COMPUTER UPGRADE IN THE IUCF CONTROL SYSTEM*

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Abstract

After 15 years of service and nine years of beam operation, the second generation Xerox Data Systems Sigma-2 computer has been replaced by a fourth generation Digital Equipment Corp. PDP-11/44 computer. Since all readout and control functions are performed via computer in the IUCF control system, this replacement affects all aspects of cyclotron operation. Whereas both hardware and software development may start from scratch because the old and new computers are of completely different architectures, the long history of cyclotron operation imposes some very strong constraints, particularly in the man-machine interface. Major design considerations and implementation features are outlined, along with operational experience to date.

Introduction

IUCF is a three stage, multi-particle, variable energy accelerator facility for doing research in medium energy nuclear physics and has been delivering beams for experiments on a 24 hour/day, 7 day/week basis since 1976 [1]. From the beginning, a computer has been used to provide the man-machine interface for all but a few specialized devices. This control system has been described elsewhere [2] and has proven to be highly reliable, flexible and easily taught to new operators. Purchased in 1969, the original computer was a Xerox Data Systems Sigma-2 with 64KB core memory, a 3MB fixed head disk and no floating point hardware. With such meager physical resources, the original developers opted to shape a system which used the disk as an extension of memory and was programmable only in assembly language, making it accessible only to expert programmers.

In the Sigma-2 system, most operator interaction with the control system was through the Standard Cyclotron Display (SCD), whereby an operator could view updated status and position values for a list of up to 17 devices simultaneously, attach meters and knob or lever control to one or two devices, turn devices on or off and start limits checking or SEEK processes (see below). A detailed description of the SCD may be found elsewhere [3]. Different device lists were selected for display via pushbuttons. While there were a number of other programs invoked by the operator in running the cyclotron, easily 90% of his time was spent using an SCD. In a sense, the SCD was the control system as seen by the operator.

In general, the Sigma-2 was a very efficient system which kept up with the demands of increasingly sophisticated operations for many years. However, the costs of operating the Sigma-2 became relatively more important as the system aged. Hardware maintenance was always contracted to an outside vendor. Being limited to assembly language meant that complex jobs, particulary calculation intensive ones, were not attempted because too much tedious development effort was required. The disk capacity was so small that program sources had to be kept on tape and transferred between tape and disk whenever an improvement or new program was to be added; even so the disk was 95% full. Eventually, these costs and decreasing responsiveness to the demands of increasingly skilled operators combined to make replacement of the Sigma-2 mandatory.

Design

Several criteria were developed against which any new system was to be measured. Predictably, greater expandability and flexibility in both hardware and software were required. Response time, primarily the time required to display a new SCD list, was to be very much faster than on the old system. Most importantly, the new system was to replace the old with as little disruption of normal facility operation as possible. Since deficiences in the Sigma-2 were seen to be more quantitative than qualitative, massive change in how the operator interacts with the control system was not desired. Put another way, if the SCD appeared unchanged, then the entire control system could be revamped and the operator would never know the difference.

Two practical boundary conditions also existed. While a hard financial limit was never specified, cost for the replacement system was targeted at $100,000. Likewise, manpower was at a premium so that all software development would be a one-man job, among other things.

The first criterion listed above is met by any modern mini-computer system. The second criterion led us to adopt a two processor system, organized as a central computer and an operator station driver, and to plan to have as much data and as many tasks as possible resident in memory. The third criterion and second boundary condition meant that differences between the old and new systems would be evolutionary.

The new control system configuration is shown schematically in Fig. 1. A Digital Equipment Corp. PDP-11/44 was chosen as the central processor. In our context, use of a PDP machine offered us a choice of mature, accessible, realtime operating systems (we actually chose RSX-11M+), a wide selection of peripherals and related CPUs and a large physical memory capacity. If the same decision were made today, a Q-Bus system

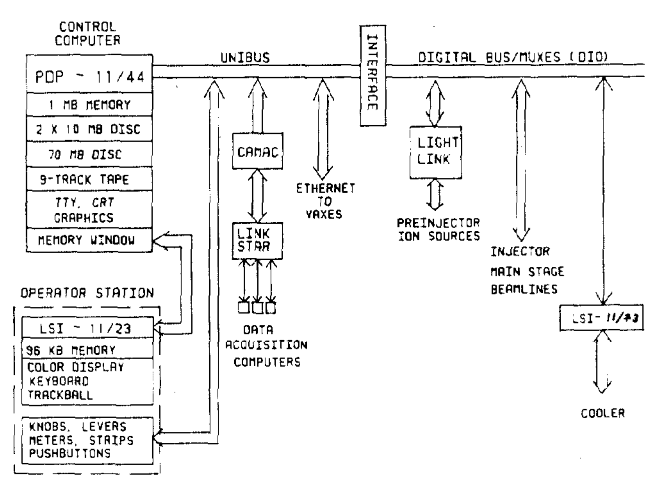

Fig. 1. Schematic representation of the new IUCF control system.

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would probably be chosen as offering a better price/performance ratio, as well as stronger vendor support in the future. At the time of selection in early 1981, these systems were not competitive in performance with the 11/44. Also at that time, at the other end of the spectrum, VAX-style machines included significantly more complex hardware, hidden software (VMS) and 32-bit computational performance we did not need in a 16-bit environment which is much closer to being I/O bound than compute bound. Hence, their price/performance ratio was seen as poor. Those arguments still seem valid today, although somewhat less compelling.

An LSI-11/23 was chosen to directly drive the operator station displays and handle input from trackballs and keyboards. This system has no mass storage; its only peripherals are the operator stations and a serial line for a CRT used for diagnostic purposes. RSX-11S is used to provide a convenient framework for interrupt and diagnostic terminal handling. A commercial "memory window" device (Ranyan PPL-1HU/PQ) uses special address decoding and DMA techniques to make physical memory on the PDP appear also to be on the LSI, although at a different physical address. It also provides a simple mechanism for each machine to issue interrupts to the other.

Hardware Implementation

The control bus that runs throughout IUCF is an extension of the Sigma-2 Direct Input/Output (DIO) bus, a high speed, parallel data transfer system using an 11-bit address space and a 16-bit data space [4]. Although it is as old as the Sigma-2 and constructed from discrete and SSI TTL logic, this system is extremely reliable and, in fact, under-utilized: during cyclotron operation, measurements show that only about 2KHz out of the 500KHz bandwidth available on the DIO

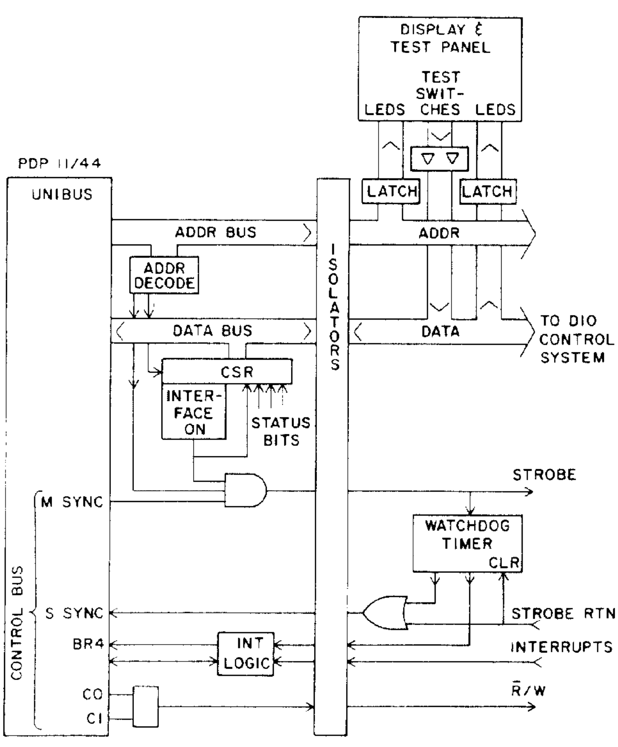

Fig. 2. Schematic representation of the IUCF UNIBUS to DIO interface.

is ever actually used. Given the boundary conditions mentioned above, replacement of the DIO bus was never seriously considered. Instead, a UNIBUS-to-DIO interface (see Fig. 2) was built which mapped the DIO address space into a 4KB region of the UNIBUS memory map space. This interface optically isolates the PDP from the electrically noisy environment of the DIO without introducing significant delays; data transfers are still completed in less than two μs. To avoid bus timeout, should a non-existent address be accessed, for example, a watchdog timer completes the UNIBUS cycle after a 10 μs wait and triggers an interrupt to inform the 11/44 of the problem. A second interrupt is provided to which are multiplexed all devices on the DIO which themselves generate interrupts. The interface can be turned on and off under computer control and contains switch and LED banks for diagnostic work.

While appearing almost identical to the originals, the new operator stations retain only the same trackball, knobs, levers and meters; everything from those devices back to the computer is new. All interfacing (and the software) are designed to support four operator stations, although only three have been implemented. For each station, a single quad-width Q-Bus video display generator board (Matrox QRGB-ALPHA) drives an RGB monitor (Princeton Graphics HX-12) and supports a membrane RCA VP601 keyboard. Trackballs and "ENTER" buttons are interfaced via DRV-11J cards to the LSI station driver while knobs, levers and pushbuttons are interfaced directly to the PDP via DR-11C cards.

Software Implementation

Basic control system functions are driven via a memory-resident database defining each device. The database is comprised of three sections containing name and miscellaneous information, acquisition characteristics and control characteristics. As an organizational aid, the database is divided into 48 segments of 32 variables each; some 750 devices are presently defined. These three sections, with accompanying vocabulary files, occupy slightly more than 56KB of memory.

To perform acquisition and control functions in a quick and standardized manner accessible by both normal user routines and interrupt routines, a memory-resident Supervisor mode library was written. Use of Supervisor mode allows access to large code and very large data areas without affecting user task address space (the one commodity which is at a premium in PDP systems). Normal user tasks enter the library by executing a single machine instruction (imbedded in a simple FORTRAN callable interface subroutine) and are re-entered from the library by a single instruction. Interrupt routines must enter the library by usurping a standard interrupt vector location from the operating system, a complex but fast process. The library is re-entrant, performs the functions listed in Table I, and occupies 6.5KB of memory for both code and internal table space. The library also implements pseudo-devices which are, in fact, combinations of acquisition and/or control functions on real devices.

Table I. I/O Library Functions

Acquire raw data
Acquire converted status, data
Set/read DAC position
Toggle status bit
Increment position (DAC or motor)
Own/free device
Generate name string
Switch loads, polarities
Start/abort task
Read device characteristics

Tasks in the PDP and the LSI computers cooperate to perform operator station functions via the memory window, the length of which is arbitrarily set to 8KB. All processes are interrupt driven. The software divides the windowed memory into areas, each associated with an unique interrupt location, which are then treated as circular buffers for data transmittal between computers. Typically, input to the PDP starts with the LSI recognizing some action by the operator, reading the keyboard or part of the display screen, loading this data into a windowed memory area if the data are legal and triggering an interrupt to a task in the PDP, which reads and acts on the data. Output from the PDP starts with a task loading data into a windowed memory area and triggering an interrupt to a task in the LSI, which then reads and interprets this data into displayable form and drives the appropriate physical I/O device.

The SCDs are driven from memory-resident lists of devices; there are 63 lists available, of which 50 are in current use. Tasks are paired in the two computers to perform SCD maintenance functions (e.g., add/drop devices, attach controls, set limits), handle knob or lever interrupts, collect and display data for screen and meter updating and do limit/fault checking on specified devices. This package of tasks requires 13KB of memory in the PDP and 14KB in the LSI.

From the SCD the operator can begin a SEEK process on any controllable device by specifying a readout value to which the device should be driven. A SEEK task uses predefined DAC slew rates and rate vs. time algorithms to reach the desired value. This is most useful for taking large magnets through reproducible hysteresis loops.

A logging task uses lists of devices with associated time periods to save readout values in disk files. From these files, values may be displayed at the operator station, printed or plotted on a medium resolution crt display.

The PDP also provides closed loop beam steering at various locations in the cyclotron system. The steering task allows control of sampling rate, DAC slew rate, desired beam current imbalance and "zero current" value to prevent magnet runaway when beam is off and readouts are noisy. Although a simple prototype hardware loop has been built and tested, the PDP task is so convenient and represents such a small load on the computer that installing them has dropped well down the priority list.

All the tasks listed above are memory-resident and written in assembly language. The operating system, all memory resident tasks and data and the memory window are located in the first 256KB of memory. All other tasks are written in FORTRAN and are loaded into the remaining 768KB from disk on demand. Such tasks include one to calculate major cyclotron parameters from first principles or fits to past values, given a particle mass and ionization state. The task can generate self-consistent values for all parameters as the user changes RF frequency or main magnet current, for example. Another task allows current DAC and ADC values to be saved in disk files for recall later. The DAC values can then be reloaded into the proper devices or DACs can be driven until the ADC values are matched. The task can also calculate ADC values from fits or tables instead of recalling them from a file. Although we have little experiece with this last method, it is hoped that it will provide good starting conditions for new beams and reduce run-to-run variations in standard beams. Of course, the most important task is that which lists the phone numbers of all lab technicians, to be consulted when midnight repairs are needed.

Summary of Experience

To date we have been very pleased with the performance of the new computer system. Online break-in tests began in October of 1984 and continued during normal cyclotron maintenance periods until mid-March of 1985, when the system was declared operational. Although minor bugs are still being corrected, use of the new computer has caused no significant loss of beam time and required no special operator education. Crude measurements show that, in normal operating conditions, with SCDs on all three stations, CPU utilization is 6% of the PDP. Operators have complained that SCDs are now generated so quickly that they must pay attention when changing SCD pages; otherwise, they often have the disconcerting perception that nothing has happened, even though the page change is complete.

Comparison of Fig. 1 with diagrams published earlier [2] shows that we have scrapped the M6800 driven status annunciator system which existed in parallel with the Sigma-2, absorbing its functions into the 11/44. The 11/44 communicates with the Harris data acquisition computers via CAMAC and with the new VAX data acquisition machines via DECNET running on Ethernet hardware. Finally, note that the cooler will have its own stand-alone control system, which will allow independent cooler development and cyclotron operation. This system will eventually be loosely coupled to the PDP-11/44.

So far this project has consumed about three man-years of software effort and slightly less than one man-year of hardware effort. Total cost has been roughly $106,000, including operator stations. While planned hardware development and purchases are complete, software development can progress much farther. It is intended that more of the operations staff become involved in programming the control computer now that higher level languages are available.

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