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Quadratic Programming Time Pickoff Method for Multivoltage Threshold Digitizer in PET

Introduction

Multi-voltage threshold(MVT) digitizing scheme employs a few comparators with programmable reference voltages for determining the time points when the scintillation pulse crosses the user-defined voltage thresholds. After obtaining the digital time samples, use of various sophisticated linear or nonlinear al- gorithms to improve the accuracy of timing information becomes possible. In the previous implementation of MVT digitizers, the arrival time of a scintillation pulse was determined by the linear fitting (LF) algorithm, which assumes leading edge as a straight line, and not involves the transition time on the falling edge. It is not unreasonable to expect achieving a better timing resolution in MVT-based PET detectors by the combinatorial optimization of MVT samples both on leading and falling edges. In this paper, a novel method, referred to as quadratic programming (QP) method is therefore proposed to mark the time stamps of sampling event pulses. In this method, the arrival time is directly expressed as a parametric combination of the MVT samples. The parameters in the combination are obtained by the quadratic programming which minimizes variation of timing error. To evaluate the perfor- mance of QP/MVT method and other time pickoff methods, we setup two gamma ray detectors using Multi-voltage thresholdcrystal and Hamamatsu R9800 PMT. The scintillation pulses are directly read out by Tektronics DPO 71604 digital storage oscilloscope. CTR of 175 ps was obtained by QP/MVT, and 191 ps by LF/MVT, when four thresholds were employed in each of the two channels. The experimental results indicate the potential advantage of QP/MVT in timing determination. Meanwhile, the assumption of linear leading edge, which is the basis of LF method, was demonstrated to be improper in the data analysis. For QP method, probably of even greater significance is the manner to define the parameters rather than the resulting detector-specified parameters.

Keywords: Coincidence timing resolution, mean square error, multi-voltage threshold digitizer, quadratic programming (QP) time pickoff method.

Design and Implementation

A.Experiment Settings and Pulses Dataset Description

To evaluate the performance of the time pickoff methods, we carried out experiments to obtain event data with two gamma ray detectors as shown in Fig. 1. The $LaBr_3$:*Ce* crystals of the size as shown in Fig.2 were optically coupled to Hamamatsu R9800 photomultiplier tubes (PMT) via the round glass of the bottom facets, while the other facets were wrapped in Aluminium housings. The supply voltages of the both PMTs were set to 1300 V and the PMT's outputs were directly connected to a Tektronics DPO 71604 digital storage oscilloscope with a 50- input impedance. The oscilloscope was operated with bandwidth of 16 GHz and sampling rate of 50 GSps per channel. One or three tubules of 1.2-mm inner diameter filled with F^{18}-FDG solution were used as the radioactive source. A pair of detectors worked in the coincidence mode, which ensured that the collected data were generated by the F^{18}-FDG solution. The coarse coincidence timing window width was set to 4 ns. The oscil- loscope was triggered by an AND-logic event generated by the two $LaBr_3$:*Ce/PMT* detectors, therefore ensuring that the majority of the resulting event pairs were coincidences. The trigger voltage was set to 180 mV to reduce false triggering. Each of the two pulses in a coincidence was sampled by the oscilloscope for 100 ns, resulting in 5000 data points. An energy window of keV was applied in the energy discrimination. The measured gain ratio of the two detectors was 0.600. Although the chosen experimental setup is far away from the state-of-the-art data acquisition systems, it has the fundamental advantages of being easily reproducible, as no custom digital electronics is required, while still allowing a full and direct comparison between the various digital time pickoff under test.

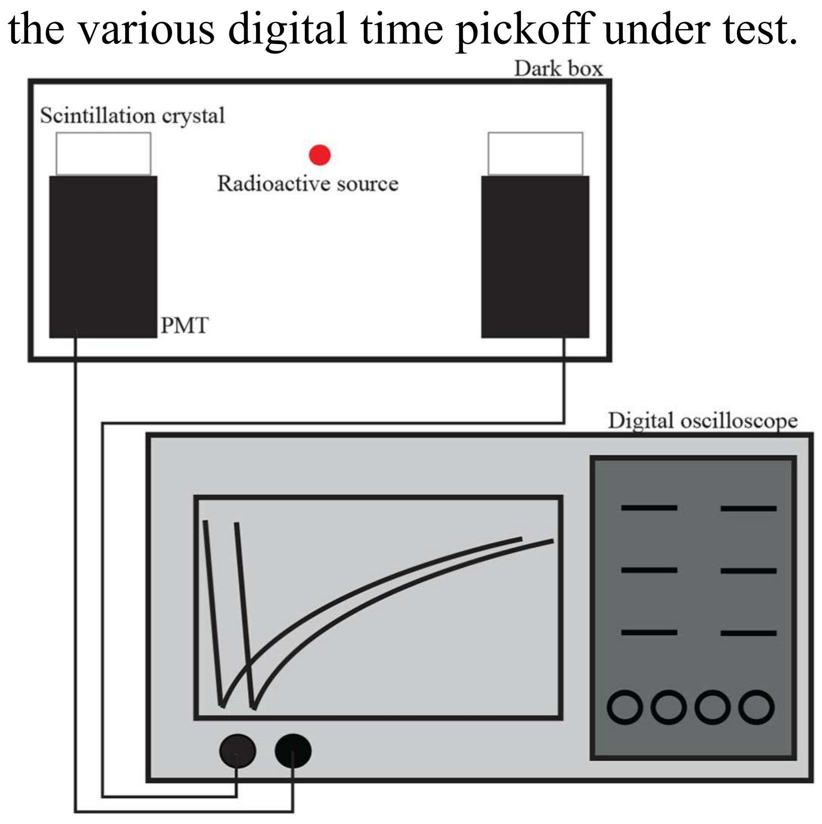

Fig. 1.Experimental system with coincidence of 4 ns time window. All the pulse pairs are saved to be analyzed in t he off-line mode. The FDG is contained in a test tube, which is fixed between the crystals.

Fig. 2. $LaBr_3$:*Ce* scintillation crystal pair contained by aluminium boxes of glass bottom windows.

Results and Conclusions

We evaluated the time performance for LF/MVT, LES QP/MVT, and DES QP/MVT when different thresholds were employed. In this evaluation, we added the employed voltage threshold one by one. Every time a new employed threshold was added into the calculation, the old employed thresholds were unchanged. The th additional threshold voltage is $V_k^{[i]} = V_b^{[i]} + V_d^{[i]} \times \lambda(k)$. where $\lambda(k)$ is

$$\lambda(k) = \begin{cases} 0, & k=1 \\ 1, & k=2 \\ \dfrac{2\times\left(k-2^{[\log_2^{(k-2)}]}\right)-3}{2^{[\log_2^{(k-2)}]+1}}, & k>2 \end{cases}$$

In Fig. 3, the performance comparison shows QP/MVT out- strips LF/MVT for each number of employed thresholds, no matter when only LES or both DES are involved. And QP/MVT with DES is better than that with only LES. This result reveals another property of QP method: the CTRs monotonically de- creased as the number of the chosen threshold increased. The ad- ditional degree of freedom does not deteriorate the CTR, when the QP optimization is employed. In the worst condition that the newly added degree of freedom is independent of the existing time information, the QP solution will define the weight of the newly added degree of freedom to be zero, and the existing time information is kept. All data points have error bars representing the errors in the measurement.

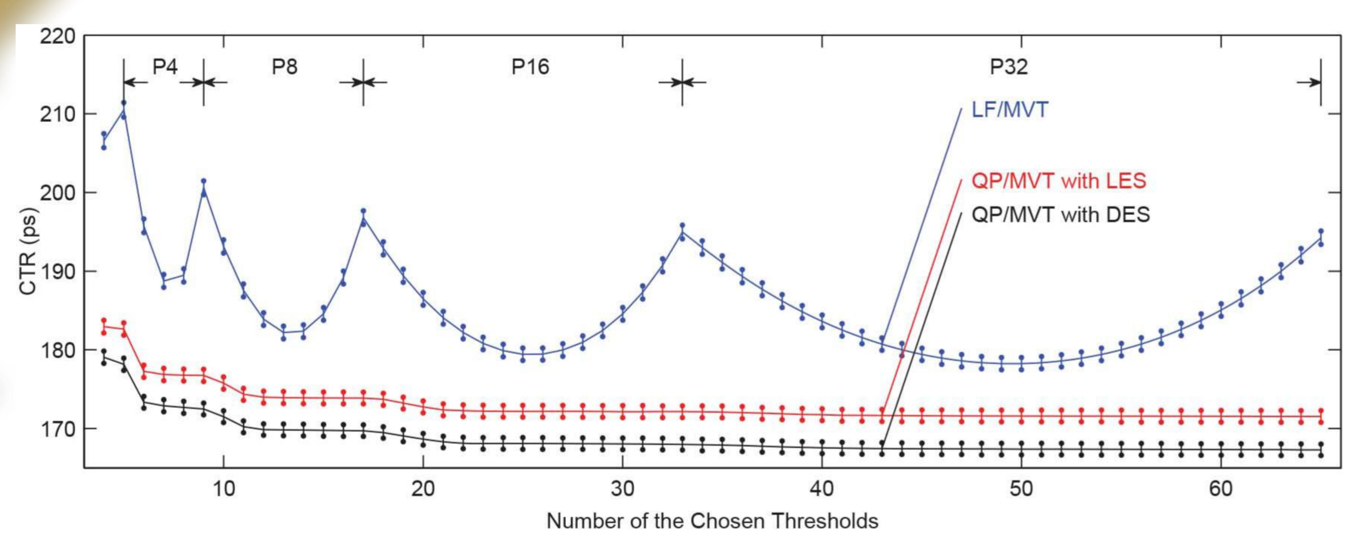

Fig. 3. CTR as function of involved thresholds number for LF/MVT, LES QP/MVT and DES QP/MVT. CTR of the QP methods show monotone decreasing feature while LF/MVT not. LF/MVT performs worse when the newly added voltage threshold is already too high.

CONCLUSION AND DISCUSSION

In this work, we have proposed a PET event timing pickoff method using QP to optimize the combination of MVT sam- ples on both leading and falling edges. QP method aims at min- imizing the variation of time differences with the constraint of the fixed time shift scale. We derived the solution of this QP problem. Experimental results showed the potential advantages of using QP/MVT to retrieve timing information.

In addition, we have analyzed the LF solution. The LF solu- tion has a similar structure to QP solution. Then the computa- tional complexity is nearly the same. Furthermore, we found the LF solution is belonging to the set of the feasible solu- tion in QP/MVT. However, the goal of LF is to approach a linear leading edge. The assumption of linear leading edge was demonstrated to be improper in the data analysis.

Last but not least, the proposed QP method can also be ap- plied to other systems of multiple pulse samples, such as mul- tiple CFD systems, PSPMT readout systems, and light-sharing systems. It offers a new way of combining the obtained samples with optimal parameters by the programming.

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