MASTER

Computers and Data Taking*

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Introduction

Delegates to some recent conferences* on multiparameter analysis techniques were somewhat surprised to find themselves in the middle of a rather heated debate. All the more surprising was the fact that the subject at issue - general purpose digital computers - seemed to be out of place at meetings which had in the past been concerned mostly with such topics as pulse-height analysis and fast coincidence circuits. However the debate was real and the issues were relevant because the proposal was being made that the digital computer could, in many cases, take over as the prime data gathering and analyzing tool for the experimenter. In such a role, it was being offered in direct competition with some of the high capacity, expensive pulse-height analyzer systems that are currently being made available by several of the traditional nuclear instrument manufacturers.

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Background

That such an issue should arise seems, in retrospect, inevitable. As the demands of physics experimentation increased, more and more complex data taking equipment was required to meet the need. Experimentalists graduated from single channel analyzers to multi-channel analyzers to multidimensional analyzers. Memory sizes increased; readouts become more elaborate, involving typewriters, line printers, paper tape punches, magnetic tape units, etc. Commercial manufacturers vied with one another in offering analyzers that could perform rudimentary arithmetic functions on the stored data. Display modes became more elaborate. In time, analyzers were even advertised as offering "programming" control over the experimental procedures.

As a concomitant to all these developments - especially the demands for increased memory size - the cost of the equipment naturally went up. Some manufacturers have recently been offering (and selling) analyzer systems for prices considerably in excess of \$100,000.

In parallel with, though quite separate from, these developments, the digital computer industry was making giant strides - though in the opposite direction. At the same time that analyzers were becoming more complex, some computers were becoming simpler. The room-filling vacuum tube computers of the '50s were evolving along two paths. One led toward the faster and more costly inhabitants of our modern data processing centers. The other led toward the compact, efficient, inexpensive, solid state units which were behind the challenge at the analyzer conferences.

Coupled with the reduction in cost of these smaller computers were improvements in their ability to interact with external equipment in ways which were less awkward than those of their ponderous predecessors.

In the very early '60s the upward slope of cost and complexity of the analyzers crossed that of the simpler general purpose digital computers. At that time it became possible to examine the more elaborate "fixed program" analyzers with the idea of replacing them with more general stored program machines.

Multichannel Analyzer Operating Principles

In the view of the digital system designer the pulse-height analyzer is a fixed (or wired) program computer since the steps it performs in response to an input signal are fixed at the time of the machine's construction. Those performance options it does possess are actually effected by changing the wiring by means of a switch. Generally speaking, when a task is relatively simple and tightly circumscribed the wired program approach is best. Thus the stored program digital computer has little to offer in the field of simple multichannel analyzers.

However, when the functions desired are widely varied and when the extra displays, data manipulations, inputs, and outputs proliferate then there is good reason for thinking that the design has passed the point where wired logic should be used.

The basic function of the multichannel analyzer is to record the number of times various digital integers are presented to its internal processor. The digital signals may, of course, be

generated by a variety of sources. Most frequently the integer is the output of a pulse-height, analog-to-digital converter which is usually an integral part of the instrument. Another source may be a time measurement. The datum might even be directly generated in digital form as in the numbering of the detector which was the source of the measured "event."

In any case the digit, however generated, is viewed as the "address" of a register to which a single count is to be added. In virtually all multichannel analyzers available today the registers are made of magnetic cores and are treated in blocks by the read-in and read-out equipment. Such a block of registers is known, in the jargon of the computer trade, as a "memory."

Thus, the sequence of steps in analyzing an event is as follows: The event is detected and/or coded into a digital integer. The integer is used as an address to refer to a particular register in the core memory. The register contents are read out into an external register. A one is added to the contents of the external register. The new contents of the external register are reloaded into the original memory location.

With this last step the cycle is complete and the recording portion of the analyzer is ready to process the next event. The time for a recording cycle is, typically, 8-20 μ sec. The total event analysis time is, however, generally much longer than this. The limitation in speed is imposed by the equipment which generates the digital address from the event. These conversion times may, typically, be measured in the hundred microsecond range or longer.

Much of the current development work is in this area - the object being to substantially reduce conversion times.

The crux of the matter, which we shall return to later, is that in the wired analyzers the core memory is used only to store the channel counts. All of the control functions are "stored" in the fixed wiring.

When we come to the problem of multiparameter analysis a difficulty arises. In multiparameter analysis an "event" is characterized by the time relationship of two or more simple events. Thus the digital integer which describes a complex event must contain digital measures of each elemental event plus, perhaps, additional digits which provide time information and counter identification. Even in the simple case of, say, a two parameter analysis where each measurement is quantized into one of 256 channels, the composite integer must span a range of 65,536 channels. Even two additional binary digits to code time and/or counter information would raise the number of required registers to 262,144. In a growing number of experimental situations even this range is not adequate (e.g. three parameter analysis).

Event Recording Analyzers

To attempt to provide core memories for this number of registers is economically unjustifiable. Recourse is taken to another strategy, therefore. Instead of incrementing a counter specified by a particular address, the address itself is stored. This mode of operation is called "event recording" to distinguish it from the other, or "accumulating analyzer," mode.

Event recording does not reduce the number of storage locations needed. In fact, it greatly increases the number required. What it does do, however, is remove the requirement that any register be capable of being read out at high speed. (A memory which possesses the property that all registers are equally accessible is said to be a "random access" memory. More commonly this term has been extended to imply, also, high speed access.)

Once the random access requirement is dropped, economical memories storing upwards of 10^7 registers are readily available. The most common of these are magnetic tape, magnetic drum, and magnetic disc. Of these, the magnetic tape provides the best solution for the high volume storage requirements of the event recording analyzers.

Recording on magnetic tape is just the first step in event analysis. To be useful to the experimenter, the events must be sorted into the channels designated by their numerical values. This is done by reading the magnetic tape into an analyzer-like instrument which sorts into a subset of channels on each reading of the tape. (Multiple passes of tape reading are necessary since, if the sorting instrument had enough channels to do all the sorting on one pass, the tape would have been an unnecessary intermediate. The accumulation could have taken place directly.)

Some laboratories operate event recording systems in which there are a number of tape writers and one central tape reading, sorting device. Others use the expedient of writing the events

on the magnetic tape in a mode compatible with that used at their computer center. The sorting is then done on the large computer.

Inherent in both these procedures is a definite loss of "contact" with the progress of the experiment. This is due to the unavoidable lag, measured in hours or days, which intervenes between taking of the data and subsequent analysis. To meet these objections, event recording analyzers are sometimes equipped with small, ancillary accumulating analyzers which sort into a subset of the main analyzer's channel range.

The Computer Challenge

The growth of these larger data taking systems has been an evolutionary rather than a revolutionary one with each year bringing new additions to the previous year's model. It is the end product of this growth (i.e. the enormously complex wired program analyzers) that is being challenged by the small stored program digital computer.

The heart of the issue lies in the use of the magnetic core random access memory. In the fixed analyzers it is used only as a repository for data. In stored program computers the memory is used to store instructions as well as data. Functionally, both the stored program computer and the fixed program computer must perform similar operations: They must both be able to take in data. They must both be able to put out data (e.g. magnetic tape). Both perform

additions and subtractions. Both accomplish block to block data transfers, operate visual displays, initiate external control signals, etc.

In both instruments these "macro-functions" are formed by stringing together a series of "micro-functions." The enormous advantage of the stored program approach is that these strings are readily alterable by the experimenter to meet the detailed requirements of any situation. The purchaser of the fixed program instrument, has just that - a fixed program device to which the experiment must be fit instead of the other way around.

The kernel of the argument for computer analyzers is this versatility of function. A stored program computer may be a pulse-height analyzer one day, an event recorder the next, and an event sorter the third. It might operate one experiment at a time or it might time-share the data recording for a group of experiments. In one program configuration it might provide elaborate visual display modes complete with manual intervention facilities. Another program might eliminate the display entirely in favor of faster data response times.

An added, though by no means decisive, feature is that when the computer is not doubling as a data taking instrument it can be used as (what it really is) a general purpose digital computer. Thus many of the simpler data manipulations can be accomplished in the laboratory using what would otherwise be dead time for the analyzer.

Existing Systems

In order to illustrate some of the ideas presented above we show in Fig. 1 a block diagram of one of the simplest computer-analyzer systems extant.¹ This is a system for performing simultaneous time-of-flight analysis in two independent experimental setups. It uses a Scientific Data Systems 910 computer with a 2048 word memory and 16 priority interrupt channels at a total cost of \$62,800. The non-computer hardware cost (largely Computer Control Corp. data cards) is approximately \$12,000.

The system is used by two teams of physicists at Brookhaven National Laboratory. With the particular program in most frequent use, the experimenters have access to the operation by using two console switches and the on-line typewriter.

At all times data taking has interrupting precedence over the system's auxiliary functions. So that, for example, typing out the contents of the number II analyzer, increases the dead time of the number I analyzer by only about .3%. In like manner, the display of either analyzer's contents on the CRT is hardly affected. In addition to choice of display, the experimenter has at his disposal 16 typewriter commands. These commands control the clearing, setting, reading, and input-output functions of the two analyzers.

To take just one of them for example, typing the letters FPUN initiates the following steps with respect to analyzer I, all with

hardly any effect on analyzer II's dead time.

1. Data taking is terminated on analyzer I.
2. The computer types, with headings, the following information in decimal form:
 - a. The absolute time.
 - b. The accumulated live time with sample-in, with sample-out, and for background.
 - c. The total number of events received, whether recorded or not, during sample-in time, sample-out time, and background taking time.
 - d. The beam monitor accumulations during sample-in and sample-out time.
 - e. The average revolutions per minute of the neutron chopper rotor since the last reading.
3. The computer then starts punching tape. Initially a piece of tape is punched which contains, in human-readable form, the absolute time figures which were typed out in step 2a. (This is to provide a way of easily correlating the punched tape with the various monitor and time counts.)
4. Following this, the computer punches leader and then the channel contents in a form suitable for later processing.

The other 15 commands initiate programs of similar complexity. These commands, it must be emphasized, were specified by the physicists who use the equipment rather than by the equipment designers.

Analyzer I is programmed to have 1024 channels. Analyzer II has 256 channels. This leaves approximately 650 memory locations for the control programs. The recording and processing of an event on either analyzer takes 96 μ sec. By adding special hardware this time could have been cut to 24 μ sec. (This was not done.)

Included in Table I is a summary of some of the real-time computer data taking systems either in operation or soon to be so. In not all cases is the computer the data taking instrument. In some instances the system described is a hybrid - with the computer "backing up" one or more multichannel analyzers. Where available, reference is made to the published literature.

Advantages

The advantages of computer-linked data taking systems fall under two broad headings: Versatility and On-Line Computing Facility.

Versatility: The versatile nature of the computer approach has been emphasized above. This may have special appeal for the moderate sized research laboratory. Such laboratories often feel the need for large analysis equipment in order to be able to participate in the more interesting current research. At the same

time, they are frequently unwilling to commit a large part of their budget to a single piece of special purpose equipment.

The computer can help answer their dilemma because it can serve as a pulse-height analyzer, time-of-flight analyzer, event recorder, counter telescope and hodoscope recorder, or even as a buffer between disparate pieces of special purpose equipment. It can provide graph displays, map displays, or isometric views of data fields. The displays may have grid lines superimposed on them, labeled axes, or even represent composites of experimental data and theoretically computed curves. The important point is that changes are provided by reading in a new program - and programs are easier to change than wiring.

Output modes share the same versatility. Output may be typewritten, punched on paper, or written on magnetic tape. The format may be altered to meet any necessity. At a later date, and if the circumstances warrant it, the computer could be linked directly to equipment at the large computer centers.

On-Line Computing Facility: Another important facility, touched on above, is the ability to couple data taking with data reduction. In many experimental situations this is unimportant but in some³ it may be crucial.

The kind of experiment which profits most from an on-line computational facility is that in which the raw data are so complex that a simple sorting operation yields a distribution that is not readily understandable to the experimenter and:

a) the experimental conditions are very costly and it is imperative that the research group know as fast as possible of system flaws; b) the experimental run is very long and it would be very tedious to have to repeat it because of an undetected fault; c) the results must be interpreted immediately because further steps depend on the initial results (e.g. space flight telemetering).

A third advantage of a computer-based system is the availability of the computer itself. It is very convenient to have even such a modest data processing facility in the laboratory in view of the two to four hour minimum "turn around times" typical of most large computer centers. Such a utilization is especially appealing because it enables a group to make use of its expensive "analyzer" even when there is no experiment in progress.

Limitations

If the advantages of a computer-linked system can be readily stated so can its disadvantages. Prime among these is the loss in data taking speed in comparison with comparable wired program instruments. This is a direct consequence of the fact that the data taking (and counter incrementing) functions must be accomplished in the computer by the normal mechanism of program steps. In most cases it is possible to circumvent this limitation by direct wiring into the computer. (This, it should be noted, is a step back towards the special purpose instrument.) Actually, in most cases where multicoincidence analysis is required, the data rates are quite low and well within the range that can be accommodated by programming.

A second disadvantage is that the computer system will cost more than the equivalent fixed program device in any single system configuration. Thus the experimenter who knows exactly what measurements he wants to make over the next five years would do well to purchase a single, fixed program instrument. The argument for the computer configuration can only be made if the research requirements are either unknown or highly varied.

A third, and by no means minor, disadvantage is that every operation must be programmed. This means that the scientist must be willing to learn the necessary programming skills. It is true that, as time passes, system and subsystem program tapes are increasingly traded between laboratories with similar equipment. Nevertheless, the unskilled recipient of such a system tape is in no better position than he would be if he had received an instrument whose function was wired in at the factory. By not being able to modify to suit his needs he has lost much of the advantage that his computer system inherently has.

Implications

Computer-linked systems of the type described here are bound to influence techniques of scientific research. But aside from these more profound and long term effects one can expect a more immediate commercial impact.

Most strongly affected are the commercial analyzer manufacturers. They are faced with some difficult problems. Should they continue to develop more and more elaborate wired

program machines? Or, should they attempt to switch to simple stored program instruments? Perhaps they should devote their attention to their small analyzer line and to making supporting equipment (ADC's, displays, buffers, etc.) for existing computers. It might even be reasonable for them to form technical liasons with some of the computer firms.

On their side, the computer manufacturers are faced with related problems. Should they make the supporting equipment to meet, what is now, a minority customer demand? To what extent should they become involved in the system programming efforts? - in user program exchange red tape, etc.?

It will be interesting to see how it all turns out.

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TABLE I

<u>Location</u>	<u>Function</u>	<u>Computer*</u>	<u>Reference</u>
Laboratoire Joliot-Curie de Physique Nucléaire de la Faculté des Sciences d'Orsay	Multidimensional Analysis in Nuclear Physics Research	IBM 1620	2
Chalk River	Multiple Experiments in Low Energy Nuclear Physics	PDP 1	3
Brookhaven National Laboratory	Study Basic Strong Interactions in the ~ 10 -20 BeV range	Merlin (non-commercial)	4
State University of Iowa	Two Parameter Analysis for Nuclear Structure Research	CDC 160	5
Bell Telephone Labs. & Brookhaven National Laboratory	Multiparameter Analysis for Nuclear Structure and Reaction Research	SDS 910	6
Brookhaven National Laboratory	Two Time-Shared Neutron Time-of- Flight Analyzers	SDS 910	discussed above
National Bureau of Standards	Central Facility for Low Energy Nuclear Physics Research	SDS 920	

* Abbreviations:

CDC: Control Data Corp.

IBM: International Business Machine Corp.

PDP: "Programmed Data Processor" - a product of
the Digital Equipment Corp.

SDS: Scientific Data Systems, Inc.

Figure Caption

Fig. 1 Block Diagram of Time-Shared Time-of-Flight Computer
Analyzer