Volume 4, Issue 8, August 2014 ISSN: 2277 128X
International Journal of Advanced Research in Computer Science and Software Engineering
Research Paper
Available online at: www.ijarcsse.com

Review of Pulse Processing in Nuclear Physics

Amitkumar Singh* Department of Physics University of Mumbai India

S. K. Dubey Department of Physics University of Mumbai India

M. G. Bhatia Ameya Centre of Robotics Andheri, Mumbai India

Abstract— In nuclear physics various methods and various platforms (hardwired circuits, microprocessors, digital signal processor, field-programmable gate array etc.) for shaping any analyzing the signals coming from detectors are found in the literature. This article provides an overview of work done by various researchers on pulse processing of nuclear detectors. Initially pulse shaping was done by analog pulse analysis system which consists of simple elements like Integrator, RC ladder, various pulse shaping circuits. As technology advances high performance digital processor, integrated into single gate array microcircuit had been developed. Digital filtering and a various pulse searching algorithm were used with help of digital processors. Finally results and setup of reconfigurable hardware platforms which uses both digital signal processors and field programmable gate array's to attain high resolution and real-time processing in nuclear spectrometry experiments are presented.

Keywords— Pulse shaping, Pulse height analysis, FPGAs, DSP, Single channel analyser, Multi channel analyser,

I. INTRODUCTION

During last four decades nuclear instrumentation had done the grate advances. Several new pulse processing technique had been developed and utilized for processing of various shapes of pulses. In nuclear physics experiment nuclear particle interact with detectors and produces a voltage pulse. The height of pulse is proportional to the energy deposited by nuclear particle in detector [1]. During analog processing detectors signals are first shaped with the help of integrator and differentiator type of analog circuitry and forwarded towards the analog comparators and counter circuitry either for counting purpose or for further processing [2]. During the year 1970 invention of microprocessors further revolutionized the pulse processing system. Now after basic analog processing of pulses by analog circuitry further counting is done by microprocessor or digital systems. Because of invent of flash analog to digital converters signals coming out from detector are directly digitized and forwarded toward microprocessor based counting circuitry for counting or plotting purpose. With the development of digital signal processors (DSPs) more complex algorithms were applied on detectors digitized signals. By using digital signal processors smoothening, filtering, correlation and convolution like operation are done very rapidly on the digital signals and more precise information are obtained which was either not possible or very difficult with the help of analog processing circuits. One of the most far-reaching developments in digital electronics has been the introduction of programmable logic devices (PLDs). Today's state of the art hardware and software tools for digital circuit can greatly improve and speed-up development of a high performance digital spectrometer. Emerging high level hardware description and synthesis technologies in conjunction with Field Programmable Gate Arrays (FPGAs) have significantly lowered the threshold for hardware development related to nuclear physics. In this paper we have tried to summarize the work done by various researchers on pulse processing of nuclear detectors.

II. REVIEW OF PULSE PROCESSING IN NUCLEAR PHYSICS

Because of potential applications in nuclear instrumentation, the pulse processing has attracted much attention. Starting from the 1970's, significant efforts have been made in trying to develop various types of pulse processing system by using various platforms such as microprocessor, digital signal processors and PLD's etc. An idea of a general signal processing system which should satisfy various pulse rate and noise requirements is explored. Time-variant filters of the gain varying class are used to realize the required optimum weighting functions of finite width. A general processing system is realized by employing filters with continuously time-variant elements. In particular, a gain-varying element can be used in conjunction with an integrator to realize arbitrary weighting functions, and therefore the theoretically maximum signal-to noise ratio [3]. Processing of signals produced by semiconductor detectors and their general problems of pulse shaping to optimize resolution with constraints imposed by noise, counting rate and rise time fluctuations was discussed. Basic elements for pulse processing system were described. Theory of preamplifier circuitry, pole-zero cancellation circuit, RC differentiator, RC integrator shapers, Gaussian pulse shapers, Gated integrator shaper, Harwell pulse shaper and Pile-up rejection circuitry and its functioning was discussed and performance of various pulse shapers were compared [4]. A high performance digital pulse processor, integrated into single gate array microcircuit had been developed. Level discriminators were included on chip. Threshold levels and pile-up pulse width parameters were microprocessor controllable. The pulse processor measures pulse height, pulse area and the required timing information (e.g. multi detector coincidence and pulse pile-up detection) [5]. A new time variant trapezoidal pulse shaper suitable for a high resolution high counting rate spectroscopy system was described [6]. A fully digital system for acquisition of NaI gamma-ray spectra was developed and tested. A fast digitizer was used to digitize unprocessed photomultiplier anode pulses to 8-bit resolution at 5 ns intervals. Digital filtering and a pulse searching algorithm were used to identify pulses, detect and correct for pileup and determine pileup corrected pulse areas. A pulse height distribution was generated, corresponding to a conventional multichannel analyzer spectrum. No electronics was used between the photomultiplier and the digitizer, eliminating the usual amplification, filtering, baseline restoration, etc. [7]. An efficient architecture for finite impulse response (FIR) filters was described. This architecture allows the implementation of high sampling rate filters of significant length on a single field-programmable gate arrays (FPGAs), as well implementation using more conventional VLSI techniques [8]. A digital pulse processor with improved differential linearity and reduced dead time had been designed. The circuit used an 8-bit flash ADC running at 36 MHz and continually sampling the signal from the preamplifier or shaping amplifier. The digitized signal was then processed by a digital moving average filter. A digital peak detector was used for measuring the amplitude of the shaped pulses. A novel, threshold-free circuit had been designed that combines both the moving average and peak detection functions [9]. A technique for the synthesis of optimal pulse shapes like symmetric triangle and symmetric trapezoid for high resolution, high throughput spectroscopy was described. Convolution of exponential input signals with rectangular function and with unit slope truncated ramp function was presented graphically and mathematically. Efficient recursive algorithms had been developed that allow real time implementation of a shaper that can produce either trapezoidal or triangular pulse shapes. Other recursive techniques were presented which allow a synthesis of finite cusp-like shapes. A prototype system was assembled that implement the algorithm developed in a personal computer on a pulse by pulse basis. Input pulses were obtained from the fast output of spectroscopic amplifier (Ortec 673) and was sampled using a 10-bit ADC (AD9020) operating at 50 MHz. Samples were stored in FIFO buffer and then transmitted to the PC for implementation of recursive shaping algorithms. Output of the shaper was stored in multichannel spectrum [10]. Recursive algorithm that converts a digitized exponential pulse into a symmetrical trapezoidal pulse was given. Given algorithm was implemented with the help of delay-subtract unit, high pass digital deconvolver, and digital pole-zero cancellation circuits. A prototype of trapezoidal/ triangular digital processor was designed. The differentiated signal from the preamplifier (exponential pulse) was amplified and then digitized. Digital data was deconvolved so that the response of the high-pass network was eliminated. The deconvolved pulse was processed by a time-invariant digital filter which allows trapezoidal/triangular or cusp-like shapes to be synthesized. These prototypes operate at clock speed of 50 MHz. All the parameter of shaped signals was digitally controlled [11]. A multichannel pulse height analysis system based on digital signal processing was developed and tested for nuclear spectroscopy. The system digitizes Gaussian-shaped pulses with widths greater than 2 μs. Input pulses were completely processed in real time on a single PC-AT bus board that replaces the standard analog pulse-height analyzer boards [12]. A new approach to design a single channel analyzer for high rate nuclear spectroscopy on accelerator-based X-ray absorption fine structure (XAFS) applications had been discussed. Gaussian input signal was simultaneously applied to two analog parts of circuit. In upper half, upper and lower discriminator circuit determine the energy window. In the lower half signal was passed through analog CR differentiator and zero cross detector to find out peak. Finally all the signals were combined to produce correct signals [13]. Digital gamma finder (DGF) digital spectrometer was used to explore digital processing approaches to Ge detector arrays problems. DGF-4C board was used to provide instrumentation support for gamma-ray energy tracking array project. The DGF-4C is a 4-channel all-digital waveform acquisition and spectrometer card. It combines spectroscopy with waveform digitizing and on-line pulse shape analysis. DGF-4C design contains single width CAMAC module, 4 high speed processing channels, acquisitation, control logic, a single DSP and CAMAC interface. A high speed processing channel includes analog signal conditioning, a 12-bit, 40 MHz ADC, a real time pulse processing unit (RTPU) implemented in FPGAs and a long FIFO acting as a circular buffer. RTPU unit consist component like fast filter, pulse detector, pile up inspector, discriminator and event trigger logic was implemented in a FPGAs [14]. The HPGe detector was cascaded by a simple analog section made of an active integrator and a low-pass three-coincident-pole ant aliasing prefilter. The quasi-Gaussian pulses seen at the prefilter output were sampled at 10 Ms/s. Each elaboration stage was built into a FPGAs device. The samples were stored into an n-tap circular buffer implemented in FPGAs. Pole zero cancellation, baseline and pulse measurement was performed by digital FIR and infinite impulse response (IIR) filters implemented in FPGAs [15]. A new reconfigurable hardware platform which uses both digital signal processors (DSP) and FPGA's to attain high resolution and real-time processing in nuclear spectrometry experiments was presented. The module was designed in order to provide a high digital pulse processing yield with the capacity of being reconfigurable according to the experimental conditions and the desired data output. This allows unprecedented real time processing capabilities implemented in the FPGAs such as pulse pileup correction through adaptive filtering and effective signal-to-noise ratio (SNR) control and optimization. The module uses a Virtex-II Pro FPGAs and a DSP from the TMS320C64xx family (Texas Instruments) and was implemented on a PCI board to be used in a host workstation [16]. An adaptive, self-calibrating instrument for digital spectroscopy was demonstrated. Most of the typical processing features (pole-zero cancellation, baseline restoration, and shaping) were digitally implemented and optimized on FPGAs. The main feature of the processor was the capability to self-calibrate and self optimize the configurable sections of the whole measurement setup, both digital and analog parts [17]. A digital pulse spectrometer was simulated by using Matlab/Simulink tools to demonstrate the basic principle and architecture of a digital spectrometer. The complete system was made of probe, conditioning, ADC, trapezoidal, baseline, control, histogram and timing units. Each processing unit in the whole signal processing procedure was modeled with the relevant mathematical function and simulated with the abundant tools provided in SIMULINK. The simulation was implemented with sample input including noise, and the results verified that the system was all correctly simulated [18]. Two types of 8k channel analyzer were designed for spectroscopy and intensity versus time measurements. Various parameters of these devices can be controlled externally via four user configurable logical input output lines. All the internal logic of both types of devices was embedded in Altera FLEX 10KE30 FPGAs and was fully designed using VHDL language and the QUARTUS 4.1 software [19]. Xilinx XtremeDSP development kit for Virtex-4 SX FPGA was used as a hardware prototyping platform for development of a multi-channel digital spectrometer. A four channel analog pre-filter had been designed and developed. This pre-filter includes digitally controlled differentiation, pole-zero cancellation, linear amplification and an anti-aliasing filter. Digital pulse processor was designed with the help of hardware and software tools like Xilinx Inc.'s XtremeDSP development Kit bundled with system generator for high resolution X and γ ray spectrometry. Such a digital pulse processor showed better performance than analog systems with high counting rates, and similar performance with low counting rates [20]. A portable digital signal processor for pulse height measurement was presented. It is implemented and processed using the low cost FPGAs technique. The pulse height measurement logic consists of an up-down counter, a comparator and a decoder. The pulse height processor can be use with portable spectrometer for field application [21]. Implementation of a FPGAs -based multi-channel pulse height analysis function for nuclear spectrometric measurement system was presented. Described algorithm had four main states: S0, S1, S2, S3. The UnIO52 universal data-acquisition and processing board was used for experiment. It consists of a fast 12-bit ADC delivering data with 24 MHz, a powerful Xilinx XC2S150 FPGA and a USB microcontroller to establish the communication with the PC. The calculated peak shift values for the FPGAs based device was compared to commercial add-on MCA card. The results show a better performance because the shifting was almost the same for large range of the count rate. It was also concluded that numerical technique can be used as an alternative solution for standard design using analog discrete chip technology [22].

III. CONCLUSION

In conclusion, the paper first reviewed the standard pulse processing analog circuitry which is still today a very important and crucial component of any analog and digital signal processing systems. But in analog circuitry hardware manipulation is necessary to adjust the measuring parameters which is either not possible all the time or difficult. At the same time analog system relies on resistors, capacitors and inductors; its stability is limited to their tolerance. It is also not very easy to implement mathematical algorithms on analog systems. In addition, as a compact alternative to bulky analog electronics, digital processing is of great benefit in many applications. Digital signal processing systems are flexible and easily upgradable. Digital signals can be easily stored on storage media. It is easy to implement mathematical algorithms and performance is also exactly repeatable. Then we reviewed the systems which were based on microprocessors. It is important to note that analog component reduced but still it exists in the processing chain. In some systems detector signals are directly applied to fast analog to digital converters and than complete processing were done by either microprocessor or by digital signal processors equipped with suitable pulse processing algorithm. In the last ten years one of the most far-reaching developments in digital electronics has been the introduction of PLDs. PLDs are superior alternative to traditional analog electronics in terms of throughputs and flexibility. Today's state of the art hardware and software tools for digital circuit can greatly improve and speed-up development of a high performance digital spectrometer. Emerging high level hardware description and synthesis technologies in conjunction with FPGAs have significantly lowered the threshold for hardware development in the field of nuclear physics.

ACKNOWLEDGMENT

Authors are thankful to the Head, Dept. of physics, University of Mumbai, for providing necessary facilities and one of the authors Amitkumar singh is thankful to Shri Jitendra Singh, Trustee, Thakur college of Science and commerce, Kandivali (E), Mumbai, for providing all his encouragement, and support.

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