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Comparison of different reconstruction methods for planar images in small gamma cameras

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ABSTRACT: In this work we present a comparison of different methods for reconstructing the position of the events detected by gamma cameras with small Field of View. This task was completed within a project aimed to the development of an ultra high resolution, MR compatible PET detector camera head based on SiPM detector. It is well known that the spatial resolution deteriorates and the displacement error (defined as the deviation of the reconstructed position from the true position) increases at the edges of the detector. Here we investigate the possibility of improving the detector performance by using different reconstruction methods. The usual algorithm based on the barycenter fails to track the true position near the edges of the detector. We implemented and tested four different algorithms: the classic barycenter, a modified barycenter method where we consider not the charge collected, but the charge squared (named "barycenter squared") [1], an algorithm based on the estimation of the skewness of the distribution of the light ("skewness") [2], and finally a method based on the minimization of the difference between the distribution of light and a suitable fitting function ("Newton"). It turns out that the use of reconstruction algorithms different from the classic barycenter can help to improve the performance of the system. In particular, the reconstruction error improves, especially at the edges of the detector. Our simulations show that it is feasible to get submillimeter planar spatial resolutions at the center of the detector and of about 1 mm at the edges of the detector.

KEYWORDS: Image reconstruction in medical imaging; Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA); Medical-image reconstruction methods and algorithms, computer-aided so

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1 Introduction

This project, named "A very high spatial resolution small animal PET scanner based on high granularity silicon photomultipliers" involves a collaboration among four different Italian Universities: Pisa, Bari, Perugia, and Bologna. The ultimate goal of the project is to develop an ultra high resolution, MR compatible PET detector camera head based upon a novel detector design and cutting-edge photo-detector technology, that can be employed for a next-generation small animal PET system, with a spatial resolution on the order of 1 mm (or below), or for a combined PET/MR scanner.

2 Materials and methods

2.1 Overview of the camera

The proposed PET camera design consists of a layer composed by a continuous slab of LSO scintillator (5 mm thick) coupled to an array of compact Silicon Photomultipliers via a non-scintillating stand-off light pipe (0.1 mm thick). The proposed small-animal PET system consists of two heads, each with surface dimensions of about 12 mm $\times$ 12 mm. The opposing camera head separation will be as small as 10 cm to maximize sensitivity and to reduce the effect of non-colinearity of the annihilation photons. For the proposed detector head, each SiPM detector element is readout separately, to estimate the point of impact.

2.2 Simulated system

Taking advantage of our previous experience in simulating apparatus for medical imaging with Monte Carlo programs as Geant4 or EGS [3–6], we carried out simulations for assessing the performance of a single detector head. For that purpose, single 511 keV annihilation photons are simulated impinging at different surface points of a single detector with a direction of incidence normal to the detector surface. After tracking the 511 keV annihilation photons and their reaction products in the detector, only those events where an annihilation photon deposits at least 50 keV are used for further evaluation. With Geant4 we simulated the production of optical photons via scintillation in the crystal [7]. The generated optical photons were then tracked until they reached the surface of the SiPM array.

2.3 Reconstruction methods

We tested four different methods for reconstructing the planar position of the detected events. The first technique implemented ("barycenter" in the following) is the most common method used in literature - the Anger algorithm:

$$
\begin{aligned}
x &= \sum_{i,j=1}^{N} Q(i,j) \cdot x_i \\
y &= \sum_{i,j=1}^{N} Q(i,j) \cdot y_i
\end{aligned}
\tag{2.1}
$$

where Q is the matrix of the light distribution, whose elements $Q(i,j)$ represent the numbers of detected optical photons, $(x_i, y_j), i, j = 1, \ldots, N$, are the coordinates of $Q(i,j)$ on the detector, and $N \times N$ is the number of pixels within the detector. This method works well at the center of the detector, where the light distribution is entirely known. On the other hand, results become worse near the edges, since here the reconstructed position is pulled towards the center of the detector.

A different algorithm was proposed to improve the position determination [1]. It basically consists in squaring the light contribution (hence, the name "squared"), which helps to produce a narrower measured distribution:

$$
\begin{aligned}
x &= \sum_{i,j=1}^{N} Q(i,j)^2 \cdot x_i \\
y &= \sum_{i,j=1}^{N} Q(i,j)^2 \cdot y_i
\end{aligned}
\tag{2.2}
$$

The third method ("skewness") exploits the fact that the 1D-directional skewness of the light distribution increases rapidly as the edge of the detector is approached. Hence, the skewness and the barycentre are used in a log-likelihood estimation of the position of the event. Basically, we supposed that that the barycentre and skewness are normally distributed and we then derived from simulations some parameters of their distribution. For a given event, the measured barycentre and skewness are calculated and the hit position can then be estimated through the well-known log-likelihood technique. More details about this method can be found in this referenced paper [2].

With the fourth method ("Newton") the position is determined by means of an iterative optimization algorithm, for the solution of a regularized nonlinear least squares problem. The idea is to choose a function, depending on unknown parameters, that describes the light distribution; to this end, a Lorentzian function was considered. The least squares method was then used to find out the parameters that best fit the chosen function to the observed data. Here, one wants to minimize the residual matrix, i.e. the matrix that measures the difference between the fitting function and the light distribution data. Because of the ill-posedness of the least squares problem, we applied regularization techniques, by adding a regularization term to the objective functional. In our case, Tikhonov regularization was considered. The minimization problem was solved with the Gauss-Newton method, a Newton-like method in which the descent direction is computed with an approximation of the Hessian matrix.

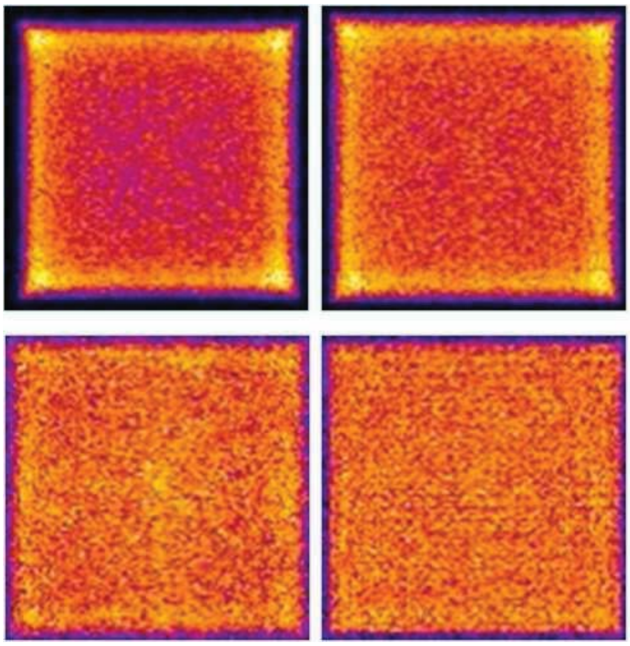

Figure 1. Examples of flood images reconstructed with the four algorithms. Top row: barycenter (left), barycenter squared (right). Bottom row: skewness (left), Newton (right).

3 Results and conclusion

Figure 1 shows an example of a simulated flood image, as reconstructed by the four investigated methods. It is worth noting that the classic Anger techinque is not able to reconstruct events located close to the edges of the detector (black regions in the pictures). This also causes a spatial distortion of the images at the edges, and especially near the four corners, typical for gamma cameras. This effect is still present in the “barycenter squared” method in a noticeable way, whereas the last two techniques (i.e. “skewness” and “Newton”) are able to improve the positioning of the events close to the edges.

This fact is confirmed by the reconstruction error shown in figure 2. Here, we show the difference between the reconstructed and the true position of the single detected events. On one hand, with all the four methods we achieve comparable results at the center of the detector (the reconstruction error is confined within ± 0.2 mm). On the other hand, as already noticed, the Anger method provides the worst response: the reconstruction error is about 1 mm at the edges of the detector. With the “barycenter squared” method the maximum error is about 0.8 mm, whereas the last two methods give a comparable performance (maximum error of about 0.4 mm).

Table 1 summarizes the spatial resolution obtained with the four methods for point sources located at the center and near the edges of the detector. All the four techniques are able to provide submillimeter spatial resolutions at the center (FWHM ranging from 0.4 mm to 0.8 mm). It also comes out that the “Newton” method can improve the spatial resolution at the edges considerably (around 1 mm).

From our simulations it turned out that using reconstruction algorithms different from the classic barycenter helps to improve the performance of small gamma cameras. In particular, methods

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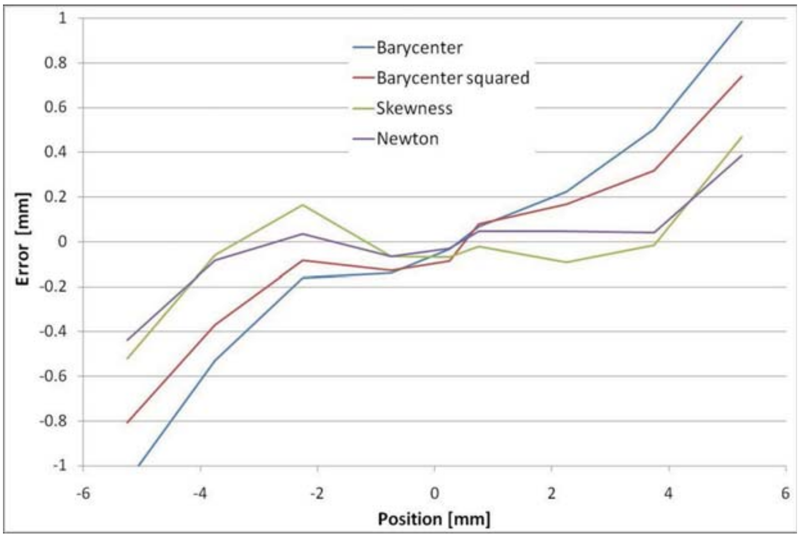

Figure 2. Reconstruction error as a function of the point source position for the different methods.

Table 1. Spatial resolution estimated for point sources located at the center and near the edges of the detector.

	Barycenter	**Squared**	**Skewness**	**Newton**
FWHM center [mm]	0.4	0.7	0.6	0.8
FWHM edges [mm]	2.4	2.1	2.7	1.1

more advanced than the barycenter can decrease the reconstruction error, especially at the edges of the detector. Further, it is feasible to get submillimeter planar spatial resolutions at the center of the detector and of about 1 mm at the edges of the detector.

Acknowledgments

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