Development of an FPGA-based Data Acquisition module for Small Animal PET

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Abstract—We report on the design of a DAQ module for a small animal PET camera developed at our institutes. During the design an important guideline was to develop a system which is built up from strictly identical DAQ modules, and which has no built-in hardware limitation on the maximum number of modules. The developed DAQ module comprises of an LSO scintillator crystal block, a position sensitive PMT, analog signal conditioning circuits, a digitizer, an FPGA for digital signal processing and a communication module through which the collected data is sent to a cluster of computers for post processing and storage. Instead of implementing hardware coincidence detection between the modules we attach a precise time stamp to each event in our design, and the coincidence is determined during post processing by the data collecting computers. The digital CFD algorithm implemented in the FPGA gives a time resolution of 2 to 3 ns FWHM for real detector signals.

I. INTRODUCTION

Laboratory experiments on small animals are one of the most suitable ways of testing the newly developed PET radiopharmaceuticals in vivo. Conventional PET cameras, however, are not suitable for small animal experiments as their 3D resolution (about 4 to 5 mm) is much worse than it is minimally required (about 2 mm). To meet such demands special small PET cameras (miniPETs) are developed that can be used for investigating small animals, like mice or rats.

Our contribution will show the design of the detector modules developed at our institutes, which is used in such miniPET cameras, and will describe the initial test results of the system.

II. THE DESIGN

During the design of the data acquisition (DAQ) module we had scalability in mind. We wanted to design a module that can be multiplied without modifications to form a PET ring, and which has no built-in hardware limitation on the maximum number of modules. Our DAQ module consists of a scintillator crystal block, a position sensitive PMT (PSPMT), analog signal conditioning circuits, a digitizer, a digital signal processor and a communication module, through which it sends the collected data to a cluster of computers for post processing and storage.

In contrast to most of the small animal PET systems [1][2] we chose not to implement hardware coincidence detection between the modules. As a PET camera obviously can not function without determining coincidences between incoming gamma photons, we attach a precise time stamp to each and every event and the coincidence is determined during post processing by the data collecting computers. This method increases...
the amount of data that needs to be transferred between the detector blocks and the data collecting computers. However, it reduces the complexity of the digital hardware design and provides enormous flexibility for data analysis: since all data are transferred from the detector blocks to the data collecting computers different selection criteria can be applied to the collected data - even off-line, long after the data acquisition.

When not using hardware coincidence detection only a limited number of global signal need to be distributed to the DAQ modules. A 50 MHz clock drives the local clocks on the DAQ modules and serves as a time base for the time-stamp generation, while an enable signal ensures the synchronization between the local times and starts/stops data collection. A slow control network sets the different parameters of the modules (e.g. the value of the high voltage). Fig. 1 shows a picture of an assembled DAQ module, while Fig. 2 shows its block diagram.

III. THE LSO CRYSTAL ARRAY AND ITS OPTICAL COUPLING

In small animal PET cameras gamma photons are usually detected by a block of scintillating material [3]. In our case the scintillator block is constructed of an 8 x 8 array of individual LSO crystals. The size of an individual crystal is 2 mm x 2 mm x 10 mm, cut to appropriate size by OPTILAB Ltd [4].

All surfaces of the crystals are mechanically polished, as initial tests showed that this surface treatment gives the best light collection performance compared to other ones [5]. A 180 µm reflective (so-called LUMIOR [6]) film is placed between and around the crystal elements in order to optically isolate them and to increase the light collection efficiency.

This film is highly non-transparent and diffusively reflective, which is, from the aspects of light collection, found to be better than other foils with a mirror-like reflection [7]. The whole crystal array is also wrapped two-fold into LUMIOR film to further improve its mechanical stability (see Fig. 3).

When developing a detector module for a miniPET, good optical coupling between the scintillator block and the PSPMT is an important issue. During the development phase we used a soft and transparent silicone film with a thickness of 0.2 mm to achieve reliable but temporary coupling. However, as the initial tests are over, we intend to replace the soft layer with a hard optical glue to improve the mechanical fixture of the crystal elements and to assure the long term stability of their original (calibrated) position.

During the test phase we found that the detector blocks have good energy resolution, which can be further improved by calibrating the individual crystals (see Fig. 4). We are convinced that the main reasons of the non-uniformity is the varying efficiency caused by the silicone film, but PSPMT tubes are also known to have some non-uniformity in energy over their sensitive surface [8].

IV. POSITION SENSITIVE DETECTOR AND ANALOG SIGNAL CONDITIONING

A HAMAMATSU PSPMT is attached to each crystal block for the amplification and the read-out of the light signals. The R8520-00-C12 PSPMT [9] with cross-plate anode was selected...
because of its compactness and because of its geometry perfectly matches our scintillator block (size, rectangular window geometry). The PSPMT produces two pairs of signals \((X^+, X^-)\) and \((Y^+, Y^-)\), so called corner signals, which are related to the \(X\) and \(Y\) coordinates of the impact point of the incoming gamma photon on the surface of the PSPMT. These signals also carry energy and time information.

The analog electronic board that we built includes a compact high-voltage supply, which can be controlled via serial line, a voltage divider that drives the dynodes of the PSPMT, and the analog circuits that do the necessary signal conditioning of the four signals.

V. DIGITAL READOUT ELECTRONICS

Digitizer boards manufactured by NALLATECH [10] are used to digitize and process the corner signals of the PSPMTs. There are four 125 MHz ADCs on the BallyRiff digitizer board along with one XILINX Virtex FPGA (Field Programmable Gate Array). The corner signals of the PSPMT are connected to the free-running ADCs and their digital output is fed into the FPGA.

The FPGA performs numerous digital signal processing tasks. For each incoming photon its energy, impact position and time of arrival has to be determined [11].

The energy of the incoming photon can be calculated by summing up the \(X^+\) and \(X^-\) or the \(Y^+\) and \(Y^-\) signals. A cut on the minimal energy of the detected gammas is applied to filter out those events that do not correspond to the annihilation of a positron-electron pair.

The \(X\) and \(Y\) coordinates of the hit can be determined from the corner signals using the Anger formula:

\[
X = \frac{X^+ - X^-}{X^+ + X^-}, \quad Y = \frac{Y^+ - Y^-}{Y^+ + Y^-}
\]  

A color coded flood-field image is shown in Fig. 5. The calculated positions of the crystal needles on the surface of the PSPMT line up very well. This makes it easy to separate the regions that correspond to the individual crystals, thus enabling event size reduction (see Section VII below).

As described above, no hardware coincidence detection is used, therefore a high resolution time stamp has to be attached to each event. Although the output signal from the last dynode of the PSPMT has excellent timing properties and could be used for timing [12], the use of this signal would unnecessarily complicate the design. According to our measurements sufficiently good time resolution can be achieved by extracting the timing information from the four position-related signals. We implemented a digital CFD algorithm in the FPGA [13] which gives a time resolution of 2 to 3 \(ns\) FWHM for real detector signals.

The digital signal processing algorithms (signal recognition, peak-finding, position calculation, time-stamp generation) are written in VHSIC Hardware Description Language (VHDL).

VI. COMMUNICATION MODULE

The energies, the \(X\) and \(Y\) coordinates and the time stamps are stored in an output buffer (a FIFO) inside the FPGA, which is read by the communication module. The communication module is a microcontroller based intelligent device with a 10 MBit Ethernet interface. The module is responsible for the communication with the data collecting computers (servers) and the master computer (see Section VII below).

Ethernet based IP technology was chosen as the carrier of the collected data, because of its numerous advantages: it is sufficiently fast, well tested, scalable, easy to implement and debug, cheap, and there are many standard hardware and software components available. User Datagram Protocol (UDP)
is used on top of IP with a proprietary protocol developed by us. While Transmission Control Protocol (TCP) would be more reliable than UDP, it is more complicated and its more demanding resource usage (CPU, memory, software) is not justified in our case. Accidental and rare loss of a UDP packet is acceptable in favor of speed and simplicity. However, to ensure correct data analysis a sequence number is assigned to each UDP packet, thus the number of lost packets and lost events can be tracked.

The collected data is transferred from the FPGA to the communication module on an 8 bit wide data bus, where they are wrapped into UDP packets and sent to the appropriate data collecting computer. The module can keep a minimum time gap between consequent UDP packages - thus limiting the output event rate and output bandwidth usage - to reduce the load on the communication lines and on the data collecting computers. It can also limit the maximum time gap between two UDP packages to help in the discovery of detector failures and the misbehaviors. It also has features to support debugging and testing of communication links (e.g. event generators, configurable packet sizes).

VII. DATA COLLECTION

The full data collecting and processing system consists of the detector blocks (the clients), the data collecting computers (the servers) and a dedicated computer which manages the data collection (the master).

After power on the master discovers the various clients and servers on the network using a Dynamic Host Configuration Protocol (DHCP) like protocol developed by us. A so called “communication channel” is built up between each client or server and the master. The control channel is used to control the various entities: the master can start and stop the data collection, configure the clients and the servers for various data collection modes (e.g. single spectrum collection on each detector for energy calibration, data collection in list mode with coincidence detection on the data collecting computers), investigate their state or reset them. This dynamic discovery and configuration of devices and the independence of the DAQ modules makes reconfiguration, expansion or reduction of the PET ring easy, and the whole design suitable for highly experimental and research projects. The commercially available Ethernet technology (Gigabit Ethernet) and the increasing computational power of Personal Computers provide enough reserves for growth in the number of DAQ modules in the system.

The data collection is based on “time slices”. A time slice is a period of time with a given (configurable) length (see Fig. 6). Using time slices the event size can be reduced, because the arrival time of the incident gammas is measured and represented as the elapsed time from the beginning of the actual timeslice, not as an absolute time.

In the present setup when data is collected for image reconstruction the events belonging to one time slice are sent from all DAQ modules to one data collecting computer. This computer sorts the events by time, and detects possible coincidences based on the time stamps and the geometry configuration. Only the coinciding events are forwarded to the master for storing and visualization.

For each event the time of arrival (measured from the beginning of the time slice, 4 bytes) and the peak value of the corner signals (4 x 2 bytes) are sent to the data collecting computers via the Ethernet link. With this configuration the achievable sustained event rate is about 10000 events/sec with no dead time at all. By eliminating the redundancy in the time stamps and replacing the peak values with a crystal index the number of transferred events can easily be increased by 2.5- to 4-fold. The main limiting factors are the capabilities of the microcontroller, and the 10 MBit Ethernet media. These can be eliminated by simply replacing the communication module with a commercially available one that has better capabilities.

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