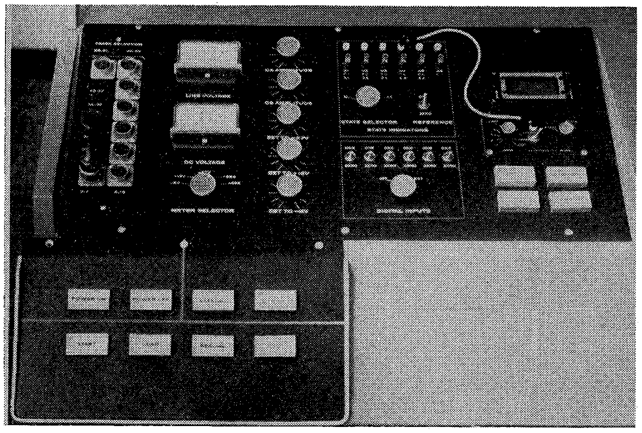

Fig. 5—Test and maintenance panel (top), and operator's control panel (lower left).

The construction of the machine is unitized and modular in nature for rapid location and replacement or repair of units, subunits, and components. The building block of the basic computer is a module as shown in Figs. 1 and 2. These modules plug into frameworks where the interconnection between the modules is minimized. Each module contains several flush-etched wiring inserts where the etched wiring on the module between the inserts represents the majority of wiring in the machine. Components are also mounted on the module bottoms. Fig. 3 shows the computer subframe which houses the arithmetic and control unit, a portion of the memory unit, and a portion of the digital input-output unit. This modular construction greatly reduces the maintenance time both in locating a trouble and repairing the trouble. The use of etched-wiring techniques increases the reliability of the machine over those using conventional wire and solder techniques. Each insert and each module contains test points which are accessible when the machine is in operation.

Fig. 6—The RW-300 digital-control computer.

The magnetic drum, as shown in Fig. 4, is a sealed unit so that corrosive gases and vapors, dust, etc. will not enter. The construction of the drum is similar to that used in drums for airborne applications so that temperature variations and mechanical shock and vibration will not alter its operation. Fig. 5 shows the RW-300 computer with the test and maintenance panel exposed. Fig. 6 is an over-all picture of the RW-300 showing its size, which is that of a conventional office desk.

CONCLUSIONS

Specifications for the RW-300 were developed as a direct result of studies of industrial processes. Because the computer was designed specifically for application to process control, it will make available to this application the flexible, sophisticated computing and control ability necessary to implement integrated control systems.

Optimized Control through Digital Equipment

E. J. OTIS[†]

BY optimum control of a process we mean the achievement of a series of objectives in the production of a specific product. The objectives to be achieved are primarily of an economic nature, although they frequently are expressed in terms of the process input and output. In other words, the problem is one of maintaining product characteristic and quality with the minimum use of raw materials and at a minimum production cost. Furthermore, the problem includes maintaining continued product output of specified characteristics in the face of changing plant conditions and variations in raw materials, as long as the cost of the product is within the limits specified by a competitive market.

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At present, the control of a process is inadequately relieved by resorting to the use of "minor control loops" and a human operator to close the major loop around them. (See Fig. 1). These minor loops consist of a transmitter-recorder-controller combination which measures a process variable and maintains it at a desired level. The control of this variable is effected with respect to a set point without regard to the state of the total process or to the value of any of the other variables. In some cases the value of one variable and its excursions is used to control another variable in a configuration called "cascade control." However, this type of control, although more sophisticated than the simple minor loop, can only be used in the few cases where a simple, known, and non-time-varying relationship exists between two variables while the over-all control remains effectively composed of the series of minor loops. The integration of each minor loop into the whole control system is then effected through the operator, who observes the process state on different recorders and adjusts (adapts) the controller to process conditions.

In other words, by adjusting a set point, after he has observed the state of the process as presented by numerous recorders, the operator's skill and knowledge of the process are resorted to in closing a second loop around the "minor control loops." Through this major loop the interactions of the different variables are now integrated into the control system.

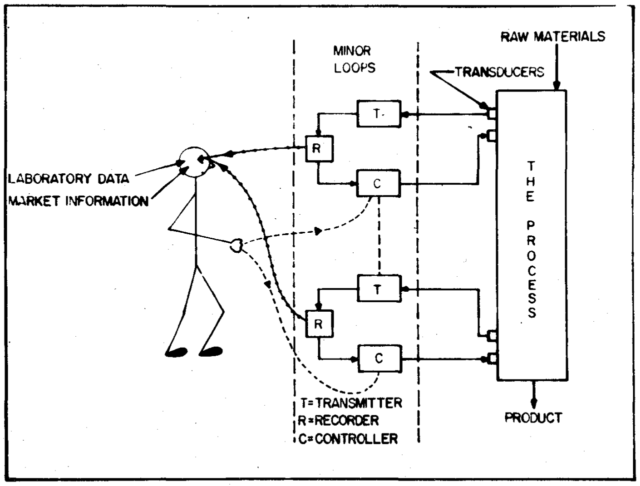

Fig. 1—Process control today.

Because of the complex nature of today's processes, however, a human operator can not keep track of all the necessary variables and their interrelationships, as well as their effects upon product cost and quality. And, although he is more intelligent than any machine that can be conceived, the human operator fails when it becomes necessary to digest large amounts of data and respond with adequate speed to an increased system complexity.

Furthermore, even though he might achieve an apparently satisfactory combination of settings for the operation of the process, he rarely, if ever, knows within a reasonable period of time whether this is the best combination, *i.e.*, whether the process is at maximum efficiency.

It is becoming evident that the operator can not attend the major loop efficiently because of increasing process complexity. An attempt has therefore been made to close the control loop through equipment rather than through the operator. This is not meant to replace the operator but rather to place him in parallel so that the control equipment can function effectively and sufficiently fast in the making of decisions. These decisions may be routine; they are almost invariably numerous. The operator can therefore be relieved of making many routine decisions, and can intelligently monitor the process and provide over-all direction in parallel with the computing-controlling equipment. (See Fig. 2.)

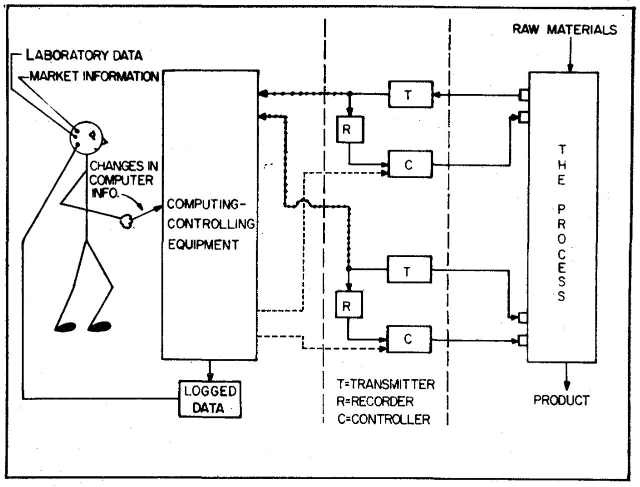

Fig. 2—Optimized process control.

Since the computing-controlling equipment is placed in parallel with the operator, it must be capable of communicating with both the operator and the process. Thus, it must be able to accept signals directly from the transducers and/or transmitters, as well as from the operator, and its output must be recognized by, and be intelligible to, the controllers and to the operator.

After considerable study of various processes, a system has been designed to close the loop around minor-loop controllers. This system centers in a general-purpose digital computer and, as is the case with any other computing system (industrial or military), the peripheral equipment becomes important. So besides the computer we have system components such as input multiplexer, analog-to-digital converter, computer input-output equipment, and control output.

Although many hours could be spent in discussing the characteristics of these component systems, at this time we shall content ourselves with indicating their main design criteria.

EQUIPMENT CHARACTERISTICS

Before discussing the particular characteristics of component systems, let us consider three of the major decisions that influenced the design of the over-all system.

First of all, it was decided to maintain minor-loop analog controllers for two very practical reasons. 1) They do provide continuous control of the different variables. In order for the computer to duplicate such control, it being time shared among all the variables, it would have to be designed to operate at a tremendously high speed—one well beyond that considered today to be *reliably* attainable. 2) In case of computer failure, the process would be held to the most recent set points, changes of which could still be made manually.

The second major decision concerned the data processing equipment. Here, the decision to be made was whether to use a general-purpose or a special-purpose computer. This decision depended upon the consideration of numerous factors. The main reasons for deciding to use a general-purpose computer were its flexibility (required to control a complex process under varying process conditions) and its capability of adapting—or better yet, self-adapting—its program to varying conditions in the process. When discussing the computer, we shall see how this capability to adapt itself enables it to provide meaningful control signals.

Last, and most important, the reliability of the equipment, which must be capable of operating continuously, must be carefully considered before installation in a process plant. This requirement for reliability dictates the use of solid-state components throughout and a minimum use of electromechanical devices. Keeping in mind the retention of the minor loops, the usage of a general-purpose computer, and the employment of solid-state components properly derated in circuits designed and constructed to withstand an adverse plant environment (temperatures to 120°F, high humidity, and a generally corrosive atmosphere), we can now look at the component systems required to close the major loop.

SYSTEM INPUT SECTION

The input section (Fig. 3) supplies the control system with the data that determine the operating conditions of the process, the present settings of variables to be controlled and, of course, the program indicating the control variables and the method of control.

These inputs are derived from two sources, the process variable measurements, and the operator.

The process variable measurements include those which yield information on the state of the process. These can be temperatures, flows, and levels, as well as physical and chemical characteristics of raw materials used, and the characteristics of the end product.

Types of analyzers (instruments which are used to measure the physical and chemical characteristics of both raw materials and end products) will be chosen for the particular process. While, control variables such as temperatures, flows, levels, etc., are derived from transducers where the signal level can be as low as 10-50 mv full scale. Since these signals are electrical analogs, they must be quantized to at least one part in one thousand. The input multiplexer must therefore be able to handle such low-level signals and to restrict noise levels in excess of 10 μv. If the multiplexer can not handle such low-level signals, an amplifier is required for each input. However since we have found that there is a large number of inputs (300-1000), the cost would be prohibitive. Therefore the use of amplifiers must be avoided.

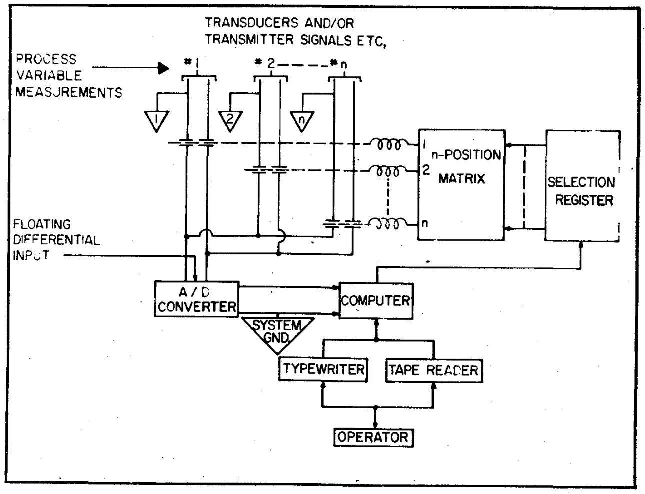

Fig. 3—System input section.

Furthermore, in order to circumvent ground-loop problems, the input multiplexer must be able to switch both sides of the signal line. The most reliable component that can switch both sides of a low-level signal line and still not introduce unpermissible noise, is the mercury-wetted relay. This component has displayed long life (billions of operations), lack of contact bounce, and a very stable contact resistance. The Clare HG2A series has been found satisfactory both from the point of view of reliability and of drive requirements. However, like any other component handling analog signals, there are noise problems that have to be contended with. Noise introduced by these relays is composed of 1) a transient portion which lasts for approximately 3-5 milliseconds and 2) a dc portion. The transient portion of the noise is caused by flux build-up and decay, while the dc portion is caused by thermocouple effects resulting from thermal gradients existing between the two sides of the relay.

The transient portion of the noise, although minimized by using appropriate circuits, still exceeds the permissible 5-10 μv level. However, as will be shown below, this transient is rejected through the use of an appropriate analog-to-digital converter.

The dc portion of the noise is minimized by appropriate packaging and by providing a "shorting-bar" wiring arrangement inside the relay. In this manner we have found that the noise level can be reduced to below 10 μv (actually of the order of 1 to 5 μv). This enables us to maintain the required signal accuracy of 0.1 per cent or better.

These relays are driven directly from transistor circuits utilizing the RCA 2N217 germanium transistor in a random-access switch arrangement. This feature, permitting us to connect any input variable at random to the system as directed by the computer, has been incorporated for three very important reasons: 1) It permits switching to a standard input for recalibration purposes at any desired time, 2) it enables the equipment to sample discrete variables at time intervals shorter than the scanning cycle (this is necessary in order to scan quantities that must be integrated with respect to time, such as flows), and 3) under a self-adaptive computer program, the equipment can sample more frequently those variables that become critical under varying process conditions.

The analog-to-digital converter must also possess special characteristics determined by the signals generated in a process plant. Besides the fact that the desired signals are very low in level, they usually contain electrical noise produced by plant power equipment, such as motors. In addition, noise pick-up is frequently found when long-signal leads (100-500 feet) are required. Because of the noise and ground loop problems mentioned above, the converter itself has been designed with the following features:

1) It provides input isolation required because of differences in ground potentials throughout the plant with respect to the control system ground. This ground potential difference can be as high as 500-1000 volts during transient conditions such as storms. Furthermore, this differential-isolating type of input rejects common noise.
2) It can resolve 10 mv (or higher signals), with accuracies to 0.01 per cent.
3) It integrates over the sampling period of 1/5 to 1 second. This sampling rate of 1 to 5 conversions per second might at first appear to be slow, but the speed has been selected to conform to the type of signal present in a process plant where there is noise pick-up. If rapid conversion were required, a tremendous burden would be placed upon the computer if it were to average many of these readings. Using an integrating converter, however, the computer is freed to perform correction and control computations while the converter is digitizing a reading.

The converter is completely transistorized and known as the DADIT (Daystrom Analog-to-Digital Integrating Translator). It integrates over the entire period of time that the input is connected to it (1/5 second) and is not affected by transient noise present in the relay multiplexer (5-msec duration). Actually, the longer the integrating period, the better the noise rejection. Although the multiplexer and the analog-to-digital converter are matched in speed to cope with the "noisy" type of signal that they are expected to switch and quantize, they might not function fast enough if readings are to be made from a number of variables at intervals closer than 1/5 second apart. By the same token, since a "faster" converter would not provide adequate filtering, and hence meaningful signals, two or more converters are used when it is necessary to solve the above-mentioned problem.

The multiplexer and analog-to-digital converter, supplemented by any special equipment used to tie in product and material analyzers, form the input to the system. It is these units which monitor the condition of the process as well as its performance.

In addition, the system is given instructions by the operator, such as pertinent results of laboratory analyses concerning a new raw material, market information, or other commands the operator wishes to introduce. The operator may even want to enter new programs. For this purpose a paper-tape reader and a typewriter have been provided. The reason for including a typewriter rather than a keyboard is so that a record containing instructions given to the computer will be always available. The typewriter is used for the manual introduction of data as well as for the control of the computer.

Computer

Once the data have been converted to the digital form, they are no longer affected by component noise and drift, and from then on we deal with digital accuracies.

The computer, in receiving these data, must first operate upon them, linearize and scale factor the numbers in order to account for different transducer characteristics and, in general, convert a set of numbers to meaningful quantities representing physical measurements as required by the computer program or for logging sheets. The values of some measurements have to be compared with alarm set points while others have to be integrated and correlated in order to provide information concerning the amount of output, the process efficiency, and the determination of product quality. This part is easy to program and is designed to yield information concerning the state of the process at the present time.

The computations that determine the control signals are complex (because we are dealing with complex processes) and nonlinear time-varying in their characteristics. They are therefore difficult to define in popular mathematical terms, and the control program is largely biased by knowledge of the process, the interactions of different control variables, and their effects upon the output (product).

The process is usually described with a set of nonlinear differential equations. The object is to make these equations linear for a particular process state, although they are over-all nonlinear. This can be achieved by creating relationships which define the coefficients of these equations in terms of the measured variables (process state), the control set points, and the process output. The system then can, for a set of inputs and outputs, select the appropriate set of coefficients, and by so doing, create a piece-wise linear approximation of a nonlinear process.

The computer can then solve these equations with respect to an optimizing criterion and create the control changes that will yield optimum performance. Actually the computer is expected to iterate through many solutions, choose the most attractive one, and introduce it into the process. It will then observe the actual results obtained as compared to the expected results, and will compensate for discrepancies by readjusting sets of coefficients. In this fashion the computer continuously adapts its mathematical model of the process to the actual case, accounting for different plant conditions that occur, many of which could not have been anticipated at the time of system design.

It is this capability of self-adaptation that dictates the use of a general-purpose computer.

The computer must be fast with respect to the process which, in computer language, is fairly slow.

The computer designed for this purpose is a 50-kc serial-binary machine. Word length is 20 bits plus sign and parity. This provides a computational accuracy of one part in 10^6, or well in excess of the accuracy of the measurements. It has a coincident-current memory that can be as large as 16,384 (2^{14}) words. It is a single-address machine with a speed of 1.3 msec for an addition, and 10.1 msec for a multiplication, including look-up. It has the full complement of arithmetic operation commands and branch and shift commands, as well as special ones used for controlling the input and output functions.

The computer, through its "analog-input" command, can select a particular input, connect it to the analog-to-digital converter, and then proceed with another computation while the signal is being converted. One-fifth second later (at the 5 integration/second rate) it causes a new input to be connected to the converter, accept the integrated reading of the previous input, and proceed with the new computations.

Again the computer, like all the circuits in the input section, is completely solid-state, uses approximately 3500 transistors, (RCA 2N217), and 3000 diodes.

SYSTEM OUTPUT

The output of the system serves the dual purpose of introducing the required control changes to the process and of informing the operator of the state of the process, the changes made, and any other information derived from the input variables. (See Fig. 4.)

It is very difficult to generalize concerning the design of actuators since they depend upon the characteristics of the actual equipment. Sometimes an on-off control will suffice, while in other instances variables are controlled in discrete steps. A digital stepping motor, such as the Sigma Cyclonome stepping motor (magnetically indexed rotor) and the Digitork, announced by The Teller Company, frequently can be used for this purpose.

The accuracy with which set points are set depends upon the process and the particular variable. It is definite, however, that today equipment can control much narrower ranges than an operator can.

The output for the operator is derived through tape punches and typewriters. The computer can select one to eight punches if the system so requires. The reason for using punches rather than typewriters directly is based on two considerations: 1) The particular punch used is faster than a typewriter (Western Electric punch type BRPE #1, 60 characters per second), and 2) they are considered to be more reliable than the relatively complicated typewriter. The typewriter can be "down" yet the system can continue to operate since the data are accumulated on punched-paper tape.

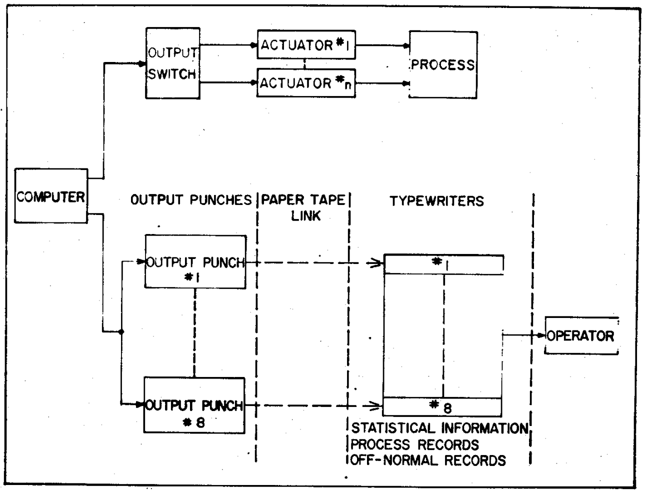

Fig. 4—System output section.

At this point, a word concerning reliability is again in order. The responsibility placed upon the control equipment described above is tremendous. In order to meet the requirements, this equipment must operate without failure for many months, if not for years. Extreme care therefore must be exercised in choosing the components to be used and in designing its circuits. There is room neither for components that have not been tested over long periods of time, nor for critical circuits. Normal maintenance must be performed while the equipment is operating, and check problems should be run through automatically at predetermined intervals of time in order to ascertain proper functioning. Finally, rapid troubleshooting procedures and faulty component location are musts.

In conclusion, rising processing costs are forcing industry to adopt automation. Optimized control will make new processes economically feasible and, therefore, practical. The challenge is here, and the future will show how well we are meeting it.

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