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Comparative analysis of digital pulse processing methods at high count rates

J. Kamleitner *, S. Coda, S. Gnesin, Ph. Marmillod

École Polytechnique Fédérale de Lausanne (EPFL) – Centre de Recherches en Physique des Plasmas, Association EURATOM – Confédération Suisse, CH-1015 Lausanne, Switzerland

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ABSTRACT

An extensive study of digital pulse processing methods is presented. Existing methods, both traditional and more recent, are compared with original advanced techniques within an appropriate modeling and benchmarking framework. This comprehensive approach ensures general applicability to the broad field of pulse processing, even though the focus lies on hard X-ray spectrometers operated at high count rates. In this regime, pile-up is the main issue and the individual pulse shape characteristics play a minor role, although they remain important for the algorithm parameter optimization.

The digital implementation of double-differentiating analog filters and trapezoidal FIR filter methods results in excellent performance that is second only to that of optimum digital FIR filters. Several more complex methods involving increased computational effort are found not to meet the expectations.

1. Introduction

A novel hard X-ray tomographic spectrometer (HXRS) apparatus [1,2] is being developed for TCV, an experimental nuclear fusion device of the tokamak family [3]. It uses (2 mm)^3 cube CdTe detectors to measure photons with energies of 10 keV to over 300 keV. The detectors are followed by fast integrators that act as charge collectors, the charge being proportional to the impinging photon energy. The pulses have a characteristic rise time of 400 ns, and the integrators are discharged with a decay time of 4 μs. The collected signal is amplified to the digitizer range and acquired at 12M samples/s.

The detection and analysis of the single photons from these time traces is a challenging task at the desired high count rates of several 100 kcps (counts-per-second) and in view of the significant noise level of a tokamak experiment environment.

To find the best-suited algorithm for the specific HXRS requirements, several standard and advanced pulse processing techniques have been implemented. The accompanying algorithm benchmarking suite was deliberately designed with broad flexibility, permitting a general study of the pulse detection and analysis problem at high count rates that transcends the specific requirements of the HXRS system. The results of this study are reported in this paper.

1.1. Analog versus digital pulse processing

Practically every particle counting spectrometer consists of an analog and a digital part with an analog to digital converter (ADC) in between. In analog pulse processing the digital part only performs a histogram. This was the only solution available till the early 1990s, when digital systems became fast enough to restrict the analog part to the charge collection and preamplification. In the latter scheme, the preamplified signal is directly sampled by a high-resolution ADC that records the time history of each individual pulse, and the pulse processing is performed digitally, either by hardware or by software [4]. In the transitional period, when the performance of digital processors was still relatively low, hybrid systems were also used, in which a digital signal processor (DSP) was triggered by an analog pulse height analyzer (PHA) [5].

The main advantages of analog pulse processing lie in robustness, decades of experience and low cost as compared to digital systems. With some additional effort even the pulse shape can be used to a certain extent to aid the pulse recognition, for instance to discriminate between particle types [6].

Nowadays digital pulse processing is used in commercially available spectrometers [7] as well as in highly specialized applications such as spacecraft [8] and magnetic confinement fusion experiments [1]. The available digital solutions continuously decrease in cost and increase in processing speed and storage, enabling real-time applications as well as storage of the entire time traces acquired. Since the shape of each pulse is

* Corresponding author. Tel.: +41 216935129.
E-mail address: josef.kamleitner@alumni.tuwien.ac.at (J. Kamleitner).

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known, it can be used to extract more information than just the height of the pulse. Therefore the pulse processing algorithms can be optimized with respect to the pulse characteristics, for instance for neutron - gamma discrimination [9] or to detect the incident position of the particle within a detector [10] and use this information to improve the determination of the particle energy [11].

Furthermore, the time and energy of each detected pulse are available. This allows one to freely choose time and energy bins after the measurement and subsequently to use advanced analysis techniques such as conditional averaging: this is very effective in particular in tokamak diagnostic applications to analyze randomly repeated events such as sawtooth crashes [2].

1.2. Existing techniques

In analog pulse processing the preamplifier signal is shaped by a shaping amplifier. This can be realized either as a single or a double delay line (SDL, DDL) or as a combination of m differentiating (CR) and n integrating (RC) circuits ($(\mathrm{CR})^m(\mathrm{RC})^n$ filter). In addition, tail (pole-zero) cancellation and baseline restoration are regularly applied to improve the signal properties further. Finally the signal is evaluated using a peak-sensing ADC and the detected pulses are digitally stored in a histogram [12].

In digital pulse processing the same analog techniques can be implemented digitally [13]. However, a large variety of additional methods can also be used, comprising more sophisticated techniques that take the whole time history and pulse shapes into account. Typical such techniques are digital finite and infinite impulse response (FIR and IIR) filters [14,15], cross-correlation [16,17] and least-squares difference [18] to template pulses, neural network pulse recognition [19], wavelet transform [20,21] and support vector machine (SVM) pulse sorting [22].

1.3. Outline

The implementation framework of the pulse processing algorithms will be briefly discussed in Section 2. The algorithms are then described in detail in Section 3. The specification of the benchmarking methods in Section 4 is followed by the discussion of the algorithms' performance in Section 5. Finally, conclusions will be drawn in Section 6.

2. Digital implementation

Although a very wide range of different pulse processing algorithms is compared, a large fraction of these algorithms shares the use of a few fundamental steps in the data analysis. This allows not only the implementation of a general framework for data input/output (I/O), storage and benchmarking, but also a generalization of the algorithm implementation itself. This in turn makes it possible to study more algorithms with little additional effort and facilitates their comparison. The common basic steps are, namely, signal treatment, pulse detection (PD) and pulse height analysis (PHA). These components are individually presented in the following. Nonetheless, the implementation can be kept flexible enough to treat algorithms that can be only partially or not at all resolved by this sequence of steps or that require additional post-processing.

For all presented algorithms, the signal treatment, PD and PHA methods are listed in Table 1.

2.1. Signal treatment

The signal treatment processes the raw data to provide an input for the pulse detection and analysis. It keeps the signal's original sampling rate and is often realized by the application of filters. Usually the signal treatment is the same for the pulse detection and pulse height analysis, although there are also a few methods where the signal treatment for analysis differs from that for detection. Since most pulse processing algorithms share the same or similar detection and analysis methods, their main differences lie in the signal treatment. Therefore, the signal treatment parts play the main role in characterizing a pulse processing method.

Table 1
List of signal treatment, pulse detection and PHA methods for all presented algorithms.

Algorithm	Detection		Analysis	
Abbreviation	Signal treatment	Pulse detection	Signal treatment	PHA
Trpz2	Trpz2	Dynamic threshold	Trpz2	Level evaluation
Trpz1a	Trpz1a: $n_r = n_d = 4$	Dynamic threshold	Trpz1a: $n_r = n_d = 4$	Level evaluation
Trpz1as	Trpz1a: $n_r = n_d = 3$	Dynamic threshold	Trpz1a: $n_r = n_d = 3$	Level evaluation
Trpz1	Trpz1	Dynamic threshold	Trpz1	Level evaluation
Trpz	Trpz	Dynamic threshold	Trpz	Level evaluation
CC-LMS	CC	Dynamic threshold	LMS	Level evaluation
LMS	LMS	Dynamic threshold	LMS	Level evaluation
$(CR)^2(RC)$	$(CR)^2(RC)$	Dynamic threshold	$(CR)^2(RC)$	Level evaluation
$(CR)^2(RC)^4$	$(CR)^2(RC)^4$	Dynamic threshold	$(CR)^2(RC)^4$	Level evaluation
$(CR)(RC)^4$	$(CR)(RC)^4$	Dynamic threshold	$(CR)(RC)^4$	Level evaluation
$(CR)\ (RC)$	$(CR)\ (RC)$	Dynamic threshold	$(CR)\ (RC)$	Level evaluation
CIS	Digital band-pass	CIS – rise threshold	Digital band-pass	Rise evaluation
PSD	MA filter	Multiple condition	MA filter	Rise evaluation
Canny	Canny	Dynamic threshold	Canny	Level evaluation
SDL	SDL	Dynamic threshold	SDL	Level evaluation
DDL	DDL	Dynamic threshold	DDL	Level evaluation
opt1na	Optimum filter 1	Dynamic threshold	Optimum filter 1	Level evaluation
opt2na	Optimum filter 2	Dynamic threshold	Optimum filter 2	Level evaluation
opt3na	Optimum filter 3	Dynamic threshold	Optimum filter 3	Level evaluation
opt4na	Optimum filter 4	Dynamic threshold	Optimum filter 4	Level evaluation
i-500 kcps	Idealized algorithm, detects all pulses spaced by ≥ 2 µs correctly			
i- 1 Mcps	Idealized algorithm, detects all pulses spaced by ≥ 1 µs correctly			
i-2 Mcps	Idealized algorithm, detects all pulses spaced by ≥ 500 ns correctly			