Design Of A Next-Generation Modular Gamma Camera For Small Animal Imaging

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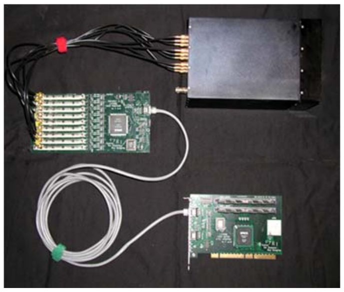
Current Generation Modular Cameras

- Monolithic scintillation crystal
- 3x3 PMT array
- ~ 2 -2.5 mm resolution in x, y
- > ~5mm resolution in z
- Timing (30ns)

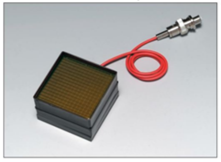


Motivation For New Camera

- Multi-anode photomultiplier tubes (MAPMTs) are good candidates as sensors for scintillation cameras (SPECT/PET applications)
- For small animal imaging experiments at least 10 cm x 10 cm area desired.
- Thus, tiled arrays of MAPMTs are required
- New MAPMTs may have 64 or 256 anodes per tube.
- Large number of channels that require amplification and digitization become practically not feasible. (speed, data management and power consumption)

HAMAMATSU

256ch Multianode PMT Assembly H9500



Objective

Design read-out electronics (*event processor*)

- that allows multiple MAPMT modules to be optically coupled to a single monolithic scintillator crystal,
- that has reduced number of readout channels,
- to be used with maximum-likelihood (ML) methods,
- that achieves precision in estimating event parameters that is close to what is achieved by retaining all signals (sufficient statistics).

Fisher Information Matrix

- We will use FIM as the tool to quantify the information conveyed by the detector signals

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

$\mathrm{pr}\,(\boldsymbol{g}|\boldsymbol{\theta})$: likelihood

$\boldsymbol{g}$: set of anode signals

$\boldsymbol{\theta} = \{x, y, z, \varepsilon, t_o\}$: set of event parameters

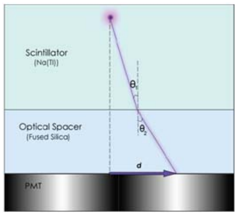
Cramer-Rao (CR) Lower Bound

- For any covariance matrix it can be shown that

$$[\mathbf{K}_{\hat{\theta}}]_{nn} = \mathrm{Var}\{\hat{\theta}_n\} \geq [\mathbf{F}^{-1}]_{nn}$$

- complementarity relation with the Fisher information.
- sets a lower bound on the variance of an unbiased estimator.
- In the case of position estimation, represents the best possible spatial resolution that can be achieved.

Forward Model



Assume a gamma camera with monolithic NaI(TI) scintillator (n=1.85) and fused-silica light guide (n=1.46), blackened entrance face blackened sides.

- Assume energy deposited at single location.
- Mean number of photoelectrons produced at the **k**th anode;

$$\bar{n}_k(r_{int}) = \eta_k\ \beta_k\,(r_{int})\,\bar{n}_{optical}$$

- Mean number of optical photons

$$\bar{n}_{optical} = \eta_{sc}\,\varepsilon$$
$$\eta_k\,\beta_k\,(r_{int}) \ll 1$$

- Assume number of photoelectrons in each PMT is independent and **Poisson** distributed.

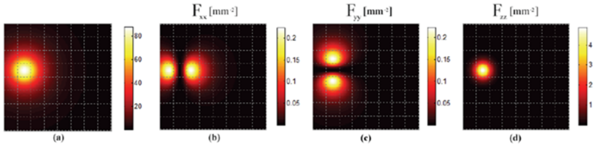
FIM of a single anode:

Poisson model : $\mathrm{pr}\,(\boldsymbol{g}|\boldsymbol{\theta})$

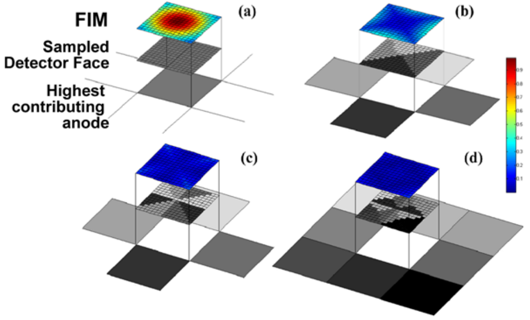
$$F_{nm} = \sum_{\substack{k=1 \\ \textbf{(anodes)}}}^{N} \frac{1}{\bar{g}_k(r,\varepsilon)}\,\frac{\partial}{\partial\theta_n}\bar{g}_k(\mathbf{r},\varepsilon)\,\frac{\partial}{\partial\theta_m}\bar{g}_k(\mathbf{r},\varepsilon)$$

For example : for anode (4,2)

a) Simulated signal
b) b-d) Corresponding x , y and z components of FIM (showing for 3mm depth)1



Rank ordering:

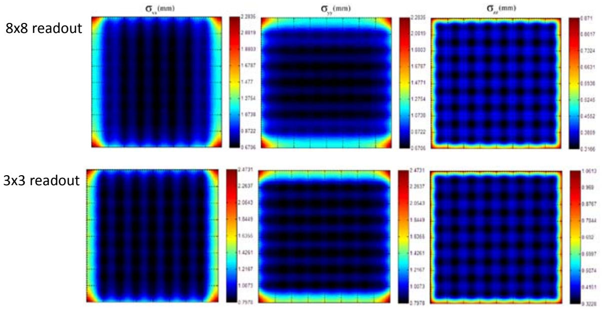


The four most significant contributions to the overall Fisher Information for positioning are identified in descending order (plots a-d)

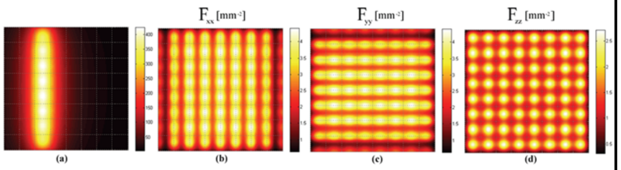
Top surface: Relative contribution to FIM

Second surface: Which color coded anode is contributing at each location on the sampled detector face.

Comparison of exhaustive vs. adaptive 3x3 readout



Column and Row Sum Readout:



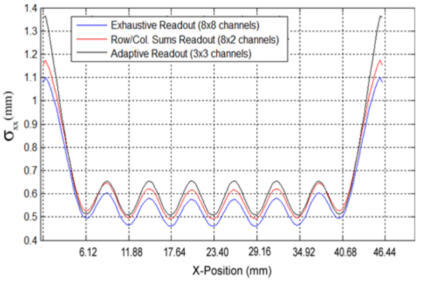
a) Simulated MDRF for a column sum ($g_3 = x_{16}+..+x_{24}$)

b-d) Total FIM (x, y and z components) for a 5 mm thick NaI(TI) scintillator and a light guide. (Showing events at 2.0875 mm depth)

V. Popov, “Advanced data readout technique for Multianode Position Sensitive Photomultiplier Tube applicable in radiation imaging detectors,” Journal of Instrumentation (JINST), Vol. 6 (2011).

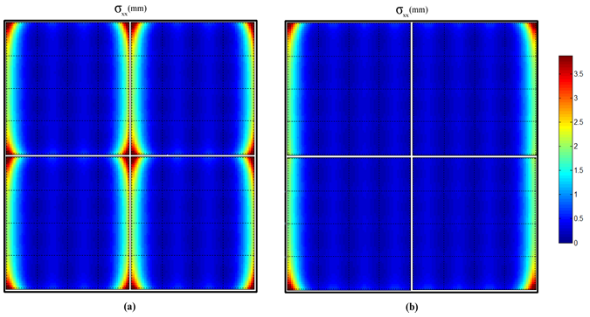
Comparison of readouts

Plot shown for shown for a cut through x-direction, where y is kept fixed across the center of the detector face for 5mm thick NaI, 2mm thick light guide and events at 2.08 mm depth.

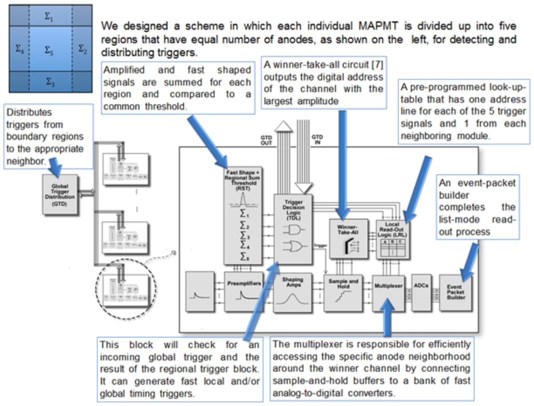


Tiling MAPMTs

- Spatial resolution decline at the edges of the individual MAPMTs
- Propose inclusion of neighboring anode signals associated for each event



Event Processor Block Diagram



We designed a scheme in which each individual MAPMT is divided up into five regions that have equal number of anodes, as shown on the left, for detecting and distributing triggers.

Amplified and fast shaped signals are summed for each region and compared to a common threshold.

A winner-take-all circuit [7] outputs the digital address of the channel with the largest amplitude

A pre-programmed look-up-table that has one address line for each of the 5 trigger signals and 1 from each neighboring module.

Distributes triggers from boundary regions to the appropriate neighbor.

An event-packet builder completes the list-mode read-out process

This block will check for an incoming global trigger and the result of the regional trigger block. It can generate fast local and/or global timing triggers.

The multiplexer is 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.

Future Work

- Support precise timing/time-of-flight experiments
- Waveform sampling (can be applied to the summation of the output pulses of the constructed anode neighborhood)
- Evaluate of Domino Ring Sampling (DRS) chip - developed by Paul Schrerrer Institute, Switzerland which offers digitization up to 6 GSPS sampling rates on 9 differential input channels using switched capacitor arrays (SCA)

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