THE NAL COMPUTER CONTROL SYSTEM

R. E. Daniels, R. W. Goodwin, and M. R. Storm
National Accelerator Laboratory*
Batavia, Illinois

Summary

Equipment associated with the accelerator and experimental areas at the National Accelerator Laboratory is distributed throughout some ten miles of beam paths. The computer control system, which utilizes fifteen interconnected computers to control and monitor this equipment, is described. The clock, closed-circuit television, beam abort, and fire and utility monitoring systems are also reviewed.

Introduction

The ten-mile expanse of beam paths at the National Accelerator Laboratory clearly indicated during the early design phase of the accelerator that manual control of machine devices would not be adequate. Since first suggested by McMillan[1] in 1958, accelerator controls have become more and more computer oriented. The founders of the NAL design recognized the value of computer controls from the start, which resulted in the following design decisions:

1. There will be one control room for the accelerator.
2. It will be possible to have several control consoles active on the accelerator at the same time.
3. It will be possible to have remote consoles for special diagnostic purposes.
4. All accelerator devices will be compatible with computer control.
5. Secondary beam lines will be under the control of the experimental areas.
6. The interlocks on all safety systems will be hard-wired and only feed status information to the control system.

In addition to the above specifications, it was also decided that the fastest way to build a control system tailored to the needs of each major area of the accelerator was to have each group design the controls required for its equipment. Eventually, each of these control systems would then be connected to a large central computer.

After the major accelerator construction effort was complete two years ago a Controls Group was formed with the responsibility of consolidating the control systems. This group was eventually assigned to the Research Services Section, where it has the responsibility for developing, installing, and maintaining the systems for both the accelerator and the experimental areas.

*Operated by Universities Research Association, Inc., under contract with the U. S. Atomic Energy Commission.

System Configuration

Device Controllers

To allow the flexibility of each group designing a system satisfying its requirements, it was realized that a computer would be required in each area. The development of the linac control system utilizing a Xerox Sigma 2 Computer was already underway when it became obvious that a minicomputer would do equally as well for the separate accelerator areas. The Lockheed MAC-16 Minicomputer was selected as the standard for the Laboratory, and each section, except the linac, was given the responsibility for developing its individual control system using this computer. Additional Xerox Sigma 2 Computers were brought in to serve as central computers.

The MAC computer in each area of the accelerator talks with a number of device controllers to which the devices are connected. Although the approach of each group designing its own control system produced several different types of device controllers, each system was ideally suited for the area it controlled. Standard communication could still exist between the central Xerox computer and the MAC-16 computers.

The MAC computers presently in use on the accelerator and the characteristics of their device controllers are shown in Figure 1. As one might expect, the rapid cycling machines, Linac[2], Booster[3], and Radio Frequency[4], where data is collected at a fifteen-hertz rate, have parallel data links between the device controllers and the controlling computer. Fortunately, the control systems in these areas extend for relatively short distances. Other areas, extending over longer distances and where the data rate is lower, have serial links. FIRUS[5] is the Laboratory Fire and Utility Monitoring System which covers the entire accelerator and experimental areas.

The word rate on the parallel data links is primarily determined by the speed of the computer I/O channels, which averages 100 kilowords per second. In the serial data links the speed of the serial link, the length of the word, and the distance are all important factors. The switchyard and experimental areas run at a one-megahertz bit rate, the main ring at one-half megahertz, and FIRUS at one-quarter megahertz. The speed of the FIRUS link was reduced to increase reliability and to allow for greater distances between repeaters.

In both the main ring[6] and the experimental areas[7], a device controller can be assigned more than one address, thus allowing

SYSTEM	NUMBER OF MAC COMPUTERS	MAC CORE (DISC)	CONTROLLER LINK: SERIAL PARALLEL	BITS PER LINK WORD	WORD RATE	TOTAL LENGTH	NUMBER INSTALLED	COMMENTS
LINAC	0	—	PARALLEL		100K	500'	4	XDS HARDWARE
BOOSTER	2	8K	PARALLEL		100K	800'	15	CAMAC
RADIO FREQ	3	8K	PARALLEL		100K	1200'	35	SPECIAL CONTROLLER
SWITCHYARD	1	16K	SERIAL	34	20K	10000'	28	CAMAC TYPE HARDWARE
MAIN RING	2	16K 8K	SERIAL	32	10K	23000'	28	SPECIAL CONTROLLER PLUS S.Y. CRATE
EXPERIMENTAL AREA	3	24K(D)	SERIAL	70	10K	11000'	38	CAMAC
FIRUS	1	16K	SERIAL	34	5K	50000'	25	SWITCHYARD HARDWARE
SPARE MAC	1	24K(D)						
SIGMA/MAC LINK (OLD)			SERIAL	19	10K			2 FUNCTION CODES 1 PARITY BIT
SIGMA/MAC LINK (NEW)			SERIAL	24	70K			8 FUNCTION CODES 2 PARITY BITS

Figure 1 MAC and Device Controller Summary

several crates to be addressed simultaneously or each separately. This has been particularly useful for controlling main accelerator power supplies and for supplying to experimenters data about the accelerator operating conditions.

All serial systems have one cable for data-in and one cable for data-out. In addition, the switchyard and experimental area systems have a third cable for block transfer of data from device controllers to the automatic data channel on the MAC computers. After this channel is initialized, data transfers take place independently of the normal data channel. This feature greatly reduces the link and computer time required for scanning A/D channels and for obtaining blocks of data from beam profile monitors.

All device controllers can revert to local control for testing and troubleshooting and are equipped for controlling a 64-channel A/D converter. The switchyard, experimental areas, and FIRUS all have provision for branching to three locations, a necessary feature in these systems. All systems include error checking on returning data to certify proper link transmission. Communication between the computers and their device controllers is always initiated by the computers.

There exist a number of NAL standard device modules for plugging into the Booster, switchyard, and experimental area systems. These include a D/A power supply module, stepping motor/induction motor module, A/D controller module, 16-bit input module, function generator module, 16-bit output module, and timing pulse generator module. In the experimental areas a 64-word buffer memory module, pulse train generator module, and experimenters' terminal interface module are also used.

Throughout the regions where device controllers are located, a minimum of ten control cables (hardline or flexible coax, or twinax) are installed for carrying the necessary control signals. These include the clock, data-out, data-in, television-out, television-in, FIRUS-out, FIRUS-in, and the block transfer data-in channel. Hardline CCTV cables are used in the switchyard and to the experimental areas because they are installed in underground flooded ducts. This is a standard practice and causes no problems if cables are properly installed.

During the past two-and-one-half years the control system has continued to evolve, particularly in the responsibilities assigned to the MAC and Xerox computers and in the manner in which the operators use the system. The present, and what is believed to be the final, role of each of the major components in the control system is shown in Figure 2.

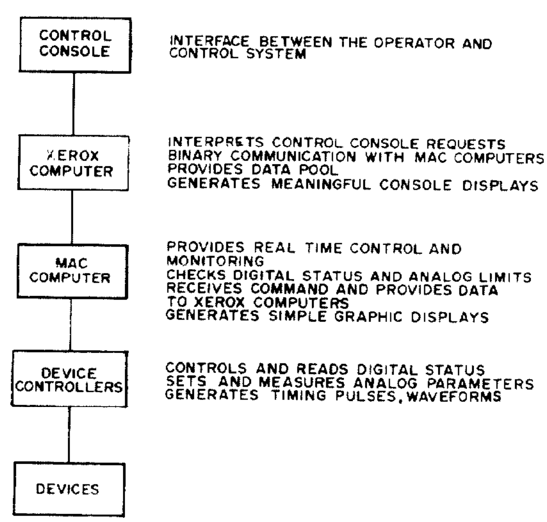

Figure 2

Hardware Hierarchy

The Xerox computer is equipped with 48 K of core, a disc, and twelve interrupt levels. It uses the Xerox RBM (Real-Time Batch Monitor) operating system, which is a relatively powerful system providing foreground/background capabilities. The Xerox computer core assignment and timing cycle is as shown in Figure 3.

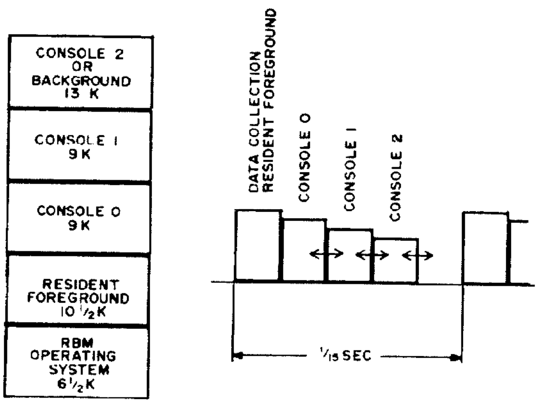

Figure 3

Xerox Computer Core Allocation

The resident foreground includes the data pool, the remote and local console servicing programs, library routines, and other short programs necessary for some auxiliary tasks.

The non-resident foreground is divided into two areas reserved for the application programs associated with control consoles 0 and 1. The background can be used either for program development or for the application program operating control console 2. In order to avoid having to keep multiple copies of application programs on the disc each relocated to run in a different region of memory, a relocating loader was developed which brings in a core image program from disc and relocates it before execution. Overlaid programs are relocated into another disc file (taking about 0.5 seconds) before execution so that no overhead is required for overlay loading during execution.

The Xerox computer operates at a fifteen-hertz rate in servicing consoles and communicating with the MAC computers. This provides a good response time to the consoles and is consistent with the pulse rate of the injector. The control console application programs are serviced sequentially with console 0 normally having the highest priority. If a console is initializing an application program or executing a program not related to on-line control, it receives lowest priority. Measurements have shown that the CPU is working approximately 90% of the time when servicing a console, and there would be no advantage to re-entrant programming.

The control console application programs are written in FORTRAN IV. There are approximately one-hundred assembly language subroutines related to the controls hardware which can be called by the application programs. Programmers, engineers, and physicists have written application programs ranging from relatively simple control programs to closed-loop optimizing programs.

The Xerox computers interpret commands from the control console, take action, or request the MAC computers to perform the required tasks. They contain the A/D data pool which is regularly updated by the MAC computers, and they generate meaningful displays for the operators. In refreshing the data pool the MAC sends only data to the Xerox computer. When sending commands to the MAC the Xerox computer sends a device code, command, and data.

The control console provides the interface between the operators and the control system. It has the necessary knobs, buttons, and keyboard with which the operator instructs the control system to perform selected tasks. Performance of the accelerator is indicated to the operator by an interactive, multicolored text display terminal, computer generated CRT graphic displays, and by the television systems located on the control consoles. Hard copies of the displays are obtained by using the Tektronix 4601 Hard Copy Unit.

An effort has been made to eliminate all "secret codes" on the interactive and graphic displays. Names for devices are used in place of call numbers to make them easier to remember. Selectable commands in each application program are clearly written on the interactive terminal. On graphic displays axes are clearly labeled, gain adjustment and zero suppression are easily set, and parameters and time of day are indicated.

A facility for ganged tuning makes it possible to adjust local orbit bumps in a circular machine. Files of device settings which may be stored, restored and compared facilitate the tuning of some 200 correction dipole magnets used in the main ring. A facility known as the "fast time plot" provides for on-line generation of a time plot of one or two A/D readings sampled at a rate of up to 300 hertz.

The general method by which an operator communicates with the control system is by requesting a load of a disc-resident application program which generates a display on the interactive terminal. By using the cursor, knobs, and buttons, he can then command a variety of tasks associated with the applications program to be done. Data presented to the operator is regularly updated so he can follow his progress.

Remote consoles are provided whereby a portable case having a trackball, knob, and keyboard can be plugged into a device controller and used in place of one of the control room consoles. Displays are then transmitted to the remote location via the television system.

The MAC computer is responsible for providing real-time control and monitoring, scanning devices for correct status and analog settings, sending alarms to the Xerox computer, generating simple graphic displays, and interpreting the commands from and sending data to the Xerox computer. It is also used as a software function generator, for making measurements at selected clock times, and for temporary storage of data needed by the Xerox computer.

If a Xerox or MAC computer fails, no commands can be sent or data collected from the affected areas. The accelerator will continue to operate, however, unless the failure occurs in the main ring power supply MAC 8. This MAC is the only one planned for operating in a real-time closed-loop system, and it regulates the main ring magnet current.

In addition to the above duties, the experimental area MAC computers each service up to ten experimenters' control consoles. These consoles consist of a keyboard, two knobs, and a CRT terminal interfaced to a CAMAC-type device controller. These consoles can monitor all devices in the experimental area in which they are located and can control devices in the same area that are assigned to them. At the discretion of the Main Control Room it is also possible to assign control for up to ten accelerator (generally switchyard) devices to selectable consoles in each experimental area.

The communication between the Xerox and MAC computers is a core-to-core block transfer via a fast serial data link[11]. The link is also used to allow a complete system restart of a MAC from a control console, requiring a few seconds.

The final NAL control system configuration which is expected to be operational by the end of the year is shown in Figure 4. Three Xerox computers will be centrally located; one for controlling the injector, one for the main accelerator/switchyard, and one for the experimental areas. A fourth Xerox computer will provide backup in case of breakdown of one of the three on-line systems; otherwise it will be used for software and hardware development. The three on-line systems are connected to the backup system by peripheral switches which can be controlled either manually or by software. The background peripherals are also connected to the computers through peripheral switches. Data exchange between the Xerox computers will be through the CIU (channel interface units) links.

Each Xerox computer will have a 48-megabyte dual spindle disc pack and floating-point hardware. The system is intended to operate on one spindle and be periodically saved on the other. Activating the backup system will require tripping the toggle switch controlling the peripheral switches and moving a disc pack to the backup system.

The MAC computers are located in the MAC Room adjacent to the Xerox Computer Room. A fully-equipped MAC will be available to back up the on-line systems, to run a device controller test station, and as an aid in software and hardware development. After the backup MAC is operating it is hoped that recovery from a MAC failure will occur in less than five minutes.

FIRUS

The Fire and Utility Monitoring System (FIRUS) extends over the entire accelerator, central utility plant, experimental areas, shop areas, and the substation. For monitoring fire detection systems, a special minicontroller compatible with the switchyard hardware was developed with a capacity of sixteen monitoring points. Each monitoring point can be computer set to check proper operation of the control hardware. This is done automatically every ten seconds, or on request. Regular device controllers from the switchyard system can be used downstream from the minicontrollers for use in monitoring and controlling the utilities systems.

Monitoring stations having a hard-copy terminal and alarm box are located in the Operations Center, at the Laboratory telephone operator's office, and at the fire station. All changes in status of monitored devices and time of occurrence are reported to all operating terminals. Computer or program failure is indicated by a special alarm. A log of unusual status is printed on all terminals every four hours, or on demand. In the

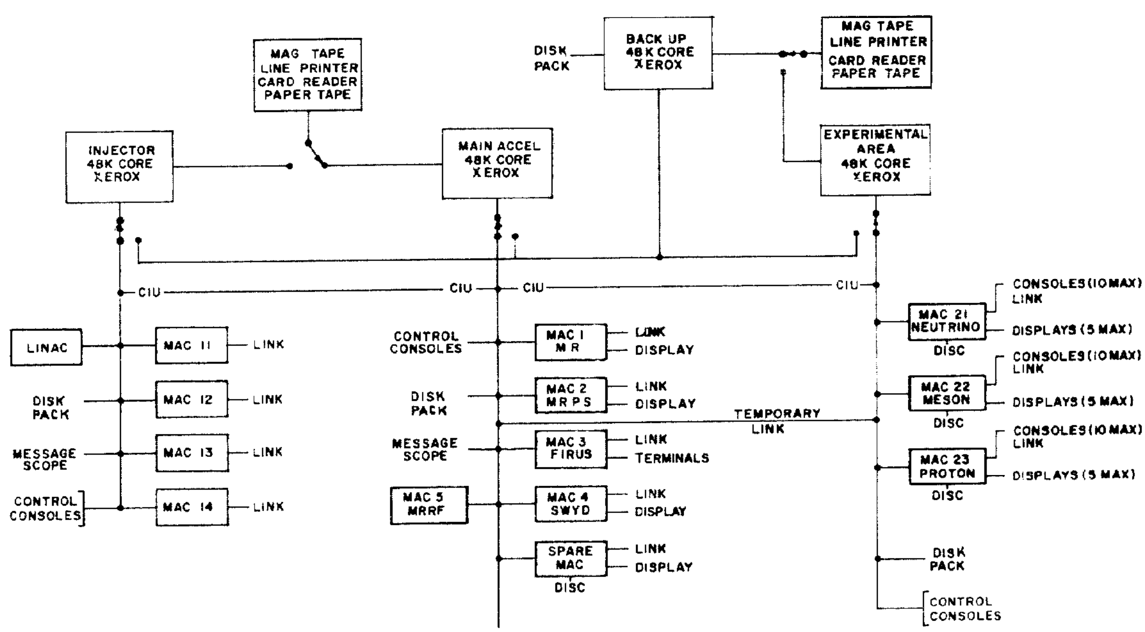

Figure 4 Final Configuration of NAL Control Computers

near future radiation alarms from throughout the site will also be reported on this system.

Clock

A clock signal having a nominal frequency of one megacycle is distributed throughout the accelerator and experimental areas to guarantee rigid control and synchronization of events. This signal is used to control the programming of the Booster line-locked, fifteen-cycle resonant power supply and to control and regulate the sixty Main Ring power supplies. Both of these systems are pulsed directly from the power line, thus requiring the clock to be phase locked to the power line frequency. Injection into the Booster always occurs at the same phase angle of the line voltage, and within the tolerance of the Main Ring power supply regulating system one can assume that the clock time and energy of the beam in the Main Ring is uniquely related.

The clock signal is also used for generating timing pulses for control of equipment and operations throughout the Laboratory; thus, it needs to be easily accessible and easy to use. The most acceptable short unit of time is the microsecond; thus, a clock signal having 16668 pulses each cycle of the power line was adopted. This provides a clock signal having a nominal frequency of one megahertz that is easily divided down for use with both the Booster and Main Ring power supplies. The actual frequency is 1,000,080 hertz when the line frequency is sixty hertz. The clock signal is transmitted on one cable and is repeated and distributed at control stations throughout the Laboratory.

Up to fourteen selected reference times can be encoded on the clock signal by using a phase reversal technique[9]. Some reference times, such as start of injector cycle, start of Main Ring cycle, start of flattop, are always encoded on the clock signal. Other reference times, such as injector extraction, are always present but jitters somewhat with respect to clock time by an amount depending on other real-time parameters. The reference time associated with Main Ring fast extraction may not be present on some machine pulses but be present several times on other pulses. A priority system in the phase reversal generator prevents overlap of reference times.

Both manual and computer-set timing modules which plug into device controllers are available. These generate a timing pulse at a settable clock time occurring after the preselected reference time.

Television

Extensive use is made of closed-circuit television in both the accelerator and experimental areas. There is a total of seven closed-circuit systems, each covering the band of frequencies from 50 megahertz to 260 megahertz. This allows transmission of the standard twelve VHF channels plus nine midband channels (A thru I) whose frequencies are between those of Channels 6 and 7. If necessary, the superband channels (J thru O) could also be added to the systems.

Each system uses two hard-line coaxial cables, connected at the Main Control Room, that extend from the Main Control Room to and throughout the area of coverage. All television channels can be monitored in the Main Control Room. One line is designated the transmitting line, and taps are conveniently located to attach modulators. The other line is the receiving line, and taps are provided for connecting signal splitters and/or standard television receivers. This arrangement allows a receiver to select any of the twenty-one channels on the system. A relatively inexpensive converter ($35) provides for receiving the midband channels.

There is one television system for the injector covering a distance of approximately 500 feet, two for the Main Ring each covering approximately 11,000 feet, one for the switchyard having three branches and covering 12,000 feet, and one in each of the three experimental areas covering a total distance of 28,000 feet. On the experimental area systems are channels from the Main Control Room indicating status of the accelerator.

Each control console in the Main Control Room has several television receivers which can be patched to any of the seven systems. Each console also has a microphone which can be switched to the audio input of any one or all seven Channel 12 modulators, a channel assigned to the Main Control Room. Receivers are located at strategic places throughout the accelerator and experimental areas, with at least two assigned to each experimenter.

Video sources connected to the TV modulators are TV cameras, scan converters, and CRT terminals. There are computer-controlled multiplexers in front of many modulators to allow selection of any one of several video sources. Selectable channel demodulators are used with Tektronix 4602 Video Hard Copy Unit to obtain hard copy of television pictures.

Acknowledgments

It is a pleasure to acknowledge the contributions of all the Controls Group personnel and the encouragement and support offered by Dr. R. R. Wilson, Laboratory Director.

References

1. D. McMillan, Internal Memo, Argonne Nat'l. Laboratory, September 1958.
2. R. Goodwin, Proc. of the 1970 Proton Linac Conference, p. 371.
3. L. A. Klaisner, et al, IEEE Trans. on Nucl. Sci., NS 18, Feb. 1971.
4. M. Birk, et al, Proc. of the 1971 Particle Accelerator Conference, p. 427.
5. W. DeLuca, et al, 1973 Particle Accelerator Conference.
6. D. Sutter, Proc. of the 1971 Particle Accelerator Conference, p. 432.
7. L. Hepinstall, 1973 Particle Accelerator Conference.
8. R. Cassel, 1973 Particle Accelerator Conf.
9. C. Swoboda, et al, 1973 Particle Accelerator Conference.
11. S. Smith, et al, 1973 Particle Accelerator Conference.