A Device to Facilitate Combined Analog-Digital Computation

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MANY computing problems present characteristics which appear to call for both digital and analog-type computers. To the operator of a small computing facility, such problems present a dilemma, for the analog-digital conversion equipment available is generally expensive, highly specialized, or both. This paper describes a device developed at Battelle Memorial Institute which can resolve this problem for a certain (admittedly rather limited) class of problems. Some applications are given.

The class of problems covered is that which admits complete simulation within the capacity of the available analog computer, but whose results must be processed subsequently on a digital computer. That is, the values of the traces of the analog output during the course of the run, not just a final single number, must be processed digitally.

The Data Collection Device

**NEED FOR THE DEVICE**

It is common knowledge that there exist classes of problems which lend themselves to combined analog-digital computation of the sort just described. It follows that a method for communication between the two types of computers is desirable.

However, since these problems are rather special in nature, their occurrence is not too frequent in a medium to small size computing installation. This means that any special equipment developed for use in these problems should be sufficiently general in nature that it could fill other data-collection needs. Investigation into other possible applications indicated several areas where a flexible device for data collection could be efficiently employed.

**CHOICE OF THE DESIGN**

After some consideration, the picture of this device became clear. It should be a very flexible sequencing device which was portable and could conveniently utilize several types of data-recording components which are already available.

This conclusion led directly to the design of a programmer. The block diagram appears in Fig. 1, and a general view of the actual machine in Fig. 2. It contains no permanent circuitry. All electrical circuits must be externally connected on the control panel, and are thus completely flexible, and there is plenty of space for addition of the components.

**Programmer Description**

**The Control Panel.** The control panel is the heart of the device, and is responsible for a large share of the total cost. It is a standard unit with 816 pluggable positions, and an assorted selection of jumper wires. By use of spare plugboards, the programmer can be quickly converted from one use to another simply by exchanging the plugboards, and changing the connectors to external measuring and recording instruments. The location of connections to the internal components are shown in Fig. 3.

**Stepping Switches.** The “program steps” connections provide access to three levels of a 4-level 22-position stepping switch. The other level is connected to neon indicators which are on the front panel for convenience in observing operation during panel wiring.

There are three single-level 10-position stepping switches for counting or selection purposes. There is also a 2-level 10-position stepping switch which is usually used for selection purposes.

**Relays.** For logic operations, there are 20 relays. Ten of these relays have two transfer points, and the other ten have two transfer points and one normally open point. In addition, the second group have indicator lights for use in checking the logic of panel wiring.

**Diodes.** There are ten diodes for isolation when the same relay is being actuated from more than one possible source.

**Toggle Switches.** Five double-pole double-throw toggle switches provide flexibility and on-off start-stop control.

**External Circuit Connectors.** The programmer presently has three external circuit connectors: one for an International Business Machines Corporation (IBM) type 16, 26, or 526 punch, one for a digital voltmeter, and one 20-pin connector for any miscellaneous circuitry required in interconnections.

**Power Supply.** A 48-volt d-c power supply provides the necessary power to operate the relays and stepping switches and provides a source for external signals when required.

**Busses.** Eleven 5-hub rows of common connections are provided to eliminate the necessity of using split wires for common connections.

**Indicator Lights.** Twenty-two neon indicators provide visual access to show which step the program stepper is on. Also, as previously mentioned, ten of the relays have neon indicators.

**Mode of Operation**

When operated as an analog-digital converter, the action of the device would be as follows: The analog computer would be wired for computation as usual. Certain additional connections which are indicated would be made from amplifier outputs to the external connector of the programmer, but these would in no way affect the problem computation wiring, nor would they affect the computed results. In addition, a timing integrator in the computer would be wired to a relay amplifier, with the gains so adjusted that the relay would operate at the time interval at which digital readout was desired. This relay amplifier would control the computer "hold" circuit, and transfer system control to the programmer. When the analog computer was manually switched into "operate" mode, computation would commence, and simultaneously the timing integrator would begin to build up a voltage. When this voltage reached the preset level and caused the relay to transfer, the computer
would go into "hold" and the programmer would take command.

The programmer would then connect the first voltage to be digitized from the plugboard to the digital voltmeter. Balancing of the voltmeter would produce a pulse to advance the program stepper switch to the next position; the voltmeter reading would then be connected to the card punch cable. Completion of the punching operation would again make a pulse available from the punch for advancing the stepper. Each voltage of interest would in turn be punched, in like manner, from its connection on the programmer plugboard through the connector. Finally, the program stepper would switch a small resistor across the capacitor of the timing integrator, causing the voltage to decay rapidly to effectively zero. With the timer so reset, the programmer would relinquish control of the computer, and the programmer would reset itself to be ready for the next cycle. The analog would then proceed with the problem solution until the timing integrator again built up to the preset voltage, at which time the punch cycle would repeat.

Special Considerations

Since the computer had been in "hold" during the punch operation, the computation would continue rather than reset. A great deal of experience with the system shows that this presumption is quite valid. Many problems have been run with hundreds of interruptions for punching and the results compared with the same problem run without interruption. Results agree to within the normal reproducible ability of any analog computer calculation.

If it were desired to control punching on the basis of some other criterion than fixed time increment, the voltage controlling the relay amplifier could be selected from anywhere in the problem, with only minor change in operating procedure.

If the punching device were an IBM-type 26 or 526 card punch, as was the case in Battelle's application, punching format could be controlled by a program card. In one application, a modified IBM-type 16 punch was also employed. There is in principle no complication associated with activating a tape punch or a data-logging device producing hard copy in lieu of the card punch. Such choices might be preferred if the available digital computer were suited for tape or keyboard input, instead of cards.

A distinctive feature of the programmer is its relatively low cost and ease of construction. No critical components are employed and construction and maintenance are straightforward. The cost of the programmer cabinet built by Battelle was under $3,000. To this must be added the cost of the digital voltmeter and the punch mechanism; however, these instruments are normally used independently and need not be charged to the programmer.

Applications

EJECTION SEAT

One interesting application for the device was in the design of an aircraft ejection seat. The parameters of the ejection capsule were to be selected to meet several requirements, one of which was that the stress on the occupant was to be minimized. Capsules pitch violently when ejection occurs under certain circumstances. Very high short-term accelerations can occur at the extremities, where the pilot's head may be located.

In the analysis of this problem, the aerodynamic equations of the capsule were written, treating it as a two-dimensional free body in the airstream. These were mechanized for the analog computer. The direction of the gravity vector and the magnitude of the effective wind force vector varied with assumed changes in aircraft altitude and attitude. The objective of obtaining a design minimizing the acceleration of the pilot's head was complicated by the fact that the actual desired acceleration was not obtained on the analog computer. Translational and rotational acceleration components were separately obtained, and used in the simulation, but the net acceleration was a highly nonlinear combination of these.
To resolve this difficulty, it was possible to employ the programmer to interrupt computation every 5 seconds and punch into cards the necessary values from which to compute the desired accelerations. Immediately following each analog run, the cards were processed on a digital computer to produce a table of acceleration values. These were then used to guide revision of design parameter values. Ultimately, a design was obtained which maximized the pilot's survival chances under all conditions.

**Satellite**

Another application was the calculation of availability of solar energy to an artificial satellite. Consider a satellite part of whose instrumentation is powered by solar batteries. These batteries can accumulate energy only when the vehicle is on the sunny side of the earth, and this energy may be attenuated by layers of atmosphere, depending on the altitude and orientation of the satellite with respect to the earth. The problem considered here is that of obtaining the history of energy level available during a few cycles of the satellite.

The elevation of the satellite is readily computed on the analog computer. Previous experience of analog-computational laboratories has indicated that trajectory problems, including orbital problems, cannot be readily solved directly on analog computers because the force of gravity is so large in comparison to air resistance, etc., that these quantities must be scaled until they are down in the noise level and, therefore, are highly inaccurate. When a preliminary investigation indicated that this was also true of this problem, it was decided to work from perturbation equations.

An initial orbit with a known elliptical shape was assumed and then equations were set up to give the perturbation from this orbit due to air resistance (all other forces were assumed minor in comparison to this one during this particular period in the lifetime of the satellite).

However, since the perturbed elliptical orbit has additional motions superimposed, a further calculation was then required. The axes of the ellipse rotate in their plane, and the plane itself regresses about the earth's axis, these effects resulting from the earth's spheroidal mass distribution. To determine the satellite's position relative to the earth and sun, the orbital calculations were interrupted by the programmer at increments of 45 degrees around the track, and time, angular position, and altitude were punched out. A subsequent digital calculation from these cards located the sun with respect to the orbit plane, in right ascension and declination. These astronomical coordinates were then converted to azimuth and elevation by the computer. A digital integration in space was then carried out from the satellite toward the sun to determine the degradation in solar energy level occasioned by atmosphere. If the satellite was eclipsed, the degradation was automatically set at 100%. The resulting energy intensity values were then punched out by the computer, and a listing of them gave the solar energy history of the satellite at 45-degree intervals as it pursued its rotating, regressing, perturbed elliptical orbit around the earth.

**Conclusions**

The need for simple inexpensive analog-digital conversion equipment arises many times in the operation of almost any computing center. Existing commercial equipment does not appear to meet this need adequately, but a general purpose plugboard-controlled programmer such as the one described can readily be applied. Experience with the preceding examples and with other data recording uses of the programmer have shown it to be a valuable and highly flexible tool to augment a computer installation.
Discussion

Chairman Rogers: Mr. W. A. Farrand, Autonetics asks Mr. Fuller: "How do you close when writing 1010 initially, when admittedly, self-clocking is necessary? That is, initially you wrote a one zero pattern all the way around the drum. If you wrote it all the way around, there was some reason for it."

H. W. Fuller: Yes.

Chairman Rogers: Mr. Farrand asks, "You should, to some degree, close on yourself so you would be writing a one where a zero was, and a zero, where a zero was when you came back around, then you started writing your specific pattern. Admittedly, you could not close because you said you had to use self-clocking. Now what trouble does this cause and how do you do it?"

H. W. Fuller: When you close on yourself, it is, as you say, not a good closure. You must print zero over zero and one over one. We do. We record these synchronously on the drum. We erase these synchronously by rerecording. Simply by recording your information you erase what you have written initially, so there is no need for closure.

Chairman Rogers: Mr. Farrand also asks, "Then was there any need for writing the 1010 pattern?"

H. W. Fuller: Yes, there is. If we have a transient occurring as a result of beginning or stopping the recording in the middle of this open zero-one region which affects us, and a zero, the track zero was when stages or formation of the track, this transient could erroneously be read as the end of the block start code. We do not want that, so we just coast along as though this were a very long start code until the first block appears.

Chairman Rogers: Mr. Reese, Hughes Aircraft Corporation asks, "What is the gap space between the head and the drum when it is running?"

H. W. Fuller: 180 microinches, I forgot to mention that.

Chairman Rogers: Mr. Reese also asks, "How much runway can you take on the drum surface to keep the heads within their operating position?"

H. W. Fuller: Within 5 or 10 mils at the present spring design, which is a pretty competent spring design.

Chairman Rogers: Mr. Farrand asks, "It would be a dynamic problem, wouldn't it; that is, with respect to suspending the head?"

H. W. Fuller: Yes. Eventually it would become a dynamic problem, but in terms of the sensitivity of separation, the results of the spring force turn out to be not much more expensive.

Chairman Rogers: Mr. Thorpe, Corning Glass Works asks Mr. Gams: "I would like to know about the difficulties in temperature variation in transistors?"

Theodore C. Gams: The amplifier that I showed when used as the input stage uses a pair of transistors such the 4JD, A168G, or other similar RCA transistors for long term stability in bistable flip-flop circuits. These transistors are designed, although no one who makes them will tell you this, to have a low-base collector current, and a low variation of that base, and that is the parameter that determines the temperature stability of the input pair. We have obtained stabilities on the order of ±0.03% to ±40 degrees centigrade change in ambient temperature. Below −55 C, I do not recommend long term operation of any germanium devices; above 71 C, which is the usual military breaking point, it is necessary for us to consider silicon. If you want to have good stability, because any two transistors of the same type and manufacture will leak differently, varying from 50 to 1, between the degrees of 70 and 85 C.

Chairman Rogers: Mr. W. Brooks, Ramo-Wooldridge asks, "At what point in voltage do you attempt to go, let us say, from series to shunt regulators?"

Theodore C. Gams: It depends upon the money available. We like to use series regulators as high as we can because for rather subtle, and often certain reasons, one can get a somewhat better response from the circuit. However, when one begins to protect those series transistors, they begin to take more voltage than the output takes at times. In order to protect the transistor, I would say that the general crossover is between 50 and a 100 volts for relatively high currents; and for low currents, where you can afford to waste power, it is perhaps between 300 and 400. However, let me say that the shunt regulator, all by itself, has certain other advantages. For example, its ability to operate over wider ranges of adjustment without having to store much energy while waiting on the shunt regulator.

Chairman Rogers: The first question for Mr. Estrin is from Mr. S. Littler, National Cash Register Company: "Why is there any necessity for the shifting operation to be definitely slower than the addition operation?"

General Estrin: It is not slower; it is usually faster than the addition operation. The shifting operation implies a simple transfer from one set of flip-flops to another; the addition operation implies a certain number of logical stages within this transfer. As I pointed out you are not talking about the carry storage in which you do not propagate the carry. At each step store the state of a one-stage carry; that is, you actually represent the sum, not by one-ended binary quantity but by two-ended binary quantity.

Chairman Rogers: Mr. Lettler asks, "Do you imply that an addition takes at least twice as long as it should?"

Gerald Estrin: No, this is just a mode of carrying out a set of additions in which you would not need to have a computation of the carriage set in one extra step. There has been a great deal of amplification of this in some of the reports that have come out of the University of Illinois.

But I still make the very simple statement that the addition process must take longer even if it is equal, with the simple transfer of one flip-flop to another.
Communication Between Computers

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The use of electronic computers to solve large-scale data processing problems has created a number of serious communication problems. Not the least of these problems is the necessity that machines be capable of communicating with each other. To achieve complete communication between machines requires that three conditions be satisfied. First there must be compatibility of the medium used for transference. Second, there must be understanding of the coded language used; and third, there must be the ability to interpret the coded language as structured by the program.

Unfortunately, present machines generate and receive information in different languages and structures. Even identical machines can and do change their language by program means. These differences are not attributable to the ignorance or to the whims of machine designers but instead are due to the operational requirements for which the machines have been designed. It seems clear that for some time, future computers will necessarily follow this pattern of incompatibility.

There are two basic methods which may be used to resolve the communication problem. The first is to legislate that a common medium, code, and language be used, and the second, is to employ other machines to solve some or all of the compatibility problems involved in machine communication. Legislation has the disadvantage that it would involve a tremendous loss of investment, in terms of existing programs, and would also stifle the future development of computers. The second approach is to use machines which may be programmed to interpret the languages of different machines. This does not introduce these disadvantages and, therefore, has been adopted throughout the industry as the preferred approach.

Communication through a transfer medium is almost always employed. Some possibilities for this are printed forms, paper tape, punched cards, and magnetic tape. Magnetic tape, because of its high packing density and high rates of access, is becoming the accepted medium for communication. The use of a transfer medium always introduces both physical and linguistic differences. Two classes of machine will be defined to handle these differences. The first class is termed "media translators." These are used to overcome the physical differences. They transfer information from one medium to another without radical changes of the language employed. The second class is termed "data converters," and these are used to overcome both physical and linguistic differences. They effect both transference and translation of information between media.

In the future a third class of machine will be introduced. This is simply an adapter attached to the existing data processing computer and represents the minimal form of media translator. The media translator will continue to exist as a special-purpose instrument. The data converter will evolve into a machine which uses stored program computing techniques to solve the linguistic problem.

The Compatibility Problem

Historically, computers were designed as either scientific or data processing machines. Each machine was considered from a system point of view, as a separate entity. As the number of data processing machines in everyday use have increased, the results obtained from one machine are used as the input data to a second machine, which is often geographically remote from the first, and which is frequently of different type and manufacture. The direct approach used to solve this problem is to employ either printed paper, punched tape, or punched cards as the transfer medium. Thus, either written human language, tele-type code, or punched card code are used.

The use of magnetic tape, as a means of mass data storage, has become more common and this is also being widely adopted as a high-speed transfer medium. It is apparent that future machines will need an increasing ability to intercommunicate. This fact has been recognized to a small degree by the manufacturers who are building new machines with capacious buffered magnetic-tape storage systems.

However, it seems clear that near term machines of the future will not utilize a common language or common magnetic tape equipment. Indeed, it is perhaps not in the best interest of machine data processing progress to permit stasis of this type. Therefore, it may be safely concluded that problems in communication will exist to an increasing degree in the foreseeable future.

In communicating from one machine to another there are both physical and linguistic differences which together create what is generally called "the compatibility problem." These problems can be defined as follows:

**Physical-Mechanical**

These are the differences: In the tape material; the length of tape; the number of heads; and the head spacing. Further problems arise due to the fact that the rate of tape motion, the acceleration time, and deceleration time vary in the different types of transport. These physi-