Nuclear Instruments and Methods in Physics Research A 784 (2015) 269–273

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Study on a digital pulse processing algorithm based on template-matching for high-throughput spectroscopy

Xianfei Wen, Haori Yang*

Department of Nuclear Engineering and Radiation Health Physics, Oregon State University, Corvallis, OR 97331, USA

ARTICLE INFO

Available online 13 November 2014

Keywords:
Digital pulse processing
Template-matching
High-throughput rate

ABSTRACT

A major challenge in utilizing spectroscopy techniques for nuclear safeguards is to perform high-resolution measurements at an ultra-high throughput rate. Traditionally, piled-up pulses are rejected to ensure good energy resolution. To improve throughput rate, high-pass filters are normally implemented to shorten pulses. However, this reduces signal-to-noise ratio and causes degradation in energy resolution. In this work, a pulse pile-up recovery algorithm based on template-matching was proved to be an effective approach to achieve high-throughput gamma ray spectroscopy. First, a discussion of the algorithm was given in detail. Second, the algorithm was then successfully utilized to process simulated piled-up pulses from a scintillator detector. Third, the algorithm was implemented to analyze high rate data from a NaI detector, a silicon drift detector and a HPGe detector. The promising results demonstrated the capability of this algorithm to achieve high-throughput rate without significant sacrifice in energy resolution. The performance of the template-matching algorithm was also compared with traditional shaping methods.

1. Introduction

Innovative systems with increased sensitivity and resolution are in great demand to detect diversion and to prevent misuse in support of nuclear materials management for the U.S. fuel cycle [1–3]. Nuclear fission is the most important multiplicative process involved in non-destructive active interrogation. Among others, unique delayed gamma-ray spectra exist for fissionable isotopes and can be used for isotopic composition measurement [4–16]. A major challenge in utilizing delayed fission gamma rays emitted after active interrogation for safeguards applications is to perform high-resolution spectroscopy measurements at an ultra-high throughput rate [17]. In our recent experimental study at Idaho Accelerator Center, the high-energy x-ray beam with maximum energy of 22 MeV generated by a pulsed linac was used as the photon source. Delayed γ-rays emitted from photon-induced fission reactions inside the samples were measured between adjacent linac pulses with several gamma spectroscopy systems. However, these systems could not work within several milliseconds following each linac pulse although they were well shielded to get rid of irradiation directly from the interrogation source [10]. In addition to modification of front-end electronics to allow rapid recovery from saturation after each linac pulse, innovative pulse analysis algorithms are needed to achieve high-throughput. Using traditional pulse processing algorithms, throughput rate could be significantly impacted when the input rate is high, due to pile-up rejection. Recently, pulse pile-up recovery based on template-matching has been proved to be an effective approach to achieve high throughput gamma spectroscopy [18–21]. The work presented here is primarily based upon the methodology developed by Scoullar and Evans [18,19]. A detailed discussion of our algorithm is given below, followed by implementations on signals from a NaI detector, a silicon drift detector and a HPGe detector. Compared with traditional trapezoidal shaping, a much higher throughput rate could be achieved using the template-matching technique. This would be very beneficial in high-rate counting scenarios such as pulsed linac based active interrogations.

2. Discussion of the algorithm

In a simplified model, the output signal $y(t)$ from a gamma-ray detector is the convolution of the incident gamma ray signal $s(t)$ with the detector response matrix M: $y(t) = s(t) \times M$. Thus, if the response matrix can be accurately determined, an estimation of the incident signal can be obtained through a deconvolution process. The incident signal is normally modeled as a train of delta functions, with random time of arrival and amplitude. The detector response is considered to be time-invariant and can be pre-determined. The first step of the algorithm discussed here is to determine the time of arrival for each pulse by the use of a narrow trapezoidal filter [22]. This can greatly reduce the complexity of the problem. Once the time of arrival for each pulse is determined,

---

* Corresponding author.

http://dx.doi.org/10.1016/j.nima.2014.11.008
0168-9002/

the detection process could be re-written as

$$\begin{bmatrix} y_1 \\ \vdots \\ y_D \end{bmatrix} = \begin{bmatrix} t_{11} & \cdots & t_{1B} \\ \vdots & \ddots & \vdots \\ t_{D1} & \cdots & t_{DB} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_B \end{bmatrix}$$

where s_j ($j=1,\ldots,B$) is a vector containing the amplitude of the B incident pulses. y_i ($i=1,\ldots,D$) is the measured signal at time i. D is the length of the digitized waveform. The elements of the response matrix t_{ij} contain the contribution from the jth pulse to the measurement at the ith time point. Assuming the time-invariant impulse response of the detector was known (i.e. the template), the matrix t_{ij} can then be calculated once the time of arrival for each pulse is determined. Each row of the matrix would just be the impulse response with various amount of delay. Ideally, since y_i is measured and t_{ij} can be calculated, one could invert the response matrix and mathematically solve for the amplitude of the incident pulses. In fact, this was carried out in our study and gave reasonably good results. However, there are some limitations that might push one away from this direct approach. For example, if the dimension of the response matrix t_{ij} is too large (e.g. emission imaging), the calculation involved in direct inversion is prohibitive. In addition, the response matrix might be sparse, which also pose serious challenge to direct inversion. Furthermore, the measured signal y_i could be noisy, preventing an accurate numerical solution. Due to these factors, the response matrix is often nearly singular and the equation above cannot be reliably solved for the amplitude of the incident pulses with direct inversion. In this case, Maximum Likelihood Expectation Maximization (ML-EM) algorithm could be used to provide an estimation of the $\mathrm{s_j}$ vector using the well-known equation [23]

$$s_k^{(n+1)} = s_k^{(n)} \left\{ (1/\Sigma_{d=1}^{D} t_{dk}) \sum_{d=1}^{D} \left[(y_d / \textstyle\sum_{b=1}^{B} t_{db} x_b^{(n)}) t_{dk} \right] \right\}.$$

The algorithm described above was first tested using simulated data. The impulse response function was assumed to be a double exponential function, simulating the anode signal from a PMT coupled with a scintillator detector. The rising edge time constant is determined by the PMT response time (normally between 20 and 80 ns), while the falling edge has the decay constant of the scintillator (e.g. 230 ns for NaI). The amplitude and the time of arrival of each pulse were randomly generated. The simulated waveform was then generated as the superposition of these individual pulses. In pulse processing, the shape (i.e. template) and the time of arrival of each pulse were assumed to be known. Using the algorithm described above, the amplitude of each pulse can be calculated. As shown in Fig. 1, if the time of arrival and the template can be accurately determined, the result is very good even when a white noise was added to the simulated anode signal.

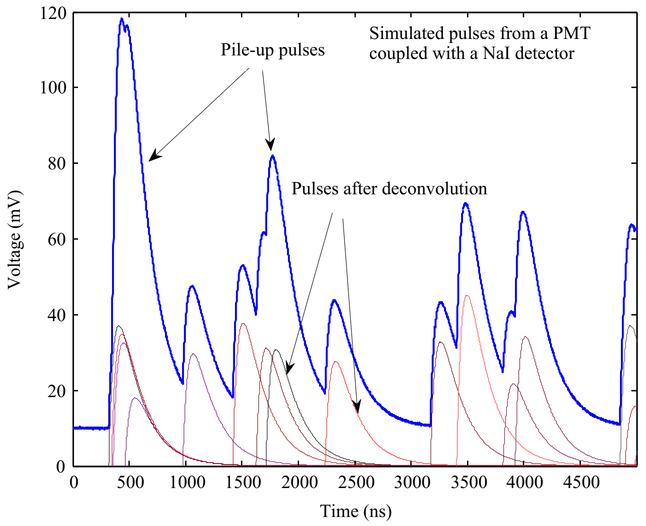

Fig. 1. The application of the template-matching algorithm to recover simulated piled-up pulses.

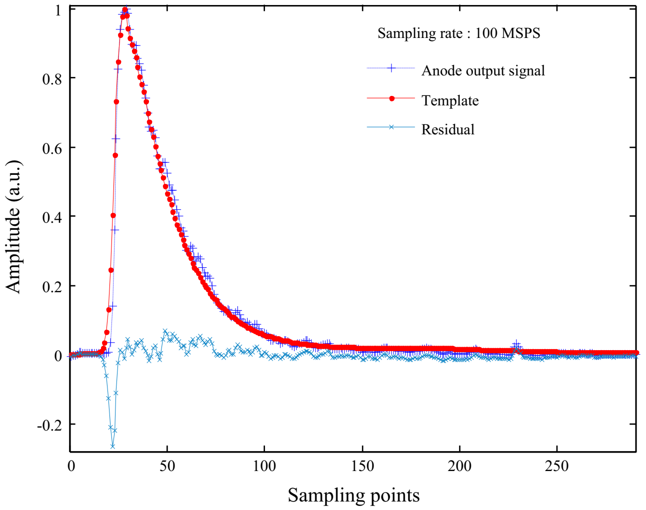

Fig. 2. The anode output signal, template and residual.

3. Results and discussion

The implementation of the template-matching algorithm on high rate NaI data, silicon drift detector data and HPGe data is discussed below. Its performance was also compared with a traditional pulse processing algorithm using trapezoidal filters.

3.1. Implementation on signals from a NaI detector

First, the algorithm was implemented on signals obtained using a NaI detector. The detector used in these measurements was a Canberra Model 802 detector with a 2″ by 2″ crystal. The anode signal was directly digitized at a sampling rate of 100 MSPS using a National Instruments digitizer, model number PXIe-5122. A LabVIEW program was developed to enable streaming of digitized data onto a hard drive array at full speed for off-line processing. The digitized signal and the template are shown in Fig. 2. Due to the large noise imposed on the anode signal, matching result was not ideal. Also, the determination of the time of arrival was challenging. Because of the fast rising edge, an offset of one or two points could cause a large deviation between the template and the measured data. In this case, the signal measured at very low count rate was used as the template for deconvolution. The performance of the template-matching algorithm was compared with traditional shaping methods. The shaping parameters used in the measurement with the Canberra Lynx system were 1 µs respectively for rise time and flat top time. At moderate count rate (~200 kcps), the results were comparable, as shown in Fig. 3.

3.2. Implementation on signals from a silicon drift detector

The performance of the algorithm was also tested on high rate data measured with a silicon drift detector, provided by Southern Innovation. During the measurements, a Mn foil was irradiated with photons generated from an Amptek Mini-X tube to produce characteristic x-rays with energy of 5.89 keV and 6.49 keV. The detector used was a Ketek 30 mm^2 silicon drift detector [24].