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Event Processing for Modular Gamma Cameras with Tiled Multi-Anode Photomultiplier Tubes

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Abstract

Multi-anode photomultiplier tubes (MAPMTs) are good candidates as light sensors for a new generation of modular scintillation cameras for Single-photon emission computed tomography (SPECT) and Positron emission tomography (PET) applications. MAPMTs can provide improved intrinsic spatial resolution ($<1\text{mm}$) compared to arrays of larger individual PMTs due to their small anode sizes, and the increased number of channels also allows accurate estimation of depth-of-interaction (DOI). However, the area of a single MAPMT module is small for a modular gamma camera, so we are designing read-out electronics that will allow multiple individual MAPMT modules to be optically coupled to a single monolithic scintillator crystal. In order to allow such flexibility, the read-out electronics, which we refer to as the *event processor*, must be compact and adaptable. In combining arrays of MAPMTs, which may each have 64 to 1024 anodes per unit, issues need to be overcome with amplifying, digitizing, and recording potentially very large numbers of channels per gamma-ray event.

In this study, we have investigated different event-processor strategies for gamma cameras with multiple MAPMTs that will employ maximum-likelihood (ML) methods for estimation of 3D spatial location, deposited energy and time of occurrence of events. We simulated anode signals for hypothetical gamma-camera geometries based on models of the stochastic processes inherent in scintillation cameras. The comparison between different triggering and read-out schemes was carried out by quantifying the information content in the anode signals via the Fisher Information Matrix (FIM). We observed that a decline in spatial resolution at the edges of the individual MAPMTs could be improved by the inclusion of neighboring MAPMT anode signals for events near the tiling boundaries. Thus in order to maintain spatial resolution uniformity throughout the modular camera face, we propose dividing an MAPMT's array of anode signals into regions such to help determine when triggers from one MAPMT need to be passed to a neighboring MAPMT so that it can contribute anode information for events between them.

Keywords

Multi-anode photomultiplier tube; Readout electronics; Scintillation camera; Fisher information

I. INTRODUCTION

Multi-anode photomultiplier tubes (MAPMTs) are good candidates as light sensors for a new generation of modular scintillation cameras. MAPMTs can provide improved intrinsic spatial resolution ($<1\text{mm}$) compared to arrays of larger individual PMTs due to their small anode sizes, and the increased number of channels also allows accurate estimation of depth-of-interaction (DOI) [1]. However, the area of a single MAPMT module is small for a modular gamma camera, so we are designing read-out electronics that will allow multiple individual MAPMT modules to be optically coupled to a single monolithic scintillator crystal. In order to allow such flexibility, the readout electronics, which we refer to as the event processor, must be compact and adaptable. In combining arrays of MAPMTs, which may each have 64 to 1024 anodes per unit, issues need to be overcome with amplifying, digitizing, and recording potentially very large numbers of channels per gamma-ray event. In the case of reporting every event data, data management and power consumption become critical.

II. CONSIDERATIONS FOR EVENT PROCESSOR

In a previous study [2], we found that by employing an adaptive readout scheme, where only a subset of the anode signals were reported, it is possible to achieve precision in estimated event parameters that is close to what is achieved by retaining all anode signals. This study was based on an analysis of information content in the anode signals that was carried out using likelihood models $\text{pr}(\mathbf{g}|\boldsymbol{\theta})$ that account for inherent stochastic processes that relate the camera signals $\mathbf{g}$ to a set of gamma-ray event parameters $\boldsymbol{\theta}$, such as spatial location (x,y,z) , deposited energy (ϵ) and time of occurrence (t_0) that are to be estimated. The information conveyed by the detector signals were quantified using the Fisher Information Matrix (FIM). FIM gives us an understanding of how well the measured signals can be used to produce estimates of set of event parameters. It is defined as the covariance of the score:

$$F_{nm} = \left\langle \left[\frac{\partial}{\partial \theta_n} \ln \text{pr}(\mathbf{g}|\boldsymbol{\theta}) \right] \left[\frac{\partial}{\partial \theta_m} \ln \text{pr}(\mathbf{g}|\boldsymbol{\theta}) \right] \right\rangle_{\mathbf{g}|\boldsymbol{\theta}} \quad (1)$$

One of the powerful features of FIM is that the n th diagonal component of the inverse of the FIM defines a lower bound on the variance of an unbiased estimator of the n th parameter $\hat{\theta}_n$. This inequality is called the Cramér-Rao (CR) lower bound which can be expressed as:

$$\text{Var} \{ \hat{\theta}_n \} \geq [\mathbf{F}^{-1}]_{nn} \quad . \quad (2)$$

For instance, for a scintillation camera employing maximum-likelihood position estimation, the standard deviation of the spatial position estimate, denoted as σ , represents the best possible resolution that can be achieved. In our model, the number of photoelectrons generated at each anode location was described by a Poisson distribution [3] with a mean equal to the product of the quantum efficiency of each tube, the geometric collection efficiency, and the mean number of optical photons generated in the initial gamma-ray interaction. The generated mean signals, $\bar{\mathbf{g}}(\boldsymbol{\theta})$, also commonly called the *mean detector*

response function (MDRF), and their first derivatives are all that is required to compute the FIM. Decomposition of FIM into individual anode elements, and rank ordering to identify the anodes with the highest contributions to the Fisher Information, suggested a read-out scheme based on selecting the anode with the largest input signal and adaptively assigning it as the central anode in a specific anode neighborhood read out with each event.

Another approach to reducing the number of channels to be read out is by using matrix networks [4] where the signals from an MAPMT are reduced to row and column sums. The output signals, $\mathbf{g}$, can be expressed as

$$g_j = \sum_{k=(j-1)N+1}^{jN} x_k \quad (3)$$

where x_k are individual Poisson-distributed anode signals. For instance, for an MAPMT with an 8×8 array of anodes, $N=8$, $g_1=x_1+x_2+\dots+x_8$ and $g_2=x_9+x_{10}+\dots+x_{16}$ and so on. Each output signal g_j will still be Poisson distributed with a mean equal to the sum of the means of the individual anode signals. It is important to note that the signals of any row sum and any column sum will be correlated since they will both include the anode at their intersection. From the Central-limit theorem, we know that the sum of a large number of random variables approaches a normal distribution. If we model a row (or column) sum of anode signals as normally distributed, then the full set of signals, a $2N$ dimensional random vector $\mathbf{g}$, can be described by a multivariate normal;

$$\begin{aligned} pr(\mathbf{g}|\boldsymbol{\theta}) &= \left[(2\pi)^{2N} \det(\mathbf{K}(\boldsymbol{\theta})) \right]^{-1/2} \cdot \\ &\exp \left[-\frac{1}{2} \left(\mathbf{g} - \bar{\mathbf{g}}(\boldsymbol{\theta}) \right) \mathbf{K}(\boldsymbol{\theta})^{-1} \left(\mathbf{g} - \bar{\mathbf{g}}(\boldsymbol{\theta}) \right) \right] \end{aligned} \quad (4)$$

where $\bar{\mathbf{g}}(\boldsymbol{\theta})$ is the position-dependent vector of mean signals and $\mathbf{K}(\boldsymbol{\theta})$ is the position-dependent covariance matrix of $\mathbf{g}$.

$$K_{nm} = \left\langle \left(g_n - \bar{g}_n(\boldsymbol{\theta}) \right) \left(g_m - \bar{g}_m(\boldsymbol{\theta}) \right) \right\rangle \quad (5)$$

Inserting eqn. (3) in eqn. (5) the covariance matrix becomes;

$$K_{nm} = \begin{cases} 0, & \text{when } n \text{ and } m \text{ are channels parallel to each other} \\ & \text{(i. e. both are column or row sum)} \\ \sigma_k^2(\boldsymbol{\theta}), & \text{k:common indexed anode number, when } n \text{ and } m \\ & \text{are channels perpendicular to each other} \\ & \text{(i. e. one is a row, one is a column sum)} \\ \sigma_n^2(\boldsymbol{\theta}), & \text{when } n=m \end{cases}$$

In this expression $\sigma_k^2(\boldsymbol{\theta})$ is the variance of the single anode that is located at the intersection of a column and a row, and $\sigma_n^2(\boldsymbol{\theta})$ is the variance of a row (or column) sum. With some algebra, the Fisher information matrix expression for the multivariate normal case reduces to the form below [5]-[6],

$$F_{nm} = \frac{\partial \bar{\mathbf{g}}}{\partial \theta_m} \mathbf{K}^{-1} \frac{\partial \bar{\mathbf{g}}}{\partial \theta_n} + \frac{1}{2} \text{tr} \left(\mathbf{K}^{-1} \frac{\partial \mathbf{K}}{\partial \theta_m} \mathbf{K}^{-1} \frac{\partial \mathbf{K}}{\partial \theta_n} \right) \quad (7)$$

where

$$\frac{\partial \mathbf{K}}{\partial \theta_n} = \begin{bmatrix} \frac{\partial \mathbf{K}_{1,1}}{\partial \theta_n} & \dots & \frac{\partial \mathbf{K}_{1,2N}}{\partial \theta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial \mathbf{K}_{2N,1}}{\partial \theta_n} & \dots & \frac{\partial \mathbf{K}_{2N,2N}}{\partial \theta_n} \end{bmatrix} \quad (8)$$

Using eqn. (7) and (8), FIM for row and column sums of anodes were computed on a grid of sampled event locations on the camera face. Selected components are shown in Figure 1.

We compare the spatial resolution of the row and column sum approach, as quantified by the Cramer-Rao lower bounds, with the FIM analyses for the exhaustive and adaptive readout from [2] in Figure 2. It is evident that the expected spatial resolutions of the three read-out methods are similar on the whole, but that there are slight variations in accordance with the total number of channels that were read out.

We have also considered the case where there is electronic noise in addition to the statistical distribution on primary photoelectrons (pp) in each anode.

In this model, we assume that the charge was integrated by a continuously-reset transimpedance amplifier, and the dominant noise source is the charge-carrier motion in the RC circuit. This thermal noise was considered to add to the anode signals.

$$\mathbf{g} = \mathbf{g}_{pp} + \epsilon \quad (9)$$

Since there is now a penalty with summing channels without significant signal, the adaptive readout method can perform better than the row and column sums under certain conditions.

In all read-out methods, the spatial resolution was observed to decline at the edges of the individual MAPMTs. In the case of tiled detectors, the resolution at the boundaries between MAPMTs can be improved by the inclusion of neighboring anode signals associated with each event. Figure (3) shows the improvement in spatial resolution in x-direction for a hypothetical 2×2 array of MAPMTs.

III. EVENT PROCESSOR BLOCK DIAGRAM

In order to maintain spatial resolution uniformity in the critical central region of the camera face, the event processors supporting each MAPMT need to be able to detect events near the boundaries and distribute triggers to the correct neighbor(s). To accomplish this objective, we designed a scheme in which each individual MAPMT is divided up into five regions that have equal number of anodes, as shown in Figure 4. Amplified and fast shaped signals are summed for each region and compared to a common threshold level in a Regional-Sum-Threshold (RST) block. A Trigger-Decision-Logic (TDL) block will check for an incoming global trigger and based on this information and the result of the RST block, it can generate

a fast local or global timing trigger. Global triggers are passed through Global-Trigger-Distribution (GTD) block that distributes triggers from boundary regions to the appropriate neighbor.

The primary purpose of the TDL block is to quickly generate triggers based on few simple decisions rules implemented using gates. For instance, if the output of RST has one trigger from a border region on the MAPMT (say γ_2) and there are no incoming triggers, the TDL will generate a global trigger requesting the nearest neighboring detector (nearest to γ_2 area) to be read-out. The TDL block will then send the trigger information to a Local-Read-Out-Logic (LRL) block. The logic of LRL can be carried out using a pre-programmed lookup-table that has one address line for each of the 5 trigger signals from the RST block and one for each neighboring module. The final decision on which anodes will be read out is implemented in this LUT. In some instances, such as if there are simultaneous trigger signals from, say γ_2 and γ_4 but not γ_5 , we may decide to drop this event due to pile up. A winner-take-all circuit [7], working in parallel, outputs the digital address of the channel with the largest amplitude. The LRL section is also responsible for efficiently accessing the specific anode neighborhood around the winner channel by connecting sample-and-hold buffers to a bank of fast analog-to-digital converters through an analog multiplexer. Lastly, an event-packet builder completes the list-mode read-out process. Figure 5 shows a potential module block diagram.

The event processor also needs to be able to support MAPMTs that are configured for experiments requiring timing information such as time-of-flight (TOF) PET. One of the techniques considered for measuring very fast pulses is waveform sampling [8]. Waveform sampling offers flexibility in handling channel-to-channel gain variation and pile-up events whose shape differs from an expected single-pulse template. The estimation of arrival time of the event based on the sampled full waveform will be less susceptible to noise compared to a single time sample. Waveform sampling can be applied to the summation of the output pulses of the constructed anode neighborhood, and pulse timing can be estimated using maximum-likelihood methods [9]. We are currently evaluating the Domino Ring Sampling (DRS) chip developed by Paul Scherrer Institute, Switzerland which offers digitization at up to 6 GSPS sampling rates on 9 differential input channels using switched capacitor arrays [10]. The DRS integrated circuit can be made to work together with the event processor when needed. Directions for future work include equipping our modular-camera PET detectors with TOF capability.

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Fig. 1.

(a) Simulated MDRF for one channel of column anodes sums, namely $g_3 = x_3 + x_{11} + \dots + x_{59}$ (units of photoelectrons), (b) F_{xx} (c) F_{yy} and (d) F_{zz} for a 5mm thick NaI(Tl) scintillator and a 2mm thick light guide. (Showing FIM for events at 2.0875 mm depth)

Fig. 2.

Comparison of expected spatial resolution (shown for x-component) for 8×8, 8×2 and 3×3 readout schemes. The plots are shown for a cut through x-direction, where y is kept fixed across the center of the detector face.

Fig. 3.

(a) A 2×2 array of 4×4 anode MAPMTs are combined together in a single modular camera. The spatial resolution in x-direction is shown across the detector face when all the four MAPMTs are individually read out. (b) Improvement of spatial resolution at the inner edges when signals of associated events from surrounding neighboring detectors are included in the estimation. (The gaps between MAPMTs are assumed to be much smaller than the anode pitch in the calculation).

Fig. 4.
The division of MAPMT into five regions.

Fig. 5.
An event processor block diagram.