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I. Abstract

We describe a hybrid data acquisition architecture integrating a conventional UNIX workstation with CAMAC-based real-time hardware. The system combines the high-level programming simplicity and user interface of a UNIX workstation with the low-level timing control available from conventional real-time hardware. We detail this architecture as it has been implemented for control of the Donner 600-Crystal Positron Tomograph. Low-level data acquisition is carried out in this system using eight LeCroy 3588 histogrammers, which together after derandomization, acquire events at rates up to 4 MHz, and two dedicated Motorola 6809 microprocessors, which arbitrate fine timing control during acquisition. A SUN Microsystems UNIX workstation is used for high level control, allowing an easily-extensible user interface in an X-Windows environment, as well as real-time communications to the low-level acquisition units. Communication between the high and low level units is carried out via a Jorway 73A SCSI-CAMAC crate controller and a serial

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interface. In the UNIX configuration, a general purpose process serves as a message center between the user interface and the CAMAC devices. The message center transfers user-specified data acquisition protocols to the tomograph hardware. A separate high priority UNIX process is used to receive sinogram data into memory during active acquisitions, thus supporting rapid data transfer for dynamic positron emission tomography.

II. Introduction

The terms “UNIX” and “real-time” are familiar to many, yet the two terms are rarely used to describe the same system. Conventional real-time software environments usually provide only the bare essentials for an operating system. This characteristic is driven primarily by trade-offs between system functionality and real-time performance. In contrast, a UNIX system is typically rich in general functionality, especially in tools for software development. Programming can usually be done at a higher level, powerful debuggers are available and modern user interfaces can be easily developed in an X-windows environment. Networking to other computers at this level is also trivial, using standard TCP-IP communication protocols over ethernet. Software developed on a UNIX system has the additional advantage that it can easily be ported to other vendor’s systems, due to the relatively standard UNIX environment. However, UNIX systems have not often been used directly as controllers in real-time systems because finely timing data I/O in these systems is difficult. Consequently, in the development of real-time systems, it is not uncommon for all development to take place on a UNIX host, and then the code is subsequently downloaded to a target embedded system. This compromise requires an extra controller (i.e. the embedded controller) and knowledge of the software environment for programming the controller. Furthermore, since development is done on different systems, debugging requires costly and often inefficient emulation systems.

To capitalize on the advantages of UNIX and conventional real-time systems, we have designed a control scheme which makes use of both. Functionality in this architecture is segmented according to which subsystem can most effectively carry out the required task. This scheme has been used to upgrade the control system for the Donner 600-Crystal Positron Tomograph (PET600). Here, a UNIX host computer is directly interfaced to a CAMAC crate controller. The UNIX system replaces a PDP 11/34-based acquisition system and a VAX 11/780-based reconstruction and display system. Like the control system for the PET600's predecessor, the Donner 280-Crystal Positron Tomograph, each acquisition component of the old system required specialized hardware and software I/O drivers to adequately perform its task [1]. The new system makes use of commonly available UNIX hardware and general-purpose software and can easily be extended for future functionality.

III. Hardware

The PET600 tomograph uses 600 bismuth germanate crystals, each with its own photomultiplier tube, arranged as a single layer ring. The tomograph ring is hinged to allow clammed sampling [2][3], and has control electronics that allow for gated, as well as dynamic time acquisitions. Parallel high-speed coincidence logic direct tomograph event data to electronics which distribute the data into eight LeCroy 3588 histogramming modules. Each LeCroy memory module provides 32K of dual-ported 12 bit words. The modules are used in double buffered mode, so that sinograms can be acquired into one half of available memory, while a previous acquisition is being read from the other half. To allow for acquisition of data at a maximum event rate, a single sinogram is distributed over four histogrammer modules. Since a single sinogram requires 60K words of memory, the eight memory modules can thus support back-to-back acquisition of two gated or two clam positioned sinograms. A more complete description of the front-end electronics and architecture of the tomograph may be found in [4].

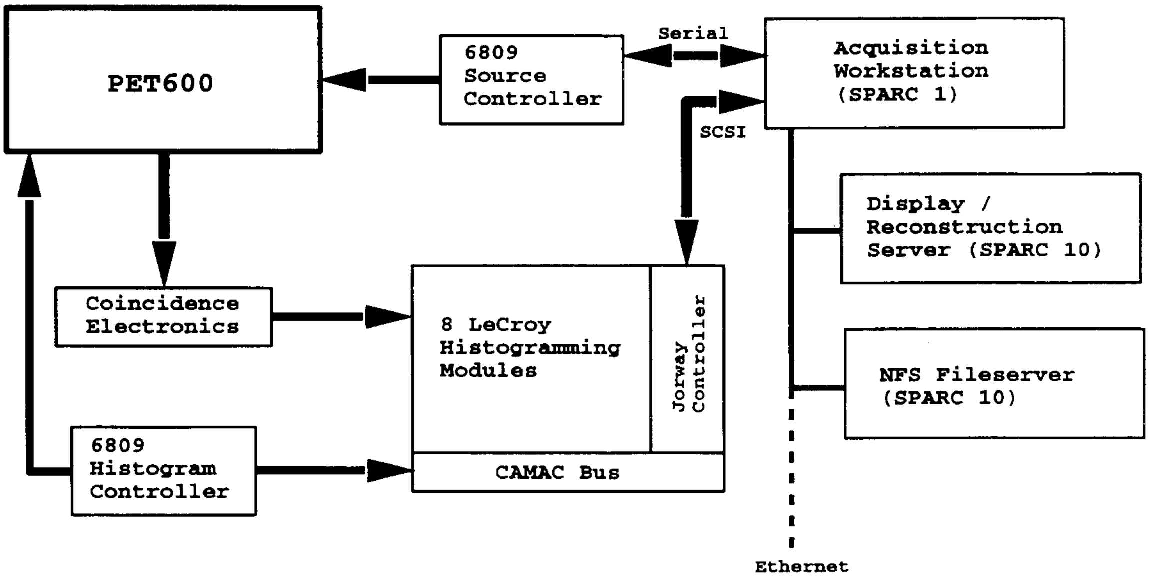

FIGURE 1. Hardware Configuration. The PET600 Tomograph electronics are interfaced to CAMAC-based histogrammers and 6809 controllers. These units communicate to the UNIX workstation via SCSI and serial interfaces.

The new control system distributes the control functions into two levels. Time critical functions are achieved at a low level using two dedicated Motorola 6809 microprocessors and the eight histogramming modules. One of the 6809 processors, the source controller, controls the position of the rotating transmission source and the position of the tomograph bed. The other 6809 processor controller, called the histogram controller, controls clamming, gating and time formatting of data during a study, and accurately keeps track of time parameters during acquisition. Time resolution at this level is based on a 2 MHz clock for the 6809 controllers. The real-time clock allows control at required resolutions ranging from 60-1200 Hz for stepper motors to 250 khz for accurate determination of study start, stop and active time parameters.

A SUN Microsystems SPARC 1 UNIX workstation is used for high level acquisition control. This computer controls functions which are not time-critical, such as the user interface, parameter formatting and downloading to the tomograph, and the copying and reformatting of histogrammed data from the histogrammers. Most of the functions at the UNIX level entail the setup of tomograph parameters before the acquisition is begun. These functions can be achieved without serious regard to timing constraints. There are two exceptions to this rule. First the UNIX system must be able to transfer data from the double buffered histogramming modules during active data acquisitions so that one half of the buffers are empty by the time the other half has been filled. Second, the UNIX controller must be able to respond to real-time serial requests from the source controller. The latter of these functions is carried out by the serial device driver, which is standard on most UNIX machines. The former function is carried out by a high priority data transfer process that continually polls the SCSI bus during data acquisition and transfers the data to UNIX shared memory as soon as one of histogram buffers is ready.

Communications between the low and high level units is carried out via a Jorway 73A SCSI-CAMAC crate controller and via direct serial interfaces to the 6809 controllers. Figure 1 summarizes the hardware configuration.

IV. Software

Figure 2 shows a block diagram of the software modules and pertinent memory structures present in this system. At the lowest level, 6809 assembly code is used to program the microprocessor-based controllers. At the high end, two UNIX processes are used: a main process serves as a general purpose user interface and message center, and a polling process serves to transfer data from the histogrammer memory. Both processes use a common I/O subroutine library based on the POSIX STREAMS protocol for serial communications, and upon a Jorway CAMAC-SCSI device driver supplied by Pacific Northwest Laboratories. Communication between the two processes is achieved using shared memory and user-defined interrupt procedures.

Because of the difficulty in developing and maintaining assembly code at the low level of the 6809 microprocessors, only a minimum amount of code is used at this level. Instead most of the data acquisition code exists at the UNIX level. The main process serves as the X-Windows based user interface as well as a messaging center between the user interface and the other modules. The user interface allows the tomograph operator to specify a study protocol or to select from predefined protocols, and download it to the tomograph. Once a given protocol is selected, this process translates user-specified acquisition protocols into appropriate low-level memory structures and sends the requisite commands to the 6809 controllers and the other UNIX process.

The UNIX polling process serves the sole purpose of providing high speed data transfers from the histogrammers during data acquisition. This process operates at a high system priority and sits in an idle state until requested by the main process to monitor data acquisition. Once awakened, it will poll the Jorway CAMAC controller frequently (every 100 microseconds) to determine whether the histogram controller has issued a transfer "Look at Me" (LAM) to the CAMAC bus, thus indicating that a sinogram is ready for transfer. When the LAM is sent, the polling process rapidly transfers the sinogram via a CAMAC block transfer through the SCSI dataway to UNIX shared memory. The polling process continues in this heightened state until the acquisition is complete. Meanwhile, the main acquisition process is busy at a lower priority level reformatting the sinograms in shared memory and transferring them for more permanent storage to an NFS-mounted disk. The main process further provides user status information via the user interface as the acquisition progresses.

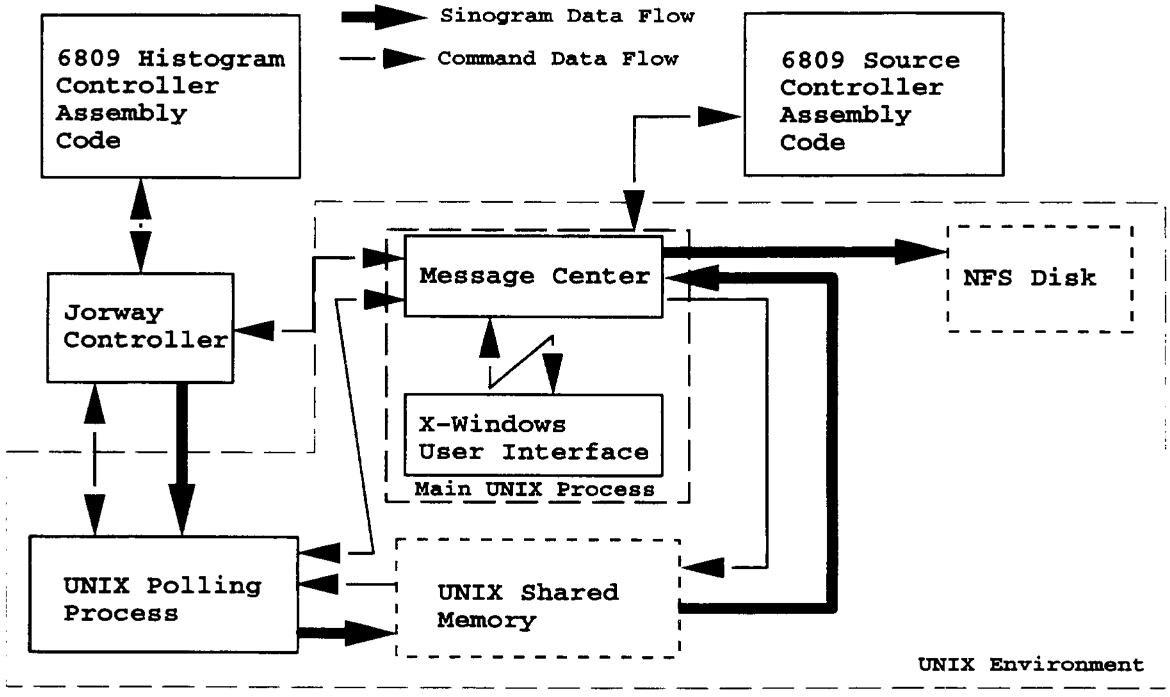

FIGURE 2. Software Configuration. A central UNIX process acts as a message center between shared memory, disk storage, the user interface and a high-priority polling process.

Once acquired sinograms have been transferred to an NFS disk, they are available to other UNIX workstations in our networked cluster. This architecture allows us to distribute the image reconstruction and display tasks. Currently, we use a SUN SPARC 10 as a display server. The display server provides the user interface to the reconstruction program and allows simultaneous viewing of image acquisitions from other modalities. Image reconstructions are achieved by the display server first reading in the sinogram data from disk, distributing the data to up to six other UNIX reconstruction servers via remote procedure calls (RPC), and then reassembling the reconstructed image. Typical reconstruction time for a 256x256 image using filtered backprojection and three reconstruction servers is 5-15 seconds, depending on system usage and network traffic.

The PET600 requires weekly tuning to compensate for variations in timing and gain among the 600 crystals and phototubes in the tomograph. Detailed algorithms for tuning the computer-controlled digital to analog converters have been previously published [5]. Tuning consists of finding appropriate settings for a large number of digital-to-analog converters. Implementing the tuning algorithm on the new system was straight-forward. The same polling process and I/O subroutine library that were used in the data acquisition program were also used for this task. The only difference between the tuning program and the data acquisition program is the user interface associated with the main UNIX process. The tuning user interface allows for selection of pre-defined acquisition scripts which allow for calculation of the optimum tuning parameters. Upon completion of a PET600 tune, a file is stored that contains the DAC settings. These settings are read and downloaded at the start of every PET600 data acquisition session.

V. Performance

The distributed nature of our acquisition system allows a relatively slow UNIX workstation to adequately control our tomograph, while using high speed workstations for subsequent data processing. Considering the individual components in the data acquisition, the LeCroy Histogrammers can each accept input data at a 1 MHz rate, thus allowing a 4 MHz event rate to be collected by four parallel histogrammers. As data are collected they can be simultaneously transferred over the CAMAC bus through the Jorway crate controller. Though the Jorway controller can theoretically transfer data over a standard SCSI-2 interface at a maximum rate of 2 Mbytes/sec., additional setup after each sinogram transfer reduces overall throughput considerably. We find typical transfer rates through the Jorway controller to be near 500 kbytes/sec. Resetting histogram memory to a preset bias requires slightly less than two seconds so that the maximum acquisition rate for the overall system is one sinogram every 2 seconds for non-gated studies, and two sinograms every 2 seconds for gated studies.

VI. Conclusions

We have developed a hybrid UNIX-CAMAC control system enabling high speed data acquisition for the Donner 600-Crystal Tomograph (PET600). The system separates functionality so that control operations which are not time critical are handled by general purpose UNIX hardware. Only the most time-critical functions are controlled by the real-time clock of a 6809 microprocessor.

In our application, we chose to retain the existing 6809 microprocessor for control of the most time-critical functions. For a generic low level control application, one could rely upon higher level units accessible directly through CAMAC dataway commands. For example, a Jorway 221 12-Channel Timing and Sequence Module, a Joerger SMC-L Stepping Motor Controller, or a LeCroy 2366 Universal Logic Module would all provide considerable low-level control flexibility without requiring assembly-level code like a processor on the level of a 6809 board. Plug-in CAMAC boards like these could have easily been used instead of the 6809 boards for the stepper motor control or acquisition timing control of the PET600 tomograph

Generally, the choice of a generic UNIX workstation for higher level control allows for increased system flexibility and simplified system maintenance. For our particular application of replacing an outdated PDP 11/34 based control system, the UNIX-CAMAC hybrid approach enabled a system upgrade at a low hardware cost and minimal software development time.

VII. Acknowledgments

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