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# A correlation-based pulse detection technique for gamma-ray/neutron detectors

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ABSTRACT

We present a correlation-based detection technique that significantly improves the probability of detection for low energy pulses. We propose performing a normalized cross-correlation of the incoming pulse data to a predefined pulse template, and using a threshold correlation value to trigger the detection of a pulse. This technique improves the detector sensitivity by amplifying the signal component of incoming pulse data and rejecting noise. Simulation results for various different templates are presented. Finally, the performance of the correlation-based detection technique is compared to the current state-of-the-art techniques.



## 1. Introduction

Recently, there has been an increasing need to develop nuclear-particle detection systems that are capable of detecting shielded nuclear materials. Typically, original source energies are decreased by energy depositions to the shielding material. This makes the detection of heavily shielded materials very challenging in the presence of detector, electronics and background noise. Moreover, in many applications, it is beneficial to classify the shielded material in real time in order to quickly identify potential threats [1–2].

A digitizing nuclear particle detection system consists of photomultiplier tubes, digitizer unit, and storage and signal processing capabilities. When a particle strikes the detector, a voltage pulse is generated by the photomultiplier tube (PMT), and attention must be paid to the data processing of these voltage pulses for accurate detection and particle identification (if required). Recently, other signal processing and digital filtering algorithms have been proposed in order to improve detection and enhance feature extraction from the measured data [3]. This work, however, focuses on further improving the detector sensitivity and improving particle detection probability through a correlation-based signal processing technique.

This paper is organized as follows. In Section 2, current state-of-the-art and the correlation-based approaches are described and compared. The normalized cross-correlation function is described in detail in Section 3. Section 4 analyzes the effect of using different templates on the correlation. Finally, simulation results and performance comparison of two techniques are presented in Section 5.

## 2. Pulse detection approaches

Traditionally, nuclear-particle detection systems have utilized analog detection techniques to classify materials. These techniques count the number of pulses which is then used in identifying radioactive materials. However, they lack the ability to extract detailed information regarding the pulses. Recent developments in data acquisition systems have resulted in various digital detection and pulse capturing techniques in nuclear particle detectors [2].

### 2.1. Current state-of-the-art approach

Fig. 1 shows the block diagram of a current state-of-the-art digital pulse detection approach. In this approach, PMTs convert light to voltage waveforms which are then digitized with fast analog-to-digital converters. The digitized data are constantly monitored to determine the arrival of pulses. When the incoming signal crosses a programmable threshold voltage level (equivalent to a particle energy level), waveform capture is triggered and the data are then stored on a computer. The stored data are post-processed in order to extract pulse features and to perform pulse shape discrimination.

This approach works well for applications where complete pulse waveforms are required. For example, to characterize detectors it is important to have a good statistical set of data, and this approach is well suited for providing complete information about pulses. However, this approach cannot be used in applications that require real-time data processing. Moreover, detection of shielded radioactive materials can be quite difficult using this technique because to detect lower energy pulses, the detection threshold voltage must be significantly lowered. In this case, false detections are likely to occur when the threshold is lowered to the background noise level.

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### 2.2. Proposed approach

Fig. 2 illustrates the approach proposed in this work. In this approach, PMT data are digitized and sent to a field programmable gate array (FPGA) device that processes the data in real time. FPGA devices have sufficient computing power to extract useful information from pulses such as accurate time of arrival and the peak amplitude of the pulse. The pre-processing that we propose to perform on the FPGA for detecting the arrival of pulses is the normalized cross-correlation (NCC). A template is required to perform NCC, which can be pre-computed as discussed in Section 4.

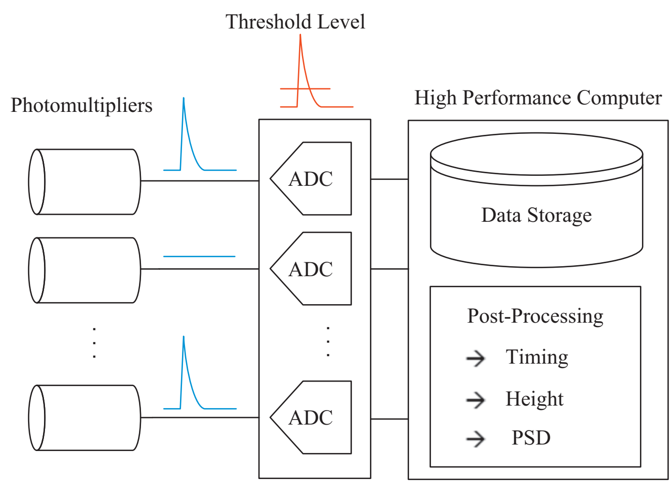


**Fig. 1.** Current state-of-the art pulse detection approach.

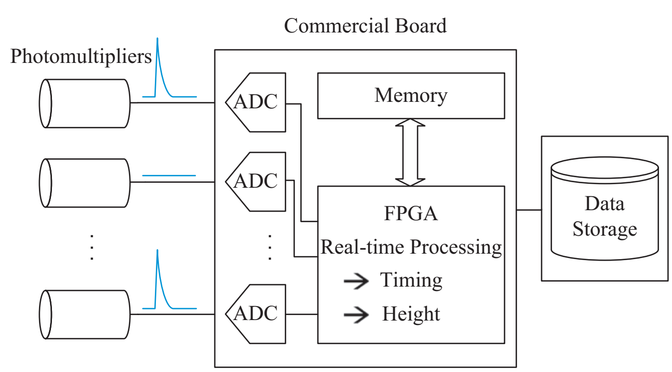


**Fig. 2.** Block diagram of the proposed pulse detection approach.

## 3. Normalized cross-correlation

Correlation has been used extensively as a metric to evaluate the degree of similarity between two signals in a wide variety of applications such as radar target identification, fingerprint matching, image processing, and wireless communication [3–4]. This algorithm can be implemented efficiently on an FPGA device to compute real-time correlation. In this work, we evaluate using the template matching ability of the NCC to improve flexibility and robustness of data acquisition in particle detectors. The NCC of signal $f(x)$ with template $t$ is computed as follows:

$$C(u) = \frac{\sum_x \left[f(x)-\bar{f}_u\right]\left[t(x-u)-\bar{t}\right]}{\sqrt{\left\{\sum_x \left[f(x)-\bar{f}_u\right]^2 \sum_x \left[t(x-u)-\bar{t}\right]^2\right\}}} \quad (1)$$

where $\bar{f}(x)$ and $\bar{t}$ refer to averages of the signal and the template, respectively. The value of NCC ranges from $-1$ to 1 (NCC=1 indicates perfect match). The NCC improves the sensitivity of detection by amplifying the signal while rejecting noise. Fig. 3 illustrates the functionality of the NCC when noisy data are received by the correlator.

Fig. 3 illustrates three different scenarios that can occur when detecting a pulse. First, when a high energy pulse arrives in the presence of noise the correlation of this pulse with the average template is, as expected, close to 1. Second, when two pulses overlap (pile-up) the correlator is able to uniquely identify the two pulses. Lastly, a pulse with peak amplitude close to the noise amplitude is also distinguished from the noise. Fig. 3 clearly illustrates that the noise level in the output of the NCC is lower than the noise in the incoming data.

## 4. Pulse template

Some attention must be paid to the template pulse since the NCC measures how similar the incoming data is to the template. Therefore, to determine how sensitive the correlation-based detection is to the

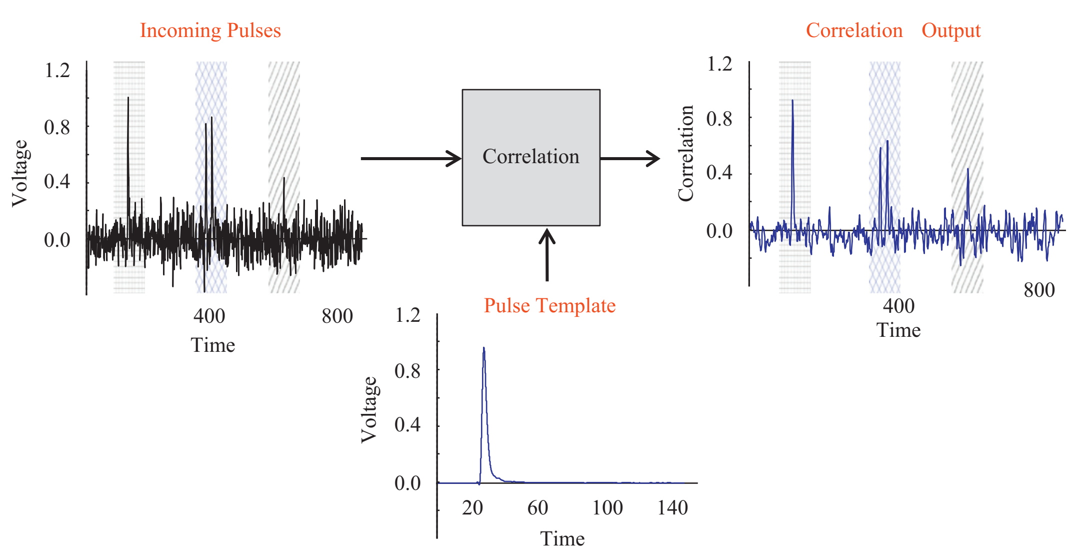


**Fig. 3.** Normalized cross-correlation functionality.

quality of the template, we simulated the behavior of the correlation-based technique with two different templates.

### 4.1. The average template

Ideally, the *shape* of the template should match the nominal pulse output from the PMTs. It is not necessary for the pulse and template amplitudes to match. Shape matching can be achieved by averaging a large number of measured pulses that all have the same energy level. This type of template pulse can be computed by capturing thousands of pulses using the current state-of-the-art system (Fig. 1), binning the pulses according to the measured energy and type (gamma or neutron), and then averaging pulses in each bin [5]. Finally, the averaged pulses should be normalized, and one of the averaged pulses is selected as the template pulse. This template can then be used to detect many different energy levels since the NCC compares the shape of the incoming pulses to the template and not the amplitude. If an average template generated from a set of only measured gamma pulses is used to detect both gamma and neutron pulses, the probability of correct detection is expected to degrade for neutrons since the shape of a neutron pulse differs from a gamma-ray pulse. For example, a 5-keVee gamma-ray pulse in 5-keVee noise has an 86% probability of detection when using a gamma average template. However, a neutron pulse of the same energy with the same noise level is detected correctly 81% of the time when using the same gamma average template. Therefore, using the same average template to detect both types of particles is feasible with minimal loss. Moreover, when the average template is correlated with noise alone, the noise is rejected because it is uncorrelated to the template, effectively lowering the noise floor.

### 4.2. The square template

Another template that was studied in this work was the square template because performing NCC with a square template significantly simplifies the implementation on the FPGA. The square template takes the value of 1 for a given amount of time (called the pulse width) and 0 otherwise. The performance of the correlation-based detection technique with a square pulse template depends on this pulse width. To determine the optimal pulse width, we compared the probability of detection as a function of energy for various widths. The results are shown in Fig. 4. For this simulation, we assumed a sampling rate of 250 MS/s (equivalently the pulse is sampled every 4 ns), and the complete pulse is 608 ns long. This sampling rate and the length of the pulses are assumed based on our current digitizer system. The plot clearly shows that the square template gives the best performance when the pulse is 28 ns (7 samples) wide. Also, it was noticed that the performance degrades significantly if the square pulse is made narrower or wider than 28 ns. In these simulations, full-width-half-max of the pulses is 16 ns, and it should be noted that the ideal square template is not simply the FWHM of the average template. The performance significantly improves by making the square template 1.75 times the FWHM of the average template.

## 5. Simulation results

In order to determine whether the NCC based approach is feasible; simulations were performed to compare its performance with the typical amplitude thresholding technique. First, we studied how the NCC will improve the sensitivity of the detector by improving the ability to detect pulses with peak amplitude on the order of the noise floor. Fig. 5 shows the plot of pulse correlation vs. energy. To emulate a realistic scenario, additive white Gaussian noise (AWGN) was added to the pulses in Matlab. First, we correlated AWGN with the average template in order to determine how the incoming noise will be affected by the correlation, and we noticed that the 3-$\sigma$ level of the noise correlation is approximately 0.245, which means that the probability of incorrect detection (i.e. noise crossing the 0.245 value) is approximately 0.3%. This allows us to set the correlation threshold to be 0.245 in order to detect pulses *regardless of the amplitude of the incoming pulse with a given probability of correct detection*. For example, the 3-$\sigma$ of the noise correlation for a 100 keVee pulse as well as a smaller pulse (e.g. 5 keVee) would not exceed the value 0.245. Therefore, both of these pulses can be detected with the same threshold correlation of 0.245. In this simulation, the energy of the AWGN artificially added to the pulses was equivalent to 5 keVee (5 keVee electron equivalents). Moreover, as shown in the plot the correlation of the pulse with peak amplitude 5 keVee has a correlation of approximately 0.35. Therefore, we can detect this pulse using NCC (86% of the time, not 100%). This is due to the template matching property of the NCC and because the template has no noise, the noise in the incoming pulses is being strongly rejected.

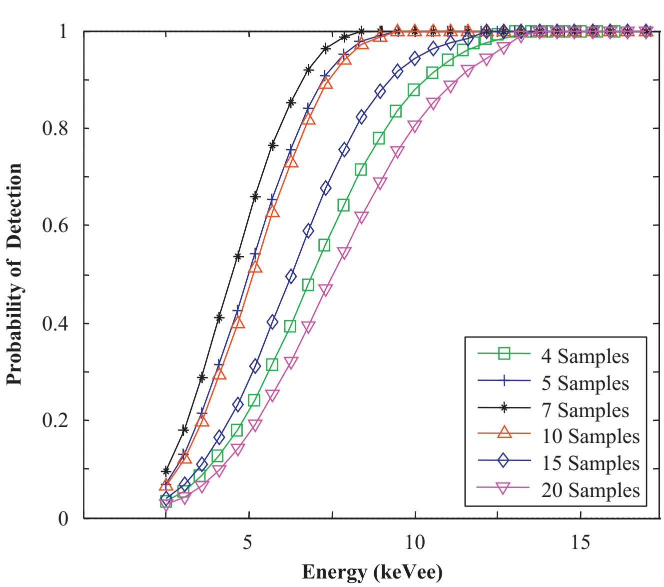


**Fig. 4.** Pulse detection performance for various square templates.

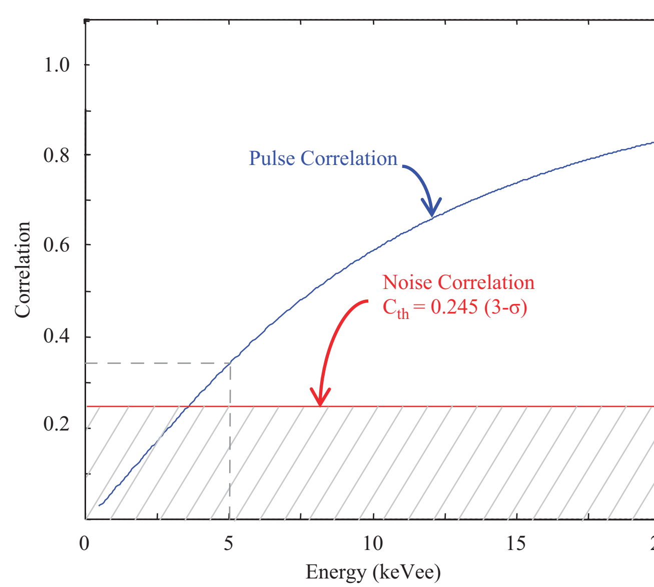


**Fig. 5.** Pulse and noise correlation. Shaded area shows the noise correlation.

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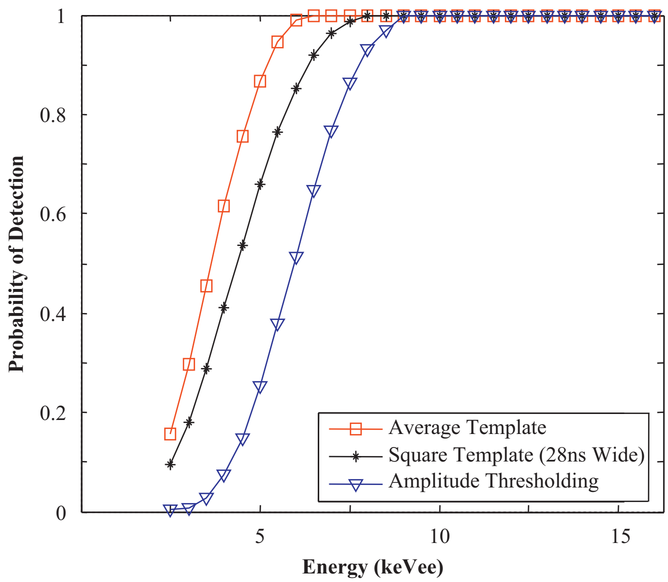


**Fig. 6.** Performance comparison: probability of detection in the presence of 5-keVee noise.

Fig. 6 compares the performance of current state-of-the-art approach to the NCC based approach. Fig. 6 shows the probability of correct detection as a function of pulse energy for both amplitude thresholding and NCC based detection techniques. This plot shows that the probability for correct pulse detection can be significantly increased by using the NCC. For example, a 5-keVee pulse in 5-keVee noise (AWGN) only has a probability of detection of approximately 20% using amplitude thresholding. However, the sample pulse can be correctly detected with a probability of 86% if the NCC with the average template is used. Similarly, if a square template is used, the probability of detection still improves to 60% for the same 5-keVee pulse. This illustrates the tradeoff between minimum pulse detection energy and complexity of the algorithms implemented on the FPGA.

## 6. Conclusion

We presented a normalized cross-correlation-based pulse detection technique that shows substantial improvements in the probability of correct detection for gamma-ray/neutron pulses. The NCC allows an efficient FPGA implementation, and it can be computed in real time. The real-time processing significantly reduces the amount of data to be stored. This technique also improves the detector sensitivity by attenuating noise, which will allow the detection of low energy nuclear particles emitted from shielded radioactive materials. Simulations show that the correlated-based technique improves the probability of correct detection (5-keVee pulse in 5-keVee noise) by 4X and 3X for the average and square templates, respectively. Therefore, this technique is appropriate for non-proliferation, safeguards and national security applications.

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