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Trigger-less and reconfigurable data acquisition system for positron emission tomography

Abstract: This article is focused on data acquisition system (DAQ) designed especially to be used in positron emission tomography (PET) or single-photon emission computed tomography. The system allows for continuous registration of analog signals during measurement. It has been designed to optimize registration and processing of the information carried by signals from the detector system in PET scanner. The processing does not require any rejection of data with a trigger system. The proposed system possesses also an ability to implement various data analysis algorithms that can be performed in real time during data collection.

Keywords: DAQ; FPGA; PET; trigger.

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Introduction

Positron emission tomography (PET) constitutes one of the most advanced diagnostic methods allowing for noninvasive imaging of physiological processes occurring in living organisms. This technique uses radioactive substances that are administered to the patient in the form of radiopharmaceuticals. PET detectors enable registration of γ quanta resulting in the annihilation of positrons emitted from the radioactive isotopes constituting part of the metabolized radiopharmaceuticals. The registration of γ quanta enables reconstruction of the density distribution of annihilation points and hence the concentration of radiopharmaceuticals in the body of the diagnosed patient. The map of such concentration reflects the metabolic rate of the specific substance administered to the patient.

PET scanners consists of plurality of scintillator detectors, electronics, data acquisition system (DAQ), and computing devices [1]. They allow to measure and elaborate signals based on their time and charge to reconstruct the density distribution of points of annihilations in the patient. Light pulses from scintillators are converted into electric signals by photomultipliers or photodiodes. At the first stage of signal processing, a trigger system selects events according to the desired criteria, and then in the next step, the time and charge of signals are measured by means of time-to-digital converter (TDC) and analog-to-digital converter (ADC) modules that convert them into digital values constituting the basis for image reconstruction. Collection of data and the control of measurement devices operation are done by the DAQ, which works in conjunction with trigger unit. There are many solutions for triggering units, such as the one described in the U.S. patent 8,164.063 [2], which introduces an advanced triggering system that makes decisions on several levels about the current processed event data. It can be done either by looking at the measured data patterns or by checking some coincidence events, meaning that several detector channels have fired in a specified period of time. An example of another approach is described in U.S. patent 7,091,489 [3] presenting a dedicated coincidence processor.

In this article, we describe a DAQ that allows a continuous processing, registration, and transmission of digital data without the need of a trigger system.

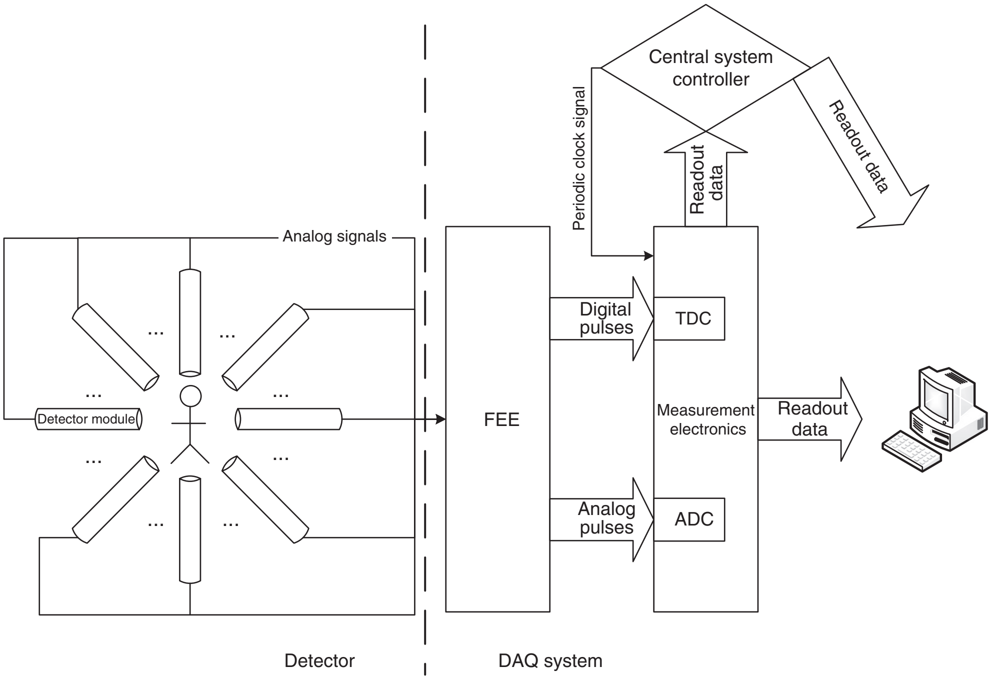

Figure 1 Schematic illustration of the entire detector system including DAQ components and showing the data path.

Materials and methods

A DAQ described below (Figure 1) allows for continuous registration of data collected during a PET or single-photon emission computed tomography (SPECT) scan [4], giving the possibility to process and save basically all events without any loss.

The DAQ system consists of front-end electronics (FEE) and TDC and ADC used for the conversion of the analog time and charge information to digital values and from the central system controller that sends periodic clock signals to the converters. By configuring the electronics in a way that a single measurement takes exactly the same amount of time as a period between two consecutive readouts (Figure 2), it is possible to process practically all the events that have been registered by detector modules and save them for further analysis. This technique is especially efficient in the case of PET modalities based on polymer scintillators [5], wherein response for a γ quanta hit is very short (~10 ns). This is an order of magnitude shorter than response of nonorganic scintillating crystals used presently in all commercial PET scanners.

In order to measure the arrival time of signals, high-precision TDCs are being used. The result of a single measurement on one channel is a digital value that represents time difference between the edge of the input and the clock signal generated with a fixed frequency by the central system controller.

For TDCs, a newly developed TRBv3 (GSI Helmholtz-zentrum für Schwerionenforschung GmbH, Darmstadt, Germany) (Figure 3) board has been selected [6]. It is a high precision and high channel density, field programmable gate array (FPGA)-based TDC readout board used in high-energy physics. The board consists of five lattice ECP3 FPGA (Lattice Semiconductor, Hillsboro, OR, USA) devices [7]. Four of them run firmware that features TDC functionality and the fifth one acts as a controller, data hub, and Gigabit Ethernet bridge of the other four. The controller FPGA has also an ability to communicate with the central system controller via optical links, each capable of reaching 3.2 Gbps bandwidth. Each of the TDC FPGAs [8] is able to readout 32 input channels with resolution

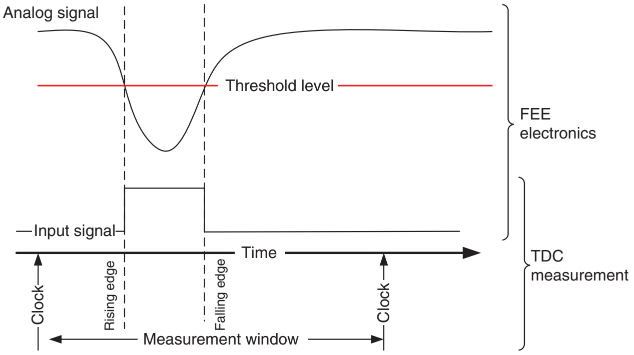

Figure 2 Example of clock signal and input signal measured by TDC.

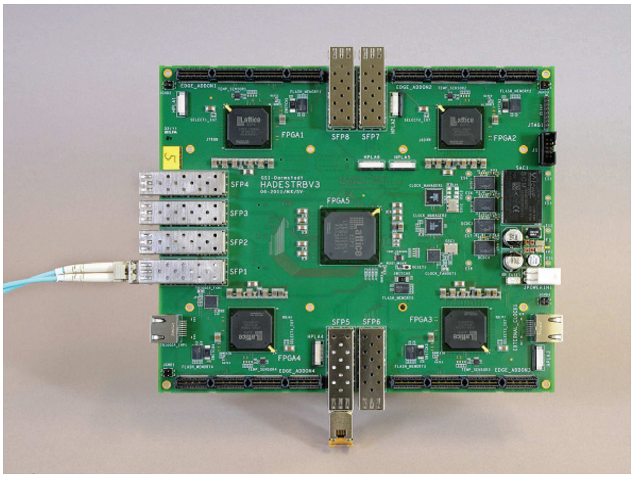

Figure 3 TRBv3 board presenting four edge FPGAs used for time measurement and the central, controlling FPGA.

of 10 ps, rising and falling edge separately and multihit registering, with 5 ns dead time between two consecutive hits. Collected data can be transmitted directly to the PC or through the central system controller. As communication protocols, low-level 8b/10b encoding has been used together with Gigabit Ethernet.

The TDC modules require a trigger that will act as a start signal for registering incoming analog pulses from FEE and convert them into a series of digital values, representing time elapsed since the trigger signal. The period during which those impulses are properly handled by TDCs is configured as time difference between two trigger signals and is called measurement window. FPGA devices have the advantage of parallel processing, which allows to collect new samples and transmit the ones collected in the previous measurement window concurrently. In that way, the dead time between two consecutive clock signals can be omitted and one can assume that the entire measurement is realized in a continuous manner.

The central system controller consists of a FPGA-based board, having a large Xilinx Zynq FPGA (Xilinx, Inc., San Jose, CA, USA) [9]. Zynq, which is a hybrid consisting of standard FPGA logic resources and also of a hardware, built-in ARM processor, represents a System-on-Chip approach. That chip has been chosen in order to assure possibility of implementing algorithms that can analyze and process data coming in real time from the TRBv3 boards. These algorithms can be used as a support for online monitoring of the ongoing measurement or as providers of additional information for offline analysis. The trigger signal for TDC modules is precisely generated by the FPGA using dedicated hardware circuitry. It provides a wide range of frequencies as the output based on fixed frequency input signal from the quartz oscillator located on the printed circuit board (PCB). Such a module, called the Digital Clock Manager, allows to dynamically tune and change the clock frequency if needed. Such possibility can be very helpful during the process of calibration of PET scanner. The output signal, adjusted to a wanted frequency, is then distributed to TRBv3 boards by twisted pair cabling in LVDS standard, which diminishes the risk of registering random noise as a real signal. Additionally to the raw electric signal, the central system controller is able to send more complex information through optical connections to all the readout modules, in this case, TRBv3 boards. Such information can contain consecutive clock numbers and some control values in order to assure the integrity of the entire readout and the correct sequence of the incoming data.

Discussion and conclusions

The trigger-less DAQ has been described for the readout of polymer scintillating detectors that are part of PET being presently developed by the J-PET collaboration. The described solution has the advantage over other systems by the continuous registration of generated signals and by giving the possibility of running real-time analysis algorithms on gathered data. The electronics being based on FPGA devices can be easily reprogrammed, introducing new algorithms, improvements, or system updates, even in the final PET device.

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Conflict of interest statement

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