§ 1035
The Argonne ZGS computer system was designed before the advent of minicomputers and after accelerator construction was well advanced. Nevertheless, we feel that a number of conclusions drawn from our experience may be useful to the designers of other computer control systems.

Optimization of the accelerator performance is and will continue to be a major goal for computer control. Unfortunately, optimization of all but the simplest of accelerators, such as a Van de Graaff, is a formidable task. In general, four main optimization methods are available. These are perturbation techniques, dynamic programming, differential dynamic programming, and the solution of sets of ordinary equations.

Perturbation techniques are well known and are useful when one or a very few variables are involved. Convergence is slow with a cyclic accelerator, such as the ZGS, because only one perturbation can be made per ZGS cycle on many of the variables. This method is virtually useless when many variables are involved or when more than one "local optimum" exists.

Introduction

At the present time, most of the particle accelerator laboratories throughout the world have used digital computers for solving accelerator control problems. These many applications of computer control have ranged from relatively simple single-task combinations of many complex tasks. The variety is now sufficiently large that general reasons for the structure of computer control systems are discernible.

Structure of Computer Control Systems

The structure of a computer control system for a particle accelerator depends strongly on three main factors. One of these is historical in nature. A second factor results from the design or type of the accelerator. The third factor is more complex since it results from the designer's decision on the division of responsibility among the computer, the analog control loops, and the human operator.

The historical factor has and will continue to influence the design of computer control systems in two ways. The first way results from the very rapid development of the computer. For the past several years, we have witnessed the growth in computational capabilities, in speed, and in the capabilities of the vendor supplied software. At the same time, prices on many computers have been reduced. These trends will continue and will make more and more control tasks both practical and economical.

The historical factor influences the design of a computer control system in a second and perhaps less obvious way. This second way results from the timing of the decision to use computer control.

If the decision to use a computer is made at the time of the conceptual design of the accelerator, computer control can be applied everywhere that it is practical and economical. In this way, maximum utilization of the computer system can be achieved.

If the decision is delayed until the construction of the accelerator is well under way, many local systems will have been built with their own controls. By that time, additional costs will have been incurred and many incentives to apply digital computer control reduced. I feel that this is the case even though these local systems are "compatible" with computer control.

If the decision to use computer control is delayed until "startup" time for the accelerator, the incentives for the computer system are very much reduced. The financial incentive must be sufficient to warrant replacement of the then existing analog and manual system. If the timing is this late, the most rewarding applications are to those control loops that are unsatisfactory, to tasks that are not practical by other means, and to tasks that are not yet being performed.

The type of accelerator and the energy of the accelerated particle are factors that affect the design of the computer control system. If the accelerator is compact and the beam lines are short, a single computer system is a logical choice for handling both the accelerator and the beam lines. If the accelerator is large and the beam lines are long, a system composed of local minicomputers for local control and data taking, coupled to a larger central facility, becomes a logical choice. Experience at Argonne indicates that some programs, such as those for tuning the external proton beam lines and those used for studying distortions in the median plane of the ring magnet, require considerable data handling and computational power. For these reasons at least one computer in a multi-minicomputer system should be a powerful one.

The third major factor that determines the structure of a computer system is at least partly under the control of the system designer. He must decide on the division of responsibility among the computer, the analog control loops, and the human operator. At one extreme he may choose to use the computer for monitoring and logging only. At the other extreme he might choose to have the computer operate everything according to a predetermined plan. He will probably compromise somewhere between these extremes as dictated by the historical factors and by the availability of the special instruments needed to interface the computer to the accelerator.

The Zero Gradient Synchrotron (ZGS) Computer

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Panel Discussion on Computer Control\(^\text{\textsuperscript{a}}\)
The Structure and Use of a Computer Control System

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\(^{a}\)Work performed under the auspices of the U. S. Atomic Energy Commission.
Dynamic programming\(^1\) is an advanced and powerful tool for finding the "global" rather than a "local optimum." It has been extensively developed\(^2\)-\(^5\) for adaptive and for optimal control problems. Its chief difficulty is that a large store of information is required for a problem that contains a small number of independent variables. For the problem of optimizing the ZGS, the number of variables is of the order of hundreds. The store of information that is required is beyond the capacity of the very largest computers and would require a prohibitive time to develop. Nevertheless, many valuable ideas can be gained by studying this method.

Differential dynamic programming\(^6\) is a new computational technique for solving nonlinear dynamic optimization problems. It reduces the size of the store of information but sacrifices the possibility of "global optimization." It may prove to be useful for optimizing major components of the accelerator.

The fourth optimization technique consists of solving sets of ordinary equations. The tuning of the external proton beam lines at the ZGS is an example of this method. Gradient methods applied to ray tracing calculations produce solutions that are "local maxima." The existence of multiple solutions to these nonlinear sets requires operator guidance at present and will, in our view, require a human operator for the foreseeable future.

Monitoring of accelerator operation has been done routinely by the ZGS computer control system. This can be extremely useful but can consume an unwarranted amount of main frame time. For example, routine monitoring of currents in each magnet in the external proton beam lines is pointless when the lines are instrumented to measure the beam spot size at the experimenter's target. Monitoring of each individual magnet current is needed only if the spot size changes or moves with respect to the target. This example shows that only carefully selected variables should be monitored routinely. Most variables need to be monitored only on command of the human operator.

The logging of data is another common function of the computer system. If it is done on a routine basis, large volumes of printed paper may be produced. It is very desirable to carefully select the variables to be logged. For example, the amount of beam on an experimenter's target and the spacial distribution are measured and transmitted to the experimenter for his records; they do not need to be logged by the control computer except as total beam for each hour or shift.

The ZGS computer system has proved to be especially valuable for the analysis of accelerator data and for presenting the results to the ZGS operator. These functions generally are performed on command of the operator when he is hunting for the source of a problem. They include, typically, measurements of pre-injector beam properties, measurements of emittance of the 20-MeV injected beam, and measurements of the position and of the profile of the injected beam.

The ZGS computer system can perform several different classes of control action. One class consists of those variables that require adjustment many times during each accelerating cycle. A second class includes those variables that can be readjusted on command of the human operator. Readjustment of a portion of the ring magnet program is one such example. The third class of control function includes those that require operator intervention and operator judgment because of the existence of multiple solutions. External proton beam line tuning is such a function. In this example, the beam profile measurements, the calculation of the emittance of the extracted beam, and the calculation of currents for the several beam line magnets are performed by the computer. The computer is not permitted to set these currents into the several magnets even though it is capable of doing so. At present the operator decides to use these currents or to seek alternate solutions and then adjusts the magnets manually. This manual operation is such a small part of the total job that little is to be gained by using the computer to set the currents.

Conclusions

The several examples described above indicate that future computer control systems will be used to gather data, present results to the human operator, and relieve the human of the more routine control functions. They will not replace the human operator.

The software for a computer control system must, of course, include the data taking, analysis, and control programs. In addition, we feel that it is extremely useful to have an EXECUTIVE routine\(^7\) that permits the development and debugging of new routines during normal on-line operation of the computer system. This procedure uses the actual hardware and avoids having to simulate much equipment and timing for off-line development.

References