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

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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. Firstly, a discussion of the algorithm was given in detail. Secondly, the algorithm was then successfully utilized to process simulated piled-up pulses from a scintillator detector. Thirdly, 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.

Keywords: digital pulse processing; template-matching; high-throughput rate

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 : $y(t) = s(t) * M$. 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, the detection process

could be re-written as:
$$\begin{bmatrix} y_1 \\ \vdots \\ y_D \end{bmatrix} = \begin{bmatrix} t_{11} & \cdots & t_{1B} \\ \vdots & \ddots & \vdots \\ t_{D1} & \cdots & t_{DB} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_B \end{bmatrix}$$
. Here, s_j ($j = 1, \dots, B$) is a vector containing the amplitude of the B incident pulses. y_i ($i = 1, \dots, D$) 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 j th pulse to the measurement at the i th 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 s_j vector using the well-known equation $s_k^{(n+1)} = s_k^{(n)} \left\{ \frac{1}{\sum_{d=1}^D t_{dk}} \sum_{d=1}^D \left[\frac{y_d}{\sum_{b=1}^B t_{db} s_b^{(n)}} t_{dk} \right] \right\}$ [23].

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 Figure 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.

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

Firstly, 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 Figure 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 μ s respectively for rise time and flat top time. At moderate count rate (~ 200 kcps), the results were comparable, as shown in Figure 3.

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

Fig. 3. Comparison between energy spectra measured with a Canberra Lynx system and reconstructed with the template-matching algorithm.

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 mm² silicon drift detector [24]. Different input count rate (between 50 kcps and 500 kcps) was

produced by tuning the tube current. The 50 kcps data was utilized to create a template by averaging over 200 pulses that did not suffer from pile-up. The energy resolution that the template-matching algorithm achieved at low input count rate (i.e. 50 kcps) was 131 eV at 5.89 keV. Good Gaussian peak shape and reasonable energy resolution could still be obtained even at very high input rate (e.g. 500 kcps), as shown in Figure 4. To compare the performance of the template-matching algorithm with traditional pulse processing using trapezoidal filters, we first adjusted shaping parameters to achieve comparable energy resolution and compared throughput rate at each input rate. As shown in Figure 5 a much higher throughput rate (e.g. 467 kcps vs 67 kcps at 500 kcps input rate) was achieved with the template-matching algorithm at very high input rate. The traditional pulse processing algorithm suffered huge decrease in throughput at high input rates due to pile-up rejection. The shaping parameters were then adjusted to achieve similar throughput rate using both algorithms at a certain input rate. Figure 6 shows the energy resolution as a function of input rate. As can be observed, using the template matching algorithm, resolution of less than 200 eV at 5.89 keV could be achieved even at 500 kcps. The resolution gradually degraded as input rate increased. This degradation is much more prominent for the traditional processing algorithm due to pile-up. In summary, Figures 4-6 clearly demonstrated the advantages of the template-match algorithm over traditional approaches: superior throughput with comparable energy resolution; superior energy resolution with comparable throughput.

Fig. 4. Energy spectra at different Input Count Rates (ICR) with the template-matching algorithm.

Fig. 5. Comparison between the template-matching algorithm and the trapezoidal filter (Output Count Rate vs Input Count Rate).

Fig. 6. Comparison between the template-matching algorithm and the trapezoidal filter (FWHM vs Input Count Rate).

3.3. Implementation on signals from a HPGe detector

The HPGe detector is the only practical choice that can provide excellent energy resolution in a wide energy range as needed in measuring delayed gamma-ray spectra following active interrogation for nuclear safeguards applications. As discussed above, in such measurements, there are two issues that greatly limit the throughput of a HPGe detector: the long saturation after each linac pulse and the pulse pile-up due to high input rate. Our approaches to address this challenge include modification of the front-end electronics of a HPGe detector to allow

fast recovery from saturation due to large energy injection from the linac and the development of advanced digital signal processing techniques to improve the throughput rate with only small sacrifice in energy resolution. Here, we discuss the implementation of the template-matching algorithm on signals from a HPGe detector. It is quite challenging to implement the template-matching algorithm on HPGe signals because of the variation in pulse shape. To be specific, for a pulse from the pre-amplifier, the falling edge is determined by the RC constant of the pre-amplifier (e.g. $\sim 50 \mu\text{s}$). On the other hand, the rising edge varies with the gamma-ray interaction position inside the detector. For simplicity, a generic template was used in current work. Pulses from the pre-amplifier were very well reconstructed at the falling edge, but a significant amount of deviation between the measured and reconstructed signals could be observed at the rising edge, as shown in Figure 7. In spite of this large deviation, good energy resolution at input rates up to 200 kcps was achieved, as shown in Figure 8. A performance comparison between the template-matching algorithm and the traditional trapezoidal shaping was again performed and summarized in Table 1. Both the trapezoidal shaping and template-matching algorithms were implemented in customized scripts written in Matlab, running on a laptop (i5-2410M, 4.0 GB RAM, 64-bit Windows operating system). The raw digitized data was converted to mat file and then imported to Matlab. The sizes of the mat files for the 100 kcps and 200 kcps data were about 29 MB and 33 MB, respectively. The processing time of the template-matching shaping algorithm was found to be much longer compared with that of the traditional trapezoidal filtering. The comparison results are shown in the last column of Table 1. The results showed the advantage of the template-matching approach despite the fact that a good template is difficult to construct.

Fig. 7. Verification of the reconstructed signal from pre-amplifier.

Fig. 8. Energy spectra reconstructed with the template-matching algorithm.

Table 1. Comparison between the template-matching algorithm and the trapezoidal filter (HPGe data).

	Input Count Rate (kc/s)	Output Count Rate (kc/s)	FWHM (keV) at 662 keV	Processing Time (seconds)
Trapezoidal (rise time = 1.6 μ s, flat top time = 0.4 μ s)	100	79.8	2.7	12
	200	141.0	3.9	13
Template-matching	100	96.6	2.8	160
	200	186.8	4.6	370

4. Conclusion

To perform high-resolution spectroscopy measurements at an ultra-high throughput rate is a major challenge in active interrogation techniques for nuclear safeguards application. In this work, the development of advanced digital signal processing technique based on template-matching has been shown as an effective approach to address this issue. The principle behind the algorithm was described in detail. This algorithm was first tested using simulated piled-up pulses from a PMT coupled with a scintillator detector. Using a NaI detector, at moderate count rate (~ 200 kcps), energy resolution comparable to traditional trapezoidal shaping was achieved (6.5 % at 662 keV). With high rate data acquired with a silicon drift detector, the advantages of this new algorithm were demonstrated through comparison with the traditional approach using trapezoidal filters. Superior performance in terms of throughput rate and energy resolution was observed at high input rates. The performance of the template-match algorithm was then

evaluated using signals from a HPGe detector. Despite the difficulty to construct an ideal template for pre-amplifier pulses, energy resolution of 4.6 keV at 662 keV and live time of 93.4% were successfully achieved at input rate of 200 kcps.

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Figure 2
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Figure 7
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