Overview of the software architecture and data flow for the J-PET tomography device


Abstract
Modern TOF-PET scanner systems require high-speed computing resources for efficient data processing, monitoring and image reconstruction. In this article we present the data flow and software architecture for the novel TOF-PET scanner developed by the J-PET collaboration. We discuss the data acquisition system, reconstruction framework and some image reconstruction issues. Also, the concept of computing outside hospitals in the remote centers such as Świerk Computing Centre in Poland is presented.

Keywords: TOF-PET, computing, image reconstruction, DAQ, positron emission tomography

1. Introduction

Positron Emission Tomography is at present one of the most technologically advanced imaging techniques used in medical diagnosis. It allows for
non-invasive imaging of physiological processes, by reconstructing the spatial
distribution of radiopharmaceuticals introduced into the patient’s body. The
radiopharmaceuticals are chemical substances labeled with radionuclides (e.g.
glucose with radioactive fluorine 18F), which emit positrons during the + decay.
The positron annihilates with an electron from the patient’s body and subse-
quently their masses are transformed into a gamma quanta pair emitted back-to-
back. The signals from gamma quanta are registered in coincidence in the PET
detector. The significant improvement of the image resolution and the faster
convergence of image reconstruction procedure can be achieved by applying the
Time-of-Flight (TOF) technique [1, 2], which consist of the determination the
annihilation point along the Line of Response(LOR) based on measurement of
the time difference between the arrival of the gamma quanta at the detectors.
The current commercial PET devices use inorganic crystal scintillators for the
detection of the gamma quanta. In contrast, the J-PET collaboration is devel-
oping a prototype PET based on polymer scintillators [3, 4, 5, 6, 7]. This novel
approach exploits the excellent time properties of the plastic scintillators, which
permits very precise time measurements of the signals allowing for the effective
usage of the TOF technique. The use of state-of-art detectors together with
a dedicated data acquisition system (DAQ) imposes new requirements for the
processing of the data streams, for monitoring, as well as for the reconstruction
procedures. The TOF-PET scanner being developed by the J-PET collabora-
tion will consist of hundreds of detection modules with double-sided readout,
measuring the energy and the arrival time of the gamma quanta. In addition,
the front-end electronics work in the so-called trigger-less mode [8], storing all
incoming events without master-trigger conditions applied. This results in a big
data flow that needs to be handled and stored efficiently. The collected data are
processed in several steps (see [1]) of low- and high-level reconstruction leading to
a significant data volume reduction. At the same time the information needed
to obtain the final image of the human body is preserved. The process starts
with the collection of the raw data (time and amplitude digitized by the time-
to-digital and analog-to-digital converters). Next, the data is combined into
signals and translated to hit positions in the individual scintillator modules. Finally, hits in the individual detector bars are combined to form LORs. The set of LORs is then used as an input for the image reconstruction procedure.

In the next sections, we describe in more details the front-end electronics, reconstruction framework and image reconstruction techniques developed by the J-PET collaboration. We also present the distributed computing architecture.

2. Front-end electronics

One of the main novelties of the proposed J-PET detector lays in the reconstruction of gamma quanta hit position in the polymer module by performing a very precise time measurement. This method puts hard requirements on the read-out electronics. A typical rising time from the polymer scintillator used in the project is about 0.5 ns and combined with the rising time of a fast photomultiplier (e.g R4998) of about 0.7 ns, results in a signal rising time of about 1 ns. This value permits to obtain an excellent time resolution but at the same time the read-out electronics must have a much better accuracy to sample those short-time signals. e.g. probing a signal with a rising time of about 1.2 ns on 16 levels, would require an accuracy roughly below 75 ps. Unfortunately, the existing solutions do not provide the needed measured time precision. There-
ore one of our main efforts is to construct the read-out electronics which would fulfill the requirements of the detector and at the same time keeping costs reasonably low. Currently we are working on two solutions. The first developed solution is a multi-threshold sampling board which gri of hybrid GaAs amplifiers of NBBi-310 type and the four ADCMP582 ultrafast comparators based on SiGe technology. The current version of the board permits to probe the signal by employing four thresholds. All thresholds levels are set with a FPGA-based board. The proposed solution enables sampling of signals in the voltage domain with a precision of 20 ps(σ). The second design is a novel technique for precise measurement of time and charge based solely on FPGA (Field Programmable Gate Array) devices and few satellite discrete electronic components [9]. Time measurement technique in FPGAs is based on the possibility of using carry-chains usually used as part of adders. It consists of five Lattice ECP3-150 FPGAs. Four of FPGAs are are used as time-to-digital converters. The last FPGA chip can play the role of a discriminator by using LVDS buffers as comparators and internal carry chain elements as delay units. This approach allows to measure time when analog signals cross a reference voltage at different threshold levels with a very high precision of 10 ps (rms) and thus enables sampling of signals in the voltage domain. In the prototype phase, the current cost of one sample together with digitization is only about 10 Euro. Described read-out electronics permit a multi-threshold sampling, which probes the signal event waveform with respect to a small number of amplitude thresholds. According to the Compressive Sensing Theory [10], the collected data points could be used to reconstruct the full signal shape e.g. by applying transformation to a sparse representation [11]. The information about the shape of the signals is highly correlated with the hit position of the annihilation gamma quantum, along the scintillator strip. Thus, with this information a better filtering of the coincidence of the two signals, and a more accurate reconstruction of the position is possible.
3. Low-level reconstruction framework

The raw data provided by the front-end electronics is processed in the low-level reconstruction framework, which serves as a backbone system for various algorithms (e.g. aforementioned position reconstruction algorithms), calibration procedures and to standardize the common operations, e.g: input/output process, access to the detector geometry parameters and more [12]. The framework has been developed in C++ using the object-oriented approach. It is based on the BOOST [13] and ROOT [14] programming libraries. The framework is used for the off-line analysis, but also as an online module being a part of the steering software system PetController. An important part of the software system is the parameter database [15], which contains information about the geometry configurations, the DAQ setups, specific run setups and HV settings. This information is implemented as a PostgreSQL database.

4. Image reconstruction

The next step in the data processing is the reconstruction of the radioactivity distribution in the patient’s body based on the collected LORs. We adopted the most popular approach based on iterative algorithms derived from Maximum Likelihood Estimation Method (MLEM) [16]. The available time-of-flight information is incorporated to improve the accuracy and the quality of the reconstruction. The image reconstruction is one of the most time-consuming parts of the whole process. In order to reduce the processing time, parallelization techniques are applied. Currently, a solution based on a multi-core CPU architecture is implemented [17]. Efforts are made to exploit the processing capability of Graphical Processing Units (GPU). The efficient image reconstruction using list-mode MLEM algorithm with approximation kernels was implemented on GPU [18,19]. The comparison between CPU and GPU reconstruction time per iteration for the sample Shepp-Logan simulated phantom is presented in [2].

The peculiarity of the J-PET detector solution is its large acceptance, which permits to perform a real 3-D image reconstruction. It should be contrasted with
Figure 2: Comparison between CPU and GPU reconstruction time per iteration for the sample Shepp-Logan phantom.

currently the most popular technique based on the 2-D slices reconstruction, which are joined afterwards to form the 3-D image.

5. Distributed processing

Apart from the presented computing schemes, in which the data processing is performed locally, using multi-core CPU or/and GPU solutions, we consider also a different approach based on remote distributed architecture. In this scenario the input data (e.g set of LORs) is not processed locally but is first transferred to the distant computing center and then it is processed by computing nodes of a grid or a cloud network. The full concept of fast and high efficient architecture scheme is presented in details in [20]. In the J-PET project the development of the concept is done by the CIS Świerk Computing Center.

6. Summary

We presented the overview of the data processing scheme developed for the prototype TOF-PET scanner. The proposed solution is optimized in view of
computation time and resources costs. Currently, our work is aimed at integration of all components and preparation of the system for test measurements with a full-scale prototype.

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