An acquisition system of digital nuclear signal processing for the algorithm development postprint

Authors: WANG Peng, Ruanyu Zhang, YAN Yangyang, HAO Dejian, HUANG Ning, WU Qingxing, AN Zhu

Date: 2023-06-18T00:00:00+00:00

Abstract

A principle and method of constructing the digital acquisition system is presented in this work, which is convenient for the study on the theories and algorithms of digital nuclear signal processing. The hardware system of the digital acquisition system consists of front-end controller, waveform digitizer and PC workstation, on which the software system has been developed based on Visual C++ under Windows environment. The alterable-frequency sampling (AFS) algorithm and the alterable-frequency trapezoidal filter (AFTF) algorithm have also been studied in the real-time environment, along with a digital nuclear spectrum acquisition system being set up based on the new algorithms and the γ-ray spectra of 241Am being shown. A useful experimental platform could be provided by this work for the successive work such as the development of global digitized nuclear measurement system and the study of digital nuclear signal processing.

Full Text

Preamble

An Acquisition System for Digital Nuclear Signal Processing Algorithm Development

Peng Wang[1]**, Ruanyu Zhang**[2]**, Yangyang Yan**[2]**, Dejian Hao**[2]**, Ning Huang**[1]**, Qingxing Wu**[1]**, Zhu An**[1]

[1]Institute of Nuclear Science and Technology, Sichuan University, Key Laboratory of Radiation Physics and Technology, Ministry of Education, Chengdu 610064, China

[2]College of Physics Science and Technology, Sichuan University, Chengdu 610064, China

Abstract

This work presents the principles and methods for constructing a digital acquisition system that facilitates research on theories and algorithms for digital nuclear signal processing. The hardware system comprises a front-end controller, waveform digitizer, and PC workstation, while the software system has been developed using Visual C++ under the Windows environment. The alterable-frequency sampling (AFS) algorithm and alterable-frequency trapezoidal filter (AFTF) algorithm have been studied in a real-time environment, and a digital nuclear spectrum acquisition system based on these new algorithms has been established, demonstrating the γ-ray spectra of ^{241}Am. This work provides a useful experimental platform for subsequent research, such as the development of fully digitized nuclear measurement systems and the study of digital nuclear signal processing algorithms.

Keywords: Digitized nuclear instrument, Digital nuclear signal processing, Digitized nuclear measurement

Introduction

Digitized nuclear instruments have been widely used in the field of digitized nuclear measurement over the past decade [1-3]. Generally, these instruments consist of concise and compact hardware combined with software encompassing various functions and algorithms. They offer advantages including light weight, small size, low cost, easy operation, and good performance when supported by effective signal processing algorithms [4 6].

Consequently, research on theories and algorithms for digital nuclear signal processing has become an important direction within the field of digital nuclear instrumentation. To facilitate the study and experimental validation of nuclear signal processing techniques, it is necessary to develop a digital acquisition system with the following features: (1) Good software compatibility and expandability, allowing existing algorithms to be easily integrated while providing interfaces for new algorithms; (2) Capability for both online and offline data processing to verify algorithm efficiency and real-time performance while providing resources for high-precision algorithm research; (3) Effective visualization functionality capable of displaying multiple results simultaneously and saving them automatically; and (4) Easy and flexible adjustment of hardware parameters for various experiments.

Based on these considerations, we have constructed a digital acquisition system platform for researching and developing theories and algorithms used in digital nuclear signal processing, as shown in Fig.1. The waveform digitization system comprises the “PCI-9820” waveform digitizer provided by AD-LINK and a front-end controller designed in-house. The acquired digital nuclear signals are transferred to a high-performance PC workstation via PCI bus for storage and further online or offline processing. The software system has been developed using Visual C++ under the Windows environment and includes two main components: a basic module containing essential software such as sampling control, data storage, and real-time display sub-modules; and an expansive module designed for studying new digital signal processing algorithms. These new algorithms can be integrated into the software system as modules and invoked by kernel programs. The expansive module will be continuously expanded as new algorithms are developed, ensuring the software system evolves alongside deepening research in digital signal processing. To validate the feasibility of the digital acquisition system discussed in this paper, a digital nuclear spectrometer was established by embedding the traditional trapezoidal filter (TTF) algorithm, AFS algorithm, and AFTF algorithm, and the measured γ-ray spectrum of ^{241}Am is presented.

2 Construction of Waveform Digitization System

The nuclear waveform digitization system has been constructed around the "PCI-9820" digitizer provided by AD-LINK. A gain-adjustable front-end controller was designed to match the amplitude of signals output from semiconductor detectors with the input range of the digitizer, thereby effectively reducing quantization error. The front-end controller connects to nuclear detectors and amplifies the analog signals to suitable amplitudes that fit the digitizer's range, minimizing quantization error and amplitude loss during waveform digitization [7].

2.1 Principle of the Front-End Controller

The gain-adjustable front-end controller operates based on the principle of adjustable gain determination, which is accomplished by controlling a digital potentiometer via CPLD to adjust the amplifier's gain. The controller consists of an input select unit, differential shaping unit, gain adjustment unit, channel switching unit, controlling unit, and power supply unit. Fig.1 shows the structure diagram of the front-end controller.

The output mode of the preamplifier can be selected as either resistive and capacitive feedback or switch reset, controlled by the input select unit. The differential shaping unit completes AC coupling of the signal. The gain adjustment unit then magnifies the signal to fit the input range of the digitizer. Channel selection is dominated by the channel switching unit, which is realized using the MAX-4729 chip. The core of the controlling unit is a CPLD (XC-95288XL) programmed to implement system reset, indicator lamp control, channel switch control, and digital potentiometer setting. Based on the status of the dial switch, the CPLD sends out corresponding timing sequences to set the value of the digital potentiometer, thereby regulating the amplification of the gain adjustment unit.

2.2 Constitution and Performance of Waveform Digitizer System

The main parameters of the digitized nuclear signal acquisition system are as follows: dual channels with small-signal bandwidth above 30 MHz per channel; programmable ADC conversion range of $±$5 V or $±$1 V; separate 14-bit ADC for each channel; maximum sample rate of 65 MS/s per ADC, reaching 130 MS/s for the digitizer when used in "ping pang" mode; and onboard 128M SDRAM used as data buffers. Data is transferred from buffers to the PC workstation via DMA mode for dynamic display, real-time processing, or data saving by the software.

3 Design of Software

The software system for the digital acquisition platform was developed under Visual C++ and contains both basic and expansive modules. The basic module includes several sub-modules such as parameter setting, sample control, basic signal processing, and graph display, enabling fundamental platform functions including waveform sampling, data saving, dynamic waveform plotting, and energy spectrum display. The expansive module is designed for users to add successive signal processing algorithms for specific applications. These algorithms are encapsulated as DLLs (dynamic link libraries) that can be easily integrated into the software system according to pre-defined user interfaces. To date, the AFS and AFTF algorithms have been implemented in our software. Fig.2 shows the structure diagram of the platform software.

3.1 Design of Parameter Setting and Sampling Control Modules

By calling the API functions of the SDK provided by PCI-9820, we can complete parameter settings for the PCI-9820 digitizer such as sampling frequency, sampling mode, triggering mode, triggering level, calibration mode, and input range, as well as control the digitizer to start or stop working [8]. The sampled real-time data acquired by the digitizer is first stored in the onboard buffer, then transferred to computer memory via DMA mode through the PCI bus when the buffer becomes full. This real-time data may be used for further handling with associated signal processing algorithms, and the results may be dynamically displayed or saved as data files in our software.

3.2 Design of Expansive Module

The expansive module consists of various nuclear signal processing algorithms in the form of DLLs that can be conveniently added to the software system following specific rules. In this work, the traditional digital trapezoidal filter algorithm was first integrated into the expansive module, which, together with the basic module, forms a traditional digital nuclear spectrometer used for basic performance testing of the platform and for comparison with other experiments. Next, the AFS algorithm and AFTF algorithm for digital nuclear signals based on digital decimation were developed to establish an improved digital nuclear spectrometer with optimal data amount.

Extract of Waveform Data

The digitized data continuously sampled by the digitizer includes both nuclear event data and interval data between events. When the nuclear event rate is low, significant storage resources would be wasted if all continuous data were saved. Since both the AFS and AFTF algorithms mentioned below handle single waveforms, only the complete waveform data extracted from the original continuous sampled data needs to be saved.

Consequently, we designed a specific data structure to store the waveforms:

```
Struct PulseWave {
    ULONG startTime;     // the start time of waveform
    ULONG endTime;       // the end time of waveform
    USHORT peakValue;    // the peak value of waveform
    ULONG peakTime;      // the peak time of waveform
    USHORT *pValue;      // the data of waveform
}
```

In this data structure, the data members “startTime” and “endTime” record the start and end times of each waveform, respectively. The data member ”*pValue” is a pointer to an array of sampled discretized data for each waveform from the start time. The “peakValue” and “peakTime” record the peak value and timestamp of each waveform, providing necessary information for successive signal processing algorithms to enhance computing efficiency. Using this data structure, we can largely decrease storage requirements while preserving effective waveform information.

Algorithm of AFS

To preserve the entire information carried by the nuclear signal during digitization, massive data reception and processing must be effectively executed. The preamplifier output signal is typically a double exponential signal with a nanosecond-microsecond rising edge and microsecond-millisecond falling edge. The rising edge lasts for a shorter time and contains high-frequency content that may include nuclear events, whereas the falling edge contains low-frequency content but consumes significant storage resources due to its long duration.

To utilize storage resources effectively [9], a novel “alterable-frequency sampling (AFS)” method is performed through the following steps: First, digitize the nuclear signal with high-frequency sampling; then apply low-pass filtering and extract the falling edge with lower sampling frequency; finally, combine the rising edge of the high-frequency sampled signal with the falling edge extracted at lower frequency to form a new waveform for saving.

According to the Nyquist law, the original signal should be processed with an anti-aliasing digital filter to eliminate frequency aliasing during sample extraction. Assuming the preamplifier output is x(nT), and yD(nT) is the output after M times of extraction, then yD(nT) = x(MnT). The output of yD(nT) after low-pass anti-aliasing filtering is yDLP(nT), and the AFS output can be described by Eq.(1).

Algorithm of AFTF

The trapezoidal shaping filter is one of the most common optimal filters for nuclear signals, providing good energy resolution and high throughput for general applications [10 14]. Here we design a new trapezoidal shaping algorithm for double exponential signals after AFS. Unlike conventional trapezoidal shaping algorithms, the double exponential signal is divided into rising edge and falling edge sections split at the peak. The rising edge section is directly shaped by the trapezoidal shaping algorithm, whereas the falling edge section is first handled by frequency reduction and then shaped by the trapezoidal shaping algorithm. Finally, the two shaped signal sections are combined into one signal through a specific method. The pulse width and flat top width of the shaped signal can be flexibly adjusted through parameter setting.

Assuming the input signal is described by Eq.(2), where τ_1 and τ_2 are the time constants of the rising edge and falling edge, respectively. The impulse response function of the trapezoidal shaping filter is described by the following formula. The shaped result of the rising edge section of the signal is described by the following formula, where Np is the time of peak. The result of AFTF is the combination of the two shaping results calculated by formula (7), where M is the frequency reduction multiple.

4 Performance of the Digital Acquisition System and Algorithm Testing

4.1 Basic Functions of the System

The digital acquisition system platform provides the following basic functions: (1) Sample rate can reach 130 MHz for single channel and 65 MHz for dual channels with 14 effective bits; (2) Sample parameters and amplitude gain of analog signals can be optimally adjusted; (3) Real-time acquisition and dynamic display of nuclear signals can be achieved; (4) User-defined algorithms can be integrated into the platform for online or offline testing; and (5) Results of signal processing algorithms can be visualized.

4.2 Test Results of Front-End Controller Performance

Fig.3 shows the experimental results for the γ-ray of ^{241}Am using the front-end controller, where the top waveform is the direct output from the CZT detector and the bottom waveform is the output from the front-end controller. As shown, the CZT detector output signal is magnified through the front-end controller, with the time constants of both rising and falling edges coinciding with the detector output.

4.3 Test Results of the Basic Module

Fig.4 shows the main software interface of the digital acquisition system, which implements basic module functions such as parameter setting, waveform sampling control, data saving, and dynamic waveform or spectrum display. The waveform displays real-time γ-ray signals of ^{241}Am detected by the CZT detector and processed by the front-end controller.

4.4 Determination of Frequency Reduction Multiple

To evaluate the effect of the AFS algorithm, we introduce a parameter δs to describe the distortion extent of the sampled signal after frequency reduction, defined by formula (8), where ta is the rising or falling time after frequency extraction, and tb is the rising or falling time before frequency extraction. The ta or tb is defined as the time interval from 10% to 90% of the peak value for the rising edge, and from 90% to 10% for the falling edge. Given an acceptable δs value (e.g., $\delta_0 = 3\%$ in our case), we can increase the frequency reduction multiple step by step until we obtain the maximum multiple satisfying $\delta\text{s} < \delta_0$.

The sample frequency must satisfy the time property requirements of nuclear signals, which are determined by the specific preamplifier output. In our platform, the rising time of output pulses from our CZT detector system is about 0.5 s, measured using a Lecroy WaveRunner digital oscilloscope with 10 GSPS sample rate. The sampled pulse data has been saved as original data, from which we extract data with different frequency reduction multiples and calculate δs for both rising and falling edges. The results show that a sample frequency of 60 MHz is optimal for the rising edge, while 15 MHz is optimal for the falling edge, with distortions of 2.7% and 0.5% respectively according to formula (8). Therefore, it is reasonable and feasible to study the above algorithms with a sample frequency of 60 MHz under our detector system.

4.5 Test Results of AFS and AFTF

Fig.5 and Fig.6 show measurement results of ^{241}Am γ-rays using the CZT detector with our digital acquisition system. The shaping parameters of the trapezoidal filter were carefully selected [15]. Waveform 1 in Fig.5 is the original signal acquired by the PCI-9820 digitizer, and waveform 2 is the output signal processed by the AFS and AFTF algorithms. Fig.6 compares the filtering results of TTF with AFTF, where waveform 1 shows the conventional trapezoidal filter result and waveform 2 shows the AFTF result with a frequency reduction multiple of 1 for the rising edge and 4 for the falling edge. These figures demonstrate that the filtering results of the two algorithms are almost consistent.

4.6 Experimental Validation

4.6.1 Experimental Apparatus To verify the validity and feasibility of our scheme, we set up two experimental apparatus to test the CZT detector output simultaneously. One is a conventional analog spectrometer composed of an amplifier, MCA, and data processing software manufactured by ORTEC; the other is our digitized nuclear instrument platform consisting of a front-end controller, digitizer, and digital acquisition system software. Fig.7 shows the block diagram of the two experimental apparatus.

4.6.2 Measurement Results and Discussion Figure 8 Figure 8: see original paper shows the γ-ray energy spectrum of ^{241}Am acquired by the analog system. Fig.8(b) and Fig.8(c) show spectra acquired by the digital acquisition system, where the former uses the TTF algorithm and the latter uses the AFTF algorithm. To compare the energy spectra obtained by the two systems, analog and digital spectra were acquired simultaneously. The resolutions of the 59.5 keV peak for the three spectra are 9.7%, 6.6%, and 6.8%, respectively.

The figures show that the energy resolutions achieved by our digital acquisition system platform are better than those obtained with the conventional analog spectrometer, particularly for the two low-energy peaks. This implies that the noise in CZT detector output signals is better rejected by the digital filter than by the analog filter. Meanwhile, the energy resolutions of the spectra in Fig.8(b) and Fig.8(c) are almost identical, meaning the AFTF algorithm does not significantly affect the spectrum resolution. The event rate of the ORTEC analog system is about 200 cps when acquiring energy spectra under our experimental conditions, whereas that of our digital system is almost the same for both TTF and AFTF algorithms.

5 Conclusion

Based on experimental results, our study can be summarized as follows: (1) The principles and implementation methods of the digital acquisition system discussed in this paper have been proven correct and feasible; (2) The AFS and AFTF algorithms have been successfully developed and tested on our digital acquisition system platform; (3) Both the traditional digital nuclear spectrometer and the optimized digital nuclear spectrometer with new algorithms have been implemented and their performances compared experimentally; and (4) The digital acquisition system platform may serve as a useful experimental platform for successive studies of digitized nuclear instrumentation and algorithms for digital nuclear signal processing.

References

1. Grzywacz R. Nucl Instrum Meth B, 2003, 204: 649–659.
2. Riva M, Esposito B, Marocco D. Fus Eng Desi, 2007, 82: Al–Adili.
3. A, Hambsch F J, Oberstedt S. Nucl Instrum Meth A, 2010, 624: 684–690.
4. Warburton W K, Grudberg P M. Nucl Instrum Meth A, 2006, 568: 350–358.
5. Fernandes A M, Pereira R C, Sous J, et al. Fus Eng Desi, 2010, 85: 308–312.

6. Yu S S, Tang B, Lai W C. Nucl Electr Detect Tech, 2009, 29: 580–583.
7. Zhang R Y, Luo X B, Xu Z R. Atom Sci Tech, 2009, 43: Adlink.
8. Software Development Kit for PCI/PXI Digitizer Data Acquisition Cards Function Reference Manual, Taibei, ADLINK Technology Inc, 2009, 18–88.
9. Tao R, Zhang H Y, Wang Y. The theory and application of multi-sample rate digital signal processing. Beijing, Tsinghua University Press, 2008, Chapter 2.
10. Imperiale C, Imperiale A. Measurement, 2001, 30: 49–73.
11. Bargholtz C, Fumero E, Martensson L, et al. Nucl Instrum Meth A, 2001, 471: 290–292.
12. Menaa N, Agostino P D, Zakrzewski B, et al. Nucl Instrum Meth A, 2011, 652: 512–515.
13. Wang J H, Wang L H, Fang Z L. Nucl Electr Detect Tech, 2011, 31: 543–546.
14. Mathy F, Bonnefoy J P, Gliere A, et al. Nucl Instrum Meth A, 2001, 458: 484–490.

Note: Figure translations are in progress. See original paper for figures.