A High-Performance VME-Based Acquisition System for Positron Emission Mammography

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***Abstract*--A prototype for a practical and economical breast imaging system for cancer detection is currently under development at Jefferson Lab. The latest advances in bright, fast, crystal scintillators, compact position-sensitive photomultipliers (PSPMT), and high-performance digitizing and readout electronics are being used to develop a compact imager based on Positron Emission Tomography (PET). To facilitate the performance demands of the detector as well as the high number of readout channels, the data acquisition system is built around an intelligent, self-contained, VME form-factor.**

I. INTRODUCTION

While standard film screen mammography is currently one of the best methods for early breast cancer detection, both the sensitivity and specificity of mammography are limited [1]-[3]. Mammography is inherently limited in its ability to detect breast cancer because it relies on demonstrating morphologic differences between cancerous and benign lesions. Alternatively, PET based imaging provides information to the physician on the biological functional status of organs or tissue. By correlating functional metabolic information with structural mammographic images, Positron Emission Mammography (PEM) represents a promising clinical tool and, over the past several years it has been investigated by many groups [4]-[8]. The Jefferson Lab Detector Group has been developing PEM detectors based on a dual planar detector configuration [7], [8]-[10]. The latest development in that work is reported elsewhere at this conference [11].

The goal of the Detector Group PEM development is to provide a high resolution, full field of view breast image utilizing dual 6″x 8″ dual planar detectors. However, the data acquisition demands of such detectors are taxing traditional interfaces in both the number of active readout channels as well as detection trigger rates. To confront this issue we have been able to take some of the hardware and software resources available at the Thomas Jefferson National Accelerator Facility that are currently used for large high-rate high channel count nuclear physics experiments and adapt them for use with the PEM prototype systems.

The PEM data acquisition system is completely self-contained within a single mini-VME crate; hence it is reasonably portable. The VME form factor, however, makes it easily expandable. All the hardware are commercially available which helps to minimize costs. The use of an embedded PowerPC single board computer running a real time operating system (VxWorks [12]) provides the necessary performance requirements to handle the PEM detector response.

In this paper we present details of the current data acquisition system and its performance in tests with some PEM detector prototypes. We will describe where the current limitations of the system are and where plans for future improvements are headed.

II. BACKGROUND

PET imaging works by injecting a positron-emitting radionucleide, labeled to a molecule of interest, into the body. This tracer accumulates throughout the body according each tissue type's affinity for the tracer. When a positron is emitted it travels a short distance (on the millimeter scale) and annihilates with an electron. Two 511 keV photons are produced which leave the body in opposite directions. The anticollinearity of the photons is used for spatial localization. When they are detected in coincidence (<100 ns) it can be assumed that they came from a single annihilation and this annihilation was on a line connecting the two detection points.

By moving gamma detectors into close proximity with the region of interest the coincident detection rate increases significantly. The ability to process these events as efficiently as possible is important in order to generate a quantitatively useful image in a minimal amount of time. It requires both a short trigger latency (e.g. ADC conversion time) as well as efficient backend processing (i.e. readout and image reconstruction).

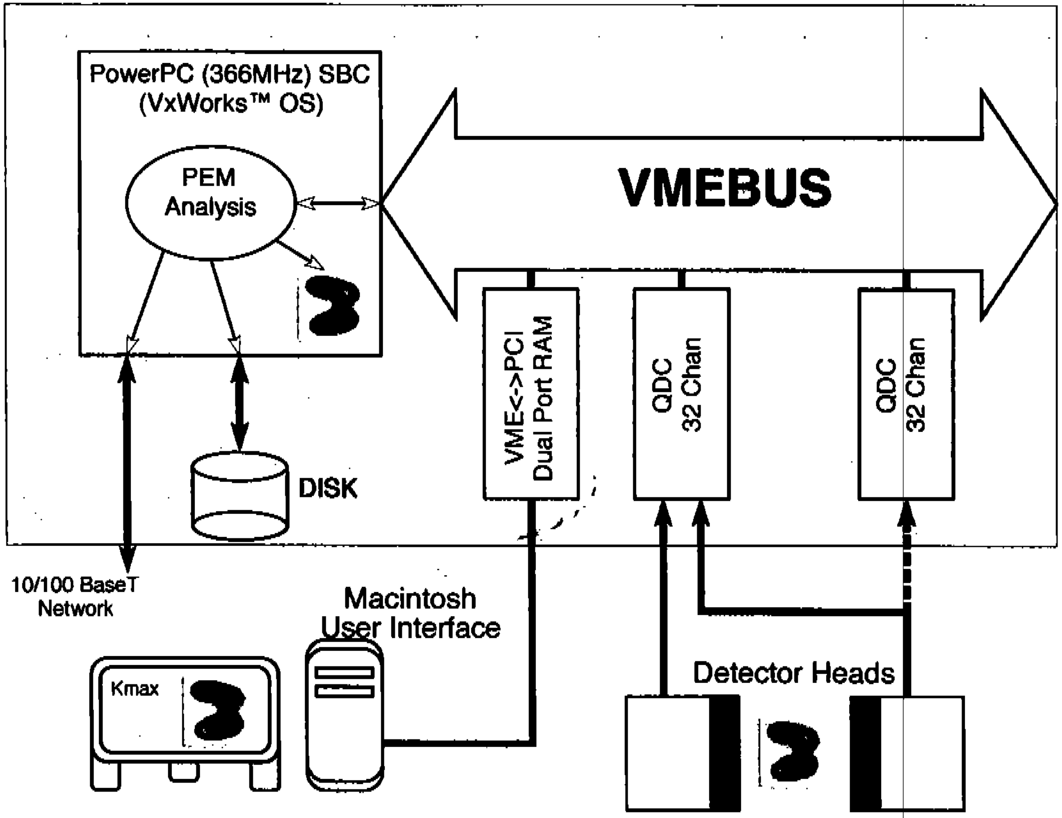

Fig. 1 Schematic of the PEM data acquisition system

Better image resolution is gained through the use of many crystal scintillators cut in the form of individual pixels, arranged in a large pixel array. This array is coupled to a compact detector head comprised of up to forty-eight position sensitive photomultiplier tubes (PSPMT). The increased pixel density requires conversion and readout of significantly more channels than in previous detector designs. The current detector prototype supports 16 x-position and 16 y-position signals for each head giving a total of up to 64 simultaneous channels in a two-head imaging system that must be digitized and stored event by event. With trigger rates expected to reach 25 kilohertz, the data acquisition system will have to process a random data stream in excess of 6 MB/sec.

III. DAQ SYSTEM

A diagram of the current acquisition system is shown in Fig. 1. It is built around a Motorola (Model MVME2700 [13]) VME single board computer (366 MHz PowerPC CPU) running the VxWorks real-time kernel. At the front-end the analog channels of the detector are digitized using two CAEN (Model V792) QDC modules [14]. These boards support up to 32 channels each of charge sensitive analog to digital conversion (12 bits). All 32 inputs can be simultaneously digitized, buffered, and enabled for a new trigger in less than 6 μsec. At an anticipated input trigger rate of 25 kHz this results in a front-end dead-time of around 15 percent.

The VME CPU manages all the data processing. As data buffers on the QDC are filled the raw data are transferred to a local memory queue. These data are then processed, and resulting image information is stored in local histograms. The image information can optionally be written to several output sources including the network, local disk storage, or VME based dual-ported RAM.

Operator control of the system and image display are currently handled externally by an Apple Macintosh G4 computer system. The computer is interfaced to the VME crate via a PCI/VME bus adapter from SBS Technologies [15] (Model 617). The user interface is an application/instrument developed using the Kmax Data Acquisition and Control System from Sparrow Corporation [16]. Control commands and image data may be passed between the Macintosh and the VME CPU using the 8 megabyte dual-ported RAM buffer resident on the 617 adapter interface. The user is able to start and stop the image acquisition, control the type of event processing and output options, and vary the real-time updates and display of current image data.

An 18 gigabyte SCSI disk resident in the VME crate is available to store image data. In addition it can be used to stream raw event data during acquisition. The user can then choose in the future to playback and analyze data from the file rather than directly from the detector. This flexibility allows one to make multiple experimental modifications to the image analysis "offline".

IV. PERFORMANCE

The primary reason for performance limitations in previous acquisition systems has been the lack of real time response to the trigger. Analysis, histogramming, and display that are too tightly coupled to the front-end as well as relatively slow data transfer also contribute to increasing system dead time. The current VME system overcomes these problems using various methods.

At the front-end the QDC is able to convert and buffer all input signals in 5.7 µsec. In addition, it can locally buffer all channels' data for up to 32 separate triggers. A feature of critical importance is that these buffers can be accessed on the VME side while data is simultaneously being digitized and buffered on the front side; hence, when these buffers are about half-full (i.e. 15 events stored) the QDC issues an interrupt request onto the VME Bus. The MV2700 is able to respond to this request in less than 5 µsec and begin executing an interrupt service routine (ISR). In the ISR a DMA block transfer between the QDC and a local memory queue is setup and started. Meanwhile, the QDC continues to accept triggers. The QDC boards support MBLT (64 bit) transfers as well as chaining so that all available data from all QDC boards in the crate may be read with a single DMA request. Block transfer performance using this method has been measured at around 27-30 Mbytes/sec.

With the data in local DRAM on the MV2700 a second level of buffering is used to decouple the image processing and event I/O from the front-end. A "message queue" is setup by which the ISR can store multiple event blocks from the QDC boards. A high priority PEM analysis task sleeps on the queue awaiting any events. As event blocks are placed on the queue by the ISR, the analysis task can unpack, process, histogram, copy, or write the data as user's run configuration dictates.

As long as the processing time plus the data transfer time for an event block (of 15 events) does not exceed on average the time to convert 15 events in the QDC then the system runs in a steady state. No additional dead time can be attributed over the QDC conversion time. However, in the situation where trigger rates or processing time are too large then a simple backpressure method is introduced to disable the acquisition. If the ISR fills the message queue on the CPU then it has nowhere to place the next buffer should one become available; hence, it must disable interrupts on the QDC. The QDC will then fill up its buffers and wait. On the CPU side a monitoring task wakes up and checks the status of the memory queue to see when space is available. At that time it re-enables the QDC interrupts.

A. *Image Processing*

At 25 kHz the system only has about 600 µsec in which to transfer and process an event block. There is a significant advantage in a real time response to minimize the time wasted in recognizing data are available and transferring them to the process that can analyze them. Once received from the queue the PEM analysis package unpacks each event and proceeds with image reconstruction.

First, the gamma-ray interaction position in the scintillator array for each detector head is determined by computing a truncated center of gravity of the signal distribution on the X and Y anodes of each of the two PSPMT arrays. The calculation of the center of gravity is achieved by using only the QDC digitized signals of those anode wires in the calculation that have a predefined chosen optimum fraction of the sum of the anode signals (typically 5% to 10%). The X and Y results from the COG calculations are used to locate which crystal of the array scintillated via a RAM based look-up table (generated during a previous calibration run). Once the struck crystal is identified, the sum of all X and Y anode signals is used to determine if the scintillation event was in the chosen energy acceptance window. Each crystal has a predefined energy acceptance window, which is also checked via an energy calibration look-up-table.

Laminographic images are reconstructed by the analysis task by implementing a back projection from the x-y locations of the pair of crystal elements giving rise to a coincident scintillation event detected by the two detector planes. In the back projection calculation, a line of response can be considered to connect the centers of the two pixels corresponding to the crystal elements in the opposed detectors that detect a coincidence event. Image events are located where this line of response intersects the desired image planes. The maximum angle from normal incidence for an accepted event can be set, as can energy thresholds. For the real time tests we generated six separate image planes that were 64 x 64 pixels in size.

Additional raw 2D image histograms, pixel position, and energy sum histograms are accumulated in real time. A total of about 3 Mbytes of information are stored in local RAM. The user does not have direct access to image data on the VME CPU; however, the system allows for these histogram data to be mirrored in the VME to PCI dual-ported RAM in real time or periodically updated at the user's request. By accessing dual-ported RAM from the Macintosh side the user may view and manipulate images without impact on the running system.

Typical performance numbers for the VME acquisition system are shown in Fig. 2. PET imaging tests were run using FDG (2-fluoro-2-deoxy-D-glucose) labeled with the positron emitter flourine-18. It was injected into a thyroid phantom. A two-head, 32 channel, PSPMT array was interfaced to the QDC for readout. As the radionucleide decayed, trigger acceptance numbers were measured and compared to input rates. In an ideal system with a random input trigger the highest acceptance efficiency is determined only by conversion and buffering time of the front-end QDC.

This function is represented by the solid line. Experimental imaging runs for the system correspond to the square data points. One should note that for input rates up to 50 kilohertz no additional dead time was introduced. The system was running at maximum efficiency. For comparison an older CAMAC-based imaging system was used with the same detector. The system performance peaks at around 6 kilohertz acceptance, and it is effectively 100% dead at an input rate of 25 kilohertz.

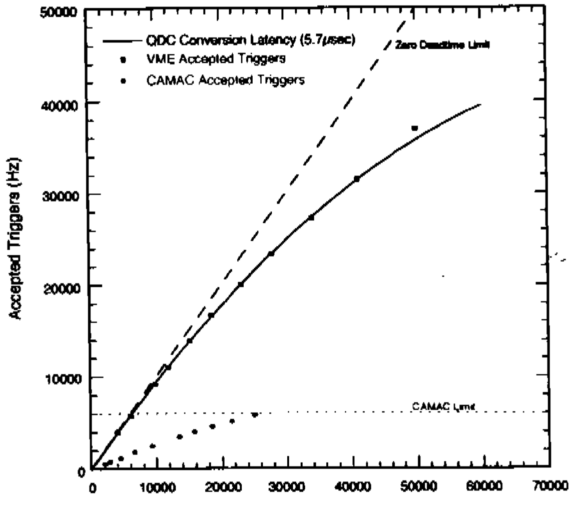

Fig. 2 Performance comparison between the current VME-based acquisition system and older CAMAC-based system. The solid curve represents an acceptance function when only the front-end hardware (QDC conversion) contributes to system dead-time.

B. Limitations

So where does the current system begin to introduce additional dead time? This is largely a function of the number of concurrent tasks the user makes active. Streaming event-by-event data to a file can limit the system, particularly if fully unsparsified QDC data (all channels stored regardless of signal level) are written. The disk is only capable of writing at 6-7 Mbytes/sec. This corresponds to an accepted rate limit of around 24 kilohertz. Performance effects can be minimized by writing only those PSPMT signals which are above some calibrated threshold - typically only a few channels per event.

Another I/O task that can be taxing is full real time updating of histogram arrays into the dual ported RAM for user access. As each event is processed, image data must be written over the VME bus to the RAM. This is in direct competition with raw QDC data that is being transferred to the CPU. Performance degradation is directly related to the number of image histograms the user wishes to monitor. By keeping these to a minimum or by only requesting image updates on a periodic basis one can minimize the impact on the acquisition system.

When external I/O requests are disabled the system is able run at maximum efficiency. To date with the current image processing, the VME CPU is still not being fully utilized, even with phantom-based tests in excess of 50 kilohertz. Pulser tests (with imaging disabled) run at around 80 kilohertz accepted rate; hence, a reasonable amount of breathing room exists for future expansion.

V. SUMMARY

New concepts and developments in scintimammography and PET instruments with larger fields of view are driving demands for faster and more efficient methods of data acquisition, display and control. We have attempted to put together a flexible system from commercially available equipment that not only meet current R&D needs but also can be expanded and customized for future clinical-based applications.

The current VME-based system has performed well for the positron emission mammography research that is ongoing at both Jefferson Lab and The University of West Virginia, but the hardware and software methods can also be easily adapted to other areas of medical imaging. We are currently investigating acquisition needs for future projects such as small animal imaging.

Pending upgrades to the existing system include a faster VME processor and a higher capacity and faster hard disk storage. The Motorola MVME5100 utilizes the PowerPC 7400 series processor running at 400 MHz. The built-in AltiVec™ unit of the 7400 chip can be taken advantage of for high speed real time image processing. The addition of an ultra wide SCSI disk should double the throughput to event files.

Another feature is the addition of a network server for the Kmax display and control system. The server runs on the VME CPU. A Kmax instrument can now connect with the acquisition system remotely via the network server and control the system or request image data. Data transfer over the network is reasonably efficient at 100 Mbits/sec, and the flexibility of not being in close proximity to the detector system can be useful.

VI. ACKNOWLEDGMENT

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