Digital Pulse Processing: A New Paradigm For Nuclear Instrumentation

R. V. Ribas

LAFN – Laboratório Aberto de Física Nuclear
Instituto de Física, Universidade de São Paulo – CP 66318-970 São Paulo, SP - Brazil

Abstract. In recent years, we have seen an impressive increase in the use of digital pulse processing in substitution of standard analog electronic modules for nuclear physics instrumentation. The main advantages of the new standard are compactness, no additional noise after digitization of the pre-amp signal, reliability (no cables and connectors), and possibility of easily reproducing the same tuning set up. Also, it opens new possibilities of pulse shape analysis, not possible with standard analog electronics.

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INTRODUCTION

High speed, precise analog to digital converters are now available at relatively low cost, the same occurring with devices known as FPGA – Field Programmable Gate Arrays. These developments have facilitated the development of a new kind of data acquisition and pulse processing for nuclear physics experiments, for which the pre-amp pulse is the first and last analog signal, followed only by digital signals. These new systems are already in production by the related industry, mainly for simple and specific applications, but it is the possibility to be used with very complex systems that gave a large impulse to their development. In low energy nuclear physics, for instance, new detecting systems now being planned, such as the gamma-ray spectrometers GRETA [1] in the US and AGATA [2] in Europe, will have their pulse analysis and data acquisition based on this new technology. In these systems, a flash ADC (Analog to Digital Converter) samples the pre-amplifier pulse at a a rate of 100 million per second, with 12-14 bits of precision. Every pulse will then produce about 1-2K samples. All the pulse processing usually performed by analog devices, such as spectroscopic amplifiers, fast amplifiers, constant fraction discriminators, etc. is now performed digitally, after the sampling of the pre-amp pulse. A large part of this processing is done in the FPGA devices, with a continuous flux of about 20-40 Mbytes per second. Several FPGA can work in parallel to process the large number of channels, normally necessary in these systems. We are now learning, testing and evaluating a simple system using this new technology, in order to develop a system for future use in our laboratory.
NIM ELECTRONICS

The standard electronics for nuclear instrumentation is defined in the Nuclear Instrumentation Modules norm, established by the US Nuclear Energy Commission in 1968-69 and revised in 1990. Besides mechanical, dimensional and power supply characteristics, the norm establishes also the levels for logical signals, connectors, impedance, etc. The functions and design of the modules are free, but the norm does not predict any kind of numerical control for the modules. The analog modules mostly used in standard nuclear electronics are those designed to recover the energy and time of occurrence of the detected radiation. Spectroscopy amplifiers shape and amplify the standard pulses produced by charge sensitive pre-amplifiers used with semiconductor detectors, producing, in general, Gaussian-like pulses, whose amplitudes are proportional to the energy collected in the detector. Several techniques have also been developed in order to recover the instant of time in which the radiation was detected. The most popular and precise is the constant fraction discrimination or its variations. The design of such modules is, in general, not an easy task, giving the necessity of stability, low noise, linearity, etc.

Besides the analog modules, several others are also of common use for logically relating pulses coming from different detectors in an event. Even with the compactness achieved in NIM modules in recent decades, the increase in complexity of the detecting system in use in this same period, makes practically impossible to rely only in this norm to build the necessary electronic pulse treatment. Several other standard have been defined in order to attain more compact and flexible control of the electronics. CAMAC, VME, VXE [3,4] are new norms used in conjunction with the old ones at the present time. These improvements are mainly in the configuration, control and digitalization of the signals (data acquisition). The basic technology of pulse processing remained analog as in the NIM standard.

DIGITAL SIGNAL PROCESSING

The impressive evolution in digital electronics, in particular for the fast digitalization of analog signals has led companies to develop a series of technologies that are present in many facets of common day life. From the digital music CDs of the early 80's of the last century, to video and photo, telecommunications, medical imaging, satellite weather forecast, and radar are typical examples of the technological revolution brought by the advent of digital signal processors. Not only the flash ADCs are responsible for these new technologies. Dedicated and very fast, efficient processing devices, like digital signal processors (DSP) and FPGA are also important players in this field. In low energy nuclear physics, new detector technology developed mainly in the last decade required the use of these new devices to take advantage of new developments. For example, in gamma-ray detection, the so called segmented germanium detectors [1,2] were developed in order to provide a way to deal with two main limitations of the earlier detectors: to correct for the large Doppler effect in the detected radiation due to the recoil velocities of the emitters, and to discriminate events produced only by Compton interaction from those for which all of the photon energy is deposited in one or more detectors. In large, present day detecting systems,
these two limitations are partially avoided, by placing the detectors at a large distance from the reaction target and surrounding them in a large mass of scintillator detectors, with the sole function of detecting and discarding Compton events in the inner detector. In this configuration, a large part of the available solid angle for the detectors is occupied by void and scintillator material. The new segmented detectors can be placed much closer to the target and no anti-Compton scintillators are needed, since neighboring Ge detectors may function as an ensemble of mini anti-Compton suppressors. The Doppler effect can be taken into account, by position determination of the primary interaction. This is possible not only by the electrical segmentation of the Ge crystal, but mainly by the detailed shape analysis of the pulses generated in the segments involved in an interaction and by the charge fluctuations in the neighboring segments. Digital Pulse Processing (DPP) is the technology that makes this possible.

**FPGA**

Field Programmable Gate Arrays are a key device for implementing these filtering and processing functions. These are basically a very large array of logical elements (gates) arranged in logic cells, RAM memory blocks, adders and multipliers, that can be interconnected by a series of software instructions. Basically acting as state machines, processing continually - serially and in parallel, these devices permit a very fast analysis of the incoming signal. High level programming languages like VHDL and Verilog (both known as hardware description languages) are available to setup the wiring of the thousands of elements of an FPGA chip. Several FPGA can be synchronized using a single clock source in order to have the necessary throughput for a large number of simultaneous signals.

**DIGITAL EQUIVALENT OF NIM MODULES**

The DPP of the detector signal starts with the digitalization of the pulse at the output of the pre-amplifier. Usually, some signal conditioning is necessary, mainly to eliminate possible fast transients in the pulse, in a time scale that is not compatible with the Nyquist-Shannon sampling theorem (anti-aliasing filter). High-resolution (12-14 bits), fast (40-100MSPS) flash ADCs are employed for this, with about 1-2K samples are taken for each pulse. The typical pulse processing done by an analog amplifier, such as CR-differentiation of the pre-amplifier pulse, in order to get rid of its long exponential tail, followed by two or more RC integrations, may be performed numerically and easily, but new filtering techniques have been developed for this to great advantage [5,6,7]. Also, fast filtering of the digitalized signal can be done, in particular to treat pile-up signals. The digital equivalent of the CFD can also be performed in a DPP system. Other functions implemented in analog modules, such as base line restoration, pole-zero cancellation and pileup rejection can also be implemented digitally.
Energy Recovering

The most typical pulse filtering in analog spectroscopy amplifiers can be simply achieved as a recursive filter in digital systems from the basic relation [8]:

\[ y[n] = a_0 x[n] + a_1 x[n-1] + b_1 y[n-1] \]

If we chose \( a_0 = (1+x)/2 \), \( a_1 = -a_0 \), \( b_1 = x \), a CR differentiation is performed. For \( a_0 = 1-x \), \( b_1 = x \), \( a_1 = 0 \), we get an RC integrator. The parameter \( x \) is related to the time constant of the filter (RC in the analog version). These techniques are seldom used in digital pulse processing. In general two or more integration steps are necessary to get rid of the long exponential tail of the input signal. Two other techniques, the trapezoidal filter [6] and the moving window deconvolution (MWD) [7] are much more convenient for this function. A simple trapezoidal filter can be realized by the following operations in the input samples:

\[ y[n] = y[n-1] + (x[n] + x[n-2m-k]) - (x[n-m] + x[n-m-k]) \]

This will lead to an undershoot of the pulse, as seen in Fig. 1a. This is not critical for low counting rates, but must be corrected if piled up pulses are to be considered [6,7].

![FIGURE 1. (a) Trapezoidal filter. (b) Moving Window Deconvolution. In both figures, the dashed curve corresponds to the operations before deconvolution.](image)

Similar to the trapezoidal filter, the MWD technique for recovering the radiation energy is performed in a sequence of two operations:
\[ y[n] = x[n] - x[n-m] \text{ (the moving window)} \]

\[ z[n] = y[n] + S \cdot f \text{ (deconvolution)} \]

where \( S \) is the sum \( y[0]+y[1]+...+y[n-1] \). Fig. 1b) shows the MW part in blue and the final result, after deconvolution in red.

**Timing**

A very simple differentiation is sufficient to produce a leading edge time mark, as shown in Fig. 2. The constant fraction discrimination can also be performed digitally with very simple operations:

\[ y[n] = x[n] - x[n-k] \]

\[ l[n] = y[n] + y[n-2] + 2y[n-1] \text{ (leading edge)} \]

\[ c[n] = l[n-k] \cdot f - l[n] \text{ (constant fraction)} \]

**FIGURE 2.** Timing signals produced from the preamplifier pulse. Typically the time interval between the dots is 10 ns.

The leading edge discrimination is normally used as an early trigger of events. Multi input systems usually have a common source of clock for all modules. In this way, an absolute time stamp for each signal in the event can be produced.
EVALUATION AND DEVELOPMENT

Several DPP system have been developed and are already in use or evaluation [9,10,11]. A few are also available in the market [12,13,14]. For beginners, there are many options of FPGA boards, with standard interface to computers (serial port, USB) that can be used for evaluation, learning the HDL languages, and also producing simple acquisition systems. We use one from KNJN [15] that is very convenient, since they also produce compatible flash-ADC boards. These are 8 bit (100 MHz) converters, with up to four ADCs in one board. Even if 8 bits are not sufficient for most applications in nuclear physics, such boards may be used in a few cases and are very interesting for testing and learning, specially for the affordable prices. Most of the FPGA makers, such as Altera and Xlinx also provide free programming software for their devices.

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