detected Compton scattering event. Since these events have a much smaller angular uncertainty, they provide more information content per photon compared with using solely the mechanical or electronic collimation. Therefore, the overall image quality can be improved. This feasibility study adapted a theoretical approach, based on analysing the resolution-variance trade-off in images reconstructed using *Maximum a priori* (MAP) algorithm. The effect of factors such as the detector configuration, Doppler broadening and collimator configuration are studied. The results showed that the combined collimation leads to a significant improvement in image quality at energy range below 300keV. However, due to the mask penetration, the performance of such a detector configuration is worse than a standard Compton camera at above this energy.

Keywords

Compton-scattering; environmental imager

I. Introduction

Over the past few decades, knowledge of the spatial and energy distribution of radioactive contamination has been shown to be of great importance for clean up and decommissioning of nuclear sites. The requirements on the imaging system will certainly differ from application to application. It is, nevertheless, possible to define a number of criteria in designing a flexible imaging system for many potential applications. These criteria include: energy range 60keV~1.5MeV; reasonable energy resolution (~15% at 662keV), angular resolution 1~3 degrees; large field-of-view (or through remotely controlled scanning); high count-rate capability (>20000c/s); compact and lightweight, etc.

A number of groups have been developing systems for mapping the distributions of radioactive isotopes for industrial applications [1][2]. Amongst these efforts, the pinhole imager, such as EPSLON [3], has been proven to be capable of providing good angular

resolution, whilst having drawbacks such as limited view angle and sensitivity [4]. Coded aperture has been studied, as a possible replacement of the pinhole, in an effort to improve system sensitivity [5]. Although the raw sensitivity, in terms of the number of counts collected, can be improved, it was shown that the signal-to-noise ratio deteriorates dramatically when a continuous background is included in the field-of-view. However, the coded aperture may still be attractive in some particular situations. For example, when the non-FOV count-rate is too high to be effectively reduced by the shielding, the use of a coded aperture with relatively large open fraction may be used to counteract the effect of shielding penetration and therefore improve the overall Signal-to-Noise Ratio (SNR) [3].

The concept of hybrid collimation has been introduced by several authors [4][5], in which a mechanical collimator is combined with a Compton scattering camera. Smith et al. presented an experimental feasibility study of an imaging system combining the URA coded aperture with a Compton camera. However, the conclusion drawn from this study is based on the use of an idealized detector. The effect of Doppler broadening and limited energy resolution achievable with the scattering detector has been neglected. In this work, we presented a feasibility of using this detector concept for nuclear environment. The performance benefit of using such a detector configuration is evaluated using a theoretical approach based on approximations developed by Fessler [6] and Qi [7]. It enables one to study the mean, variance and resolution properties in images reconstructed using Maximum *a priori* algorithms.

II. Detector Design

The proposed detector concept is shown in Fig. 1. It consists of a multiple pinhole collimator, a semiconductor first detector and a position-sensitive scintillation detector as the secondary detector. For the collimator, several pinhole configurations and mask were studied, which will be detailed in the following sections. Adding the mechanical collimation in front of a Compton camera reduces the angular uncertainty and therefore improves the information content carried by each detected photon. However, it also reduces the raw sensitivity of the system. In order to study the feasibility of this detector concept, we adapt a theoretical approach to derive the resolution-variance trade-off achievable with different detector configurations.

The basic detector configuration used in this study is shown in Table 1. In order to study the effect of amount of multiplexing, four pinhole configurations were used. The number of pinholes was 25, 49, 121 and 225. All the pinholes were arranged in a square pattern and the pinhole distances were 2.0, 1.5, 1.0 and 0.75 cm respectively. A $48 \times 48 \text{ cm}^2$ 2-D source object was modeled, having 32×32 square pixels.

III. Theory

A. Variance-Resolution Trade-off

In gamma ray imaging applications, the reconstructed image is a biased estimate of the true object, due to the presence of statistical noise and imperfections in the system model. This is true for the popular MLEM, Maximum *a priori* (MAP) algorithms and analytical

reconstruction methods such as Filtered Backprojection. It is, therefore, important to compare the detector performance or the image quality achievable with the detector as a function of the bias. The most accurate method for this purpose is Monte Carlo simulation. However, for system having a large number of detector bins and source pixels, generating a large number of realizations is extremely time consuming. In this study, we adapted a theoretical approach proposed by Fessler and Qi et al., which analysis the image properties based on MAP reconstruction method. Here, we briefly re-state some of the key steps and the final results. Given a measured data set $\mathbf{y}$, the log-likelihood of an estimator $\mathbf{x}$, of the underlying object is

$$L(\mathbf{y} \mid \mathbf{x}) = \sum y_i \log \bar{y}_i - \bar{y}_i \quad (1)$$

where $\mathbf{x} \in \mathbb{R}^n$ is the image and $\mathbf{y} \in \mathbb{R}^m$ is the measured data. The mean of the data is related to the image $\mathbf{x}$ through transformation

$$\bar{\mathbf{y}} = \mathbf{P}\mathbf{x} + \mathbf{r} \quad (2)$$

where $\mathbf{P}$ is the detector response function and $\mathbf{r}$ is the mean contribution from object scattering events and background radiation. In MAP reconstruction, the solution achieved is also influenced by our *a priori* information about the object, represented by the function $R(\mathbf{x})$. In order to control the amount of influence of this information on the final solution, a Lagrange multiplier is introduced, which results in an object function

$$\Phi(\mathbf{x}, \mathbf{y}) = \mathbf{L}(\mathbf{y} \mid \mathbf{x}) + \beta \mathbf{R}(\mathbf{x}) \quad (3)$$

In this study, we only used the quadratic roughness penalty with the form

$$R(\mathbf{x}) = \sum_j \frac{1}{2} \sum_i w_{ij} \phi(x_j - x_i) \quad (4)$$

where w_{ij} is the weighting factor that takes into account the 26 neighbours and

$$\phi(t) = t^2/2 \quad (5)$$

The MAP estimator can be achieved by maximising this objective function

$$\hat{x} = \arg \max_x \Phi(x, y) \quad (6)$$

By assuming the system is locally shift-invariant, the local-impulse response and variance at a particular pixel are:

$$l^j(\hat{\mathbf{x}}) = \mathbf{Q}' \mathbf{D} \left[\frac{\lambda_i}{\lambda_i + \beta \cdot \mu_i} \right] \mathbf{Q} e_j \quad (7)$$

$$\text{Var}_j(\hat{\mathbf{x}}) \approx \frac{1}{N} \sum_i \frac{\lambda_i}{(\lambda_i + \beta \cdot \mu_i)^2} \quad (8)$$

where the λ_i and μ_i are the eigenvalues of Fisher Information matrix $\mathbf{F}$ and penalty function $\mathbf{R}$, which are derived approximately using FFT. $\mathbf{Q}$ and $\mathbf{Q}'$ are the unitary Fourier transform operator and its transpose. Here we denote the j th element of $l^j(\hat{\mathbf{x}})$ as contrast recovery coefficient (CRC). This quantity has a strong correlation to the Full-Width-at-Half-Maximum (FWHM) and therefore was chosen as a representation of the spatial resolution.

Based on these results, one can also calculate the pixel wise signal-to-noise ratio (SNR) of the reconstructed image as:

$$\text{SNR} = \frac{\text{CRC}_j}{\sqrt{\text{var}_j \cdot \frac{1}{x_j}}} = \frac{\text{CRC}_j \cdot \bar{x}_j}{\sqrt{\text{var}_j}} \quad (9)$$

B. Monte Carlo Integration

In order to calculate the approximation of resolution and variance at a fixed point (the j th pixel) in the image, the approach described above requires the value of the j th column of the Fisher Information Matrix (FIM). For system with a large number of detector bins, this remains a very computationally expensive task. In the proposed detector, there are 1024 pixels in the image and $256 \times 10^4 \times 10^4$ detector bins. In reality, as the SRF has to be factorised into several sub-matrixes to save memory space required, the amount of calculation needed would be at the order of $\sim 10^{14}$.

In order to reduce the amount of computation required in deriving the FIM, one can apply the technique called Monte Carlo Integration (MCI). With $y_i, i=1, \dots, N$ the actual measured events. If we have a fixed number of counts in the data,

$$F_{ij} \approx \frac{N}{N^{(used)}} \cdot \sum_{l=1}^{N^{(used)}} \frac{p(\mathbf{y}_l | i) \cdot p(\mathbf{y}_l | j)}{\left(\sum_{m=1}^m p(\mathbf{y}_l | m) \cdot x_m \right)^2} \quad (10)$$

where $p(\mathbf{y}_l | i)$ is the probability of detecting an event $\mathbf{y}_l$ given a photon is emitted from source pixel i and x_m is the number of emitted photons from pixel m during the period of measurement. Note that F_{ij} corresponding N measured counts can be calculated by using a different $N^{(used)}$ events. It is easy to see that a better accuracy can be achieved when $N^{(used)}$ is larger than N .

IV. Design Study and Results

A. Monte Carlo Verification

The CRC and variance approximation (7) and (8) have been carefully studied for many image applications. They generally showed very good accuracy for systems that are reasonably close to the shift-invariant approximation. In this study, we concentrated on verifying the accuracy of using FIM_{MCI} instead of FIM_{true} for these calculations. Fig. 2 showed the variance approximations as a function of β . These results were compared with the empirical values from 100 Monte Carlo realizations, which are also shown in the figure as circles with error bars. For calculating the FIM_{MCI} corresponding 125k detected events, we used 1.25M events for the Monte Carlo integration. The variance approximations showed very good agreement between with both empirical results and the one derived using FIM_{true} . When calculating CRC with FIM_{MCI} , the resulting CRC-Beta curve again showed very good agreement with the one based on FIM_{true} (Fig. 3).

B. Performance as a Function of Gamma Ray Energy

At low energies, the performance of Compton camera is limited by the detector electronic noise, spatial resolution and the effect of Doppler broadening. Adding a mechanical collimator in front of the Compton camera can effectively enhance the angular information possessed by each detected event and improve the image quality given the same measured counts. This is demonstrated by the reconstructed images shown in Fig. 3. These reconstructions were controlled to produce the same CRC (0.7) and therefore similar spatial resolution. However, this improvement is achieved at the cost of lowering the raw sensitivity. In this study, we evaluated the effect of this trade-off at three energies, 200, 400 and 662keV. In order to reduce the bias that might be introduced by using a particular collimator, all comparisons were made using two different pinhole configurations, with 49 and 121 pinholes respectively.

The resolution-variance curves for the Compton camera, mechanically collimated detector and the proposed the detector at 200keV, are shown in Figure 4. These curves are normalised to the same measuring time. In this comparison, we also included a rational system that detects both Compton scattering and non-Compton scattering events. It has a raw detection sensitivity close to that of the mechanically collimated detector. At 200keV, we assumed

such a system would provide a data set that contains 25% Compton scattered events and 75% non-Compton events. These results clearly showed that the proposed detector outperforms both Compton camera and mechanically collimated detector at 200keV. Using both Compton scattering events and non-Compton scattering events results in the lowest standard deviation and therefore highest SNR at given resolutions. This can also be seen in the reconstructed images (Fig. 5).

Unfortunately, the mechanical collimation becomes less effective at higher energies, whilst the performance of Compton camera is much improved due to the reduced effect of Doppler broadening. In this case, the increase in the information content per detected event, through adding the collimator, may not be able to compensate the reduction in sensitivity. As a result, although the proposed detector greatly reduces the variance compared with the mechanically collimated detector, it is outperformed by Compton camera by itself. These conclusions are demonstrated in Figure 6. At 662keV, Compton camera has the most desirable resolution-variance curve amongst the detector configurations compared. Although not offering superior image quality, the use of the collimator reduces the gamma ray flux reaching the Compton camera. This would help to reduce the challenge in handling high count-rate as in standard Compton camera and may therefore be attractive in high count-rate environments

C. Effect of Multiplexing

After proving the benefit of the combining mechanical and electronic collimation, a natural question is what is the optimum collimator to use with the Compton camera. This is, no doubt, a very complicated problem. Here we choose to study the effect of the amount of multiplexing. The issue of coding scheme will be left for future research. In this study, we kept most of the detector configurations unchanged, whilst modifying the number of pinholes and pinhole distance on the collimator. The number of pinholes used were 25, 49, 121 and 225. The pinhole distances were 2, 1.5, 1.0 and 0.75cm respectively.

The relative performance of detectors using these four apertures without Compton scattering enhancements are shown in Fig. 7. Although more information content per photon is provided by aperture with less pinholes, the best resolution-variance trade-off for the same measuring time was achieved with the 49 pinhole aperture. After adding the Compton scattering information, the best resolution-variance trade-off was offered by the 225pinhole aperture. The difference between 121 and 225 pinhole apertures is small (Fig. 8). This indicated that the for the proposed detector, the best trade-off between the information per detected photon and sensitivity may be achieved with a collimator having relatively large open fraction, whilst this benefit becomes saturated after the amount of multiplexing reaching a certain threshold.

V. Conclusions and Discussions

In this study, we applied a theoretical approach to evaluate a detector design that makes use of the combined mechanical and electronic collimation. This detector design was proved to be attractive for imaging low energy gamma rays. The results are summarized as follow:

- The combination of mechanical and electronic collimation results in a superior imaging performance at low energies.

- This performance benefit will be limited at below 300keV. For higher energies, Compton camera by itself would be a better choice in terms of resolution-variance trade-off.
- The proposed detector design works best with a collimator having a relatively large open fraction.
- It is important to use scattering detector with low electronic noise and less Doppler broadening.

The analytical approximation for variance and resolution provides a reasonably accurate way to assessing detector performance without the time consuming Monte Carlo simulations. This would be very valuable for feasibility study involving a complicated detector configuration and multiple variable parameters.

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Fig. 1.
The detector design using combined mechanical and electronic collimation.

Fig 2.

Comparing standard deviation derived using FIM_{TRUE} (central solid line) and FIM_{MCI} . The ten thin lines correspond to 10 realizations of FIM_{MCI} . The circles with error bars are the empirical values from 100 Monte Carlo simulations.

Fig 3.
Comparing the CRC as a function derived using FIM_{MCI} and FIM_{true} .

Fig 4.

Standard deviation as a function of CRC for the four detector configurations. Results are normalized to the same measuring time. A 49 pinhole collimator was used.

Fig 5. Phantom (a) and the reconstructed images using data collected with Compton scattering enhanced detector (b), mechanically collimated detector (c) and Compton camera (d). All data contain the same 250k events.

Fig 6. Point wise signal-to-noise ratio as a function of CRC at 662keV with the same measuring time and the 121pinhole collimator.

Fig 7. Point wise signal-to-noise ratio as a function of CRC. The detector configurations are exactly the same except with different multiple pinhole apertures. The data sets containing no Compton scattering information

Fig 8.

Point wise signal-to-noise ratio as a function of CRC. The detector configurations are exactly the same except with different multiple pinhole apertures. All events used containing Compton scattering information

Table I

PARAMETERS USED IN THE SIMULATION

	First Detector	Second Detector	Multiple Pinhole Aperture	Object
Total Size (mm)	200×200×20	400×400×6	250×250×7.5	32×32
Pixel Size (mm)	2.0×2.0×2.0	4×4×6	(Pinhole size) Ø1.5mm	15
No. of pixels	100×100×10	10 ⁴	(No. of pinholes) 25, 49, 121 and 225	16×32×32 (16384)
Z-location (mm)	−100	−250	0	250
Material	Si	BGO	Tungsten	--
Energy Resolution	1keV	--	--	--
Energy threshold	2.5keV	20keV	--	--
Notes	1. Doppler Broadening is included	1.Depth of interaction not included. 2.Spatial resolution is equal to pixel size	1.Aperture penetration is modeled 2.Photons scattered in collimator ignored	