Process Computer Control Concepts

"Off-Line" Operating Guides • "On-Line" Operating Guides
Automatic Optimization by Mathematical Model and Direct Experimentation
Sampling in Digital Control Loops • Computer As An Experimental Controller

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WE ARE, AT PRESENT, in the early stages of computer process control. In 1954, the first widespread use of digital techniques appeared in the petroleum and chemical industries in the form of the data logger. The primary function of these devices is to convert analog measurements into more concisely recorded digital data; in addition, loggers perform other functions such as flow integration, alarm scanning, and relatively simple calculations for mass flow. The literature contains many articles on the virtues and faults of data loggers. Certainly, in applications such as pilot plants where the end product of the operation is data, the logger is an economically justifiable device. However, the general results of process installations seem to indicate that in operating units, the data logger cannot be justified on the basis of economics, except in unusual cases.

Why is this true? Basically, the benefits of the data logger in a process unit are of a fringe nature. The logger does not appear in the control loop, either directly or through the human operator, except to the same extent that a conventional recorder would. The logger does not affect the unit throughput; it is an adjunct to the already well instrumented control room.

The use of the data loggers has, however, been an important step in the advent of control computers. The data loggers introduced data handling techniques, both analog and digital, to the field of process control. The economic evaluations of data loggers showed possible uses for computing devices which could affect throughput and improve efficiency, quality or yield.

The initial concept for a computer in the control loop was the on-line calculation of operating guides.

Operating Guide Calculations

Consider the flow of information around a process unit with a data logger in the control room, as shown in Figure 1. The process is controlled by the instruments on the graphic panel. *The operator receives information from the instruments and the logger and uses these data to supervise the control system and reset the instrument control points.* The operator bases his decisions on the primary process variables such as temperature, pressure, flow and level. Combining this with his past experience, judgement and operating instructions, he sets the controllers to produce a specified product at a certain production rate.

Accounting supervision of the process is an "off-line" operation and provides data to define controller settings for minimum operating costs, responsive to the dictates of overall plant operation. *By "off-line", we mean that the input data does not enter the computer immediately but is stored and then processed in the computer at a later time.* In Figure 1, the daily summary of operations produced by the logger is transferred to a central computer where, at some future time, the secondary process variables are calculated, based on the averaged daily information. These secondary variables are such quantities as yields, efficiencies and heat and material balances. The secondary variables or operating guides are not directly measurable but, must be calculated from the primary measurements. The results of the calculations are then used to generate changes in process operation to reflect production scheduling and process engineering changes. These changes are later relayed to the operator and eventually appear as changes in the controller set points.

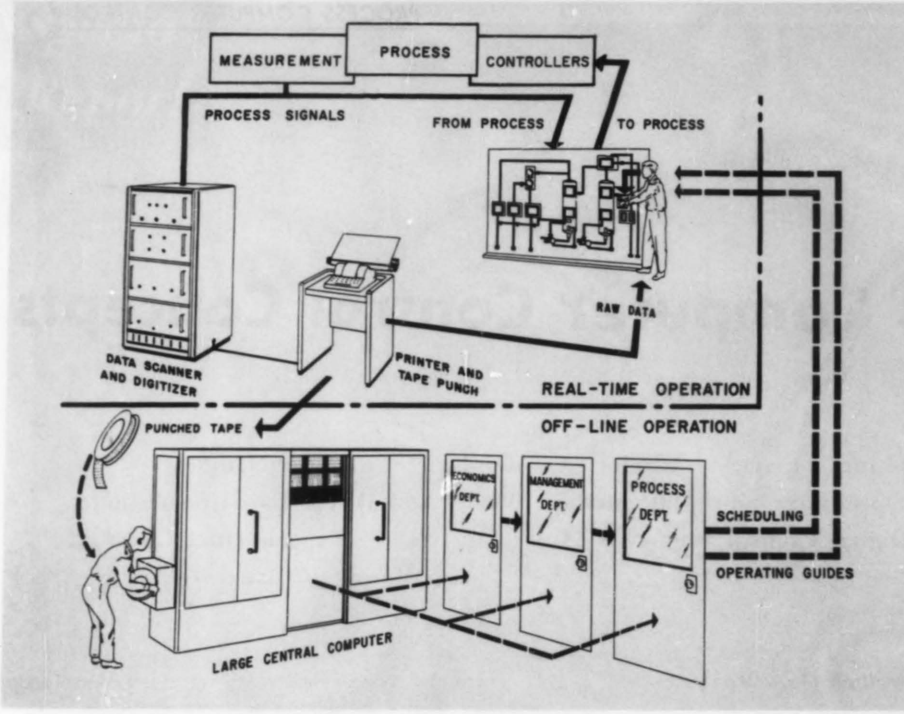

Figure 1. Flow diagram of a process using conventional control instrumentation and operating guides through an "off-line" general purpose computer.

The concept of "on-line" calculation of operating guides as shown in Figure 2 is based on presenting the secondary variables to the operator in real-time, that is, in time to use these data to change process operation to reflect changes in the secondary characteristics. Actually, it is the secondary characteristics that are controlled by holding the primary variables at fixed values. But since in the past, it was impossible to calculate the secondary variables in real-time, it was necessary to control almost exclusively from the primary variables.

Figure 2 shows the incorporation of a small digital computer in the control room. (Although digital techniques are indicated in this figure, the same concept applies equally well to analog techniques.) *The computer is "on-line," that is, input data enter the computer directly from the process or source of data. The* process measurements are fed into the computer and the operator receives periodic data not only on the temperatures, pressures and flows but also on the heat balances, material balances, catalyst consumption rates, yields, and other operating guides. He utilizes this information immediately in resetting the control points of the instruments on the board. There is still the "off-line" feedback of scheduling information, but the operating guides are now utilized in the supervisory control loop which is closed, in real-time, through the operator.

The advantages of on-line operating guide calculations, it is hoped, will be improved yields, efficiencies and product quality, through constant monitoring of the secondary variables. Time variations in the process, such as heat exchanger fouling and catalyst activity changes, can be detected and compensated for by the operator. Yields can be maintained at a high level at all times, rather than at an average level over a long period.

Early On-Line Operating Guide Experiments

The initial experiment in calculating operating guides on-line for a continuous process was performed early in 1956, by engineers from DuPont and Burroughs Corporation. In this experiment, a chemical process in the Electrochemical Department of DuPont at Niagara Falls, N.Y. was linked, via telephone line transmission, to a general-purpose digital computer in Philadelphia, where calculations of the operating guides were made. Approximately ten primary measurements were transmitted, and the calculations were used to determine the yield, yield rate, production rate and material balances and losses for the process. This was a temporary installation, designed to determine experimentally whether or not such "on-line" operation was feasible from the standpoint of process operation. It was the first time, as far as is known, that a digital computer was operated in real-time with a chemical process.

Shortly after, in August, 1956, a somewhat different application was handled in the same manner. In this case, a Bailey DATAK logger was installed on a new boiler at the West Penn Power Company, near Pittsburgh, Pennsylvania. The logger measured the boiler variables during start-up of the plant. The data was then transmitted by teletype to Babcock & Wilcox's New York office where a Burroughs Datatron computer was used to calculate boiler test data. These data included such factors as boiler efficiency, gas temperatures, heat absorptions, and overall conductances. The data were transmitted back to the boiler site within one hour. In less than one month, 322 tests runs were made. It was apparent that variations in the secondary variables could be detected with measuring instruments of commercial

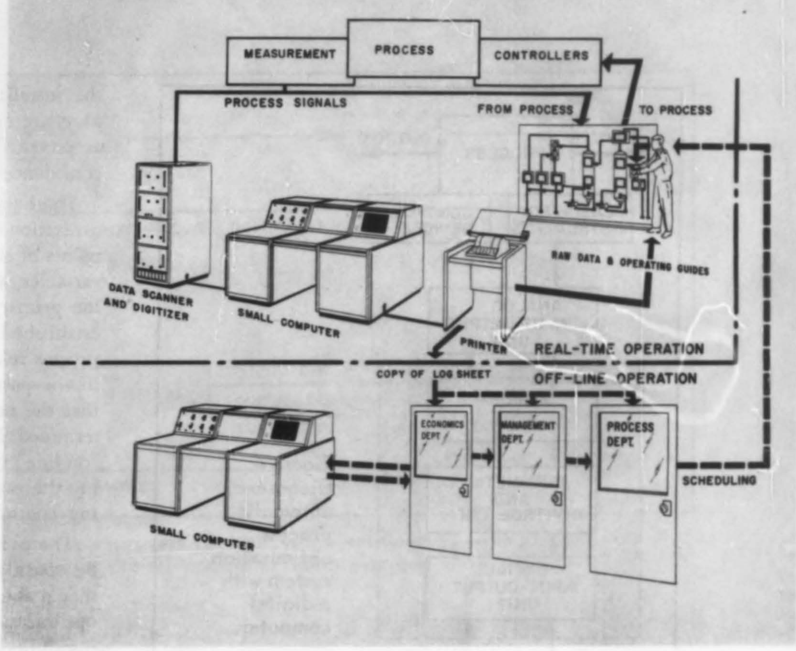

Figure 2. Flow diagram of a process using conventional control instrumentation, operating guides through a computer in real-time, plus additional instructions through an "off-line" computer.

quality. In addition, the elimination of averaging over long time periods produced useful short time data. Here again, the installation was a temporary one.

Recent Installations, Operating Guides

The first permanent installation of an "on-line" computer for calculating process operating guides was made by Leeds & Northrup and Esso at Esso's Baton Rouge refinery. Here, an L & N analog-to-digital conversion system is linked to a Royal Precision LGP-30 digital computer installed in the control room area. Approximately 160 primary measurements of temperatures, pressures, flows and other variables on a catalytic cracker are scanned, measured and digitized at the rate of one point per second. In addition to reading out scaled results for these 160 primary variables, the computer also calculates about 30 operating guides which are printed out for the operator.

This system has been operating on-line, 24 hours a day since June 23, 1958. As of September, 1958, the average time between equipment failures had been 2.5 weeks. The LGP-30 computer is a vacuum tube machine, with no tube failures up to that time.

It is hoped that this installation will be justified on the basis of operating the process nearer the optimum economic conditions, with near maximum feed rate, faster recovery from upsets and more efficient stripping of the hydrocarbon from the catalyst. Early experience with the installation indicates that economic justification may be realized although it is too early, as yet, for definite conclusions.

A smaller scale installation utilizing an analog computer was made at about the same time on a fractionating tower at Humble Oil. The analog computer is the CM-2 produced by Southwestern Industrial Electronics Co. This computer originally accepted analog signals from the primary sensors on the tower, as shown in Figure 3 and calculated from these readings the tower efficiency, which is displayed on a dial for the operator's use in adjusting the tower. It has been operating on closed loop control of the tower since December 1958. Here again, it is hoped that justification will be derived from increased efficiency of plant operation.

A discussion of various other computer installations will be found on page 66 of this report.

Is the Concept Valid?

It appears that we are on the brink of proving or disproving the concept of operating guide calculations. Some of the questions which have to be answered are:

1. *Will the operator be able to utilize the secondary variables in adjusting the controllers?*
2. *Will such data actually increase the economic yield from a unit?*
3. *Can all the necessary measurements, particularly product quality values, be made at present?*
4. *Do the advantages derived from the on-line computer exceed the advantages which could be gained by utilizing the same capital investment in other ways, such as improved process equipment?*

The operating guide concept has certain system features which are likely to increase its chances of success.

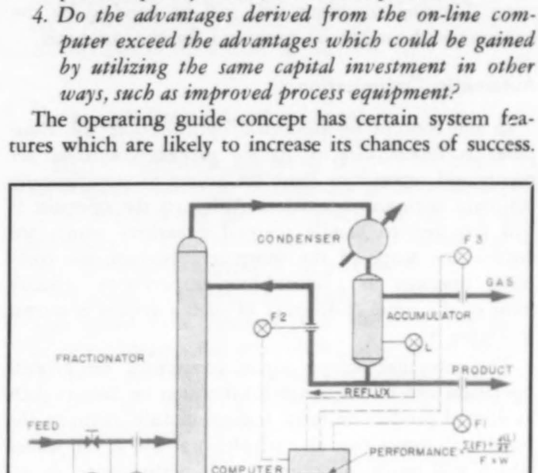

Figure 3. Diagram of Southwestern Industrial Electronics analog computer installed on Humble fractionating tower to provide tower performance index readings. (See ISAJ, April '59, page 56.)

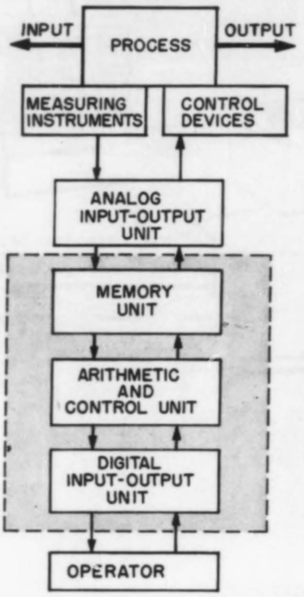

Figure 4. Diagram of automatic process optimization system with a digital computer.

For example, since the computer operates in a supervisory manner, linked to the controllers through the operator, computer failure will not cause plant shutdown. The process will be no worse off with computer shutdown than it is under normal operations today. The judgement of the human operator will still be available, supplemented with the data provided by the computer. Unusual situations will still be handled by the operator without special programs for the computer.

Automatic Optimization

In the concept of automatic optimization, the computer is linked directly to the process controller set points and repositions these set points to automatically maintain optimum operation. Although the operator is still required to handle unusual situations which are outside the scope of the computer program, the computer operates in a closed-loop supervisory capacity most of the time. A diagram of such a system is shown in Figure 4.

The computer accepts inputs concerning the process operation and also receives information on factors such as desired production rates. It continuously monitors the process to insure that all variables are held at the values which will result in optimum unit performance, in accordance with predetermined criteria. The computer takes into account the required production rates, the operating characteristics of the unit, the cost data for the unit and the time variations in operating characteristics.

The output of the computer is linked to the set points of conventional analog controllers. These controllers then function in the normal manner, controlling individual loops at fixed values. The computer, however, has taken the place of the operator during normal plant operation, resetting control points as required. Some of the installations for "on-line" operating guide calculations are capable of automatically positioning set points as soon as the necessary operating data and operating confidence are established.

There are several problems in applying automatic optimization. Since the computer must position the set points of the primary variables based upon the secondary variables which it calculates, the relationships between the primary and secondary variables must somehow be established. Although this lack of knowledge concerning process relationships was often cited as a major obstacle in the past, it is generally agreed by process engineers that the necessary knowledge is available or can be determined. Many of the presently planned installations of "on-line" computers are designed to yield data concerning the process relationships, on which to base optimizing control in the future.

The problems inherent in closed loop operation must be considered also. One difficulty stems from the fact that many processes exhibit large time lags. Automatic optimization under these circumstances is difficult if instability is to be avoided. In addition, fast, accurate analytical instruments are required to provide data on product quality and endpoint conditions. Primary elements will have to be accurate enough to permit the computer to recognize and evaluate small changes.

The links between the controllers and the computer can be designed to "fail safe," so that computer shutdown will merely leave the process at the last set of operating conditions. The availability of the operator, to override during unusual conditions or computer maintenance time, makes this system feasible from the standpoint of the reliability of existing hardware.

Optimization by Mathematical Model

One approach to automatic optimization is to use the computer to solve the equations relating the measured variables to the secondary characteristics. This type of optimization is also known as predictive control. From the measured primary variables, the computer calculates the secondary characteristics or other control criteria. Then, it relates these factors in accordance with fixed mathematical expressions to determine the corrections for the controller settings.

When the computer is used in this manner, the relationships of the process must be established clearly, and the process must be studied with care.

Either an analog or a digital computer could be utilized to mechanize such an approach. Since the process is controlled dynamically by the instruments, the optimization routine of the computer remains in the supervisory control loop and places no heavy time burden on the computer operation. This permits time-sharing the computer among several problems without need for high-speed computing. The various techniques of this method of optimization are described in detail in the article by Lefkowitz and Eckman, Case Institute, on page 74.

One interesting aspect of the work at Case is the study of optimizing systems where the characteristics of the process are not known in detail. An attempt will be

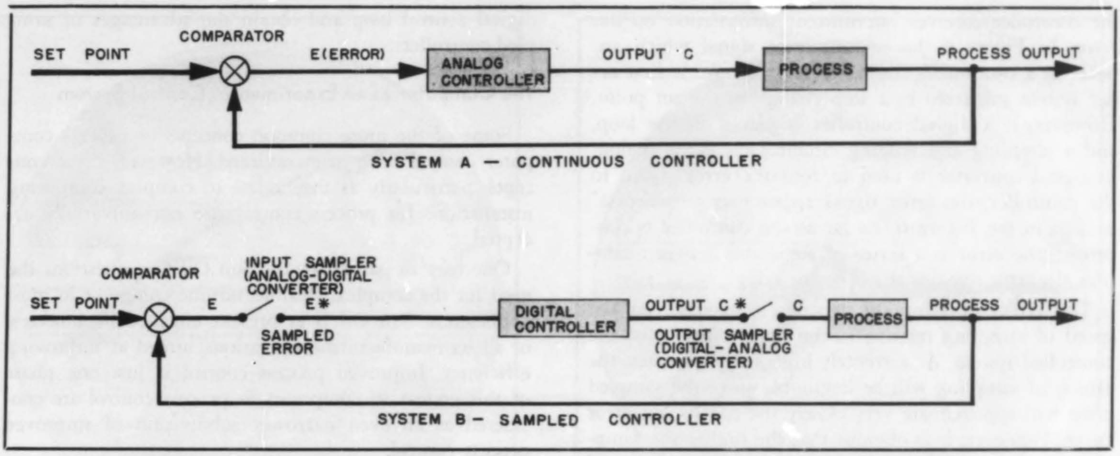

Figure 5. Comparative diagrams for a process control system employing continuous analog signals and one employing a digital controller using sampled data input.

made to determine whether a digital computer can be self-checking in the sense that it will change the assumed mathematical relationships which define the process in order to force the mathematical model to agree with the actual process. This is a very important concept since it means that, if successful, optimizing control may be feasible where the system is too complex for complete definition or where some of the necessary measurements cannot be made industrially. The concept of a control system which changes its mathematical model or its control parameters based on changes in the system being controlled is known as "adaptive control." Adaptive control techniques are being studied at length for possible military and industrial applications.

There are several installations, in addition to the SIE analog computer at Humble Oil which operate in this automatic optimization mode. One installation is at Texas Co., in Port Arthur where a Thompson-Ramo-Wooldridge RW-300 digital computer is used. The article on page 70 discusses two techniques for developing the mathematical model for such installations.

Optimization by Direct Experimentation

Another approach to the optimization problem is to use the computer as an automatic experimenter. The computer receives primary measurements, calculates secondary characteristics, changes one or more primary variables to determine how the changes affect secondary characteristics and continues this procedure until optimum conditions were attained.

Where more than two variables are involved in this procedure of "bumping" the process, choice of the computer is restricted almost completely to the digital type, since the experimental procedures become complex, and must be varied according to the previous results. However, as mentioned previously, the time constants of many processes are measured in hours. This can seriously impair the "bumping" technique, since the results of a single perturbation may not be felt for long periods, during which time uncontrolled variables may affect the system. Another difficulty is introduced in systems where large numbers of variables are involved, making the experimentation extremely slow.

There are advantages to automatic experimentation. One of these is that the relationships of the process are not required beforehand but emerge as a result of the experimentation.

One mechanization of the automatic experimentation approach is the Westinghouse OPCON controller. This device, which has been used in manufacturing operations at Westinghouse and on the optimization of a chemical process at Dow Chemical Co. will soon be installed on a fractionating tower at Sun Oil Co. The computer is described in the article on page 78.

Sampling in Digital Control Loops

Digital computers are being utilized for closed loop supervisory control in installations being made now. In the future it is possible that computers will replace, in some cases, the individual control instruments and take over the dynamic control of the process.

Some chemical processes being considered, such as high speed flow reactors, will probably require extremely fast-response controllers, of a speed unattainable with present conventional instruments. The use of parallel, high speed, digital techniques may offer a solution to these control problems.

However, the effect of sampling which is introduced by a digital element in a control loop is a factor which must be considered not only in dynamic closed loop systems where the computer replaces the individual control instruments but also in supervisory control systems where a computer periodically resets the control points.

Referring to Figure 5, in a continuous control loop such as System *A*, the controller output varies continuously based on the error signal (the difference between the measured variable and the set point). However, where sampling is introduced, as in System *B*, the controller receives intermittent information on the error. In Figure 6 the smooth error signal which appears in a continuous controller is shown for a first order system subjected to a step change in the set point. However, if a digital controller is placed in the loop, and a sampling and holding circuit such as an analog-to-digital converter is used to feed the error signal to the controller, the error signal appears as a "staircase" as seen in the Figure 6. As far as the controller is concerned, the error is a series of steps and between samples, the error remains at a constant value.

The effect of sampling depends, of course, on the speed of sampling relative to the time constants of the controlled system. At extremely high sampling rates, the effects of sampling will be negligible since the sampled error will approximate very closely the continuous error curve. However, it is obvious that the higher the sampling speed, the faster is the computer that is required and the fewer the number of control loops among which the computer can be shared or multiplexed.

Figure 7 shows the effect of reducing the sampling rate in a control loop. Curve A shows the error signal in a first order system subjected to a step change in set point with continuous control action. The controller in this case has only proportional control action; there is no reset (integral control) or rate control (derivative control).

Curves B, C, and D show the response of the same system with a sampled controller with the same proportional band setting, but with varying sampling rates. As the sampling rate is decreased, the system becomes increasingly unstable.

(The curves in Figures 6 and 7 are the control responses generated by an analog computer simulation of the sampled data digital controller and the continuous analog system shown in Figure 5B.)

In addition to the effect of sampling of the input, there are similar undesirable effects due to sampling at the output through the digital-to-analog converter and due to delays introduced by the finite time required by the computer to carry out the necessary control computations.

In order to reduce the required sampling speeds without degrading the response of the system, it is necessary to utilize different forms of control in the digital controller than in the continuous controller. Fortunately, in supervisory control loops, the time constants of the process are measured in minutes and hours and therefore, the sampling and computing speeds which are required in resetting control points for optimization are not restrictive for digital computers. In control loops where conventional controllers are replaced by the computer, the computing speeds become economically unfeasible for most installations unless sophisticated control computations are used. Where such control computations are used, however, the response of the sampled control system can often be improved to a point not attainable with continuous analog control.

The studies which are being made today in sampled data control for both military and industrial applications are designed to solve the problems inherent in the digital control loop and obtain the advantages of sampled controllers.

The Computer as an Experimental Control System

Some of the more common concepts of process computer control have been outlined. However, these concepts, particularly as they relate to complex computing installations for process control, are not universally accepted.

One user in particular, the Sun Oil Co., questions the need for the complex, flexible, on-line computer in most applicatons. Sun Oil is at present engaged in a review of all its manufacturing operations, aimed at improving efficiency. Improved process control is just one phase of this endeavor; computers in process control are considered as an even narrower subdivision of improved process control.

This philosophy has led to a three step approach at Sun Oil:

1. Arrange to measure the significant process variables.
2. Find the mathematical expressions which define the best economic operating conditions for each process.
3. Establish the means for maintaining these conditions.

On-line computers would be required only in step three, and then not in all cases. Sun Oil feels that in many cases, extremely simple mechanisms may be used to accomplish the best economic control although in some cases, elaborate computing schemes may be necessary.

However Sun Oil feels that in one area, the computer holds an important place. This is the use of small, transportable digital computers as experimental process controllers. Such a computer could be used to simulate a variety of process control systems. When the "best" kind of control has been determined, a permanent control system of this type would be installed and the flexible, experimental computer used for other studies.

Sun Oil has started a program based on this approach. They plan on experimentally controlling a distillation column with several different computers. The tower separates a mixture of normal butane and isobutane with a charge rate of about 200 barrels per hour. The tower is a full size refinery unit in commercial service but equipped with special measurement and control facilities. The feed, overhead and bottoms are equipped with gas chromatographs — two designed by Sun Oil, one by Perkin-Elmer. Other special measuring devices, designed by Sun Oil, are also installed on the tower. In addition, temperatures and compositions can be measuerd on alternate trays and feed composition can be varied.

Initially, this tower will be run under a variety of conditions to determine the static and dynamic characteristics. This will involve the collection and analysis of considerable data.

Next, Sun Oil plans to use a Litton-80 Digital Differential Analyzer as a control computer. Special input-

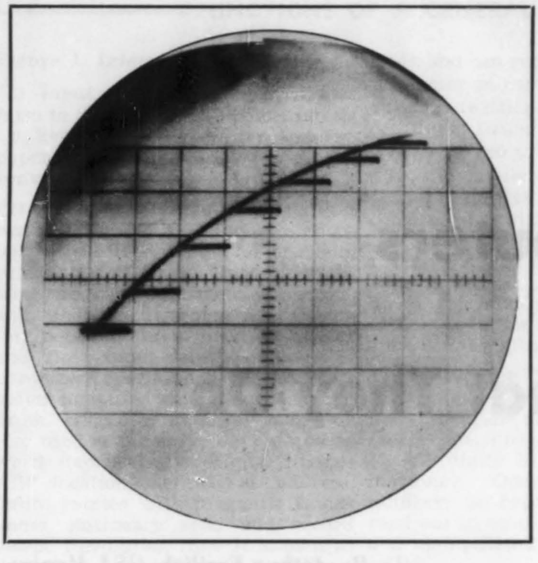

Figure 6. Oscilloscope view of a simulated control system error signal. The smooth curve is the error signal with a continuous analog controller. The "staircase" lines are error signals when using a sampled data system and digital controller. As far as the controller is concerned, the error is a series of steps and between samples the error remains at a constant value.

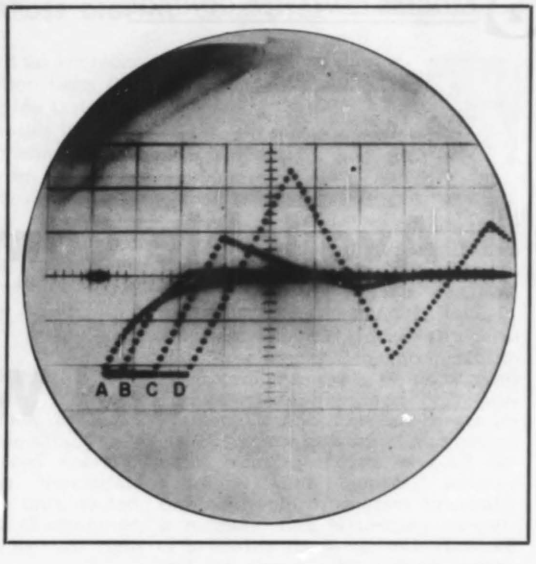

Figure 7. Oscilloscope view of a simulated control system error signal in response to decreasing sampling rates. Curve A shows error signal with continuous analog controller (proportional response) with step change in set point. Curves B, C & D show increased instability of same system with a sampled data controller (same settings) as sampling rate is decreased.

output equipment will link the DDA computer to the process and to the set points of the controllers on the tower.

A third series of experiments will employ a Westinghouse OPCON Optimizing Control Computer specially assembled for this purpose. OPCON will experimentally manipulate control valves to produce the most economic operation. From these experiments, Sun Oil hopes to evolve a better control system for its particular tower and others like it.

Although the overall concepts of the Sun Oil philosophy do not conflict with the basic concepts discussed previously, the important difference lies in the idea that the computer will be used primarily for *experimentation*. Once the "optimum" control system is determined, the computers will be replaced with the simplest possible mechanization required to do the job. If operating guides are required, for example, a rather elementary type of computer might be used for the specific computation needed. Automatic optimizing would be done by special purpose units arranged for the specific logic required for the particular installations.

Another study program is also being undertaken by Sun Oil Co., in cooperation with Genesys Corp. The philosophy of the Genesys computer control system embraces the concept of a flexible computer for experimental purposes which can then be replaced by a less costly fixed-program computer to mechanize the functions found necessary during the experimental phase. The flexible computer can then be utilized in the study of other processes.

The joint Genesys-Sun Oil program will cover the study of the performance of a catalytic cracking unit at Sun. Based on the results of studies of the unit's performance, with heavy reliance on stream analyzers for the investigation, it is hoped to evolve specifications for a suitable computer control system.

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Available Computers and What They Do

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THE MOST SIGNIFICANT CHANGE in the status of process computer control during the last 18 months is the increase in commercially available hardware. Concepts have not changed much. But for the first time there are several control computers available, and many manufacturers are on the verge of announcing new equipment. At present there are three general classes of computers available:

(1) General Purpose Logic Digital (G.P.)

(2) Analog Computers

(3) Incremental Digital Computers

In this section we will discuss each of these computers — how they operate, what they do, and equipment available.

GENERAL PURPOSE DIGITAL COMPUTERS

Through common usage, the term "general purpose" or G.P. Digital Computer has become the generic name for a class of computers which operates on the principle of integral transfer; that is, digital data is processed through the computer based upon the entire numerical value of the quantity. This distinguishes the general purpose computer from the incremental transfer computer. The digital differential analyzer is an example of an incremental machine. The general purpose computer is defined in terms of its internal logic rather than its general applicability. Because of its flexibility and ability to perform logical functions, the general purpose digital computer is extremely valuable in a control system. Its logic permits it to perform all arithmetic functions such as addition, subtraction, multiplication, and division. It can compare quantities, make logical decisions based on results of comparisons, vary its sequence of operation as a result of its own decisions, and detect its own failures plus those of components in the system. The G.P. digital computer can perform many other functions and operations such as shifting numbers to right or left and extracting specific digits from a number.

The general purpose digital computer is more accurate and more flexible than analog computers but requires a larger outlay of initial capital since it is not modular in construction as far as computational ability is concrned. Therefore, the analog computer holds an advantage in the smaller installation; the general-purpose digital machine is more powerful and more economical in larger systems.

In terms of speed, the general-purpose digital computer is relatively slow, with a frequency response of less than 5 to 10 cycles per second for most serial computers. However, since it operates on the entire numerical value and can have a completely different program for different inputs, the general-purpose digital computer is well-suited to multiplexed systems where the computer is time-shared among many varied inputs. Present investigations into sophisticated routines for control may increase the frequency response of G.P. digital computers by a considerable factor.

Figure 1 is a block diagram of the basic elements in a general-purpose digital computer showing the flow of information. Figure 2 is a more detailed block diagram showing major components and their functions.

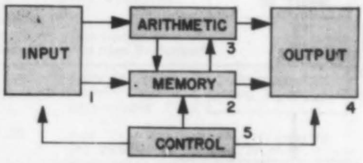
FUNCTIONS OF A GENERAL PURPOSE DIGITAL COMPUTER

Figure 1. Information flow.

(1) Input. Supplies data in digital form to the computer. Typical inputs are keyboard, magnetic tape reader, paper tape reader, analog-to-digital converter, switches.

(2) Memory. Storage place within machine. Stored data includes problem to be solved, inputs for problem, constants and other values for problem, program, intermediate results, and final results. Memory is buffer between high-speed computer and slow input-output units; synchronizes operations, and permits better computer utilization. Magnetic drum, magnetic cores, or magnetic disc used as memory. Data stored as words (consisting of digits) in specific location, defined as address. Drum rotates with magnetic tracks under stationary read and record heads. Revolution time is known as access time, usually runs 8 milliseconds, and can represent an appreciable factor in computation time. Circulating registers provide faster access time. Drum memories inexpensive compared to core memories. Disc memories similar to drum except data stored on flat magnetic disc. Core consists of matrix; for writing the core is driven to desired state of magnetism; for reading this magnetism is sensed. Data addressed by wires representing x, y and z coordinates in the matrix. Core access time is millionths of a second.

(3) Arithmetic Unit. Performs addition, subtraction, logical functions, and others in succession on digits (serial machine) or simultaneously on all digits in a word (parallel machine). Operations necessitate numbers be read into unit, stored, read out to other parts of computer, and manipulated such as shift right or left.



(4) Output. Path for data out of computer. Common output units are: typewriters, printers, digital-to-analog converters, digital displays, magnetic tape and punched tape.

(5) Control. Synchronizes all operations in computer. Sequence performed according to series of instructions (program) stored in memory by programer. Control unit interprets instructions, controls input and output units, transfer of data, and all calculations. Most general purpose computers store program internally in memory unit, permitting computer to modify the program is required and self-check itself and all inputs.

Figure 2. Functional diagram.

(1) Input Switching Unit. Analog signals from primary elements and transducers are coverted into compatible electrical signals before being switched into the system. Switching unit is a multiplexing device which selectively connects any one input to the analog-to-digital converter. Selection is under control of the computer; need not be sequential but can be random, permitting sampling of critical inputs at more frequent intervals or varying the input program during unusual conditions.

(2) Analog To Digital Converters. Selected analog inputs converted into digital codes and entered into the computer, generally through a buffering section in the computer.

(3) Digital Input Selection. Digital inputs can originate from digital transducers, manually set switches or A/D converters on individual analog channels. Any of the digital inputs can be read when required by the program.

(4) Digital Clock. Provides time-of-day readings in digital form as a real-time reference for the computer.

(5) Control Panel. The means for manually controlling the computer and manually feeding input data.

(6) G.P. Digital Computer. The principal functions of the computer are: (a) Alarm detection for critical trends and references generated by the computer based on changing process conditions. (b) Operating computations on process inputs to calculate operating guide information and determine the secondary characteristics in real-time. (c) Analysis of process operation and dynamics, and updating of the mathematical model of the process. Computer can also perform correlation studies to determine effects of variables on process behavior. (d) The computer calculates the desired set points for the process controllers, based on input data and equations in memory.

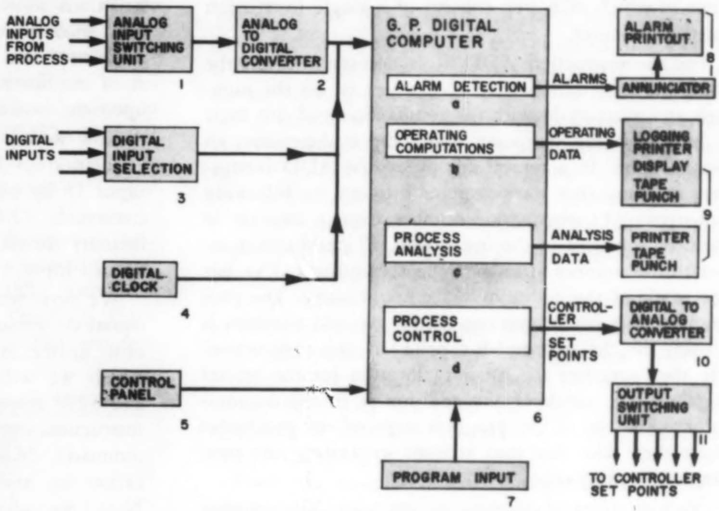
(7) Program Input. This is the means for loading the computer program into the machine and for making changes in the program. Input usually consists of typewriter for preparing the program on punched tape and a tape reader for introducing data into the computer.

(8) Alarm Annunciator and Printout. Data can be displayed on conventional annunciators and also recorded digitally on typewriters or tape printers, under computer control.

(9) Logging Devices. Digital output devices for recording process operating data, results of process analysis, and operator instructions generated by the computer; operates under control of the computer.

(10) Digital to Analog Converter. Since most present controller set point mechanisms accept analog signals, the computer digital output is converted to analog form.

(11) Output Switching. Analog set points are sent to controllers by means of this unit under control of the computer.



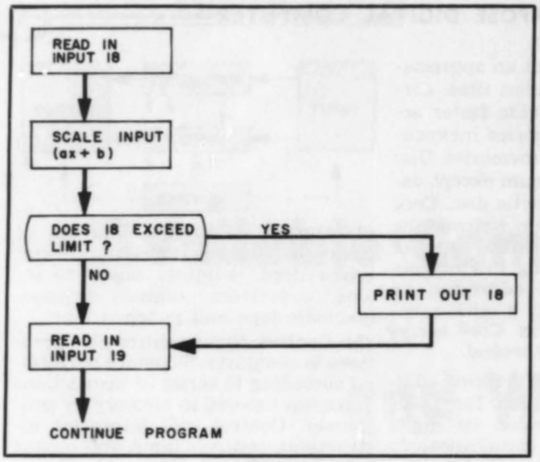


Figure 3.

Operation of a G.P. Digital Computer

Perhaps one of the best ways to illustrate the operation of a general purpose digital computer is to explain programing of a simple calculation such as:

(1) Read in the value of pressure input 18 and store

(2) Scale the pressure signal.

(3) Determine whether the pressure exceeds a predetermined safe limit. If it does, print out the data, then read in input 19. If 18 does not exceed safe limit, read in input 19 immediately.

A block diagram (Figure 3), known as a flow diagram, is a graphical statement for this calculation. It illustrates immediately a very important feature of the computer: the ability to change its program depending on the results of logical decisions which it makes. In this case the computer takes one of two alternate paths depending upon whether or not 18 exceeds the safe limit.

It is the job of the programer to translate the flow diagram into computer language, or a sequence of steps in which each step consists of a single instruction for the computer.

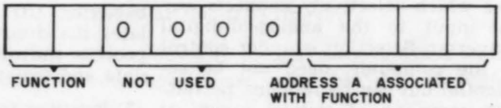
For the instruction ADD, it is necessary to tell the computer what numbers to add, where to get the numbers and what to do with the results. Some of this logic is built into the computer, and some is dependent on the program. In a typical computer, the ADD instruction may sequence the computer through the following sub-steps: (1) obtain one number from a location in memory specified in the instruction. (2) add this number to the number already in the accumulator. (3) put the result of the addition in the accumulator. The programer must insure that one of the two add numbers is already in the accumulator prior to this instruction. He then specifies the memory location for the second number. The result of the addition is in the accumulator at the end of this program step and the programer must then take this into account in writing the next step of his program

Various types of instructions are used. The simplest type is the *single address* instruction where the programer specifies the function to be performed and a single memory address. Each function (ADD, DIVIDE, SHIFT LEFT, COMPARE, ETC.) is assigned a numerical designation which the control section of the computer interprets prior to sequencing the computer through the required steps. A counter in the control units keeps track of the instructions and supplies the computer with the address of the next instruction. The instructions are taken in numerical sequence, based on the address of the instruction, with the counter furnishing the address of the next instruction.

In a *double address* machine, the instruction generally specifies the operation, the location in memory of the data to be operated upon, and the location of the next instruction. This particular double address instruction format is know as (1+1) and permits locating the next instruction on a drum or disc memory so that access or waiting time between instructions is reduced to a minimum (optimum coding or minimum access program).

Instructions stored in the computer must conform to the format of digital data. Normally, a G.P. computer has a fixed word length, i.e. each stored information unit consists of a fixed number of digits. Assume a word length of 10 decimal digits, then it would be possible to store, in one memory location, a 9 digit number plus the sign of the number (+ or —).

The same 10 digits, when containing an instruction, could have the following format:



Such a format would permit specifying any one of 100 instructions, designated as 00 to 99, and any one of 10,000 memory locations or addresses, ranging from 0000 to 9999.

Let us assume a single address machine with the instructions shown in Table 1. These instructions are a very small part of the repertoire of instructions normally used in a computer. Note that the address portion A of the instruction has various meanings depending upon the instruction involved.

How would we write the program to carry out the calculation in Figure 3? The first step is to read in input 18 by placing, as our first instruction, the input command: *32 0000 0018*. This command is the first memory instruction, and stored in location *0000*. The desired input (18) is now in the accumulator.

We now wish to scale this value by means of the equation: $y = ax + b$ where x is the value of the input now in the accumulator and a and b are constants which we will assume are stored in addresses *4098* and *6792* respectively. If we now give, as our second instruction, stored in location *0001*, the following MULT command: *24 0000 4098* we will perform the multiplication ax, and leave this result in the accumulator. Next, we add b to ax by the ADD instruction: *20 0000 6792*, and the value of the accumulator is now

$ax + b$ or, in other words, y, the desired scaled value of input 18.

If we look at Figure 3, we can see that we may need this scaled value later for print-out purposes, so let us store it in memory location *2235* by using the STORE instruction: *10 0000 2235*. We have now compiled the following program:

Code	Instruction Word	Location of Instruction
INPUT	32 0000 0018	0000
MULT	24 0000 4098	0001
ADD	20 0000 6792	0002
STORE	10 0000 2235	0003

It is now necessary to determine whether the scaled value of input 18 exceeds a predetermined limit, which we will assume is stored in memory location *1259*. (This limit could be inserted by the operator thru a keyboard, and stored in the memory location until it is replaced by another value manually inserted through the keyboard.)

The scaled value of 18 is in the accumulator, as well as in memory location *2235*. If we subtract the stored limit in location *1259* from the value in the accumulator, the result will be negative if input 18 does not exceed the limit; the result will be zero if the two values are equal. If, however, the input exceeds the limit, the result will be positive. Therefore, our next instruction, in location *0004*, should be the SUB command: *22 0000 1259*, which subtracts the limit stored in *1259* from the scaled value of input 18.

Next, we wish to determine the sign of the result in the accumulator, and depending on the sign, proceed through one of two program branches. To do this, we use the conditional transfer command (COND). If the result is positive, the limit was exceeded and we must print out the value of input 18. The COND command would be stored in location *0005* as: *42 0000 xxxx*, assuming that we do not, for the moment, specify the location of the instruction to be transferred to if 18 is not positive.

If no transfer occurs, we must print. Therefore, the next instruction in sequence would be in location *0006* and should prepare us for printing. Assume that the desired printer is selected by an address of *0004*. However, the OUTPUT command prints the contents of the accumulator. Therefore, we must obtain the scaled value of 18 from memory location *2235* and put it in the accumulator. This is done with a READ command stored in location *0006*: *36 0000 2235*. We can now print input 18 by using, in memory location *0007*, the OUTPUT instruction: *58 0000 0004*.

The next instruction is then to read in input 19, and store in location *0008*, so that we now use this location as the A address portion of the COND instruction previously written for storage in *0005*. The INPUT instruction in *0008* becomes: *32 0000 0019*. The complete diagram is now:

Code	Instruction Word	Location of Instruction
INPUT	32 0000 0018	0000
M[illegible]	24 0000 4098	0001
ADD	20 0000 6792	0002
STORE	10 0000 2235	0003
SUB	22 0000 1259	0004
COND	42 0000 0008	0005
READ	36 0000 2235	0006
OUTPUT	58 0000 0004	0007
INPUT	32 0000 0019	0008

TABLE I

INSTRUCTIONS

Code Designation	Numerical Designation	Description of Function Performed
STORE	10	Store the number in the accumulator in memory location A leaving it also in the accumulator.
ADD	20	Add the number in the accumulator to the number in memory location A and leave result in accumulator.
SUB	22	Subtract the number in memory location A from the number in the accumulator.
MULT	24	Multiply the number in the accumulator by the number in memory location A and leave the result in the accumulator.
INPUT	32	Set up input unit to select input identified by address portion A of instruction, have input converted to digital form by A/D converter and read digital value into accumulator.
READ	36	Clear the accumulator and place in it the number in memory location A.
COND	42	If the number in the accumulator is (−) or zero, do not perform the next instruction in sequence but transfer to the instruction in memory location A, and proceed in sequence from there. If the number in accumulator is (+) take next instruction in sequence. (Conditional transfer)
TRANSFER	46	Do not perform the instruction which is next in sequence but transfer to the instruction in memory location A and proceed in sequence from there. (Unconditional transfer).
OUTPUT	58	Read out the number in the accumulator on the output device specified by ,

This program could now be loaded into the computer, along with the necessary constants, either through a keyboard or tape reader and the computer could proceed to carry out the calculation.

This is a very primitive decision in varying the program. The same principles are used in making complex decisions or in making major changes in programs internally with the computer.

Comparison of General Purpose Digital Computers

Table II is a comparison of nine digital computers and computing systems which are presently commercially available for on-line computing and control applications. All these computers are of the general purpose digital type with the exception of the Genesys machine which is a hybrid computer (G.P. logic and incremental logic combined). All of the machines are of the internally stored program type except the Ferranti ARGUS computer which uses pegboards for the storage of program steps and constants. (Only limited data is available at present on the Ferranti ARGUS.)

In addition to the nine computers in Table II, there are at least two other general purpose digital computers being developed for process control:

1) A computing system is being developed jointly by Leeds & Northrup Co. and Philco Corporation.

2) Minneapolis-Honeywell, through the Industrial Products Group and the Datamatic Division, is developing the D-290 Computer for process control. The first unit is scheduled for installation at Philadelphia Electric Company in 1960.

There are several points of comparison in Table II which should be clarified, although most categories are self-evident.

TABLE II

Manufacturer	Thompson-Ramo-Wooldridge Prod., Inc. Los Angeles, Calif.	General Elec. Co. Phoenix, Arizona	G.P.E. Controls Chicago, Illinois	Daystrom Systems La Jolla, Calif.	Panellit, Inc. Skokie, Illinois	Genesys Corp. Los Angeles, Calif. (11)	Autonetics Downey, Calif.	Bendix Corp. Los Angeles, Calif.	Ferranti Electric, Inc. Hempstead, N. Y.
Computer	RW-300	GE-312	Libratrol—500	Complete Daystrom Computer System	Panellit 609	Unit Memory Processor	RECOMP II	G-15	ARGUS
Internal Number Base	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Operating Mode	Serial	Serial	Serial	Serial	Serial	Serial in G.P. mode Parallel in incremental	Serial	Serial	—
Bulk Memory Type	Drum	Drum	Drum	Magnetic Core	Magnetic Core	Magnetic Disc	Magnetic Disc	Drum	Cores (15)
Bulk Memory Capacity Minimum	7,936	2,048	4,096	1,024	4,096 (7)	10,000	4,080	2,176	256 (15)
Maximum	7,936	16,384	4,096	16,384	4,096 (7)	30,000	4,080	2,176	256 (15)
Word Length	17 bits + sign	20 bits + sign	30 bits + sign	20 bits + sign	38 bits + sign	19 bits + sign	39 bits + sign	28 bits + sign	9 bits + sign
Logic	Diode	Transistor	Diode	Diode-Transistor	Core-Transistor	Hybrid logic	Diode gating	Diode	—
Active Components Cores (in logic)	None	None	None	None	800	157 to 350	None	None	—
vacuum tubes	13	None	171	None	None	None	None	450	—
transistors	approx. 580	approx. 1,600	approx. 250 (4)	approx. 1,800	2,400	212 to 280	1,137	None	—
diodes	approx. 4,000	approx. 2,000	1,850	approx. 5,000	1,000	85 to 125	10,628	3,000	—
Instruction Type	Double address (1+1)	Single or double address (1+1)	Single address	Single address	Single address	Single address (12)	Single address	Modified (1+1) (12)	Single address
Words/Instruction	Two	—	One	One	One	One	—	One	One
No. of Different Inst. Normal	20	>60	16	46	—	20	49	56	—
Maximum	>34	very high	—	85	64	Up to 500	—	1300 W/micro-coding	—
Clock Frequency	153.6 Kc.	250 Kc.	136 Kc.	50 Kc.	167 Kc.	50 to 500 Kc.	151 Kc.	100 Kc.	—
Add Time w/o access	0.78 ms.	0.096 ms.	0.25 ms.	0.44 ms.	0.720 ms. (8)	—	0.54 ms.	0.27 ms.	—
Mult. Time w/o access	2.99 ms.	0.29 to 2.02 ms.	15.0 ms.	9.24 ms.	2.80 ms. (8)	—	10.8 ms.	15.12 ms.	—
Time to Perform Calc. in Fig. 4	42 ms. (1)	30 ms (1) (17)	900 ms. (5)	75 ms.	31.7 ms.	50 ms. (13)	98 ms.	216 ms.	—
Max. Input Switching Speed	3,840 pts./sec. (1,000 pts./sec. typical)	300 pts./sec.	200 pts./sec.	284 pts./sec.	350 pts./sec. (9) 5-10 pts./sec. (10)	300 pts./sec.	Can be tied to commercially available A/D input and D/A output systems.	Can be tied to commercially available A/D input and D/A output systems.	A/D input and D/A output conversion equipment are included in system.
A/D Conversion Input Range	0-10.23 V. (2)	0-10 mv.	0-10V. std.	0-50 mv.	0-60 mv.	0-8V.			
D/A Conversion Output Range	0-15 V. or 0-5 ma.	0-20 V.	as required	as required	as required	as required			
Time to Perform Calc. in Fig. 4a	42 ms. (16)	63 ms. (3)	915 ms. (5)	79.2 ms. (6)	39.7 ms. (19)	100 ms.	105 ms. (typical)	Varies for application.	—
Weight	600 lbs.	3,000 lbs.	1,000 lbs.	2,000 lbs.	2 cabinets	200 lbs.	197 lbs. (computer only)	800 lbs.	—
Size	36" x 56" x 29"	76" x 108" x 24"	30" x 42" x 60"	4 std. racks	66" x 56" x 16"	desk size	23" x 21" x 16.5"	60" x 27" x 32"	48" x 48" x 24"
Power Requirement	500W, 120V, 60 cy.	4KW, 120V, 60 cy.	1500W, 117V, 60 cy.	less than 2KW.	1 KVA.	350 watts	500W, 115V, 60 cy. (14)	3.5 KW, 110V, 60 cy.	—
Price	$98,000 with basic input-output.	Varies depending on application.	$65,000 with A/D input & output logic.	$135,000 and up for complete sys.	$125,000 for complete control sys.	Varies depending on application.	$86,000 for computer only.	$49,500 for (18) computer only.	—

NOTES

(1) Time shown is based on use of optimum coding. Computer routines are available to automatically code programs for minimum access.
(2) Complete input system including amplifiers, filters, electronic switches, etc. can handle input ranges as low as 0-10 mv., floating input for thermocouples.
(3) Assumes settling time of 20 ms. for low level differential amplifier and a 5 ms. settling time for the scanner.
(4) This figure includes transistorized A/D and D/A conversion units.
(5) Based on accuracy of nine decimal digits in square root calculation. Faster on special order.
(6) Assumes 20 ms. stabilization time, concurrent with computation.
(7) Magnetic film back-up storage available as required.
(8) Includes random access time.
(9) Clean, high-level signals.
(10) Process signals, low-level with noise.
(11) The Genesys machine is a hybrid computer, combining the logic of the G. P. computer and the incremental computer.
(12) Microprogramming available.
(13) In hybrid mode. Calculation time is 150 ms. in G. P. mode.
(14) Includes power for paper-tape reader, paper-tape punch typewriter and console.
(15) Core storage is for data only. Program steps and constants are stored on pegboards (128 constants and up to 4,096 program steps.)
(16) Input switching and conversion system is independent of the arithmetic computer which has immediate access to most recent data.
(17) Based on square root calculation accuracy of 10 bits; for 19 bit square rooting accuracy, time is 34 ms.
(18) $1,485 per month lease including maintenance.
(19) Does not include settling time.

(*1*) *Word length.* The size of the word in the computer and memory is not too critical since all machines provide between 9 and 39 binary bits, equivalent to a precision of 1 part in 500 to approximately 1 part in 10^{14}. In addition, most of the machines can operate with either single or double precision arithmetic, so that even greater accuracy is available.

(*2*) *Number of different instructions.* The normal number of instructions shown is the number which are available as standard in the machine. The maximum number represents the largest number of instructions which the logic of the machine can handle in terms of available digits in the instruction code, etc. In some machines, computer operations on a level of detail lower than a normal instruction are available to the programer to permit so-called microprograming or microcoding in which the programer constructs his own instructions from detailed steps.

(*3*) *Time to perform calculation in Figure 4.* The calculation shown in Figure 4 was programed by the manufacturers of eight of the computers in the table. The results are listed to indicate relative computational speeds of the machines. Note that no input switching, analog-to-digital conversion or readout times are included in this calculation. It is primarily a means of comparing arithmetic speeds. The sample problem involves memory access, add times, multiply times, etc. It represents typical calculations encountered in scaling an input, comparing it to high and low limits for determining abnormal conditions, calculating a flow from a differential pressure reading and calculating an operating guide involving several variables.

Where fast access memories such as circulating registers are available in a drum or disc computer, the calculation time is based on use of the fast access memory. Drum computers which feature optimum coding list calculation time with optimum coded program.

(*4*) *Input switching speed and A/D conversion input range.* Various input switching speeds and A/D conversion ranges are shown in Table II. The maximum input switching speeds shown are not necessarily attainable with typical low-level process inputs (0 - 10 mv.) with pick-up and noise problems. In many cases, an individual amplifier on each low level input (or an amplifier shared among a few inputs) would be required along with a filter for each input in order to attain the switching speeds shown as maximum. In most process applications at present, such switching speeds result in less costly input systems. In all cases, amplifiers can be used on low level inputs to make them compatible with the A/D converter input range.

In the case of the RECOMP II and G-15, these computers are not normally furnished with integral A/D and D/A input-output converters but are generally tied to commercially available A/D and D/A systems.

(*5*) *Time to perform calculation in Figure 4a.* The calculation previously shown in Figure 4 is used, with the added requirement that the computer select an input, convert it from analog form to digital form and read it into the computer prior to computation.

SAMPLE CALCULATION (1)

(1) READ IN NEW INPUT X (exclusive of input switching time or A/D conversion)

(2) CALCULATE $AX + B = Y$

(3) COMPARE Y TO C TO INSURE THAT $Y < C$

(4) COMPARE Y TO D TO INSURE THAT $Y > D$

(5) CALCULATE $Z = \sqrt{EY}$

(6) CALCULATE $J = \dfrac{[ZF - G]\,K}{H + L}$

(7) STORE J IN BULK MEMORY (use average access time)

(8) STORE Z IN BULK MEMORY (use average access time

Figure 4. A typical problem used to compare digital computer computational speeds.

SAMPLE CACULATION (2)

Same as above except:

(1) Assume input X must be selected by computer, switched into A/D converter and read into computer from converter.

Figure 4a. A second problem with selection, conversion and switching time in addition to computation.

Because of variations in the methods of handling input signals, the calculation times for Figure 4a should be used only as a general guide. Exact input speeds will generally depend on the type of input signal, the input equipment used in the particular installation and the requirements of the application.

(*6*) *Price.* Since all computer control systems are tailored to the application, the prices shown are only general figures. In some cases, prices are for basic systems with a minimum of analog input-output equipment. In other cases, typical complete process computer systems are included in the price. In the case of the RECOMP II and the G-15, the prices shown cover only the computer. In considering pricing for a computer control system, one should also bear in mind the cost of transducers, measuring devices and control elements which might not otherwise be required in the installation. Such additional costs, plus engineering and systems analysis costs, can easily equal the cost of the computer system itself.

Available General Purpose Digital Computers

More than 30 computer manufacturers were contacted for information. This listing includes those companies replying with data on general purpose digital computers which are within the scope of this report.

Autonetics RECOMP II. This is a general purpose digital computer, all transistorized, single address, disc memory machine. It has floating point arithmetic and automatic decimal conversion. It is designed primarily for engineering and scientific calculations. However, with appropriate input-output units, it can be used for process control installations. It has 4,080 word storage capacity, each word containing 39 bits plus sign.

Bendix G-15. A general purpose digital computer with drum memory, modified double address for optimum coding and microcoding which permits programer to construct own commands. A 16 word fast access memory is provided on the drum. The G-15 is a commercial computer, widely used for engineering, business, and scientific data processing. It has also been used in a wide variety of on-line applications including wind tunnels, navigation, tracking, and processing plants. This computer does not include A/D and D/A input-output units, but most such commercial units may be used under control of the computer for complete on-line computing system. Beckman Systems is now using a G-15 with their equipment for a computer control package.

Daystrom Computer. The computer is the heart of the Daystrom Operational Information System. It is a solid state digital system using magnetic core memory with single address instructions. Although a relatively slow clock speed (50 kc) is used, the random access core memory permits relatively fast computation speeds without need for optimum programing. The Daystrom A/D input system normally integrates each sampled input for 100 ms. so as to obtain a high noise rejection rate without use of filters. Where practical to filter each input or no noise is present, input sampling can be made at 284 points per second. Specifically designed for process monitoring and control.

Ferranti Argus. The Ferranti Argus is a transistorized process control computer manufactured in England and marketed in the U.S. by Ferranti Electric in Hempstead, N.Y. It is unique among computers available in that it does not have an internal stored program. A 256 word core memory is provided for storage, but program steps and constants are manually stored in pegboards, contained in trays in the computer. In this manner 512 program steps and 128 constants can be stored in the computer. A unit is available to expand this to 4096 steps. Input A/D and output D/A conversion equipment is an integral part of the Argus system. The computer is designed for closed-loop control.

General Electric GE-13. An all solid-state digital computer, using magnetic drum storage for both data and program. Specifically designed for process monitoring and control. Available in housed upright air conditioned cabinet. Uses removable printed circuit cards. Instructions can be either single address or double address (1 + 1) for optimum coding. Computer itself can be used to code program for minimum access. In addition, routines are available for simulating the 312 on an IBM 704 to assist in programing. An optional feature is circulating registers on the drum to provide 4 to 16 words of fast access memory. Includes A/D and D/A conversion units and input-output switching. The application determines scanning and input-output requirements.

GPE Controls Libratral 500. Manufactured by Librascope and marketed by GPE Controls (both subsidiaries of GPE). This computer is an adaptation of LGP-30, a commercial digital computer widely used for many engineering, scientific, business, and accounting applications. Over 250 LGP-30 computers now in use. Libratral-500 uses drum memory, with 3 single word fast access circulating registers for instructions. Specifically designed for process monitoring and control. Basic unit includes scanner, voltage-to-digital converter, and output logic. Computer operation is serial, fixed binary point, with internally stored program, using single address instructions.

Genesys Unit Memory Processor. This is a hybrid unit, combining both general purpose digital and incremental logic. It operates as either or both. It is housed in a desk type enclosure. All functions of the computer are achieved with a magnetic disc memory (10,000 to 30,000 words capacity) and a small magnetic core-transistor sequential network. The general purpose logic is used for decision making, arithmetic, etc., and the incremental logic for integration, etc. This combination uses a minimum of active components, relying heavily on the reliable passive storage elements of the magnetic disc memory. A/D conversion is by an all-electronic feedback encoder. The system is built according to individual applications. Process operation is optimized through adaptive control methods.

Panellit 609. This all purpose digital computer uses magnetic cores for both storage and logical operations in the computer. Transistor drivers operate the core logic circuits. It is housed in two upright cabinets. The core memory permits random access to any memory location with relatively high computing speed and without need for optimum programing. The input-output system contains buffering and fast arithmetic units to permit processing inputs and outputs with a minimum of interference with main computer arithmetic units. The 609 uses one channel for computation and a second channel for on-line data logging. Attachments include a magnetic film memory for 250,000 words on a single reel. A/D and D/A conversion are available as required as a part of the system.

Royal Precision LGP-30. This is a desk-size, drum memory, fixed binary point, general purpose digital computer marketed by Royal McBee Corporation. It is widely used for many engineering, scientific, business and accounting applications. Over 250 LGP-30 computers are now in use. Primary input unit is tape typewriter, with paper tape reader on the typewriter. Word storage is 4,096 in memory, each word containing 30 binary bits plus sign.

Thompson-Ramo-Wooldridge RW-300. A digital computer using diodes and transistors for logic. Magnetic drum storage for both data and program. Available in desk size or upright model. Specifically designed for on-line process control. Removable printed circuit cards used for internal circuitry and component mounting. Double address instructions (1 + 1) used for optimum coding. Computer itself can be used to automatically code program for minimum access. A 16 word circulating register on the drum provides fast access during computation. The A/D conversion and input system operates independently on the arithmetic computer, so that inputs are sampled and converted to digital form and entered directly into the memory without interfering with computation. Thus, most recent input data is used in computation without waiting for selection of an input and receiving of data.

Westinghouse OPCON. A fully transistorized logic control unit designed to automatically experiment with a process and optimize performance. It contains no numerical computation ability, depending on a small analog computer to calculate optimizing equations. Process equations are not necessary since the control unit uses the process itself as a model. Analog-to-digital conversion range is ± 0.5 volts. Digital-to-analog conversion range is 0 - 5 ma into 2000 ohm resistance (max.). Weight is 500 lbs.; size 60" x 22" x 30"; power requirements are 260W, 120V, 60 cycles.

ANALOG COMPUTERS

Although various types of analog computers and computing elements are in use today, including hydraulic, pneumatic and mechanical devices, the most prevalent type of analog computer is the electronic unit.

The electronic analog computer operates by means of an electrical model of the system described by the mathematical expressions being solved. The voltages at various points in the computer represent the values of the variables involved. Operation of the analog computer is on a continuous basis, with the electrical parameters behaving precisely as the continuous physical system or equation variables do.

The basic component of the analog computer is the operational amplifier. The principal requirements for this DC amplifier are that it be extremely stable, have a high open loop gain (100,000 or greater), linearity over a wide rang of operation (typically ± 100 volts) flat frequency response from DC to several hundred cycles per second, high input impedance and low noise level. In addition, most operational amplifiers reverse the polarity between the input and output of the amplifier.[1]

The operational amplifier is usually chopper stabilized to eliminate drift. The operational amplifiers are used to perform a variety of mathematical functions, by use of different input and feedback configurations. Interconnections to set up the individual amplifier configurations and the interconnections between amplifiers are generally made at a patchboard or terminal strip to permit ease of set-up and changing of the computer operation. Figure 5 shows several of the more common configurations which are used. Because of the amplification of noise in a differentiation circuit, it is generally preferable to avoid use of differentiators and rearrange the system equations to permit integration instead. For multiplying by a constant less than 1.0, manual potentiometers are used. The circuitry is shown in Figure 5 (attenuators).

The analog computer is, at present, a parallel device. Computations take place continuously and simultaneously. A separate calculating module is used for each computational function and these are wired up by the programer to solve the desired equations.

For multiplication or division of variables special multiply-divide modules must be provided. Other special modules or circuit configurations are used for non-linear functions such as simulating the saturation of a power drive, limiting the simulated travel of a control valve, etc. Extremely non-linear or empirical relationships, such as the relationship between pH and concentration, can be duplicated by the use of function generators of various sorts.[2]

The primary use of the analog computer is in the solution of differential equations. Since most control problems involve differential equations, the analog computer is well suited to a wide range of control computations. Since it is basically a parallel modular device; the addition of extra amplifiers increases the computational ability of the computer, and also increases the size and cost of the computer.

The accuracy of the analog computer decreases as the number of computations performed on the signal increases. As in conventional instrumentation, each manipulation of the signal introduces an error, usually between 0.1% and 0.5%. Generally, analog computations are accurate to within a few percent. Where extremely high quality components are used and care is taken, the accuracy can be within 1%—2% on fairly large computations.

The analog computer, being essentially a continuous device, is not well suited to applications requiring time-sharing of the computer among many channels, although some investigations of multiplexed analog computers are being undertaken.

Operating in fast-time permits the analog computer to simulate a plant and experimentally determine the best control action prior to imposing the control output on the actual plant. The greatest advantage of the analog computer is on relatively small scale problems, where large scale digital equipment cannot be justified. Several analog control computers are estimated to cost about $5,000 for a typical fractionating tower installation. Contrast this to a cost of at least $35,000 for the smallest digital computer system available today and the tremendous advantage of the analog computer on smaller processes is readily apparent.

It is expected that the applications of analog process control computers will be widespread among smaller unit operations such as fractionating towers, catalyst regeneration and small batch processes.

[1]Superior numbers refer to similarly numbered references at the end of this article.

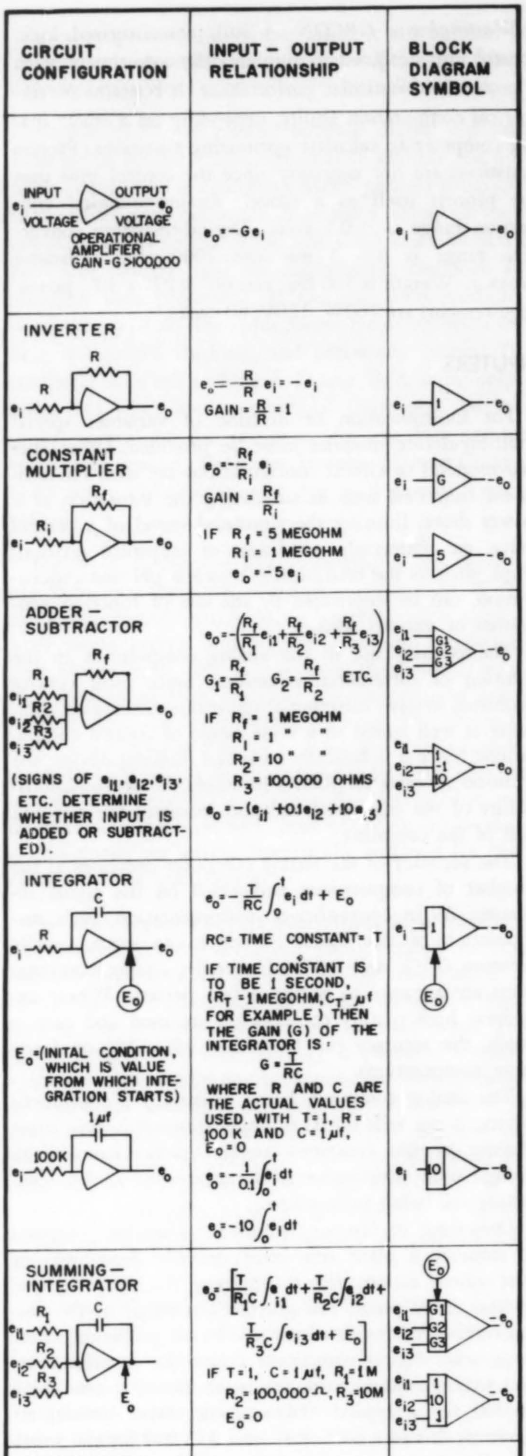


Figure 5, (left). Common computation circuits used in electronic analog computers.

Programing an Analog Computer

Suppose that we wish to solve a typical second order differential equation such as would describe the motion of the spring mass system shown in Figure 6. The system dynamic behaviour is described by the equation:

$$M\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + K\theta = O \qquad (1)$$

One simple approach to mechanizing this equation on the analog computer is to rewrite the equation, equating everything to the highest order derivative:

$$\frac{d^2\theta}{dt^2} = -\frac{D}{M}\frac{d\theta}{dt} - \frac{K}{M}\theta \qquad (2)$$

Now, if we assume that we have, at point I in Figure 7a, a voltage equivalent to $\frac{d^2\theta}{dt^2}$ *we can then integrate this voltage once to obtain —* $\frac{d\theta}{dt}$ *and then integrate the resulting voltage to obtain* θ. *This is shown in Figure 7a.*

We can now insert attenuators as shown in 7b so as to produce the quantities which appear in equation 2.

If we now change the sign of point II with an inverter, and sum the values at points III and IV in Figure 7c, we would have the sum as shown by equation 2.

By successive integrations and calculations, we now have the quantities available which, when summed, will actually equal $\frac{d^2\theta}{dt^2}$. So now, we simply close the loop by summing the quantities at III and IV in Figure 7c, at the input to the first integrator, as shown in Figure 7d.

If the first integrator is externally set to zero initially (that is, the system is at rest with zero velocity and zero acceleration) and the second integrator is externally set to θ_o this will be equivalent to manually displacing the rotor through an angle θ_o. If we then remove the externally imposed initial condition voltage θ_o, the system will respond as if we had suddenly released the rotor. Depending on the strength of the spring and the amount of air resistance, various responses will be obtained.

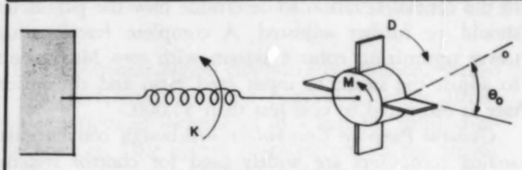
In Figure 8, we see the results of solution of this equation on an analog computer. Assuming that M = 1.0 and θ_o is some constant initial displacement in all cases, the curves show the effect of spring strength.

Curve 1 — K = 1, D = 1
Curve 2 — K = 0.5, D = 1

The weaker spring in Curve 2 slows up the system's return to zero displacement. In Figure 9, the effect of air resistance or damping is shown.

Curve 1 — K = 1, D = 1
Curve 2 — K = 1, D = 0.5
Curve 3 — K = 1, D = 0

As damping is reduced, the system overshoot becomes greater until, with no damping, the system oscillates without end (i.e. frictionless motion).



K = spring force (rotational torque)
M = mass
D = air damping
θ = angular displacement
$\frac{d\theta}{dt}$ = angular velocity
$\frac{d^2\theta}{dt^2}$ = angular acceleration

Assuming that K, D, and M are constant, the dynamic behavior for the system is given by:

$$M\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + K\theta = 0;$$

If the system is manually displaced through some angle θ_0 and released, then initially $\theta = \theta_0$

Figure 6.

Amplitude and Time Scaling[3]

Every problem requires scale factors. They relate voltages to problem variables, and solution time to problem time. In the simple example given, all of these factors were assumed to have convenient values of unit. This "one-to-one" correspondence is rarely convenient, for the variables of a physical system usually change through values which are either too small or to great to be represented directly by voltages within the linear amplifier range of plus or minus 100 volts available on most computers. Furthermore, it is common for changes to occur either too rapidly or too slowly in the physical system for convenient appraisal, and thus a slowing-down or speeding-up is desirable. There are two types of scaling in an analog computer.

Amplitude Scaling. Amplitude scaling deals with the magnitude of a problem's dependent variables. A criterion for good amplitude scaling is that all voltages on the computer will remain less than the maximum permitted value and yet will have as large a value as possible. For accurate solutions the values of voltages and their excursions during a transient must be made as large as possible, for then the effects of any constant errors that might be present in the operation of a component will be minimized. The scaling of any variable is independent of that or any other variable, including any or all of its derivatives.

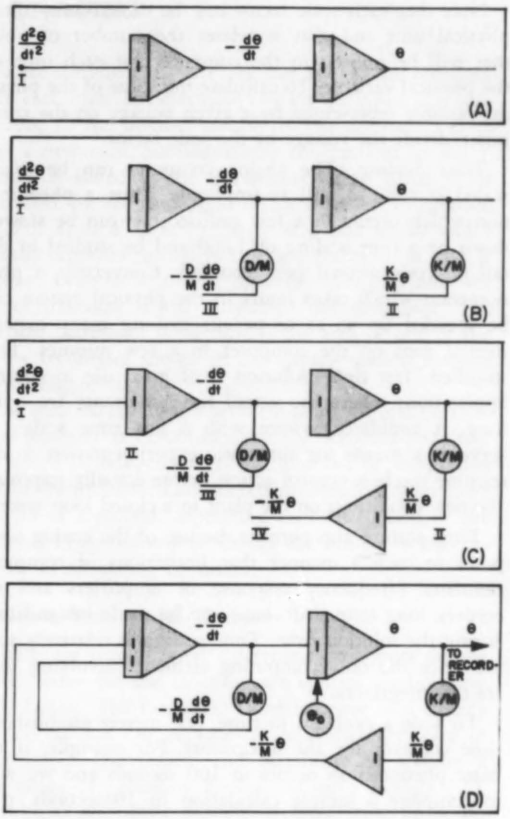
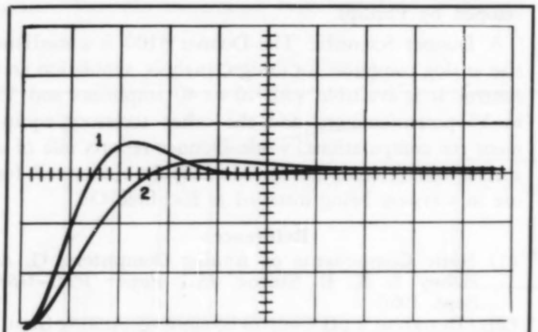


Figure 7. Analog circuit development for solving the typical second order differential equation representing the system shown in Figure 6.



Figur 8. Analog computer results of solution of the equation shown in Figure 6. Each curve represents different spring strength.

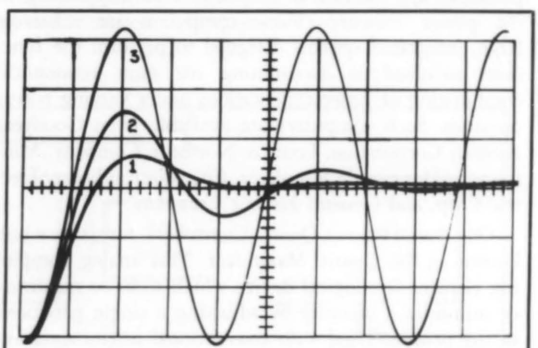


Figure 9. Analog computer results of solution of the equation shown in Figure 6, showing the effect of air resistance or damping.

Note that each scale factor has the dimensions volts/physical unit and that it relates the number of volts that will be present in the computer for each unit of the physical variable. To calculate the value of the physical variable represented by a given voltage on the computer, divide the voltage by the scale factor.

Time Scaling. The analog computer can be easily scaled in time as well as amplitude. Thus, a phenomenon which occurs in a few milliseconds can be slowed down by a time scaling of 1,000 and be studied in detail on conventional pen recorders. Conversely, a phenomenon which takes hours in the physical system can be speeded up so as to permit making many experimental runs on the computer in a few minutes. This so-called "fast time" solution is of great use in control applications where the actual time constants are quite long. A simulated system with a fast time scale can serve as a means for automatic experimentation to determine the best control action before actually imposing the new conditions on the plant in a closed loop system.

Time scaling also permits the use of the analog computer in such a manner that limitations of computer elements (frequency response of amplifiers and recorders, long term drift, etc.) can be made insignificant during the solution time. Time scaling is relatively simple since the only computing elements involving time are the integrators.

To scale a problem in time, one merely establishes a time constant for the integrators. For example, if the basic phenomenon occurs in 100 seconds and we wish to complete a sample calculation in 10 seconds, then all integrators should have a time constant of 0.1 seconds. This time scaling in no way affects the amplitude scaling; it merely determines the rate at which the solution proceeds. Note that the gain of the integrator is independent of the system's basic time constant but is related instead to the amplitude scaling. Wherever a circuit is time dependent, then a corresponding time scaling will be necessary.

Analog Computers Available

Special Purpose Computers—Because of their modular nature, analog computers have been assembled into control computers for special purpose uses. One of the principal applications is economic load dispatching in the power industry. These computers are relatively large, integrated systems designed to perform the functions involved in determining the most economical combination of generating stations under varying power demands. Such computers are available from Goodyear Aircraft Corporation, Leeds & Northrup Company, Minneapolis-Honeywell Regulator Co., Westinghouse Electric Corp. and General Electric Company.

One manufacturer, Quarie Controllers, furnishes a unit known as the Quarie Maximizer. This analog computing element is a logical device which seeks to maximize or minimize a quantity by adjusting a single parameter in the process. Used with conventional instrumentation, retransmitting slidewires, manually set potentiometers and other simple analog devices, the Maximizer can be utilized as an optimizing analog controller which disturbs a process parameter and uses the resulting change in the control criterion to determine how the parameter should be further adjusted. A complete fractionating tower optimizing control system with two Maximizers to adjust the steam to input feed ratio and the reflux rate is estimated to cost less than $5,000.

General Purpose Computers—Although conventional analog computers are widely used for control systems studies, only three manufacturers offer a variety of analog computer components and analog computers specifically for on-line process control applications. A number of companies offer analog computer components for custom construction by the user.

1. Southwestern Industrial Electronics Company (Div. of Dresser Industries, Inc.) SIE CM-2 analog computer is a solid state device which utilizes magnetic amplifiers for the operational amplifiers. Although there is no limit to the number of amplifiers which can be used, a single CM-2 cabinet is designed for up to 12 amplifiers, 8 attenuating potentiometers and 6 logarithmic networks. The logarithmic networks are used to convert computer signals to their logarithmic values, thus permitting such functions as multiplication or division to be performed by summing amplifiers.

The SIE computer is designed to operate from commercial electronic transducers. Special purpose components are available for time-delay, square-rooting, storage, thermocouple and strain gage amplification, etc. The necessary interwiring between computing elements is made at a terminal board to program the desired calculation. A SIE CM-2 computer for a fractionating tower control system is priced at about $5,000.

2. Electronic Associates, Inc. PACE TR-10 analog computer is a small, desk-top computer using fully transistorized computing components. The computing components are also designed for use as solid state low cost analog control computers. Each module is packaged in a small metal housing; the front of each module contains a color coded patch panel for interconnecting components. A basic system with 6 summing amplifiers, 4 integrating amplifiers, 10 attenuators and solid state power supply costs under $4,000.

Electronic Associates has also been licensed by Phillips Petroleum Co. to manufacture and sell a special-purpose solid state analog computer for the control of distillation columns employing an analog program developed by Phillips.

3. Donner Scientific. The Donner 3100 is a medium size analog computer for design, analysis, simulation and control. It is available with 10 to 40 amplifiers and 35 to 55 potentiometers, and the other accessory equipment for computational work. Donner reports sale of a special analog computer to Minneapolis-Honeywell for use in a system being installed at Richfield Oil.

References

(1) Basic Components of Analog Computers, G. A. Behey & K. E. Sterne, *ISA Paper PTC-3-58*, Sept. 1958.

(2) "Design of a pH Control System by Analog Simulation", W. B. Field, *ISA Journal*, pp. 46-47, Jan. 1959, v. 6, #1.

(3) "The Analog Computer: Its Operation and Use in Engineering", A. E. Rogers, *ISA Paper #PCT-2-58*, Sept. 1958.

The incremental digital computer is commonly called a digital differential analyzer because it solves differential equations in increments of a variable using digital techniques. This hybrid character retains the analog ease of programing and the computation feature of a digital system. The DDA is capable of solving ordinary linear or non-linear differential equations or sets of such equations. It is functionally equivalent to a mechanical differential analyzer. The arithmetic circuitry is simple since summation and storage is performed a bit at a time.

The digital differential analyzer is being used in combination with the general purpose digital computer in process computer control installations. In order to solve differential equations on a general purpose digital machine it is necessary to transform the equations into suitable arithmetic form by use of numerical analysis and then to formulate coded instructions for the computer. The programing time is extensive and specialized knowledge is required. The DDA, however, can be programed with the relative ease of an analog computer. Since the solution is digital, much greater accuracy can be obtained than with analog computation. In the DDA, integration with respect to variables other than time can be performed and drift is no problem. The DDA can perform summation of inputs, sign change, multiplication by a constant, and other functions with no additional circuitry except that internal to its design.

The basic component of a digital differential analyzer is the integrator. Figure 10 is a block diagram of this unit and shows the mathematical progression as it integrates. A simple equation may require only 3 or 4 integrators; a complex problem may require from 20 to 100 integrators. These are interconnected in the same sense as analog integrators with the variables being represented by repetition rates of digital pulses. The integrator comprises two registers. The *Y* register (one channel on a magnetic drum) sums incremental *Y* inputs, and the *R* register (a second channel on a magnetic drum) sums the products of *ydx*. An incremental *ydx* output is produced only when the number in the *R* register overflows. Fractional values remain in the *R* register. Variable increments represented by a pulse train are summed in the *Y* register as they are received. Once each cycle, as determined by the *dx* input, this sum is added to the number already in the register (Y_o) to form a new sum. Simultaneously the number in the *Y* register is added to the *R* register, being gated in or controlled by the independent variable or integration (dx/dt). Thus *Y* is added to *R* at a rate dx/dt and a quantity approximating *ydx* is accumulated in the *R* register. Eventually the *R* register overflows and the rate of overflow is the output of the integrator. The overflow increment is *ydx* and is the area of one of the narrow rectangles shown in the approximation integral curve (Figure 10).

The solution time for a problem using a digital differential analyzer is determined by the accuracy required. The speed is independent of the number of integrators used in the problem. Each increment requires from 1/35 to 1/65 of a second, depending on construction of the machine. Programing and scaling are similar to that required for an analog computer.

Available Incremental Computers

There are three digital differential analyzers on the market today for use in computer control applications.

(1) Litton. The Litton 80 DDA is being used experimentally at Sun Oil because of its availability, ease of input-output conversion, and flexibility in solving a wide range of problems. Litton has three models (20, 40 and 80) indicating number of integration units. Input is by keyboard, punched tape, or graph follower. Outputs are by direct reading, plotter, converter or print out.

(2) Bendix DA-1. The Bendix digital differential analyzer is designed to operate in conjunction with the Bendix G-15 general purpose digital computer. Its dimensions are 22" x 24" x 60", and has 108 integrators which operate 34 times per second. Input can be programed from G-15 equipment, including typewriter, punched tape, punched cards and magnetic tape. Outputs can be recorded on graph-plotter.

(3) Genesys. This digital computer is described under general purpose digital computers. It contains both integral and incremental computation facilities.

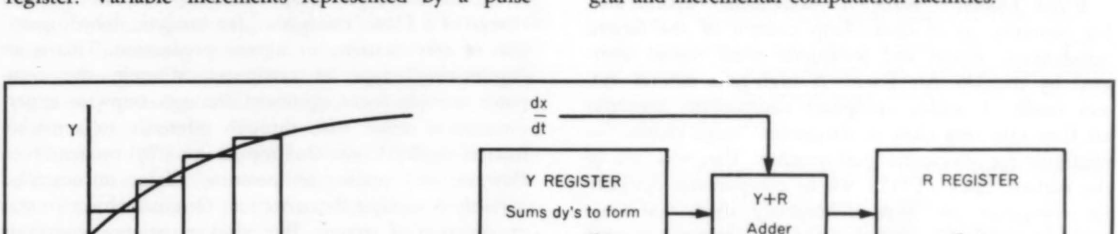


Figure 10. Block diagram of digital integrator used in the digital differential analyzer and approximation of the integral by summation. (Courtesy, Litton Industries.)

Computer Control Installations

WITHIN THE LAST 18 months a relatively large number of companies in the processing industries have installed or contracted for installation of computer control systems. Obtaining information of these installations is difficult because users are reluctant to divulge proportionary data and reveal their plans. Searching known sources the ISAJ has compiled a list and description of installations which may be reported.

This listing covers the more complex installations involving multiple loop control, with many inputs and appreciable data reduction. These installations, in general, meet the definition of computing control given in the introduction of this special report. This listing does not include the many relatively small installations involving simple, specialized and inexpensive computing elements such as pneumatic relays. Generally, in these cases the user has designed and assembled his own system for a one or two loop system with excellent results.

Installations are listed according to user name, with a description of the application, and the computer supplier.

The inclusion of wind tunnel control, weather forecasting, and traffic control perhaps stretches the general interpretation of "process", but justifiably so as the general field of industrial control problems gravitate toward a common denominator for solution.

Arnold Engineering Development Center, Tullahoma, Tenn.

Wind Tunnel Control. A "homemade" hybrid analog computer is in closed-loop control of the largest aerodynamic model and jet-engine wind tunnel operated by the US Air Force. A high-gain control system made of analog computer components regulates air flow rate very close to dangerous "surge points" — necessary for maximum performance. This was one of the earliest cases (1955) where components designed for computer use were deliberately used, combined with conventional control units, for process control. (See ISAJ July, August, September, October, November and December, 1956.)

B. F. Goodrich Chemical Co., Calvert City, Ky.

Vinyl Chloride Monomer Plant Control. A Thompson-Ramo-Wooldridge RW-300 computer will go "on stream" this month in what Goodrich claims is first use of digital equipment on a chemical process specifically designed for computer control. Computer takes instrument signals, quickly computes, makes logical decisions, and adjusts set-points of conventional process controllers to optimize efficiency. Total investment, reports Goodrich, including equipment, installation, programming and training: $200,000.

Carolina Power & Light Co.

Power System Generation Optimizing Control. Recently installed was an advanced data handling and analog computer system by Leeds & Northrup Co.

A second, future installation is scheduled by Carolina Power for its Darlington Station. This one will be a Daystrom Systems Division operational information unit. It will be expanded into an on-line digital control computer.

Cornell Aeronautical Laboratory, Ithaca, N. Y.

Air Traffic Control. A Bendix G-15 digital computer controls entry of planes into a Bell Aircraft automatic carrier landing system. This is an experimental project for the US Navy, eventually intended for shipboard use. Computer transmits altitude, compass heading and airspeed command signals at exact time intervals. Thus, the airplane flies in on a "conveyor belt" as it were, avoiding the "stackup" usual with human control.

Dow Chemical Co., Midland, Michigan

Styrene Plant Control. Since June, 1958, a Westinghouse Model OPG1 "Opcon" computer has been in charge of a Dow "miniplant" for catalytic dehydrogenation of ethyl-benzene in styrene production. This is an "optimizing" type of computer, wherein the computer actively seeks optimum through stepwise experimentation rather than through reference to a mathematical model. Controlled inputs are ethyl-benzene feed flowrate and reactor temperature. Major uncontrolled variable is catalyst deterioration. Original objective was maximation of styrene. But, after experience, economic considerations revealed the fallacy of optimums selected on technical bases only.

Federal Aviation Agency, Atlantic City, N. J.

Airways Control System. A Model RW 300 digital computer, by Thompson-Ramo-Wooldridge, has been used since February this year at FAA's National Aviation Facilities Experimental Center. Equipped with special analog inputs and outputs, it simulates complex air-traffic control problems by means of stored geographical reporting points and flight plans. Computer calculates aircraft arrival time over each "fix" along its route and communicates with existing control devices such as radar, direction finders and displays, without interrupting calculations. The system uses seven Stromberg-Carlson 1030 "Charactron" hi-speed digital cathode-ray readouts displaying position, point of conflict, and plane identity. Computer flashes 30-minute warning of impending mid-air conflict.

Electricite de France, Chinon, France

Nuclear Power-Reactor Control. France's first commercial nuclear power plant will start up this summer with a Thompson-Ramo-Wooldridge RW-300 digital computer detecting and locating ruptured fuel cartridges — first digital computers directly connected to reactor instruments. Computer will monitor carbon dioxide cooling gas radioactivity, calculate radiation value of each channel, and actuate alarms if preset limits are exceeded. From background-gas and relative-gas activity counts, computer will calculate and log cooling-gas radioactivity change in each channel, and switch to "fine scan" if limits are exceeded. To insure absolute reliability, a second RW-300 will parallel the first: if one stops, the other takes over. One computer was U.S. built by T-R-W; the other built in France by "Intertechnique."

Florida Power & Light Co.

Power System Generation Optimizing Control. This analog data-handling and computer system, by L&N, was installed and put into operation in recent months.

Gulf States Utilities, Louisiana

Electric Power Performance Guide. Gulf States has for about three years been using a combination data logger plus analog computer built by Panellit, Inc., for calculating total station and unit heat rates on a gas-fired boiler. Gulf States has bought several Panellit Model 607 units, and now has on order (1960 delivery) a Panellit 609, which will be an all solid-state digital machine. It will be in closed-loop control through set-point adjustments to conventional controllers, accomplished through special output matrices, as needed. Interesting note: On its newest station, Gulf States has gone back to a simple scanner for all temperatures, showing how a single company can use a wide variety of units.

For their Willow Glen Station, Gulf States has on order a Daystrom Systems digital operational information computer system plus future expandability to digital computational facilities.

Humble Oil & Refining Co., Baytown, Texas

Fractionator Control. Since December, 1958, Humble has had a Southwestern Industrial Electronics Co. Model CM-2 on closed-loop control of a fractionation tower. SIE's computer is of the analog optimizing type, using magnetic amplifiers. (See ISAJ 4/59, p 56).

Bendix G-15 digital computer installation at U. S. Naval Supersonic Lab at MIT.

Jones & Laughlin Steel Corp., Aliquippa, Pa.

Annealing Line Control. A General Electric model C-312A digital computer is to be installed on the Continuous Annealing Line. This line, on which the steel is uncoiled, the ends sheared back to gage and welded to the opposite end of the preceding coil, cleaned, annealed and recoiled, operates at speeds up to 2000 feet per minute.

Inputs to computer will be welder, furnace temperature, footage tachometer, thickness gage, pin-hole detector, weld detector, shear, and provision for accepting hardness measurements. Signal lights will show continuously the position of welds along the line. Desired anneal will be achieved by strip speed and furnace temperature control. Computer will log data from each foot of strip, warn of critical conditions, record metallurgical and operating data and accounting department calculations. Results: faster production, fewer errors, lower costs.

Kansas Gas & Electric Co.

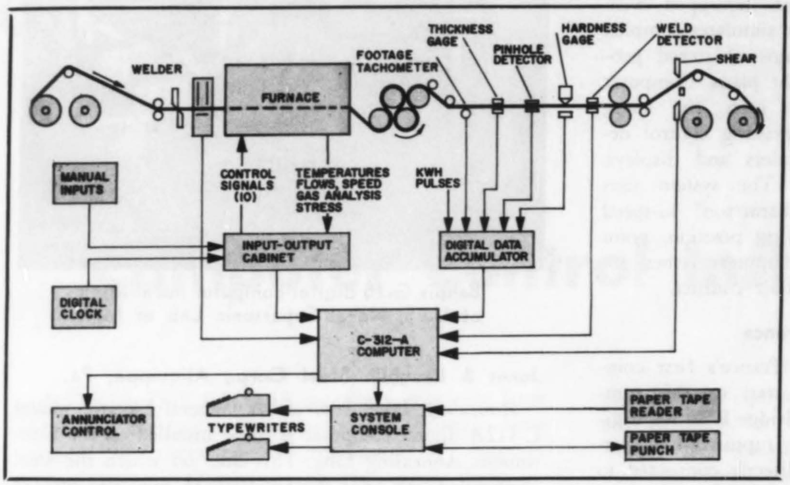
Power Generation Control. We learn that this utility has on order a Daystrom Systems digital operational information computer system with provisions for expansion to closed-loop control.

Louisiana Power & Light Co., Sterlington, La.

Power Station Operational Guide. For over a year, a Daystrom digital on-line computer has scanned temperatures, scaled primary variables and calculated operating guides. Has analog front end with a single A-to-D time-shared converter. Computer is a general-purpose, internally-programed, single-address machine with randome-access magnetic-core memory. Outputs are logged on a typewriter and punched tape. Ebasco Services were the consultants. (ISAJ 7/58, p 32; ISAJ 10/58, p 32).

Louisiana Power & Light Co., Little Gypsy Station

Power Station Automatic Control. Based on their year's successful experience with an operation guide system at Sterlington (above), LP & L now has ordered a complete Daystrom digital computer control system. For the first few months, it will log operational data. Eventually, from this data, it will sequentially control 800 steps in plant startup and shutdown, continuously monitor operation at 10 times per second, automatically signal and correct abnormal conditions,



General Electric's concept of a computer control installation for a continuous annealing line.

and control combustion, steam and feedwater temperatures to maximize efficiency. With a 100% solid-state system, Daystrom is guaranteeing 99% operational availability. In Little Gypsy, LP & L probably will have the most automatic station anywhere.

Mass. Institute of Technology, Cambridge, Mass.

Wind Tunnel Control. In the US Naval Supersonic Lab, analog data from the wind-tunnel transducers is converted to binary code, punched into paper tape and at once entered into Bendix G-15 digital computers. The computer scales the quantities to represent real variables, calculates, and correlates the functions

Monsanto Chemical Co., St. Louis, Mo.

Chemical Process Control. Another claim to "industry's first computer-controlled chemical plant" (on stream late in 1959), is being staked out by Monsanto, who isn't saying what process is to be controlled nor where. Objective: to maximize productivity at minimum cost, computer (a T-R-W RW-300) will continuously monitor process conditions, calculate optimums and automatically adjust the controllers to maximize results: i.e., closed-loop process control.

Ohio Edison Co., Massilon Ohio Station

Automatic Power Dispatching. One of the very first real-time computer process controls is this Ohio Edison job using a Goodyear GEDA analog computer, which operated closed-loop as early as November 1956. Under its "Computer-Controller" mode of operation, the dispatch of station generation is calculated by the computer on an *economic* basis and instantly applied to automatic control of a 12-station power system. Computer simulates individual unit fuel-costs, turbine and boiler characteristics, transmission system losses, plus composite station heat-rates. All heat-rate determinations are subject to automatic high-and-low limit controls. This historic installation scored high in setting a 95.5% availability record for 45-days of operation back in 1956! (ISAJ 10/57, p 454).

Philadelphia Electric Co.

Power System Generation and Power Exhange Control. Scheduled to go on line in late 1960, is a Minneapolis-Honeywell Datamatic Division (Boston) Model D-290 computer. It will be an all-transistor digital machine, which will on the basis of memory-stored production costs, line losses, etc., plus continuous process data supplied by control instruments: 1. Compute most economical allocation of generating capacity and automatically send this command to generators; 2. Figure costs for billing of power bought and sold from other interconnected power companies. Computer outputs will be converted back to analog signals, telemetered to load controllers at the several stations, and there apportioned among the generators to provide the called-for power at the specified calculated cost.

Public Service Co. of Colorado

Gas Distribution. A Libratrol 500 computer will scan 55 telemetered flow variables for more economic distribution of natural gas.

Riverside Cement Co., Oro Grande, Calif.

Rock Blending and Crushing Control. Unusually ambitious are the plans of Riverside Cement, a division of American Cement Corp. Beginning with a Thompson-Ramo-Wooldridge RW-300 digital computer to go on-line this month, Riverside envisions eventual, almost-completely automatic operation of their entire Oro Grande plant. At first, computer will keep track of amount, composition and location of rock and raw materials; periodically calculate proportion and kind of materials for proper cement ingredients; indicate most-economical procedures based on hauling distance and quarrying costs in various areas. X-ray analysis of rock samples will form one computer input. Computer will log temperatures, fuel-gas flow and rotary-kiln speed; and when not busy, will collect and analyze data for planning automation for the entire cement process.

Southern California Edison Co.

Power Generation Optimizing Control. An advanced form of Leeds & Northrup analog data acquisition and computer system has been installed for some months.

Southern Company Power Pool

Automatic Load Distribution. Another historic "first" is claimed for this installation of Leeds & Northrup analog computers, which went on-line in 1954. Named "Early Bird" after its designer E. D. Early, manager of the Southern Pool, it continuously calculates the most economical distribution of power loading throughout a four-company network involving 40 million kw of generating capacity. Important system parameters come in via telemeter; computer calculates best assignment of load based on unit capacities, fuel costs, boiler heat rates and efficiencies, waterpower availability, maintenance schedules, transmission losses, etc.; load is assigned in most-economic pattern through L & N automatic tie-line load-control equipment.

Standard Oil Co. of N. J. (Esso), Baton Rouge, La.

Catalytic Cracker Operating Guide. Probably the first permanent example of computer use to generate process operating guides (June 23rd, 1959) is that of a Royal Precision Model LGP-30 digital machine, combined with Leeds & Northrup data-acquisition and A-to-D conversion equipment. A total of 160 process variables — pressure, temperature, flows, etc. — are scanned, measured and scaled at one-per-second speed. Twenty seven process operating guides are calculated and printed out on a log sheet. Esso's studies are now directed toward closed-loop computer control.

For the Linden, N.J., Esso refinery, Consolidated Electrodynamics will use with their equipment another Royal Precision LGP-30 digital computer, shortly to be installed on an Esso microplant.

Standard Oil of Ohio (Sohio)

Refinery Process Optimization. Jointly exploring use of computers for refinery process automatic control are Thompson-Ramo-Wooldridge and Sohio's Process Engineering Division. This is a systems engineering approach to process optimization built around T-R-W's "desk-size" digital computer. Now control techniques developed will be applied to actual refinery practice.

Sun Oil Co., Marcus Hook, Pa.

Fractionator Tower Control. Another cooperative computer-control research project is that by Westinghouse and Sun Oil. Delivered to Sun this April was a Westinghouse Opcon—optimizing analog computer.

Also still under Company security wraps is Sun's study project for computer process control at their Marcus Hook refinery involving computer equipment by Genyses Corporation (for use in Sun's Number 12 plant); and an experimental study with Litton Industries. Here a Litton Model 80 "DDA" (digital differential analyzer) incremental computer was selected because of its easy input-output conversion.

The Texas Co., Port Arthur, Texas

Polymerization Control. In operation since late in 1959 has been a T-R-W RW-300 digital computer on a 1,800 barrel-per-day, $4 million polymerizer unit. Texas, too, claims a "first" in closed-loop computer control of a full-scale plant operation. Computer gathers data from 110 sources and provides closed-loop control through set-point adjustment to pneumatic controllers on 16 different streams. It evaluates variables by comparison to a mathematical model. Computer also checks its own accuracy automatically, and scans for alarms, and prints out any off-spec data. Preceding was a 2½ year feasibility study. The whole job cost about $200,000 more than conventional instrumentation would have normally cost during modernization of the plant. However, resulting increase in efficiency should be 6 to 10%—fast payout for a relatively-small investment. Extra dividend: longer catalyst life will save $75,000 yearly.

Union Carbide Nuclear Co., Paducah, Kentucky

Electrical Power Load Monitoring. Gigantic power needs for the AEC gaseous diffusion plant, coming in over 17 lines from three utility companies, complicated by possible power-out flow on 5 lines, was too much for conventional watthour and demand meters; they were too slow to permit alteration of plant load to stay below contracted demand rate. Bailey Meter Company designed the solid state digital computer that not only solved the problem by providing the operator with a calculated prediction of ½-hour demand (based on 5-minute increments), but produces 10-times better resolution of the electrical load measurement, as well! Bailey calls it "revenue metering load anticipator." Two-month initial operating period (ending 1/15 59), set this reliability score: one failure—a transistor; two logic circuit errors; four printer malfunctions—97.5 reliability.

USAF, Wright Air Development Center

Weather Reconnaissance. This one will be airborne! Bendix Aviation Systems Division has developed the AN/AMQ-15 continuous weather reconnaissance system on a $12 million AF contract. A special upright, 850-pound, RW-300 digital computer will fly in a Boeing 707 jet transport. System will gather and process meteorologic and geophysic data through rocketsondes, dropsondes, radars and other sensors. Computer will process all automatic and manual input data, convert it to meterological quantities, prepare data for transmission, and display data on an airborne console. Computer accepts 16 digital and 32 analog inputs.

United States Steel Corp., South Works, Pittsburgh

Iron Ore Sintering Control. A specially-designed analog computer, built around a standard L & N recording pyrometer, has been in experimental use for three years. In the U.S. Steel System (patented), several thermocouples, feeding into the simple, low-cost computer, calculate the "burn-through" (maximum temperature) location along the moving bed of the sintering machine, at which sintering reaches completion. This computation, in turn, controls the feedrate of material to hold the process at its manually-selected production rate.

Universal Oil Products Co., Des Plaines, Illinois

Refinery Pilot Plant Control. Since late 1958, a pilot plant at UOP has been under on-line control by a Daystrom Systems digital, solid-state computer. This recent disclosure is the outcome of a 2½ year joint study program by UOP and Daystrom. Daystrom has been licensed by UOP to make and market control systems developed by this joint study program. Reportedly, this system is capable of actual on-line control.

Westinghouse Electric Corp., Bloomington, Indiana

Automatic Capacitor Testing. This first installation of the Westinghouse "Opcon" optimalizing analog computer, winner of the 1958 Industrial Science Achievement Award (AAAS), has been operating for many months, applied to automation of capacitor testing.

Developing Mathematical Models for Computer Control

by Dr. David B. Brandon
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ONE OF THE FASCINATING PROBLEMS facing the control system designer is the development of computer control systems for processes. If a predictive control scheme (generally employing a digital computer) is planned, the system requires a set of mathematical equations, called the mathematical model of the process. It serves to interrelate important process variables and provide the means for optimizing plant performance. The development of a useful model is dependent on the combination of information of a quantitative, semi-quantitative, and qualitative nature into an all-encompassing set of mathematical equations. The purpose of this paper is to describe a method which has been successfully employed in establishing the mathematical models of processes, and to emphasize that the required equations can be written for many incompletely understood processes.

A relatively small change in the value of process variables results in a definite change in production rate, product quality, utility use rates, or other key measures of operating efficiency. Depending upon the process involved, the mathematical model for a computer control system may be linear or nonlinear, and may represent steady-state or dynamic process conditions. The choice of a model to be derived depends on the information available and the manner in which it will be used. *In this paper, a nonlinear, steady-state model is developed.* The computer is able to control a dynamic process with such a model by employing it in conjunction with process dynamic information already understood and presently used by the operators. This combination of a steady-state model and process dynamics results in a realistic set of equations which are entered into the control computer. Dynamic models have also been described or inferred [1,2,3,4] but are regarded as being outside the scope of this paper.

When a significant change occurs in one or more of the important operating variables, the operator knows the direction and estimates the magnitude of appropriate compensating changes, which he then makes to maintain production and prevent the plant from going out of control. Thus, the operator continuously steers the process from one steady-state to another. The mathematical model of this kind of plant is derived, at least in part, from the data logged by the operator, thus a steady-state model is frequently found to be best for chemical and related production units now in service. In the future when operating philosophy changes and more is understood theoretically and practically about transient phenomena, the preferred dynamic models may replace present steady-state models.

An Approximate Model is Sufficient

The relationships inherent in this model are subject to error as are the data from which they would be derived. However, when the full consequences of a digital computer control system are recognized, it is apparent that only an approximate model is initially needed. The reason is that the computer, in addition to controlling the plant, is normally programed to compare its predictions (based on this approximate model) with actual operations. Any discrepancy between the predicted and later measured values (under steady-state conditions) is then employed to up-date the model; that is, adjust the coefficients in the equations, so that the predicted values do in fact equal observed values. This up-dating procedure is conducted at sufficiently frequent intervals to ensure that the mathematical model will remain as close as possible to a representation of the plant.

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[1] Superior numbers refer to similarly numbered references at the end of this article.

The first model can be obtained only after a detailed study of the plant as a whole. In particular, it has been found that an effective model for control purposes may be constructed from equations which express:

1. **the process objective,**
2. **material (and heat) balance relationships,**
3. **transformation relationships (described below),**
4. **constraints and limitations on operations,**
5. **a suitable optimizing scheme.**

These topics have been discussed in earlier papers,[5,6,7,8] and will be repeated here only in so far as they are directly involved. We shall be most concerned with the formulation of an expression for the present steady-state transformation relationships, the major bottlenecks in the development of the mathematical model.

The transformation relationships express the essential features of the chemical and physical changes occurring within the bounds of the computer control system. They relate the effects of the variables on process performance and provide the basis whereby variables, which are controllable, may be manipulated to compensate for changes which inevitably occur in the uncontrollable variables. Examples of the usual uncontrollable and controllable variables which are involved in the transformation relationships are process flows, compositions, temperatures, pressures, catalyst activity, feed availability, and product quantity and quality requirements. The interrelationships among these variables are often only partly understood, which means that the operator's decisions are frequently based on information which is qualitative or semi-quantitative at best. A few of the presently employed relationships may be known quantitatively; but these generally pertain to just two variables, resulting in an incomplete mathematical description of a system comprised of several independent variables.

A representative transformation relationship for the model may be expressed in function form as,

$$Y = f\ (v_1,\ v_2,\ v_3, \ldots) \tag{1}$$

where Y denotes a process parameter such as yield of product which is introduced for convenience, and v_i corresponds to the process variables which a systems analysis has shown to be of importance in determining process performance. The reason for the choice of a particular parameter on the left side of Equation 1 is clarified by Equation 2, which defines material balance in terms of the same parameter.

$$Y = g\ (\text{flows, concentrations}) \tag{2}$$

Equation 2 is indicated as a different and well-known function g of suitable flows and concentrations. The v_i in Equation 1 and some of the flows and concentrations of Equation 2 may overlap to some extent, but the variables of Equation 1 encompass other quantities besides flows and concentrations, as listed above. Writing the transformation and material balance relationships in this form serves to interrelate the two, and thus provides the missing link needed for the mathematical model. Where by-products are produced in the process, at least two independent parameters would be involved, with each expressed in terms of material balance and transformation equations.

With the above functions f and g known, it becomes possible to compute production rate or other measures of process performance for any set of operating conditions. Further, combining these relationships with the remaining equations developed during a system analysis serves to establish the model.

This entire procedure hinges on a valid determination of the function f in Equation 1. This function may not be derived from a theoretical analysis of the problem. Rather, it must be expressed empirically, based on a variation analysis of appropriate current and historical operating data. Standard linear regression methods may be used provided that steady-state data are employed ("averaged" data are usually not acceptable), and the terms expressing essential interactions among variables are included. A general regression equation may be written for four variables as,

$$Y = c_0 + c_1 v_1 + \ldots + c_5 v_1 v_2 + \ldots + c_{11} v_1 v_2 v_3 + \ldots + c_{15} v_1 v_2 v_3 v_4 \tag{3}$$

where the c_i are constants.

Graphical Procedure

As an alternate method· a graphical procedure which has been successfully applied will now be described. For convenience in evaluating the desired nonlinear function, Equation 1 may be written in the form,

$$Y = C \cdot f_1(v_1) \cdot f_2(v_2) \cdot f_3(v_3) \ldots f_n(v_n) \tag{4}$$

with little loss of generality. In Equation 4, C denotes a constant corresponding to the average value of the parameter Y, and the separated functions f_i are multiplicative factors dependent upon the v_i. The values of the f_i may all be defined to be near unity with the variables in their normal ranges.

The separated f_i may be evaluated much more simply than the original function f in Equation 1. A non-simultaneous procedure is applicable. By plotting known values of Y versus v_i for a group of k production runs, the relationships between the two quantities may be established by drawing least squares lines or by means of any other regression method (not necessarily linear). This determines the function, f_1. A new quantity, Y_1, is next defined as,

$$Y_1 = \frac{Y}{f_1(v_1)} \tag{5}$$

The values for Y_1 are determined for each of the k production runs which have been included as data for the analysis. Thus, a new yield factor is obtained for each of the k runs. This residual yield is no longer dependent on the variable v_1, since by Equations 4 and 5,

$$Y_1 = C \cdot f_2(v_2) \cdot f_3(v_3) \ldots f_n(v_n) \tag{6}$$

Since Y_1 is a function of all the variables except v_1, it is now plotted against one of the remaining variables, let us say, v_2. This serves to establish a relationship between Y_1 and the variable v_2, or in other words, it defines the function f_2. A new residual yield, Y_2, is determined.

$$Y_2 = \frac{Y_1}{f_2(v_2)} = \frac{Y}{f_1(v_1) \cdot f_2(v_2)} \tag{7}$$

and

$$Y_2 = C \cdot f_3(v_3) \ldots F_n(v_n) \tag{8}$$

such that Y_2 is a function of all of the variables except v_1 and v_2. This procedure is continued until the last residual yield, Y_n, is reached where

$$Y_n = \frac{Y}{f_1(v_1) \cdot f_2(v_2) \ldots f_n(v_n)} \qquad (9)$$

It is observed by a comparison of Equations 9 and 4 that Y_n is equal to C. Equation 4 is now established.

In the above discussion, it is tacitly assumed that the various functions f_i may be determined with sufficient accuracy that a valid mathematical model of the process may be formulated. The validity of the resulting model may be tested by making step changes in the variables (preferably one at a time) during normal operations. The results (production rate, concentrations, etc.) predicted by the model are then compared with those observed in the plant. Minor adjustments may be made in certain of the coefficients, if warranted, so that the model will be a close equivalent of the process.

It is most important that the relationships of Equation 4 (also Equations 1 and 3, for that matter) reflect essentially all of the pertinent existing knowledge about the process. This knowledge is incorporated by taking into account two factors relating to the manner in which the plant is presently run. *The first factor stems from the customary operation of the plant within a rather small area.* This exerts a linearizing influence which may be used to advantage. In many cases, the functions f_i may be approximated quite closely by linear relationships. This by no means assumes that the nonlinear process is a linear one, as the f_i are multiplicative factors which when taken together express this lack of linearity. The choice of linear f_i in most cases simplifies their evaluation. All of the separated functions may be assumed to be linear except when theory or experience dictates to the contrary. When such occurs, the known nonlinearity may be built into a particular f_i, such as by expressing it as an exponential, a reciprocal, or a power series in a v_i. The coefficients are evaluated in this case, given the form of the function f_i.

TABLE I – OBSERVED DATA

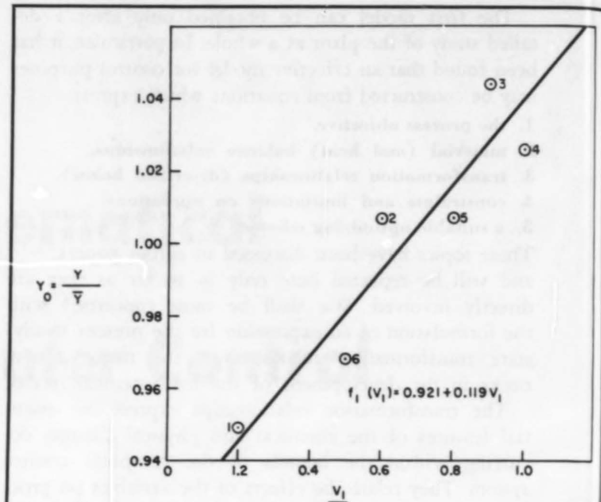
Run	Y	v_1	v_2	v_3	v_4
1	0.87	0.2	26	4.2	10
2	0.93	0.6	22	4.1	15
3	0.96	0.9	21	4.3	35
4	0.94	1.0	19	3.7	40
5	0.93	0.8	25	4.4	50
6	0.89	0.5	23	4.5	75

TABLE II – CORRELATION DATA

Run	Y_0	$f_1(v_1)$	Y_1	$f_2(v_2)$	Y_2	$f_3(v_3)$	Y_3	$f_4(v_4)$	Y_4
1	0.949	0.943	1.006	0.990	1.016	0.996	1.020	1.024	0.996
2	1.007	0.992	1.015	1.004	1.011	0.991	1.020	1.019	1.001
3	1.044	1.028	1.016	1.008	1.008	1.001	1.007	1.005	1.002
4	1.026	1.040	0.986	1.014	0.972	0.970	1.002	1.001	1.001
5	1.007	1.016	0.991	0.994	0.998	1.006	0.992	0.994	0.998
6	0.968	0.980	0.988	1.001	0.987	1.012	0.975	0.977	0.998

TABLE III – SUMMARY OF RESULTS

$$f_1(v_1) = 0.921 + 0.119v_1$$
$$f_2(v_2) = 1.079 - 0.00341v_2$$
$$f_3(v_3) = 0.775 + 0.0525v_3$$
$$f_4(v_4) = 1.029 - 0.000377v_4$$
$$Y = 0.92 \cdot f_1(v_1) \cdot f_2(v_2) \cdot f_3(v_3) \cdot f_4(v_4)$$
$$Y = 0.728\,(1 + 0.129v_1)\,(1 - 0.00316v_2)\,(1 + 0.0678v_3)\,(1 - 0.000368v_4)$$



The second factor pertains to the wealth of experience which may have been established during the operation of the unit. As this most often is of a qualitative or semi-quantitative nature, it is not readily formulated in strict mathematical terms. However, good use of this information is made in assessing what independent variables are involved and the manner in which they should be expressed, the relative magnitude of their effect on each parameter, and the sign of the slope to be expected when the parameter is plotted against these variables.

Illustrating the Graphical Method

The described graphical method is illustrated by developing a yield function of four independent variables. Data are given for six selected, typical, steady-state runs including each variable at the extremes of and at several levels within its normal range. Equation 10 expresses the desired relationship,

$$Y = C \cdot f_1(v_1) \cdot f_2(v_2) \cdot f_3(v_3) \cdot f_4(v_4) \qquad (10)$$

The observed data are listed in Table I. Rather than plotting the observed yield, Y, this quantity was replaced by a normalized yield, Y_0, which is defined by

$$Y_0 = \frac{Y}{\overline{Y}} \qquad (11)$$

where $\overline{Y}$ refers to the average yield. After following through the outlined procedure assuming linear functions f_i, the correlation data of Table II are obtained. The four plots are presented in Figure 1. In each case, the regression line has been drawn subjectively, being based on the positions of the individual points and the known sign of the slope of each line. A summary of the results appears in Table III.

The last residual yield, Y_4, of Table II should be unity under ideal circumstances. In this example, perfection was almost achieved. However, experience has shown that a considerable deviation from unity of the last residual yield may be tolerated. The magnitude

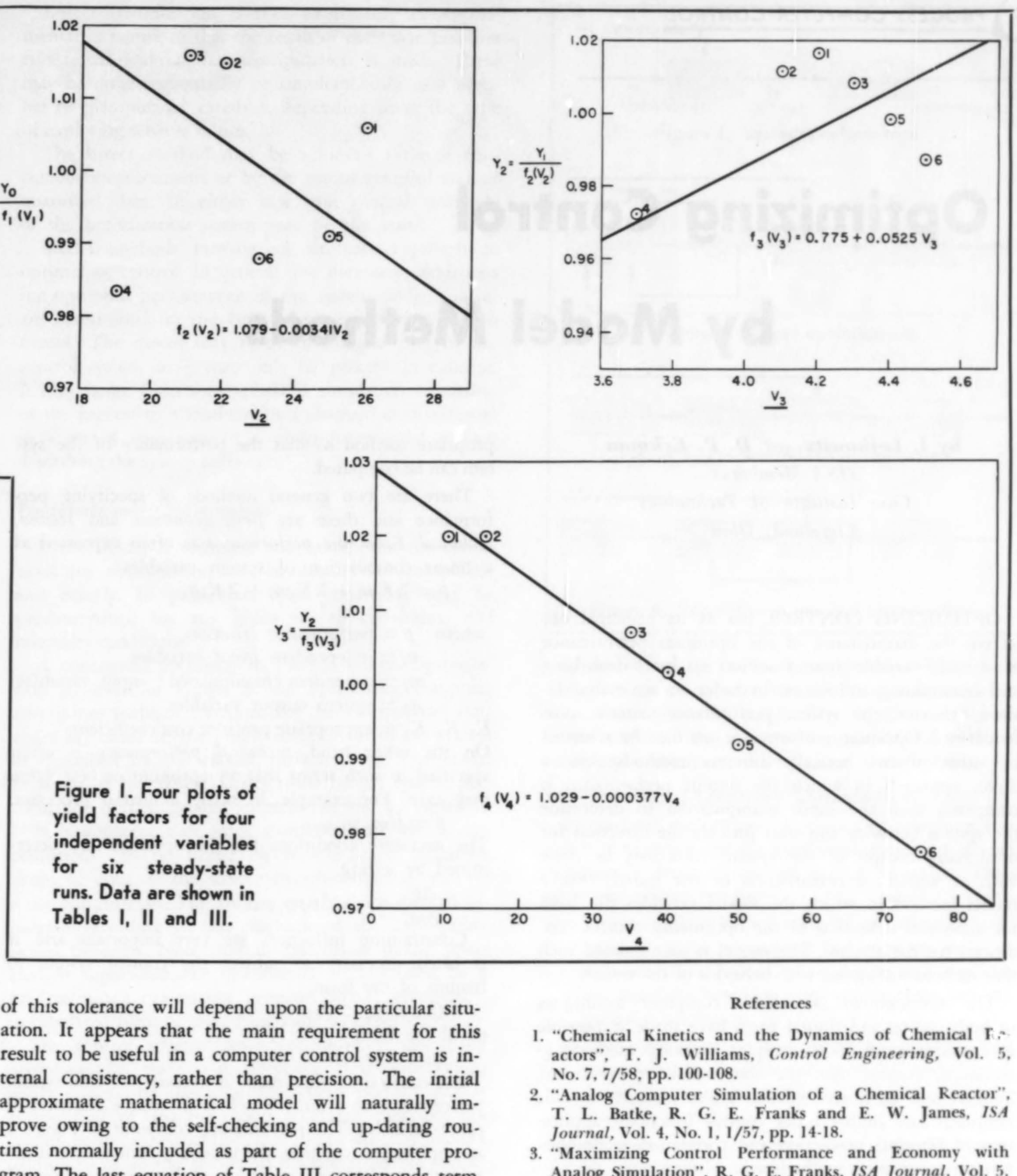


Figure 1. Four plots of yield factors for four independent variables for six steady-state runs. Data are shown in Tables I, II and III.

of this tolerance will depend upon the particular situation. It appears that the main requirement for this result to be useful in a computer control system is internal consistency, rather than precision. The initial approximate mathematical model will naturally improve owing to the self-checking and up-dating routines normally included as part of the computer program. The last equation of Table III corresponds term by term (after the indicated multiplications are carried out) to Equation 3. This equivalence is not obtained owing to the fact that at least one of the f_i is nonlinear.

Developing mathematical models of industrial processes is a very time-consuming task, requiring considerable effort from scientists and engineers familiar with industrial processes and computer control systems. Because of the limited quantity of information on which mathematical models may currently be based, it is felt that this technique will serve as one practical means of arriving at the desired end result.

References

1. "Chemical Kinetics and the Dynamics of Chemical Reactors", T. J. Williams, *Control Engineering,* Vol. 5, No. 7, 7/58, pp. 100-108.
2. "Analog Computer Simulation of a Chemical Reactor", T. L. Batke, R. G. E. Franks and E. W. James, *ISA Journal*, Vol. 4, No. 1, 1/57, pp. 14-18.
3. "Maximizing Control Performance and Economy with Analog Simulation", R. G. E. Franks, *ISA Journal*, Vol. 5, No. 9, 9/58, pp. 80-84.
4. "Simulation of Process Control with an Analog Computer", F. A. Woods, *Industrial and Engineering Chemistry,* Vol. 50, No. 11, 11/58, pp. 1627-1630.
5. "How to Plan Computer Control", M. Phister, Jr., *ISA Journal*, Vol. 6, No. 1, 1/59, pp. 51-55.
6. "How to Establish the Control Problem for an On-Line Computer", E. W. James and A. S. Boksenbom, *Control Engineering,* Vol. 4, No. 9, 9/57, pp. 148-159.
7. "System Considerations in Computer Control of a Semi-continuous Chemical Process", T. M. Stout, *Applications and Industry (AIEE)* No. 40, 1/59, pp. 640-651.
8. "Digital Control of an Alkylation Plant", D .B. Brandon, The Princeton University Conference, "Computer Control of Chemical Processes", Princeton New Jersey, 2/59.

Optimizing Control by Model Methods

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OPTIMIZING CONTROL has as its principal objective the maintenance of the optimum performance of a multi-variable system subject to both disturbing and constraining influences. In order to achieve a desired behavior, the system performance criteria must be defined. Optimum performance can then be achieved by either of two basically different methods: *one,* a direct approach in which the output performance is compared with the input manipulation to determine the system behavior and thus provide the direction for optimizing control of the system: this may be done with or without a perturbation or test signal; *two,* a model method in which the model provides the basis for analytical definition of the optimizing control conditions for the system. The model is manipulated such that its behavior agrees with behavior of the system.

The development of reliable computer techniques in both analog and digital form have made it possible to consider much more complex working methods in automatic control than the conventional proportional, integral and derivative effects. These methods include nonlinear and higher order control functions, application of filtering, prediction and correlation techniques, repetitive computer methods, etc.

Performance Computation

The system under control can generally be described, as in Figure 1, as having k outputs under the influence of i independent inputs (determined by factors external to the system under consideration), and under the influence of j dependent inputs which may be manipulated.

The system presumably is put into use with the outputs forming a valuable product or service. It is assumed that the utility can be judged by some appropriate method so that the performance of the system can be computed.

There are two general methods of specifying performance and these are *first, economic* and *second, technical. Economic performance* is often expressed as a linear combination of system variables

$$p = \sum_i K_i u_i + \sum_j K_j m_j + \sum_k K_k q_k$$

where p = performance criterion
u_i = independent input variables
m_j = dependent (manipulated) input variables
q_k = system output variables
K_i, K_j, K_k = appropriate profit or cost coefficients

On the other hand, *technical performance* is often specified in such terms that an optimum or best value may exist. For example, in many industrial processes,

$$p = f(m_j, u_i, q_k).$$

The necessary conditions for the optimum are determined by setting

$$\frac{\partial p}{\partial m_j} = g_j(m_j, u_i, q_k) = 0 \quad (j = 1, 2, \ldots)$$

Constraining influences are very important and it is often necessary to subject the control system to bounds of the form,

$$Q_{1k} < q_k < Q_{2k}$$

or of the form

$$q_k \geqq h(q_1, q_2, \ldots)$$

These constraints often make it necessary to find system performance at a limit which is in turn a function of other variables. The performance computer of Figure 1 is employed to compute the necessary functions and obtain the variable p on which to base system control.

Direct Optimization

Direct optimization proceeds with a minimum of knowledge about the system under control. As shown in Figure 2, the optimizer receives data on the variations in the manipulated variables m_j and the resulting changes in performance p and in turn manipulates each of the m_j inputs in the indicated direction for improving the performance. Sometimes a perturbation or test signal is employed to initiate changes upon which the control measurements are based.

Direct optimization is thus exploratory or experimental in nature in that the result of each manipulation is assessed and another manipulation is made. These may be done sequentially or simultaneously in a number of manipulated variables, depending upon the type of exploring scheme in use.

The direct method may be achieved through continuous measurements or by the use of sampled and/or quantized data. In either case, the general principle of the optimization system may be the same.

Model methods provide an alternate approach to optimizing control. In general, the necessary conditions for optimum performance of the system under control are determined on the basis of an appropriate system model. The model may form an integral part of the control system or it may only be present in concept. It may range from some physical simulation or analog of the process to a mathematical abstraction manifested as a set of equations or a multi-dimensional surface describing the system behavior.

Predetermined Optimization

If the model is complete and exact, then the conditions for optimization can be determined completely and exactly. In particular, these conditions may be predetermined for any given set of constraints and boundary conditions.

A conceptual approach to Predetermined Optimization is given in Figure 3. An optimizing computer determines paths or functions for the manipulated variables, m_j, based on the predicted behavior of the system as described by the model variables, w_k. The actual behavior of the system is described by q_k; system performance is then gauged in terms of the q_k variables.

It is apparent that, once computed, the optimizing conditions can be stored on punched-tape, magnetic drum or even, in the simple two-dimensional case, on a mechanical cam. The system variables are then manipulated according to the playback of the appropriate stored program. Note that in systems manually operated or supervised, the operator is often guided by a predetermined optimizing program stored graphically, in tabulated form or stored mentally as experience.

The control scheme described above is essentially open-loop; i.e., there is no feedback of information to verify either that the resulting system performance is as specified, or that the model accurately describes the system behavior. Accordingly, if there are any factors tending to cause the system to deviate from the model as, for example, the influence of disturbances u_i, the system performance may be expected to deviate from the computed optimum.

Repetitive Computed Optimization

The predetermined optimization concept is modified by repetitive feedback of information describing the state of the system. Thus, as shown in Figure 4, the q_k variables are periodically sampled into the optimizing computer providing the basis for repetitive recomputation of the optimizing conditions. In this way, each computation is based on the most recent information describing the state of the process. As a result, deviations of the system from the postulated model do not cause cumulative errors. The repetitive computer action tends to force the system to the desired performance despite significant inadequacies of the model.

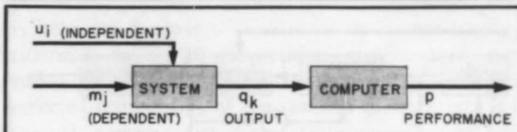

Figure 1. System performance.

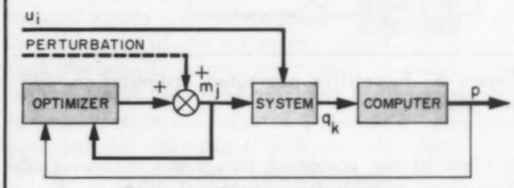

Figure 2. Direct optimization.

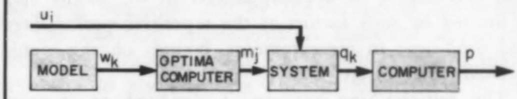

Figure 3. Predetermined optimization.

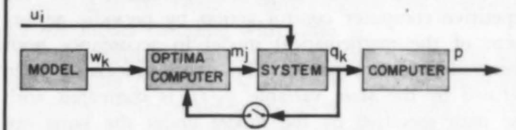

Figure 4. Repetitive computed optimization.

Self-Checking (Adaptive) Optimization

In practical applications of optimizing computer control, it is expected that the postulated model will deviate significantly from the actual system behavior. There are several reasons for this:

1. Not enough is known about most industrial processes to derive a complete and accurate analytical representation. Indeed, plant design and operation are generally based on very approximate and empirical relationships.
2. The complexity of most processes preclude very great detail in the formulation of the mathematical model because the resulting computer capacity would be prohibitive.
3. Many variables affecting process behavior cannot be satisfactorily measured with existing instrumentation (e.g., catalyst activity); hence, they cannot be employed directly in the computer control function.
4. The state of the process can be specified only within statistical limits because of non-homogeneity, random fluctuations of measured quantities, etc.

An essential adjunct to the concept of process optimization by computer control is a means of adapting to this purpose, relationships which are neither exact nor complete. Inadequacies of the model are compensated, in part, by the repetitive control technique

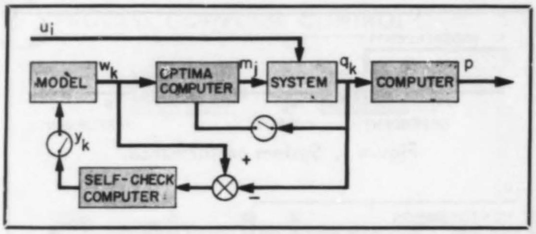

Figure 5. Repetitive computed optimization with self checking.

described in the preceding paragraphs. However, the effectiveness of such compensation depends on the nature and degree of approximations in the model and is limited by such factors as the repetitive period, lags and dead-time in measurements, bounds on the manipulated variables, etc.

The self-checking concept is designed to increase the effectiveness and range of applicability of the repetitive computer control action by periodic adjustment of the mathematical model in accordance with observed process behavior. The actual processing path, defined by the state variable $q_k(t)$, is compared with the path specified by the model under the same operating conditions in terms of the variables, $w_k(t)$. Deviations between the two paths are employed as error signals to correct the parameters of the model such that process behavior is adequately described in the vicinity of the operating point. A schematic representation of the self-checking concept is shown in Figure 5 where it is presented in the form of a second feedback around the repetitive control loop.

The self-checking technique introduces an element of flexibility in the overall design of the computer control system. The model may be intentionally simplified so as to reduce the size and complexity of the on-line repetitive optimizing computer at the expense of the self-checking facility. In general, as the model becomes less accurate, either the parameters must be adjusted more frequently to maintain a given performance, or additional adjustable parameters must be introduced. It is expected, however, that the overall computer requirements can be minimized by a judicious compromise; in particular, the model may advantageously describe only the dominant first order effects relating those variables which change rapidly relative to the process dynamics. The self-checking computer may then be a large general purpose machine, time-shared.

Application of self-checking raises questions of dynamic stability of the feedback loops, convergence of the parameter correcting operations and validity of the resulting mathematical model. There are also limitations imposed by the accuracy with which the state of the process can be described to the computer and the speed with which parameter corrections can be computed and applied relative to the rate of change of the parameters. Random errors in measurement lead to false and inconsistent parameter adjustments which must be minimized through statistical smoothing and interpretation of the measured data. There is indeed a close relationship between the order of approximation of the model and the information rate required for adequate self-checking.

Optimizing Control of A Batch Chemical Process

The model method concept has been applied to the optimizing control of a batch chemical process. Successive application to a pilot plant hydrogenation reactor is described in references (4) and (5). Extensive studies were also made on the computer control of a simple prototype process simulated on mechanical and hydraulic analogs (see references (4) and (6)). A brief description of this process is presented below.

The reaction mixture is made up of three chemical components identified as X, Y, and Z. Hydrogen under pressure and in the presence of catalyst reacts with X and Y according to the following reaction scheme:

$$X + H_2 \xrightarrow{k_1} Y$$
$$Y + H_2 \xrightarrow{k_2} Z$$

where k_1 and k_2 represent kinetic reaction coefficients.

A reasonable approximation to the kinetic behavior of this process is given by the equations,

$$\frac{dx}{dt} = -k_1 x \tag{1a}$$
$$\frac{dy}{dt} = k_1 x - k_2 y \tag{1b}$$
$$x + y + z = 1 \tag{1c}$$

where x, y, z represent molar concentrations of components X, Y, Z, respectively.

The kinetic coefficients are functions of the operating conditions: pressure, temperature, catalyst, agitation, etc. Assuming only pressure is to be manipulated and that all other influencing factors are relatively constant, the coefficients may be expressed,

$$k_1 = A_1 p^{N_1} \tag{2a}$$
$$k_2 = A_2 p^{N_2} \tag{2b}$$

where A_1, A_2, N_1, N_2 are assumed constant

$p =$ process pressure.

Based on a mathematical model consisting of Equations 1 and 2, the necessary conditions for optimum process performance may be derived. In the particular case under study, control to a specified product composition consistent with minimum processing time is established as the performance criterion.

It is convenient to transform the above equations to new variables, u, v and k defined as follows:

$$u = y/x \tag{3a}$$
$$v = \log_e x_o/x \tag{3b}$$
$$k = \frac{k_2}{k_1} = \frac{A_2}{A_1} p^{N_2 - N_1} \tag{3c}$$

Making the substitutions in Equation 1a and b, a single equation defining the processing path independent of the time variable is obtained:

$$\frac{du}{dv} = (1 - k)u + 1 \tag{4}$$

Since the kinetic coefficient ratio, k, may be varied during the course of the reaction by manipulating the pressure (Equation 3c), there are an infinite number of operating paths which can satisfy the boundary conditions (x_o, y_o, z_o) representing the initial composition and (x_f, y_f, z_f) representing the desired final composition.* This degree of freedom permits the introduction of an optimizing condition. Assuming that the processing time is the predominant factor in the cost equation, the optimizing problem reduces to the determination of a control path which will minimize the time to go from the raw material state to the desired product state.

An expression for the processing time, t_f is derived from Equations 1a, 2a, 2b, 3b, and 3c:

$$t_f = A\int_0^{\sqrt{f}} k^{1-B} dv \qquad (5)$$

where $A = \left[\frac{A_2^{N_1}}{A_1^{N_2}}\right]^{\frac{1}{N_2-N_1}}$

$B = N_2/(N_2 - N_1)$

The necessary condition for minimizing the above integral is supplied by the calculus of variations. Applying the Euler-Lagrange equation,

$$\frac{\partial f(v)}{\partial u(v)} - \frac{d}{dv}\,\frac{\partial f(v)}{\partial u'(v)} = 0$$

where $f(v) = k^{1-B}$

$$u' = \frac{du}{dv}$$

the following optimizing equation is obtained:

$$\frac{dk}{dv} = -\frac{1}{B}\,\frac{k}{u} \qquad (6)$$

The optimizing computer is programmed to solve Equations 5 and 6 simultaneously for the given boundary conditions $(u_o, 0)$, (u_f, v_f).

If Equations 1 and 2 described the process behavior exactly, then one computation based on Equations 5 and 6 and the specified boundary conditions would suffice to define the optimum control path, $p(t)$. Thus, the $p(t)$ schedule could be recorded on tape or other storage medium and played back through appropriate transducers and pressure controller to manipulate the process pressure according to the schedule. In the example under consideration, however, the model only approximates the process kinetics because of the neglect of such factors as variations in catalyst activity, other components in the reaction mixture, higher order terms in the kinetic equations, etc. Open-loop control of the process would lead, therefore, to very significant deviations from the desired end-point.

The repetitive control concept was applied here. Equations 5 and 6 are solved for the optimum control path leading from the current state of the process (based on the most recent composition measurement of the reaction mixture) to the specified final composition. Thus, each time a new composition measurement is made available to the computer, a new control path is computed. This technique was demonstrated to be very effective in forcing the process to the prescribed performance.

Self-Checking Offers Advantages

Application of the self-checking concept to this system is currently being implemented. It is assumed, in this approach, that the inadequacies of the model may be absorbed in the parameters of Equations 2a and 2b .

* In terms of the u, v coordinates, these boundary conditions are expressed as (u_o, o) and (u_f, v_f), respectively.

Specifically, the model deviates from the observed process behavior because of variations in catalyst activity, systematic errors in composition measurement, suppressed higher order terms in the kinetic equations, neglected components of the reaction mixture, etc. It is assumed, however that these "disturbances" cause only a slow drift of the model and may be adequately compensated within a given operating region by appropriate adjustment of the parameters, A_1, A_2, N_1 *and* N_2. Thus, the actual composition paths $x(t)$ and $y(t)$ are compared with the paths predicted by the model; the parameter values are adjusted periodically such as to minimize the discrepancy between these paths.

There is a significant random component of error in the composition measurement introduced by the sampling operation and by the sensitivity limitations of the analytical instruments. A statistical smoothing technique is coupled with the self-checking operation in order to filter out the random fluctuations in the composition data while retaining the trend. Also under consideration are means of weighting the data to account for the model changing with time.

The combination of repetitive computer control and self-checking provides the basis for wide practical applicability of the model approach to optimizing control. In particular, the control effectiveness becomes very much less dependent on the accuracy or completeness of the model employed, providing there is an adequate information feedback to the control computer. Thus, optimizing control for very complex systems may be realized with computer control with economic justification.

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References

1. C. S. Draper and Y. T. Li, "Principles of optimalizing control systems," *American Society of Mechanical Engineers,* New York, 1951.
2. H. Ziebolz and H. M. Paynter, "Possibilities of a two-time scale computing system for control and simulation of dynamic systems," *Askania Regulator Company,* Chicago, 1953.
3. D. P. Eckman, T. J. Walsh, and F. E. Brammer, "Computer control of chemical processing," *Case Institute of Technology,* Cleveland, 1953.
4. Process Automation Project: *Report I, Case Institute of Technology,* Cleveland, 1956.
5. D. P. Eckman and I. Lefkowitz, "Optimizing control of a batch chemical process," *Control Engineering,* Vol. 4, No. 9, p. 197, September, 1957.
6. I. Lefkowitz and D. P. Eckman, "Application and analysis of a computer control system" paper, *ASME-IRD Conference,* University of Delaware, April, 1958.
7. I. Lefkowitz and D. P. Eckman, "A review of optimizing/computer control," *Proceedings of the Self Adaptive Flight Control Systems Symposium,* Wright Air Development Center, January, 1959.
8. M. Phister, Jr. and E. M. Grabbe, "Fitting the digital computer into process control," *Control Engineering,* Vol. 4, No. 6, p. 129, June, 1957.

Optimizing Control by Automatic Experimentation

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IN A CONVENTIONAL FEEDBACK control system the actual value of the quantity to be controlled is compared with the desired value of this quantity (set point), and the control system operates to reduce any differences (or reduce error signal) with allowable tolerance. Controls of this type are widely used in the processing industries to maintain pressure, flow, temperature, level, etc. Despite the fact that such processes are completely instrumented and set points are maintained, the operation is not quite automatic. A human operator is needed for start-up, emergencies, shut-down, and to make minor adjustments to meet changing conditions. Since it is generally recognized that process operations might be improved by proper coordination of many set point values, and thus optimize control, the operator is an optimizing control, as he attempts to change settings for changing conditions. He, however, is seldom given the opportunity or proper information to seek optimum settings for a complex control system.

An optimizing control system can be termed a system which attempts to get the best performance from a plant or process according to a criterion such as maximum production or minimum unit costs. It can do this by adjusting the input variables, noting the effect on performance criterion, and deciding on a logical basis what changes of input variables should be made. The purpose of such a control is to provide adaptability to changes in external conditions which may be untrollable, unmeasurable, or unknown. The Westinghouse Opcon control system basically duplicates the informed behavior of a human being in controlling industrial processes, with simplicity and unsophistication. Opcon control differs from the digital computer equation solving procedure in that it uses the process itself rather than a mathematical model in its search for optimum conditions. As a part of simplicity, the Opcon control makes no attempt to interpret "trends". Once optimum conditions are found, it compensates for drift caused by uncontrolled variables by continual search.

Previous thinking in the field of optimizing control has been characterized by: the one-variable-at-a-time

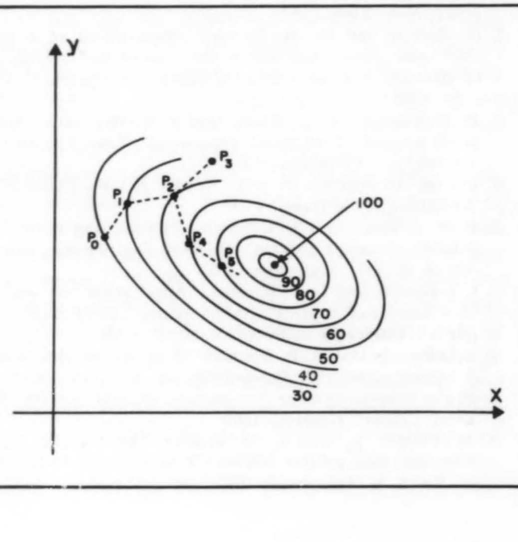


Figure 1. OPCON operation is illustrated by this problem. Let X and Y be the controlled variables, and let the maximized output be represented by contour curves (100 is optimum). The controlled variables are set arbitrary values (P_0) and the resulting output is a point on contour 30. The variables are changed to P_1 and new output is compared with P_0. The next change depends on whether P_1 is greater or less than P_0. Changes are kept within reasonable limits to prevent serious deterioration in the output, with the restriction that earlier moves are large enough to insure that a highly profitable possibility is not overlooked. Successive moves are made according to a built-in strategy (P_1 to P_2, then P_2 to P_3, etc.) with evaluation after each move, and with adjustments as the optimum is approached. When the optimum is apparently reached, experimentation stops and periodic tests are made with inputs fixed at their optimum settings. When significant changes occur, the whole procedure is repeated.

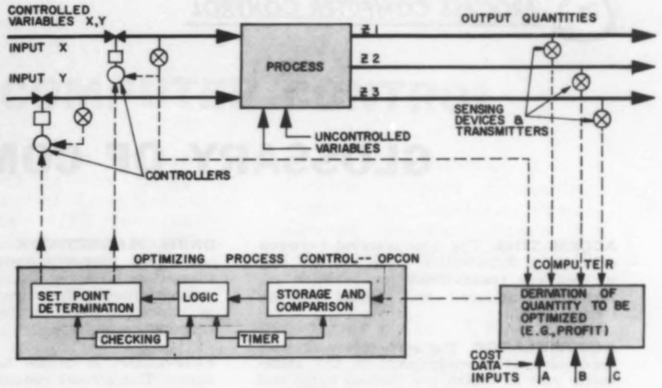


Figure 2. Schematic diagram of a process with two controlled variables and three outputs which is optimized for maximum profit by OPCON control. Inputs X and Y are controlled by set point controllers. The three outputs Z_1, and Z_2 and Z_3 are measured and the signals fed to a special purpose analog computer. Also the magnitude of input Y and cost inputs A, B and C are fed to this computer which solves the profit equation for the process. The equation is relatively simple and does not involve the process equations. The computer output to the OPCON control is a voltage proportional to operating profit and is the value which the control maximizes, by adjusting set points of the two flow controlled variables through strategic experimentation as described in Figure 1.

approach, the feeling that continuous sensing is necessary, a tendency to try to solve completely nonlinear problems by starting with linear approximations, and a general attempt at great sophistication in making use of information. Most applications involve more than one input variable and these variables interact, that is, the optimum level for one variable depends on levels of the others. Under such circumstances, it is a well-known fact in the theory of design of experiments that experimenting only with one variable at a time is inefficient and often doomed to failure. Further, in many processes the sensing could take place only at finite intervals, so that a discrete system would be more desirable than a continuous one. The continuous approach to a problem is more likely to succeed when it is suggested by essential continuity of the situation than when it is dictated by the engineer's false impression that mathematics begins and ends in the theory of calculus and differential equations.

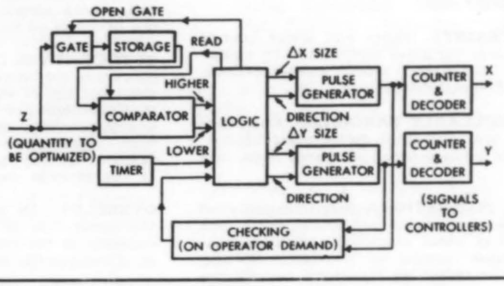
The method of solving nonlinear problems by beginning with linear approximations and making subsequent adjustments is a time-honored procedure, and can be quite successful when the nonlinearity is minor. When the nonlinearity is at the very heart of the problem, as it is in the optimization problem, this is no longer the case. It is logical to resist the temptation to compute derivatives and make inferences from them.

Built-in Strategy

In seeking an optimum condition the Opcon makes discrete steps in the values of the process variables, rather than continuous changes. A strategy is built into the machine for experimenting with the process to determine optimum settings. As Figure 1 shows, the optimum condition in a two variable system is determined by strategic adjustment of controlled variables and evaluation of the process output as a result of these changes. This procedure is adaptable to processes where the output can be measured infrequently, for example once an hour. It can also be used in problems where the output is essentially continuous, such as electrical systems. The discretely-made output measurements are simply made with greater frequency.

Figure 2 shows how an automatic experimentation type control is employed to optimize a process with two controlled variables and three outputs. Note that a small analog computer is used to calculate the maximum profit equation, since the Opcon does not contain any numerical computation ability. The control unit is a logic system using transistor circuits. Figure 3 is a block diagram of the control unit. The basic logic circuit is a p-n-p transistor. These are assembled on printed circuit boards in various combinations to perform any logic function. Flip-flops are used for memory storage in the control unit.

Figure 3. Block diagram of OPCON optimizing control. When it is time for a move, the incoming signal z feeds into the storage and comparator, where it is compared with the last best value of z. The "higher" or "lower" signal from the comparator goes to the logic unit. Here this signal plus information from past moves is used to make a decision as to which variable is to be moved, and its magnitude and direction. This signal goes to the proper pulse generator, where it is converted to series of pulses. The counter and decoder takes the pulse and produces an output voltage or current level going to controller set points. With new set points there is a new value of z. If the move is successful, the logic provides an open gate signal, and the new value of z is put into storage. If a failure, the old value of z is retained in storage, waiting for comparison with the next move.



GLOSSARY OF COMPUTER TERMS

ACCESS TIME. The time interval between calling for information from storage and its delivery (read time); or between information delivery and actual storage (write time).

ACCUMULATOR. The zero-access register (and associated equipment) in the arithmetic unit in which are formed sums and other arithmetical and logical results; a unit in a digital computer where numbers are totaled, i.e., accumulated. Often the accumulator stores one quantity and upon receipt of any second quantity, it forms and stores the sum of the first and second quantities.

ADDRESS. A label such as an integer which identifies a register, location, or device in which information is stored.

AMPLIFIER, BUFFER. An amplifier used to isolate the output of any device, e.g. oscillator, from the effects produced by changes in voltage or loading in subsequent circuits.

BINARY. A characteristic or property involving a selection, choice or condition in which there are but two possible alternatives. A binary digit is a single digit or whole number in the binary scale representing the total, aggregate or amount of units utilizing the base two; using only "0" and "1" digits to express quantity. "Bit" is the abbreviation for this term.

BRANCH. A conditional jump in a program that causes the computer to make a proper choice as a result of comparison during computation.

BUFFER. A circuit having an output and a multiplicity of inputs so designed that the output is energized whenever one or more inputs are energized.

CHANNEL. A path along which information, particularly a series of digits or characters, may flow. In storage, which is serial by character and parallel by bit (e.g., a magnetic tape or drum in some coded-decimal computers), a channel comprises several parallel tracks. In a circulating storage a channel is one recirculating path containing a fixed number of words stored serially by word.

CODE, INSTRUCTION. An artificial language for describing or expressing the instructions which can be carried out by a digital computer. If more than one address is used, the code is called a multiple-address code.

CONSTRAINTS. Upper and lower bounds on process variables determined by equipment limitations, safety considerations, product specifications, etc.

CONTROLLABLE VARIABLES. Quantities which are subject to direct manipulation, such as temperature, pressure, flow, and level.

CORE, MAGNETIC. A magnetic material capable of assuming and remaining at one of two or more conditions of magnetization, thus capable of providing storage, gating or switching functions, usually polarized by electric currents carried on wire wound around the material.

DRUM, MAGNETIC. A rotating cylinder on whose magnetic-material coating information is stored in the form of magnetized dipoles, the orientation or polarity of which is used to store binary information.

FLIP-FLOP. A device having two stable states. The circuit remains in either state until caused to change to the other state by application of a corresponding signal.

GATE. Logical circuit with one output and multiple inputs in which the output is energized when and only when certain input conditions are met.

INSTRUCTION. A set of characters which defines an operation together with one or more addresses (or no address) and which, as a unit, causes the computer to operate accordingly on the indicated quantities; preferable to the terms "command" and "order".

INTERMEDIATE VARIABLES. Quantities whose values depend on values of both controllable and uncontrollable variables, such as concentrations, yields, and efficiencies.

JUMP. An instruction or signal which, conditionally or unconditionally, specifies the location of the next instruction and directs the computer to that instruction. A jump is used to alter the normal sequence control of the computer.

LOGIC. The science of the formal principles of reasoning; the basic principles and applications of truth tables, gating, interconnection, etc. required for arithmetical computation in a computer.

MATHEMATICAL MODEL. A set of relationships by which process behavior can be predicted. Models may be steady-state or dynamic.

MATRIX. An array of circuit elements; diodes, wires, magnetic mores, relays, etc. which are capable of performing a specific function, such as conversion from one numerical system to another, and for encoding and decoding.

OBJECTIVE FUNCTION. A quantity, such as profit, production rate, or costs, to be maximized or minimized by a computer control system.

ON-LINE OPERATION. System in which input data is fed directly from the measuring devices into the computer with results being obtained in real-time during the progress of the event.

OPTIMIZATION. A procedure by which a process is continually adjusted to the best available set of operating conditions, i.e., that combination of process variables which provides the maximum (or minimum) value of the objective function attainable at any particular time in view of the process constraints.

OVERFLOW. In an arithmetic operation, the generation of a quantity beyond the capacity of the register or location which is to receive the result.

PARALLEL. Handled simultaneously in separate facilities; operating on two or more parts of a word or item simultaneously; contrasted with serial.

PARITY. Condition of a binary code in which the total number of 1's is always either odd or even.

PROCESS DYNAMICS. Characteristics of a process which determine its behavior as a function of time, commonly specified by its response to specific disturbances.

PROGRAM. A plan for the solution of a problem consists of planning and coding, including numerical analysis, systems analysis, specification of printing formats, and any other functions necessary to the integration of a computer in a system.

RANDOM-ACCESS. Access to storage under conditions in which the next position from which information is to be obtained is in no way dependent on the previous one.

REGISTER. The hardware for storing one or more computer words being manipulated. Registers are usually zero-access storage devices.

ROUTINE. A set of coded instructions arranged in proper sequence to direct the computer to perform a desired operation or series of operations.

SERIAL. Handle one after the other in a single facility, such as transfer or store in a digit by digit time sequence.

STORAGE. Preferred to memory; any device into which units of information can be copied, which will hold this information, and from which the information can be obtained at a later time.

STORAGE, CIRCULATING. A device using a delay line, or unit which stores information in a train or pattern of pulses, where the pattern of pulses issuing at the final end are sensed, amplified, reshaped and reinserted in the delay line at the beginning end.

TRACK. In a serial magnetic storage element, a single path containing a set of pulses.

TRANSFER. To copy, exchange, read, record, store, transmit, transport, or write data; to change control; to jump to another location.

UNCONTROLLABLE VARIABLES. Quantities over which little or no control can be exercised, such as ambient temperature, raw material characteristics, or market conditions.

WORD. A set of characters which occupies one storage location and is treated by the computer circuits as a unit and transported as such; treated by the control unit as an instruction, and by the arithmetic unit as a quantity.

Above terms adapted from a preliminary listing in "Communications of the Association for Computing Machinery", June, August, Sept., Oct., Nov., 1958; also from The Thompson-Ramo-Wooldridge Products Co. and Daystrom Systems.

BIBLIOGRAPHY OF COMPUTER CONTROL

Aiken, W. S. — "Programing a Digital Process Control Computer for System Reliability." *Short Course & Conference on Automation and Computers,* Vol. 1, Transactions, University of Texas, Austin, Texas, June 3, 1958.

Ayres, E. — "An Automatic Chemical Plant." *Scientific American,* September, 1948, Vol. 179.

Bail, J. H., Jones, C. E., Hoffman, H. J., — "Boiler Test Via A Digital Data System." *Instruments & Automation,* June, 1957, Vol. 30, No. 6, pp. 1096-1101.

Bertram, J. E., Franklin, G. — "Sampled Data Feedback Improves System Response." *Control Engineering,* Sept. 1955, Vol. 2, No. 9, pp. 107-111.

Bertram, J. E. — "Effect of Quantization in Sampled Feedback Systems." *Applications and Industry."* Sept. 1958, pp. 177-182.

Blynn, M. S. — "A Digital Recording and Computing System." *3rd Nat'l. Conference on Analog and Digital Instrumentation,* AIEE, April 20-21, 1959.

Braun, E. L. — "Design Features of Current Digital Differential Analyzers." *1954 IRE Nat'l. Convention Record,* Pt. 4, pp. 87-97.

Braun, E. L., Post, G. — "System Considerations for Computers in Process Control." *IRE Nat'l. Convention Record,* 1958.

Braun, E. L. — "Digital Computers in Continuous Control Systems." *IRE Transactions on Electronic Computers,* June, 1958, Vol. EC-7, No. 2.

Braun, E. L. — "A Digital Computer for Industrial Process Analysis and Control," *Western Jt. Computer Conference,* March 4, 1959.

Brown, J. J., Leaver, E. W. — "Caveat on Computers." *Automation,* Feb. 1956, Vol. 3, No. 2, pp. 38-42.

Burns, L. F., McGregor, W. K., Russell, D. W. — "The Analog Computer as a Process Controller." *Control Engineering,* Sept. 1957, Vol. 4, No. 9, pp. 160-165.

Cushman, R. H. — "Are Adaptive Servos Here?" *Automatic Control,* Feb. 1959, pp. 23-24.

Daniels, G. S. — "A New Stored Program Information System." *3rd Nat'l. Conference on Analog and Digital Instrumentation,* AIEE, April 20-21, 1959.

Elgerd, O. I. — "An Analog Computer Study of the Transient Behaviour and Stability Characteristics of Serial Type Digital Data Systems." *AIEE Communications & Electronics,* No. 37, July 1958, pp. 358-366.

Engel, H. L. — "Computing Control Applied to Fractionating Column." *Control Engineering,* Sept. 1957, Vol. 4, No. 9, pp. 144-147.

Freeman, H., Lowenschuss, O. — "Bibliography of Sampled Data Control Systems & Z-transform Applications." *IRE Transactions on Automatic Control,* Vol. PGAC-4, March 1958, pp. 28-30.

Freilich, A. H. — "Computers in Process Control." *Chemical Engineering,* June, 1957, pp. 280-284.

Freilich, A. H., Doherty, W., Stevens, D. L. — "Data Logging Systems as a Direct Source of Information for Process and Accounting Calculations." *Proceeding of ISA Symposium on Data Logging Systems,* Phila, Pa., Nov. 7-8, 1956.

Gallagher, G. G., Robinson, R. A. — "Future Trends in Automation." *ASME Paper No. 55—PET-5,* Sept. 25, 1955.

Goodman, T. P., Reswick, J. B. — "Determination of System Characteristics from Normal Operation Records." *ASME Transactions,* Vol. 78, No. 2, Feb. 1956, pp. 259-271.

Gordon, B. M. — "Adapting Digital Techniques for Automatic Controls." *Electrical Manufacturing,* Nov. 6, 1954, Vol. 54, No. 5, pp. 136-143, 332.

Grabbe, E. M. — "Some Recent Developments in Digital Control Systems." *Instrumentation & Control in the Process Industries Conference,* Armour Research Foundation and ISA, Feb. 7, 1957.

Grabbe, E. M. — "Computers in the Control Loop—Fact or Fancy." *Proceedings of 12th Annual Conference,* Cleveland, Ohio, Sept. 9-13, 1957, pp. 143-149.

Gunning, W. — "Computers in the Process Industries." *IRE Transactions on Electronic Computers,* Vol. EC-7, June, 1958, pp. 129-133.

Harder, E. L. — "Impact of Computational Developments on Systems of Automatic Control." *Proceedings ISA Annual Conference,* Cleveland, Ohio, Sept. 9-13, 1957, pp. 39-56.

Harple, K. G., Baconnet, J. — "A General Purpose Computing-Logger for On-Line Process Control Studies." *Paper No. PMT-7-58, 13th Annual ISA Instrument-Automation Conference,* Phila., Pa., Sept. 1958.

Hines, C. K., Walker, J. K. — "Computer Controlled Pilot Plant." *Instruments & Automation,* Oct. 1958, Vol. 31, No. 10, pp. 1688-1689.

Hooke, R. — "Control by Automatic Experimentation." *Chemical Engineering,* June, 1957, pp. 284-286.

Hurd, C. C. — "Computers as Controllers." *Proceedings ISA Annual Conference,* Cleveland, Ohio, Sept. 9-13, 1957, pp. 89-96.

James, W. E., Johnston, J., Martin, M., Yetter, E. W. — "How A Systems Team Engineered a Plant Computer Test." *Control Engineering,* Nov. and Dec., 1956, Vol. 3, Nos. 11 & 12.

Johnson, C. W. — "Adaptive Servos and The Human Operator." *Automatic Control,* April, 1959, pp. 16-24.

Kalman, R. E. — "Design of Self-Optimizing Control System." *ASME Paper No. 57-IRE-2,* April, 1957.

Kerley, J. G. — "Instrumentation of Petroleum Processes." *A.P.I. Proceedings,* Vol. 36, Section 3, 1956 pp. 120-129.

Kerstukos, A. — "Telelogical Control—It Learns by Doing." *Westinghouse Engineer,* Sept. 1957, Vol. 17, No. 5, pp. 138-139.

Kiefer, J., — "Optimum Sequential Search and Approximation Methods Under Minimum Regularity Assumptions." *J. Soc. Indus. Appl. Math., 5,* 1957, pp. 105-136.

Kirchmayer, L. K. — "An Optimalizing Computer Controller for the Electric Industry," *ASME Instruments and Regulator Conference Paper 58 IRD-2,* Newark, Del., April 1958.

Klein, M. L. — "Digital Differential Analyzers." *Instruments and Automation,* June, 1957.

Kompass, E. J. — "The Early Bird Goes Automatic." *Control Engineering,* Dec. 1956, Vol. 3, No. 12, pp. 77-83.

Laspe, C. G., Stout, T. M. — "Digital Computers for Process Control."

Industrial & Engineering Chemistry," July, 1957, Vol. 49, p. 38A.

Laspe, C. G. — "What Is Ahead for Digital Computers in Refinery Process Control." *Petroleum Engineer,* Sept. 1957, Vol. 29, No. 10, pp. c-30 - c-38.

Lemmon, A. W., Gordon, B. B. — "Computers and the Chemical Processing Industry." *Battelle Technical Review,* Vol. 8, No. 3, March 1959, pp. 3-8.

Li, Y. T. — "Optimalizing System for Process Control." *Instruments & Automation,* Jan. 1952, pp. 324-27.

Long, M. V., Holzmann, E. G. — "Approaching the Control Problem of the Automatic Chemical or Petroleum Plant." *ASME 1378-81,* Oct. 1953.

Michels, L. S. — "On-Line Computation with General Purpose Computers." *Automatic Control,* April 1959, pp. 2DC-10DC.

Moore, H. F., Stern, R. K., Taylor, C. H. — "Belot Logger-Computer." *Control Engineering,* March 1957, Vol. 4, No. 3, pp. 23-29.

Moore, H. F. — "Automatic Computing for Process Unit Operation Guides," *ASME Paper No. 57-EIC-1,* June, 1957.

Otis, E. J. — "Optimized Control Through Digital Equipment." *Proceedings of the Eastern Joint Computer Conference,* Wash., D.C. Dec., 1957.

Phister, M. — "Digital Computers in Process Control." *13th Annual Instrumentation - Automation Conference & Exhibit,* Phila., Pa., Sept. 1958.

Phister, M. — "Controlling a Process with a Computer." *Industrial and Engineering Chemistry,* Vol. 50, 1958 pp. 1624-26.

Phister, M. — "Application of Digital Systems to Process Control." *Proceedings of 1958 ISA Symposium on Progress and Trends in Chemical and Petroleum Instrumentation,* Feb. 3 & 4, 1958, Wilmington, Del., Paper W-5-58.

Phister, M. — "Digital Control Systems - - Present and Future." *Conference on Industrial Instrumentation and Control,* Armour Research Foundation, Chicago, Ill. April 14-15, 1959.

Phister, M., Frady, W. E. — "System Characteristics of a Computer Controller for Use in the Process Industries." *Proceedings of the Eastern Joint Computer Conference,* Wash. D.C., Dec. 1957.

Pink, J. F. — "Three Ways to Use Computers in Process Control." *ISA Journal,* April 1959, Vol. 6, No. 4, pp. 56-60.

Post, Geoffrey — "Digital Differential Analyzers." *Symposium on Analog and Digital Computation,* Denver Research Institute, Denver, Colo., August 1956.

Ragazzini, J. R. — "Digital Computers in Feedback Systems." *IRE Convention Record,* Vol. 5, Pt. 4, *Automatic Control,* 1957.

Richards, R. K. — "Arithmetic Operation of Digital Computer." *D. Van Nostrand Co., Inc.* pp. 303-313, 1955.

Rutishauser, R. W. — "Litton 20 Digital Differential Analyzer." *7th Region IRE Conference,* San Diego, Calif., 1956.

Rutishauser, R. W. — "DDA—The Chemical Engineer's Computer." *Industrial and Engineering Chemistry.* Vol. 50, p. 52A, July 1958.

Schrage, R. W. — "Optimizing a Catalytic Cracking Operation by the Method of Steepest Ascents," *Operations Research,* 6-(1958).

Schuerger, T. R. — "Computing Control Applied to Sintering Process *Control Engineer,* Sept. 1957, Vol. 4, No. 9, pp. 130-133.

Schwent, G. V., et al — "A New Approach in Process Control System Design." *ISA Journal,* July, August, Sept., Oct., Nov., & Dec. 1956.

Sollecito, W. E. — "Fitting Computers into Control Systems." *Electrical Engineering,* May 1958, Vol. 77, No. 5.

Sperry, Albert — "Computer Control of a Power Plant." *New York Power Conference,* ISA NY Section, May 6-7, 1959.

Spielberg, A. M. — "The GE 312 Computer Controller System." *3rd Nat'l. Conference on Analog and Digital Instrumentation,* AIEE, April 20-21, 1959.

Sprague, R. E. — "Fundamental Concepts of the Digital Differential Analyzer Method of Computation." *Mathematical Tables and Other Aids to Computation,* Vol. VI, No. 37, pp. 41-49, Jan., 1952.

Stout, T. M. — "Analog or Digital Computers for Process Control?" *IRE Transactions on Automatic Control,* Vol. PGAC-3, Nov. 1957.

Stout, T. M. — "Computer Control of a Butane Isomerization Process." *3rd Nat'l. Conference on Analog and Digital Instrumentation,* AIEE, April 20-21, 1959.

Stout, T. M. — "Mathematical Relationships for Computer Control Systems." *ASME Semi-Annual Meeting,* Detroit, Mich., June 1958.

Summers, W. A. — "Central Station Control Today and Tomorrow." *ISA Journal,* July '58, pp. 32.

Taylor, D. F. — "Solid State Computer Automates Power Station Operation." *ISA Journal,* Oct. 1958, Vol. 5, No. 10, pp. 32-37.

Thomas, R. J., Gustafson, J. O., Foster, G. E. — "A Solid State Digital Computing System for Electrical Load Monitoring," *3rd Nat'l. Conference on Analog and Digital Instrumentation,* AIEE, April 20-21, 1959.

Tierney, J. W., et al — "How Digital Computing Functions Control Process." *Control Engineering,* Sept. 1957 Vol. 4, No. 9, pp. 166.

Travers, R. H., Yochelson, S. B. — "First Computer Controlled Power System." *ISA Journal,* Oct. 1957, pp. 454-458.

Ushakov, V. B. — "Soviet Trends in Computer Control of Manufacturing Processes, *Instruments & Automation,* January, 1959, Vol. 32, No. 1, pp. 102-105.

Van Nice, R. I. — "Optimizing Control, Theory and Practice," *3rd Nat'l. Conference on Analog and Digital Instrumentation,* AIEE, April 20-21, 1959.

Van Nice, R. I., Kaupe, A. F. — "Evaluation of Strategies for Automatic Experimentation." *ASME-IRD Conference on Automatic Optimization,* Univ. of Dela., April 2-4, 1958.

Vick Roy, T. R. — "Data Handling Systems." *Chemical Engineering,* June 1957, pp. 274, 279.

Weber, N. E. — "Computer Control or Control Computers?" *13th Annual Instrument-Automation Conference and Exhibit,* ISA. Sept. 1958, Paper PFT-6-58.

Weiss, E. — "The CRC 105 Digital Differential Analyzer." *IRE, PGEC Transactions,* pp. 19-24 Dec. 1952.

White, B. — "The Quarie Optimal Controller." *Instrument & Automation,* Nov. 1956, Vol. 29, No. 11, pp. 2212, 2216.

Williams, T. J. — "Analog Computing in the Chemical and Petroleum Industries." *Industrial and Engineering Chemistry,* Vol. 50 (1958) pp. 1631, 35.

Young, A. S. — "Prerequisites of Automatic Chemical Factory." *Canadian Chemical Processing,* Sept. 1955, Vol. 39, No. 10, pp. 99-110.

Ziebolz, H. — "Suggestions for the Development of a Self-Determining Computer Control System." *AIEE Conference on New Developments in Instrumentation for Industrial Control,* T-88, Aug. 1956, pp. 160-168.

(Other References, page 73 and 77)