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A scalable FPGA-based digitizing platform for radiation data acquisition

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ABSTRACT

Regulating the proliferation of nuclear materials has become an important issue in our society. In order to detect the radiation given off by nuclear materials, systems implementing detectors connected to data processing modules have been developed. We have implemented a scalable, portable detection platform with a data processing module about the size of an external DVD drive. The data processing component of our system utilizes real-time data handling and has the potential for growth and behavior modifications through custom FPGA code editing. The size of our system is dynamic, so additional input channels can be implemented if necessary. This paper presents a scalable, portable detection system capable of transmitting streaming data from its inputs to a PC or laptop. The system also performs tail/total integral pulse shape discrimination (PSD) in real time on the FPGA to filter the data and selectively transmit pulses to a PC. The data arrives at the inputs of the data capturing module, is processed in real time by the onboard FPGA and is then transferred to a PC or laptop via a PCIe cord in discrete packets. The maximum transfer rate from the FPGA to the PC is 2000 MB/s. The Detection for Nuclear Non-Proliferation Group at the University of Michigan will use the detection platform to achieve pre-processing of radiation data in real time. Such pre-processing includes PSD, pulse height distributions and particle times of arrival.

1. Introduction

Digitizing of discrete, fixed length data pulses from organic scintillation detectors allows for the determination of the types of particles being emitted by a certain material. This knowledge in turn reveals information about the type of material under examination. We are using a four-channel, 250 MHz analog-to-digital data detection platform from Innovative Integration [1] that is scalable in sample rate and number of channels, portable and reprogrammable. In this paper, we focus on the advantages of using an FPGA-based digitizer for such data detection platforms. This system is being developed for nuclear non-proliferation measurements that will employ multiple organic scintillation detectors.

2. Scalable measurement platform

The scalability of our data capturing platform is beneficial in case there is ever a need to correlate times of pulse arrivals from multiple detectors, or if multiple data sources need to be processed at the same time. The system is expanded by adding PCIe slots on the PC or laptop, and adding more data processing modules that are time-synchronized through an external cable. The X5-210 module connects to the back of a PC or laptop through a PCIe expansion card, so additional PCIe slots can be added to accommodate multiple modules. A layout of the system is shown in Fig. 1. By adding more modules, more channels can be included and so streaming data from additional sources can be processed. The dimensions of the FPGA-based data processing module are $28.5 \times 106 \times 160\ \mathrm{mm}^3$, which make transportation of the system easier.

Fig. 2 shows pictures of components in our setup. The radiation source emits particles into the scintillation detector, which in turn sends an electrical signal to the X5-210m digitizer for processing.

3. FPGA architecture

A key component of this system is the Virtex 5 FPGA [2] housed inside the Innovative Integration X5-210 module [1]. A block diagram of the FPGA architecture is shown in Fig. 3.

This FPGA processes the incoming Analog-to-Digital Converter (ADC) data stream and can be programmed to implement custom pre-processing on the data. Programming of the FPGA is accomplished through the editing of source pages written in Verilog and VHDL (Hardware Description Languages). The ability to adjust the data processing procedures on the FPGA is highly advantageous in multiple ways. Calculations usually performed on the data pulses

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after they have been recorded can be done in real time on the FPGA as the data is streaming in. This significantly reduces the overall time required for processing pulses. Furthermore, pulses can be cleaned (e.g. remove clipped signals, etc.) and the appropriate information extracted (e.g. gamma/neutron discrimination, pulse height, etc.) on the FPGA, eliminating the need to transmit raw pulse data to the PC entirely. For example, for tests recording pulse data, we typically use around 1 TB of storage space on the PC for acceptable statistical analysis. Pre-processing on the FPGA can reduce this by nearly 100 × , which is much more manageable.

As data streams from the ADC channels, the data values are synchronously compared to a programmable trigger threshold value at a rate of 250 MHz and when the input values achieve the user-specified comparison, a trigger event occurs and data capture begins. The data acquisition rate is limited by three factors: (1) the memory on the FPGA module is 512 MB of DRAM and 4 MB of SRAM, (2) transfer rate over the PCIe link from FPGA to PC of 2000 MB/s and (3) Memory on the PC [1]. The number of data samples to be captured every trigger event is user-specified.

When a trigger event occurs, if we began capturing the incoming data at that exact moment in time, we would miss the beginning of the overall waveform. Therefore, in order to capture the entire waveform, we implement a pre-trigger on the FPGA that buffers the incoming data for a programmable number of samples (ΔT). In this manner, when a trigger event occurs, the start time of the data acquisition becomes the trigger time minus the pre-trigger interval ΔT.

A software program on the PC side created by Innovative Integration [1] allows the user to specify parameters related to data streaming, such as how much data to capture, the manner in which the X5-210 digitizer should trigger (whether from software or hardware), the trigger threshold, etc. Through, this software program the user is able to write numeric values to registers on the FPGA over the PCIe link. These register-stored values are in turn used in custom logic programmed on the FPGA. For example, the trigger threshold value used to mark the beginning of data capture is written to a certain register on the FPGA via this program.

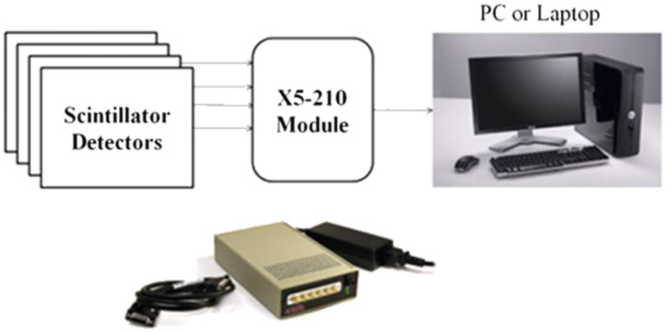

Fig. 1. Overall data capture system.

Every trigger event, a specified number of samples (usually 256) is captured and sent to the PC or laptop. The first 100 samples of the waveform associated with each trigger event are actual data samples recorded from the ADC input channel. We reserve 20 data samples for information specific to the pulse window in a footer. The footer information includes which of the four channels triggered, a timestamp of the trigger event, the total and tail integral of the pulse, a bit indicating whether or not the pulse is clipped at the limit of the input range, two bits indicating the result of a pulse shape discrimination comparison, plus supplementary, unused bits available for future expansion and debugging. The structure of data for each pulse waveform is shown in Fig. 4. In the software on the PC, these footer samples are treated as recorded data samples that arrived at the ADC inputs, but in reality they contain custom information of our choice. After all the data is saved on the PC, we use custom software to strip off the footer

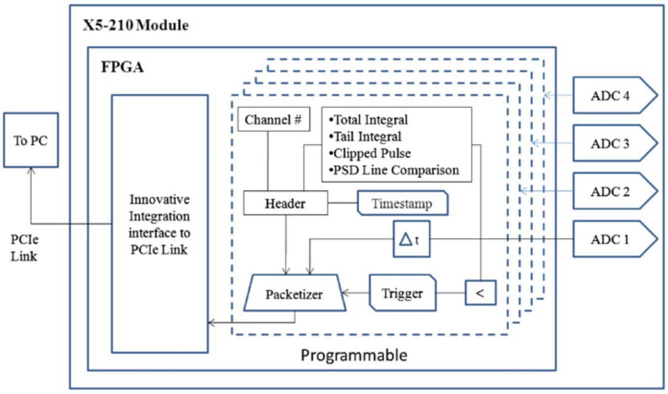

Fig. 3. FPGA architecture.

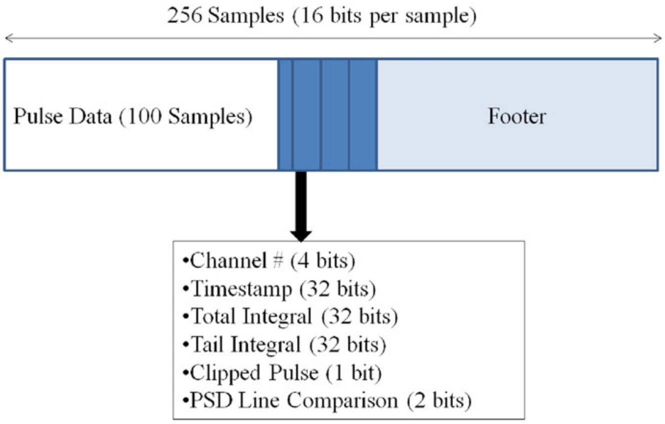

Fig. 4. Pulse data structure.

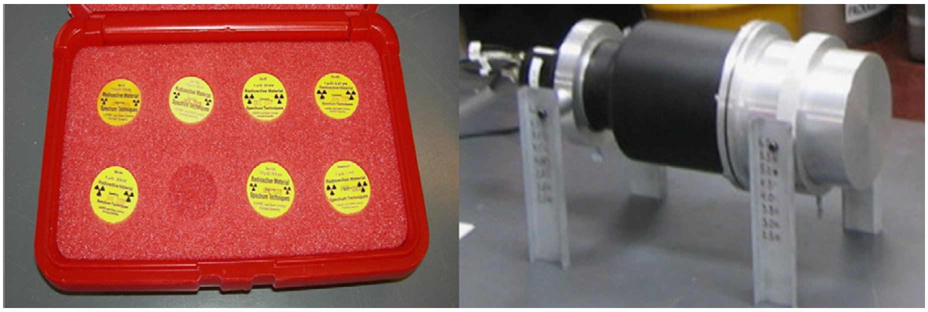

Fig. 2. Radiation sources (left) and standard liquid scintillation detector (right).

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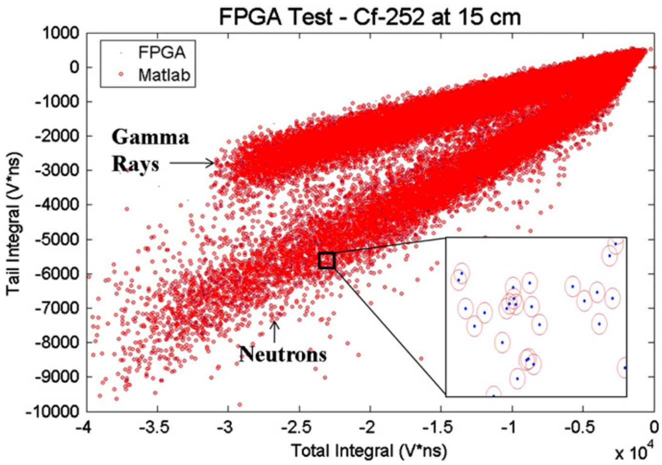
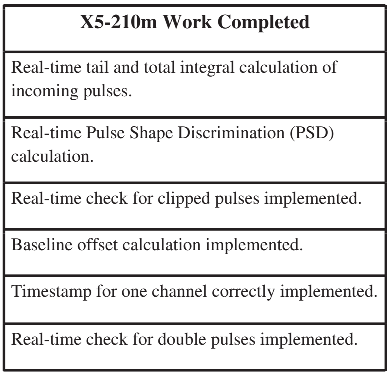


Fig. 5. FPGA measurements.



X5-210m Work Completed
Real-time tail and total integral calculation of incoming pulses.
Real-time Pulse Shape Discrimination (PSD) calculation.
Real-time check for clipped pulses implemented.
Baseline offset calculation implemented.
Timestamp for one channel correctly implemented.
Real-time check for double pulses implemented.

Fig. 6. Summary table.

information and perform additional post-processing on the pulses. For example, Fig. 5 shows a plot of tail and total integrals calculated by the FPGA in real time and transmitted to the PC in the footers, overlaid by the same plot of tail and total integrals calculated in Matlab on the pulse data after the pulses had been captured.

A clear distinction can be seen between neutrons and gamma rays in Fig. 5 of the tail-to-total integrals of captured waveforms. These measurement results were obtained with a Cf-252 source placed 15 cm from an EJ-309 liquid scintillation detector. Neutrons produce larger tail integrals than gamma rays, which can be clearly seen in the plot. The measurement threshold was set to 80 keVee (keV electron equivalent).

The algorithm on the FPGA used to distinguish between neutrons and gamma rays (whose result is stored in the footer of the pulse waveforms) checks if the tail integral is less than $(a \times \text{total} + b)$, where a and b are linear line coefficients. This line intersects directly between the neutron and gamma ray clusters (shown in Fig. 5), so if the tail integral is above this line for a given total integral, the pulse is marked as a gamma ray, otherwise it is marked as a neutron.

4. Conclusions

The final goal of this work is to pre-process liquid scintillator detector data in real time through custom modifications to the FPGA for the purpose of identifying special nuclear materials. A summary of all of the work completed on this platform is shown in Fig. 6. Some of the applications stemming from the ability to identify special nuclear materials include nuclear non-proliferation, safeguards and national security. Using such a detection system in airports and coastal shipping ports to screen the movement of nuclear materials into and out of the country could be one of the most direct applications of this data detection system. Special nuclear materials emit radiation and so our detection platform would be able to detect these materials.

Acknowledgement

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