COMPUTER CONTROL OF HIGH ENERGY ACCELERATORS

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Abstract

The complexity of high energy accelerators has increased to the point where digital control techniques offer significant advantages. The basic techniques and equipment have been developed over the last ten years for use in chemical and steel plants. Some of these techniques can be used in modified form on high energy accelerators. The amount of time required for analog-to-digital conversion and for computer input-output operations limits computers to supervisory type control. The relatively slow output rates from the computer, in combination with the precise timing requirements of the synchrotron, indicate that a special buffer is required between the computer and the synchrotron. This buffer should be able to store and execute the instructions necessary to adjust all variables (magnitude and time) that are under computer control. Present control computers are so well perfected that most of the development effort goes into suitable sensing equipment and into computer programs. Injector alignment, analysis of coasting beam, control of tune, and control of characteristics of the beam to each of several experiments are some of the functions that appear to be realizable.

Introduction

Digital control of a high energy accelerator represents a unique application and extension of techniques that are well known in industry. The development of these techniques was accelerated by three seemingly unrelated events in the late 1940's. These three were the development of digital data logging systems for the process industries, the development of small fire control computers for military aircraft and perhaps most important, the teaching of the dynamic concepts of servomechanism theory to chemical engineers.

These developments, coupled with the attempts of military suppliers to diversify into the industrial market, produced proposals for computer control of specific chemical and petroleum plants. Serious consideration was given to computer control about 1955.[1] Application to a catalytic polymerization plant soon followed. Since that time, the technical development has been so rapid that over 500 process control computers were in use at the beginning of 1965. Orders indicate that an additional 200 systems will be installed this year.

A survey[2] in September of 1963 showed 92 computer control systems in petroleum and chemical plants. It showed 55 control computers in metal industry plants such as steel mills. Power plants, including nuclear ones, contained an additional 117 computer control systems. The other 75 systems that were publicaly announced before September, 1963, control a diverse range of processes.

During the last decade, a very large research activity has developed in the computer control field. This research has included theoretical work in the universities as well as work on new methods and systems. Topics have ranged from advanced theoretical ones such as operations research techniques, Pontryagin's maximum principle, and dynamic programming techniques to hardware topics such as multiplexing methods, noise rejection techniques and analog-to-digital converter accuracy and reliability. We in the accelerator field can get an over-all perspective of the present state-of-the-art by noting that over 1000 papers were published last year. The Annual Review article by T. J. Williams[3] gives an excellent, although restricted, summary of the more recent progress. The Annual Review article by R. F. Sweeny and others[4] gives a similar summary of the field of mathematics in chemical engineering.

The designer of a computer control system for high energy accelerators may learn much from studying the wealth of experiences with industrial computer control systems. He can learn the values and pitfalls of certain techniques even though commercial companies are reluctant to publish failures and "process secrets."

Data Loggers

The data loggers built about 1950 were of the wired program type. The data points were scanned

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at a fixed rate and in a fixed sequence. The output was usually by typewriter on a preprinted log sheet. High-low alarm circuits were often incorporated into the system.

Operational experience showed several shortcomings that greatly reduced interest in these logging systems. During "normal" plant operations, the logger produced page after page of nearly identical records. This caused the plant operator to disregard all but an occasional reading. During "upset" plant operations, the logger typed-out data at its maximum rate. These data were seldom very useful in pinpointing the cause of the "upset," since many variables such as bypass valve positions and product compositions were not logged and because a large fraction of the logged variables would go "off normal" at nearly the same time. These experiences convinced many who managed process plants that the recording of a large mass of raw data was of little value.

It is interesting to note a parallel in the data recording techniques used in some experiments today. Little preselection of data results in the need for a very powerful recording system and for a large amount of computer time to reduce the data. It will be interesting to see if chance discoveries can make this approach economically justified.

Some of the data logging equipment typed-out in the owner's accounting office so that a business type computer could keep plant records. Two problems were immediately brought into sharp focus. One was that conventional plant instruments were not very accurate. The other was that accountants didn't know what to do with data containing 5 to 10% errors.

The designer of a computer control system for an accelerator must solve similar problems today. He must not design a system that takes too much data for the computer to analyze on-line. He must be willing to devote a large effort to improving beam sensing devices and to making the computer control insensitive to "noise" or errors in input data.

Supervisory Control System

The digital control computers built in the late 1950's were often modified versions of the fire control computers or were similar. They used magnetic drums for working memory and consequently were relatively slow. Data inputs were usually analog voltages or currents that were switched sequentially to a single analog-to-digital converter. Output was usually through a single digital-to-analog converter. This analog output was switched in turn to the "set point" or command input of each of the several analog control instruments.

This type of control computer system is referred to as a supervisory system. It periodically monitors the performance, compares this with a predetermined norm, and then readjusts the commands to the several control instruments. This type of system is the natural choice for those processes whose variables change too fast for the computer to follow.

More recent control computers have used magnetic cores for working memory. Some use cores for a limited amount of data storage while others use magnetic drums or disc files for "bulk" storage. This has increased the computing speeds. The control computer, however, still tends to be a factor of ten to a factor of one hundred slower than the best scientific computers.

Experience with supervisory control computers has led to a number of general conclusions.[5] (1) The design study for a computer control almost invariably is much more detailed than would otherwise be needed. This leads to a much better knowledge of the process. (2) The justification for computer control increases with plant size. It is almost always justified if the process plant costs over ten million dollars. (3) The use of the computer for alarm functions ties up too much computer time. A separate system is cheaper. (4) More tasks are assigned to the computer than originally intended. This requires that the system be easily expandable.

Recent trends in supervisory control systems are toward multilevel computer systems[6] and toward systems that analyze the process on-line to discover how to control.[7] None of the present systems seems have enough computer capacity to utilize the advanced mathematical techniques available for dynamic optimization.

Direct Digital Control

The improvements in computer capabilities and speeds during the last few years have made possible the elimination of analog control instruments in some processes. In this type of system, the primary measuring device transmits directly to the computer. The computer then transmits a command directly to the control device. This has been tested on a pair of distillation columns.[8] A complete direct digital system for a soda plant has been in use for two years.[9] Performance has been so good that nine more systems are on order. A direct digital control system for eight neutron spectrometers has been described.[10] This is expected to be in operation by mid 1965.

Computer Systems for Use with an Accelerator

Several computer systems have been used to analyze experimental data on-line or to control experimental apparatus.[11] Most of these systems are concerned with data from pulse-height analyzers. One system[12, 13] extends this type of operation to include an aperiodic changing of the energy of the Van de Graaff to fit the needs of the experimental program. These systems are aimed primarily at acquisition and analysis of experimental data, hence they do not provide the capability for optimizing the accelerator.

Work now underway at several laboratories is aimed at extending digital computer control to high energy accelerators. Some of the progress will be described in papers given later at this conference.[14]

Work at Argonne National Laboratory's Zero Gradient Synchrotron is aimed at evaluating the effectiveness of computer control. Optimization of the accelerator performance from injection to the delivery of a beam to each of the experimental areas is a prime objective. The present computer control system is capable of handling a few control loops simultaneously. Additional computational capacity will be needed to perform optimization calculations on-line when these involve orbit calculations in the ring and in the external beam lines.

The design of the present computer control systems at the ZGS has required solutions to a number of problems that are common to other accelerators. Because of this, the characteristics of the system at the ZGS, and the reasons for these choices, may be of interest. The simplified block diagram of Figure 1 shows the major systems. These systems are the result of design and development work performed by W. H. DeLuca, F. B. Hall, A. Hemel, R. Herrmann, M. J. Knott, L. G. Lewis, and R. Trendler.

The ZGS Monitoring System

The ZGS monitoring system provides the control computer with digital data taken during each accelerating cycle. A few of the measurements, such as oscillator frequency, are made digitally. Most data however exist in a form that must be translated into digital notation.

The position of a focus in a beam pipe is an example of a set data that is difficult to translate into digital form. This particular problem can be solved with the aid of sets of special electrodes in the beam pipe. The electrodes and associated special sample-and-hold amplifiers translate data on the lateral position of the beam into analog voltages. These then can be converted to digital form by conventional equipment. A series of such measurements made at different values of computer adjusted currents through quadrupole and bending magnets can provide the required data.

Two conclusions are made obvious by this example. One is that a considerable effort must be put into the design of special beam sensing electrodes and associated amplifiers. These should provide data to the control computer without disrupting delivery of the beam to the experimental area. The second conclusion is that much of the data for describing the performance can best be obtained over a number of accelerator cycles. This suggests that the computer control must be of the supervisory type.

This last conclusion is strengthened by two other factors. Most of the available analog-to-digital conversion equipment, that is capable of 0.1% to 0.01% accuracy, requires times of the order of 50 to 100 microseconds per conversion. The second factor is the input/output speed of the computer. Many control computers today have I/O speeds as low as 25 kc character rates. Even the best speeds, which are equivalent to about 1.5 megacycle character rate, are inadequate for the synchrotron injection period.

The ZGS monitor contains seven analog-to digital converters of ten bit accuracy (0.1%) and two systems of 14 bit accuracy (0.01%). Each of these is preceded by a sample-and-hold amplifier. Each of these amplifiers is preceded by a 32 or a 64 point multiplexer that is addressable from the computer. A maximum of 352 analog voltage sources may be connected to this system. This "slow" system is operated to provide a minimum time of 100 microseconds per conversion.

ZGS injection takes place over an interval of roughly 200 microseconds. Data on injection conditions and on coasting beam must be taken therefore at a rate of several megacycles. One "fast" monitor system consists of an A to D converter that requires 0.2 microseconds per conversion to a 7 bit accuracy (~ 1%). This same converter requires 0.5 microseconds per conversion to an 8 bit accuracy (~ 1/2%). This system is provided with two multiplexers. One is a fixed sequence 24-channel multiplexer that can operate at a one megacycle switching rate.

The other is an 8-channel multiplexer that can work at a five megacycle rate. This system includes a special fast buffer memory that can transmit data words to the computer on request.

These several monitor systems are provided with an interface that makes the ZGS look like a piece of computer peripheral equipment.

The ZGS Control Computer

The present ZGS control computer has a 24 bit word and utilizes five megacycle clocked logic. This makes possible a full 24 bit addition in 1.2 microseconds. A 32,000-word core storage is provided. The input/output channels and the synchronizer have been improved so that the fully buffered input/output operation proceeds at a rate of one 48 bit word per 11 microseconds. A priority interrupt system is included for I/O operations. The computer connects to five magnetic tapes, a line printer and an X-Y plotter.

Data taking at the maximum rates of the ZGS analog-to-digital converters can generate the equivalent of about 500,000 decimal characters per second. This includes data identification bits. This number is so large that continuous data taking at the maximum rate is impossible and undesirable.

This problem is solved by controlling the data taking with the computer. The computer does this by transmitting bits to each of the multiplexers. These bits cause a particular analog input to be connected to the associated sample-and-hold amplifier. The computer then transmits a word to the ZGS Programmer to define the "time" at which the next measurement should be made. The timing pulse causes the sample to be taken and the digitizing to proceed. In this way, only those data that are requested are transmitted to the computer. The amount of data that can be analyzed on-line is limited by computer capabilities rather than by this data taking system.

Computer programs analyze parts of these data to produce printer and plotter output for the operator and for the ZGS engineers. Other computer programs analyze parts of these data to determine changes in the program for operating the ZGS.

Present experience with the control computer indicates that more advanced optimizing calculations will require built-in floating point hardware and commands. A higher language such as ALGOL should be available in addition to FORTRAN. In addition, self-checking routines are needed to test the up-dated operating program for reasonableness.

The up-dated operating program calculated by the computer is in digital form and contains a series of instructions. Some of these instructions specify the points in the ZGS cycle at which specific synchrotron functions shall occur. Other instructions specify magnitudes of ZGS parameters such as voltage levels or servo positions. These instructions are not converted by the computer to signals suitable for the ZGS because the output rate from the computer is too low to permit the timing accuracy required for injection. Instead, the up-dated operating program is transferred to the ZGS Programmer system for translation into appropriate signals to the ZGS.

The ZGS Programmer System

The Programmer system is based on a 1024-word by 40 bit ferrite core memory that can be read nondestructively. Access time to a word or instruction is less than 100 nanoseconds. A complete cycle that consists of reading a word, executing the instruction and transmitting the time signal can be performed in 700 nanoseconds.

Ten bits in each word select the cable over which the signal will be sent, thus determining the function to be performed. Each cable has a single purpose and destination so that "cable number" and "function code" are equivalent. A part of the total number of cables is used internally in the Programmer to select subroutines or to select or reset clocks. A total of 512 cables or function codes is provided.

Four bits in each programmer word are for clock identification. Up to 16 clocked intervals may be used in one ZGS acceleration cycle. Each of these clocked intervals uses one of the four clocks available in the Programmer.

Two real time clocks are available. One consists of a one megacycle oscillator that feeds a counter. This has a range of 0.1 second. The other contains a divider on the one megacycle oscillator to provide a 10 kc signal to feed the counter. This has a range of 10 seconds. Either of these clocks may be selected at will or zeroed at will by programmer instructions.

Two clocks depend on the magnetic guide field B. These operate from signals induced in single-turn coils mounted around the poles of each ring magnet octant. The induced voltages go to voltage-to-frequency converters. Pulses from these converters go to reversible counters. The scale factors are chosen such that both are direct reading in gauss. The clock which is used for injection has a range up to 999.98 gauss in steps of 0.02 gauss. The other has a range of 0-25,000 gauss in steps of 1 gauss. These are preset each cycle to 433.00 gauss by a pulse from an electron resonance probe. The slower gauss clock will count up to 21,500 gauss and back down to the starting point to within about 2 gauss or 1 part in 20,000.

Eighteen bits in each word are used for the "value" portion of the instruction. In the case of timing signals, this is interpreted as the number of one microsecond intervals or the number of 100 microsecond intervals or as the number of gauss in the guide field, depending on the clock selected.

Table I

Word Number	Cable Number	Clock Interval	Value
.	.	.	.
5	0011	02	+00500
6	0707	03	+00001
7	0641	03	+00001
.	.	.	.

Table I shows a portion of an operating program. Word number 5 selects the 10 kc real time clock, zeros the counter and starts the oscillator when the ring magnet guide field has fallen to 500 gauss after a ZGS pulse. A timing pulse is generated on cable 0707 to 100 microseconds after the clock starts. This calibrates the "slow Q" system. At 700 nanoseconds after the cable 707 pulse,a pulse is generated on cable 641 to turn off an analog beam positioning system.

The Programmer controls the magnitude of the ZGS parameters by transferring digital words from the programmer memory to remote locations. Those parameters that are adjusted before injection may be changed with single word control instructions. The first ten bits of each word control the parameter to be adjusted while the last 18 bits determine the magnitude. Target servo positions, supply voltages, DC magnet currents and main generator initial speed are set this way. Scale factors are adjusted so that the digital value is in amperes, volts, thousandths of an inch or some other appropriate unit.

Table II

Word Number	Cable Number	Clock Interval	Value
1	1001	01	+00000
2	1021	01	+00330
3	1773	01	+01934

Table II shows the portion of an operating program that makes initial adjustments of ZGS parameters before injection. The first instruction resets the main generator voltage to "normal." Instruction 2 sets the ZGS pulsing period to 3.30 seconds. Instruction 3 selects the speed of the generator at which the main rectifiers are turned on. The value is 0.01934 seconds per cycle of generator voltage.

The words which are transferred to a remote location are held in a digital register. The number in the register serves as an input to a digital servo or an input to a digital-to-analog converter.

Any of the parameters that are set before the beginning of the ZGS acceleration may be changed during the acceleration. A two-word instruction and a subroutine accomplish this. The first word selects the subroutine, cable 0004, at the "time" specified in the 18 bit "value" portion. The second word in the group specifies the parameter to be adjusted and the magnitude. A series of such two-word instructions is used to program the ring magnet generator voltage. In this case the output of the digital-to-analog converter feeds a pseudo analog integrator so that the function to the exciter is a series of ramps of different slopes.

Table III

Word Number	Cable Number	Clock Interval	Value
97	0004	06	+07650
98	1001	00	+01025

Table III gives a section of a program for changing the main generator voltage during an acceleration. When the ring magnet reaches 7650 gauss, a pulse on cable 4 causes the number +01025 to be transmitted over cable 1001 to the power house. This adjusts the generator voltage to 10.25% above "normal."

The digital words transferred from the Programmer in response to the single-word instruction or in response to the "cable 0004" subroutine are sent as serial pulse-trains by multiplexing methods. These are restricted to those parameters that do not need to be changed with time resolution of less than 100 microseconds.

Two-word instructions provide for parallel transfer of the bits of the magnitude portion of the word within one microsecond. A series of such groups is used to program the ring magnet DC voltage.

Table IV

Word Number	Cable Number	Clock Interval	Value
76	0001	06	+01083
77	0000	00	+01740

Table IV gives a portion of an operating program that adjusts the voltage applied to the ring magnet. At 1083 gauss, a pulse on cable 0001 causes the number 1740 to be transferred to the circuits that control the main rectifier firing. The number cannot be made equal to the voltage on the magnet because of variable IR drops in the rectifier transformer circuits.

Several of these cable 0001 instructions may be used to produce any gauss versus time curve that is within the capabilities of the power house. These instructions provide control of the shape of a flat-top and control of shape of the B versus time curve during a "pause" in the acceleration. Figure 2 shows some of the general features of the gauss time curve. Experience so far shows that this system can maintain the flat-top to ±2-1/2 gauss in 21,000 for that part of flat-top beyond about 20 milliseconds after start.

A second series of such two-word groups is used to program the rf master oscillator frequency.

Three word instructions are provided for beam steering. In this case, the first word selects the subroutine at the specified "time." The second word specifies the rate of change of the orbit radius while the third word specifies the new final value of the orbit radius. A series of such three-word groups provides a part of the control commands necessary for beam splitting and control of spill by the control computer.

The ZGS Programmer is provided with a manual control console. The operator may load in a new program from punched paper tape, or punch-out a record of a program already in memory. He may use thumb-wheel digital switches to add, delete or change an instruction in a program that is in memory. He may also obtain a typewritten record of the instructions stored in the programmer memory. These manual controls make it possible to operate the Programmer and the ZGS independently of the control computer. Figure 3 shows the block diagram of the programmer input/output paths.

Operating experience with the Programmer has demonstrated an unusual capability and flexibility. This flexibility appears to be sufficient to provide a satisfactory execution of the control computer output. The longest programs used so far contain about 200 instructions so that six different complete operating programs are generally stored in the programmer memory at the same time. A repertoire system permits executing these in any sequence.

Operating experience has also revealed a surprising number of ways that operator errors can cause a sudden halt to ZGS operations. Most of these have resulted because the logic is designed to cause the Programmer to stop functioning when certain wrong instructions are encountered. This was done to help prevent operation on a faulty program. After the error is corrected, the accelerator is restarted.

Future Effort

The future of computer control of particle accelerators is difficult to predict. If one judges by the rate of progress in the process industries and in computer development, the progress in control of accelerators should be exciting to follow for the next several years.

We at Argonne plan to continue development of beam sensing devices and of computer optimizing routines.

Present work indicates that data taking with the monitor and computer provides information that is difficult to obtain by hand methods. Attempts to control various machine parameters with complex programs has indicated that considerable accelerator operating time must be devoted to debugging each of the parts of the system. These debugging times complicate machine scheduling because of the pressure to operate for high energy physics experiments and to conduct accelerator improvement experiments.

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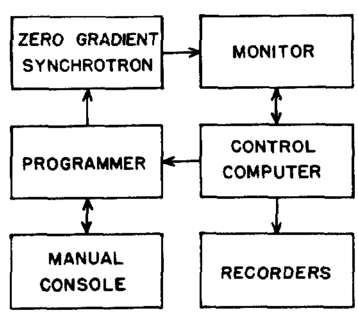

Figure 1.

This figure shows the general relationships between the major systems at the ZGS. The monitor gathers data requested by the control computer. These data and the results calculated from them can be recorded for the benefit of the ZGS operator. The computer can change the set of instructions that the Programmer executes in operating the ZGS through an accelerating cycle.

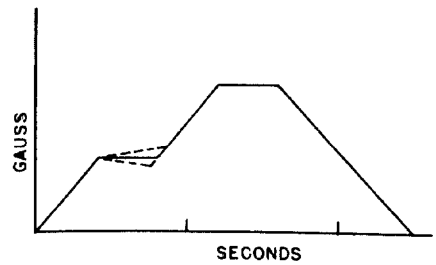

Figure 2.

Any ring magnet gauss vs. time curve that is within the capability of the power house may be programmed using the cable 0004 and cable 0001 Programmer commands. This may include any number of pauses in the acceleration and positive, zero or negative slope of the B curve during the pause.

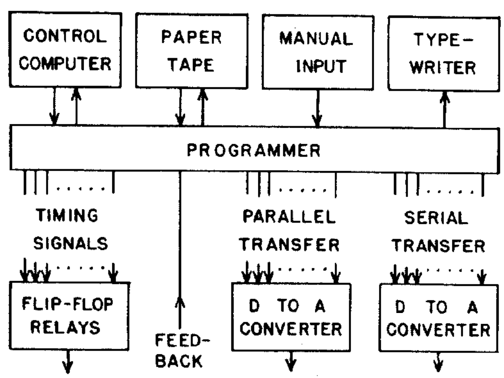

Figure 3.

This shows the several input and output channels of the Programmer. All of the outputs at the bottom of the figure are control signals to the ZGS and feedback pulses from the ZGS.