Applying image processing method to treat digital signals (Postprint)

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Abstract

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Full Text

Preamble

Applying Image Processing Methods to Digital Signal Processing

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Abstract

We present a novel method for digital nuclear signal processing based on image processing and recognition techniques that can effectively improve the signal-to-noise ratio of digital nuclear signals without altering the signal shape. A digital nuclear signal represented as a "time-amplitude" series is converted into a grayscale image with adjustable pixel dimensions. The template of the converted image is extracted using modern image processing methods, including spatial digital low-pass filtering, image binarization, and skeleton extraction. The required parameters are then extracted from the template image. The template extraction method described in this paper can be applied flexibly to obtain templates of nuclear signals, whether for the entire signal or only portions thereof, yielding multiple templates corresponding to whole or partial characteristics of the signals. The image processing results, along with the γ-ray energy spectrum of ^{241}Am acquired using this method, demonstrate that this new approach provides a pathway for developing future digital nuclear instruments with high efficiency, flexibility, density, and multi-parameter capabilities.

Keywords: Digital nuclear signal image, Skeleton extraction, Waveform information extraction
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Introduction

Digital nuclear instruments have been widely employed in high-energy physics, nuclear physics, and applied nuclear physics. Time-domain analysis represents a conventional approach in digital nuclear signal processing, involving techniques such as filtering or shaping for signals described as amplitude-sampled series with equal time intervals. For instance, nuclear signals are typically shaped into trapezoidal or triangular forms for energy spectrum measurements, while bipolar shaping is used for precise timing measurements. Different measurement requirements necessitate distinct hardware and software configurations, and the complexity of real-time, multi-task systems consumes substantial resources while degrading real-time performance.

To address these challenges, we propose a method for digital nuclear signal processing that leverages image processing techniques to extract nuclear information. This approach is based on three key considerations: (1) the shape of output signals from nuclear detectors is determined once system parameters are established; (2) different types of nuclear radiation information are carried by various parts of the signal, such as the rising edge, flat top, and overall pulse shape; and (3) valuable theoretical and experimental achievements from digital image processing can be directly adopted. This paper focuses on converting digitized nuclear signal waveforms into digital images, extracting templates from these converted images, and reconstructing waveforms from the templates.

Compared with the original digital signal, the reconstructed signal exhibits effectively eliminated overshooting and significantly improved signal-to-noise ratio without any change in shape. A γ-ray spectrum of ^{241}Am was collected to validate our image processing algorithm, demonstrating that the energy spectrum resolution achieved by our method surpasses that obtained using ORTEC' s MCA.

Image Conversion of Digital Nuclear Signals

2.1 Principle and Method

Consider an output signal from a nuclear detector, denoted as (t), with time duration T and amplitude A, which is discretized into a digital signal (n) by an ADC with N-bit precision and sampling frequency 1/T . In other words, (n) consists of a series of amplitude values at equal time intervals of 1/T . This waveform can be converted into an image of w × h pixels with grayscale levels of 2 (where M is a positive integer). From this, we can deduce that the maximum horizontal and vertical resolutions of the image are W = [T/T] and H = [A/V • 2], respectively, where V is the maximum output value of the ADC, N is the bit number of the ADC, and when A = V , we have H = 2 . The notation "[]" indicates that W and H must be integers.

The conversion procedure proceeds as follows. First, assuming the width and height of each pixel are Δw and Δh respectively, the waveform (n) is divided into w × h rectangular grids of size Δw × Δh. Thus, w = [W/Δw] and h = [H/Δh], with each grid representing a pixel of the converted image, as illustrated by the thick-border rectangles in Figure 1: see original paper. Typically, Δw ≥ 1 and Δh ≥ 1, meaning that multiple sampling points at different times may be "drawn" into the same grid if their amplitude and time resolutions belong to the same pixel (x, y). Second, we count the number of points in each pixel, as shown in Figure 1: see original paper, and calculate the grayscale value ( ) of each pixel based on its count number using Eq. (1):

$$\psi(x,y) = \left\lfloor \frac{Z(x,y)}{Z_{\mathrm{MAX}}} \cdot (2^M - 1) \right\rfloor$$

where Z(x, y) is the count number of pixel (x, y) and Z_{MAX} is the maximum count among all pixels. Finally, by rendering each pixel with its corresponding grayscale value, the "amplitude-sampled" series with equal time interval is converted into a two-dimensional grayscale image represented as an "x-y" series (Figure 1: see original paper).

2.2 Parameter Confirmation of Image Conversion

The data volume of the converted image is determined by the size of Δw and Δh. The maximum possible data volume of image pixels for the waveform is W × H, though the actual number of pixels in a converted image depends on the chosen

Δw and Δh values. [Figure 2: see original paper] shows a digitized nuclear waveform converted into grayscale images with different Δw and Δh values. The largest Δw × Δh (i.e., the smallest data volume) yields the most distinct image profile, which is suitable for image conversion of waveforms sampled from low-frequency ADCs. Conversely, the smallest Δw × Δh (i.e., the largest data volume) presents the most detailed waveform, making it appropriate for image conversion of waveforms sampled from high-frequency ADCs.

Image Enhancement and Template Extraction

The converted image still contains noise and interference superimposed on the nuclear signals. These can be reduced through an image enhancement procedure for digital nuclear signals (IES). The essence of IES is to attenuate scrambled noise imposed on the waveform through spatial smoothing filtering of the image, thereby improving the image profile via waveform analysis and recognition as described below.

3.1 Spatial Digital Low-Pass Filtering

For an image f(x, y) of size w × h, spatial averaging filtering of the grayscale waveform image is accomplished through 2-D convolution with a filter mask ω of size m × n, yielding the filtered result using Eq. (2):

$$g(x,y)=\sum_{s=-a}^{a}\sum_{t=-b}^{b}\omega(s,t)f(x+s,y+t),\quad a=(m-1)/2,\quad b=(n-1)/2$$

where s = 1, 2, ···, m and t = 1, 2, ···, n are independent variables of the mask function; f(x + s, y + t) denotes the grayscale value of pixel (x + s, y + t) in the image, with x = 0, 1, 2, ···, w - 1 and y = 0, 1, 2, ···, h - 1. The filtering results are shown in [Figure 3: see original paper], where Figure 3: see original paper shows the nuclear signal image before filtering and Figure 3: see original paper–Figure 3: see original paper show images after filtering using different filter masks. The filtering effect is related to the filter mask size. Generally, a smaller filter mask exhibits poorer spatial smoothing performance, while a larger filter mask introduces greater statistical error in signal amplitude acquisition. Therefore, when selecting the filter mask size, the actual noise characteristics imposed on the signal must be considered. Taking into account both the mean square value of the noise and the statistical error of the acquired signal amplitude, a 15 × 15 filter mask represents an optimal choice under our experimental noise conditions.

3.2 Image Skeletonization and Template Extraction

A critical factor in constructing an optimal signal processing system for digital nuclear measurement and analysis is the accurate recognition of detector system parameters. A method called “template extraction” is introduced to accomplish this task based on image skeletonization, which is developed from mathematical morphology theory.

The skeleton S(f) of a specific image f(x, y) can be expressed as the union of a series of erosion and opening operations in morphological image processing, described as follows:

$$S(f) = \bigcup_{k=0}^{K} S_k(f), \quad S_k(f) = (f \ominus kB) - (f \ominus kB) \circ B$$

where B is the structuring element, “ ” denotes the opening operation, and (f kB) represents k successive erosions of f:

$$(f \ominus kB) = \{(f \ominus B) \ominus B \cdots \ominus B\} \quad \text{(k times)}$$

where k is the number of the final erosion iteration before (f kB) becomes an empty set, as described by Eq. (6):

$$K = \max\{k \mid (f \ominus kB) \neq \emptyset\}$$

For practical applications, K can be set to a fixed value as a trade-off between computational speed and skeleton extraction effectiveness. According to digital image processing theory, the waveform image after spatial low-pass filtering is converted into a binary image, where any pixel with a grayscale value above 1 is forced “on” and any pixel below 1 is forced “off.” The image template is then extracted by skeletonizing the binary image with the appropriate structuring element.

In this work, we use MATLAB’ s “bwmorph(BW, ‘skel’ , K)” function to perform skeleton extraction on the binary image. The “bwmorph” function can perform various morphological operations on binary images depending on its parameters. The three parameters are: “BW” denotes the image to be processed, “skel” indicates that the operation extracts the skeleton by removing pixels on object boundaries without allowing objects to break apart, and “K” specifies that the operation is applied K times. We used a 3 × 3 structuring element (Eq. (7)) to implement a fast erosion algorithm based on a look-up table:

$$B = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

[Figure 4: see original paper] shows the template of a nuclear signal waveform after skeletonization. Figure 4: see original paper displays the time-amplitude waveform of a ^{241}Am γ-ray detected by a CZT detector and sampled by a Lecroy

WaveRunner 104Xi-A oscilloscope at 100 MSPS, while Figure 4: see original paper demonstrates the waveform skeleton obtained through image conversion, enhancement, and skeletonization. Furthermore, we can obtain multiple-style templates from a single system by extracting skeletons from different parts of the same waveform through processing different regions of the waveform image. [Figure 5: see original paper] shows extracted templates for the rising edge portion and the flat top portion based on Figure 4: see original paper. The image skeletonization of digital nuclear signals from different radiation sources, detectors, and sampling rates can all be accomplished using this method with appropriate parameter adjustments. The method we present establishes the foundation for high-precision parameter recognition of waveforms.

As evident from [Figure 4: see original paper], compared with the original image, the noise imposed on the skeleton is significantly reduced while the skeleton shape remains virtually unchanged for both rising and falling edges. The skeleton captures the features of the whole or key parts of the nuclear signal waveform acquired from the detection system under specific working conditions, making it suitable for use as a template for nuclear signal waveforms.

Results and Discussion

4.1 Acquisition of Template Image Amplitude

After establishing the template image, we describe its basic features in parametric form. The signal amplitude represented by the template image is defined by Eqs. (8) and (9):

$$\nu_N = (N - N_0)\Delta\nu, \quad \Delta\nu = \nu_{\text{range}}/H$$

where _N is the amplitude value represented by row N of the template image, N_0 is the row number of the template image that denotes zero amplitude, Δ is the amplitude value represented by a single row, _{range} is the input range of the digitizer, and H is the maximum vertical resolution of the image as defined in Section II(A).

4.2 Spectrum Acquisition

To demonstrate the effectiveness of the proposed method, we established a system to acquire nuclear energy spectra using both this method and a conventional MCA for comparison.

[Figure 6: see original paper] shows a block diagram of the experimental apparatus. The ^{241}Am γ-ray signals from the CZT detector are fed simultaneously into the digital spectrometer and the MCA, which consists primarily of an ORTEC-527 amplifier and ORTEC-926 ADC. The digital spectrometer comprises an FA-001 front-end controller and a PCI-9820 digitizer (AD-LINK). The ADC sampling rate is 66 MSPS with 14-bit conversion accuracy and an input range of $±$1 V. The digital nuclear signals acquired by the waveform digitization system are transferred to a workstation for data processing and result analysis. The data are processed using the image processing algorithm discussed above. [Figure 7: see original paper] illustrates the flowchart for collecting the energy spectrum from the digitizer using this algorithm, with parameters for each step provided in .

Parameters used in the algorithm | Steps | Parameters | |—–-|——–| | Convert to grayscale image | W = 5000, H = 28, Δw = 10, Δh = 25 | | Spatial average filtering | Filter mask: 15 × 15 pixels | | Skeleton extracting | Structuring element: 3 × 3 pixels, K = 10 |

[Figure 8: see original paper] compares the two spectra acquired by the conventional MCA (Figure 8: see original paper) and the image processing algorithm (Figure 8: see original paper). The results demonstrate that our image processing algorithm effectively acquires nuclear information, particularly amplitude information from the waveform. The resolution of the 59.5 keV peak is 9.7% and 9.1% in Figure 8: see original paper and Figure 8: see original paper, respectively, showing clear improvement in energy resolution achieved by our digital image processing method. Ongoing efforts continue to further refine and improve this new method.

Conclusion

Based on the experimental results, the following conclusions can be drawn: (1) It is feasible to adopt digital image processing methods for digital nuclear signal processing to acquire nuclear information; (2) Digital nuclear signals can be successfully converted into grayscale images with adjustable grayscale levels and dimensions through our method; (3) The skeleton of nuclear signal images can be effectively extracted through the combined approach of spatial linear filtering and mathematical morphology, offering potential advantages for establishing template libraries for nuclear signal recognition; and (4) The method we present enables simple and effective implementation of various potential applications, including signal accumulation discrimination, weak signal detection, and compression and transmission of digital nuclear signal data, which will be investigated in future work.

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