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Uppsala 2018-03-09

Review of PhD thesis
"Hit-time and hit-position reconstruction of gamma quanta in the J-PET tomography system based on a library of model signals"
by MSc Neha Gupta Sharma

Research described in the thesis is a part of development of a novel gamma detection system for medical imaging using Positron Emission Tomography (PET) at Jagiellonian University. The goal of the J-PET project is to build a cost effective PET scanner, thus enabling wider spread of this nuclear medicine imaging technique. The system is based on the use of relatively cheap low density plastic scintillators instead of the scintillating crystals. This poses several challenges related to different interaction mechanism of the annihilation gamma quanta in the detector: instead of calorimetric type measurement, where nearly all gamma energy dissipates in the crystal, the detection relies on a single Compton scattering event. Only the kinetic energy of the recoil electron will be dissipated and converted to the light, and finally to electronic signal. The cross section of the gamma interaction is low and the spread of the energy deposits is large. On the other hand, plastic scintillators have a very good time resolution and allow to cover large field of view.

The doctoral thesis focuses on few specific aspects of the signal processing. The signal is acquired by reading out the produced light in the scintillator bar by two photomultipliers. A set of two signals measured by a pair of photomultipliers connected at the ends of scintillator is called an event - a result of one particular gamma quanta interaction in the scintillator strip. For the normal operation the signals in J-PET will be digitized using voltage domain (VD) sampling. However, for the development of the procedure presented in the thesis all the signals were collected using high frequency (10 GHz) time domain (TD) sampling using Serial Data Analyzer. The VD sampling was emulated and optimized offline.

The goal of the analysis is to determine hit-position (along the bar) and hit-time information, to be used as the input to an image reconstruction program. The proposed original reconstruction method is based on the determination of degree of similarity between registered and synchronized model signals stored in a database. The data base of the average TD sampled signals for each scintillator bar (with 300 or 500 mm length) is constructed using scan of collimated annihilation photon beam every 3 mm along the bars. The TD events collected at each point were synchronized (time shifted) and averaged (p32).
There method was validated and it was proven the design accuracy and resolution was achieved. The algorithm is also compared to the reference method based on a linear fit to the leading edge of the signal. It is shown that the proposed method outperform the reference one providing similar or better resolution, but requiring less input information. This result means a significant reduction of the cost of the readout electronics, what is a significant contribution to the main goal of the J-PET project.
In addition to the development and the validation of the reconstruction method, the author has taken active part in the experiments and tests aiming at "selection of efficient polymer scintillator, search for the best reflecting foil, study of scintillator strips with different orientation, testing and calibration of photomultiplier tubes etc."

The dissertation has nine Chapters, 67 pages and Bibliography with 66 positions. Neha Sharma is a co-author of 12 peer reviewed publications related to the J-PET project.
Chapter 2 (p4-p12) gives an introduction to the detection techniques i.e. interaction of gamma quanta with matter, scintillation processes, light conversion to the electrical signals. Chapter 3 (p13-p20) describes and compares commercial PET systems and the J-PET concept. Chapter 4 (p21-p26) gives the detailed description of the test setup as well as of the procedures for collection and filtration of data. Chapter 5 (p27-p38) describes the principle of the proposed reconstruction method and gives a detailed explanation of the mathematical basis of the algorithm. In Chapter 6 (p39-p51) optimization of digitalization procedure is reported. The results are presented in Chapter 8 (p54-p64) and discussed in Chapter 9 (p65-p67).

My main questions to the results presented in the thesis could be summarized as follows:

I do not understand Fig 5.5. In Sec 5.3.1.1 it is written and further explained in Fig 5.4 that both signals of the event are synchronized meaning that tL=-tR. How it is possible that δt in fig 5.5 and in Eq 5.4 can shift both signals in the same direction? The signals would be desynchronized by such procedure... Maybe it was meant that the time shifts for the two signals should have the same absolute value but opposite signs?

I cannot understand how the Chi2 minimization (Eq 5.4) could be applied in the case when there is only one voltage threshold. There seems to be too few information to perform the fit.

p40 Why time spread of the L PMT is much bigger than R (see the covariance matrices)? Variance is much bigger for L but when one compares to figure 4.3 b) the L,R signals are very similar.

A prerequisite for using Mahalanobis distance is that the multivariate distributions have Gaussian distributions. Since all the relevant distributions are known it would be good to show them and to discuss to what extend the assumptions are fulfilled. The extensive information collected in the database allows in principle to use a more general maximum log likelihood method instead of Mahalanobis distance.

The most puzzling and counterintuitive result of the thesis is given in the following statement (p47): "It was noticed that resolution deteriorate by including charge [ratio] as another parameter in the formulation of Mahalanobis distance." I would expect that adding extra parameter in the worst case should lead to the same resolution and by no means to deteriorated resolution.

p55 If I understand correctly the proposed method has intrinsic resolution of 3 mm FWHM (due to the step of 3 mm used for the creation of the data base). I wonder if the use of interpolation could help here e.g. instead of selecting the closest signal from the library maybe two best could be selected and then the hit position obtained from interpolation between them? Maybe this method would also allow for reduction of measurements needed for creation of the data base?

Questions to the presentation

In some places it was quite difficult to follow the logic of the dissertation. Here I give examples:

In chapter 2 the author describes how the two anti-collinear photons are detected by a pair of detectors. In particular one could expect the specific aspect relevant to J-PET will be explained, since they will determine properties of the analyzed signals. The author correctly states that the main process will be Compton scattering (sec 2.1.2). However, I cannot agree with the statement that "Compton effect is inelastic scattering of gamma", specially if the interaction is with a free electron. Next, the author focuses on the energy of the scattered photon (Eq. 2.2 is called wrongly "energy of scattered electron") instead of explaining that for J-PET the recoil electron energy is of importance since it will be converted to the light and finally registered as the signal. In sect 2.2 the author states that scintillating material will "absorb the incident gamma-ray and convert its energy into a pulse of visible (or UV) photons". This is not true for the J-PET case!

In section 2.3 a confusing definition of energy resolution is introduced by relating to the incident gamma energy which is not appropriate for J-PET type gamma detection. The author should have explicitly stated the difference between photon energy and the energy deposited in the scintillator.

p51 In Fig. 6.9 the caption does not agree with what is shown in the picture.

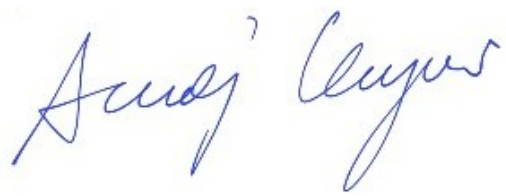
Sec 8.1: Unfortunately fig 8.6 (8.7) and 8.4 use different origin for (z,y) coordinate system. It would be also nice to have parameters of the Gaussian peaks. Not only PSF but also a possible bias.

Sec 8.2: Measurements with non-collimated beam: it would be good to see qualitative conclusions in this section, not only the pictures. At least the coordinate system should have the same origin in Fig 8.10 and 8.11-12. Fig 8.10 uses also different order of Y and Z coordinates to denote the points.

Conclusions

In summary the proposed, developed and validated hit-position reconstruction method is shown to provide resolution sufficient for the J-PET application and it allows to significantly reduce cost of the readout electronics. Thus the goal of the project was successfully achieved. MSc Neha Gupta Sharma has participated actively in many parts of the J-PET project what is reflected by the fact that she is a co-author of 12 peer reviewed publications related to the project.
I hope that all my question will be satisfactory answered during the public defense of the thesis. Therefore in my opinion MSc Neha Gupta Sharma is ready for the next step of the doctoral procedure.

Andrzej Kupść



Some editorial remarks:

Notation of Eq 5.2 and Eq 5.5 is incompatible. Three different notations are used for x and two for the covariance matrix.

p36 I understand that there is a typo and i,j are varied from 1 to $2m$ to have $2m \times 2m$ covariance matrix?

The bibliography has clean and consistent layout, contrary to many other PhD thesis which I have seen.