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Fitting the Digital Computer Into Process Control

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Applying digital control to a process involves much more than simply connecting a computer into the system. Prerequisites to integrated design are familiarity with digital techniques and lots more knowledge about the process itself than was needed before. The resulting complexity of the design efforts may bar wider computer usage unless orderly approaches to system analysis and synthesis are mastered. Here, a systematic approach is described and illustrated by a case in point.

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The move to the revolutionary "computer-type" control has been slow in the process industries, despite the fact that the groundwork for such control is already well established. As a result of pioneering work done in other fields, the hardware and the design techniques for digital controls are already available. Most people in the process areas are already alert to the many advantages promised by the new systems: advantages such as improved product quality, increased yield, and reduced operating costs. But, certain obstacles are holding up more widespread application.

One major problem stems from the fact that before digital controls can be applied to a given process, formulas must be developed relating operating variables to the measured variables and to the desired product characteristics. However, at the present time very few processes are so completely understood that all variables can be related on a theoretical basis.

Another impediment is the lack of instrumentation for measuring some process variables. The fast-moving instrument industry, however, is making rapid progress in easing this restriction. There are variables that cannot be measured directly, of course, but even this obstacle may yield to some indirect method of measurement.

Reliability is an important factor in digital control systems and must be considered as a system parameter. Techniques for reliability are manifold, but are not included within the scope of this article.

These problems, and others that arise in the course of applying digital control systems to new processes, can best be solved by a careful analysis of the process and of the possible control systems that may be employed. A systematic approach to analysis and synthesis will now be described. This will be followed by a case-history study of a typical design project. A typical "control engineering team" for system design must have experience and know-how in process engineering, instruments, computers, servo theory, etc.

SYSTEM ANALYSIS

The first step in designing a digital control system is to analyze the process to be controlled. A thorough appraisal is assured if the following organized approach is taken.

1. Decide upon limits or boundaries of the process. In many situations the limits will be obvious. A plant may make only one product, and the designer's problem may be to control the entire plant. On the other hand, the process to be controlled may be only one of a large number in the plant, all of which interact. Setting a boundary to the process to be controlled is then a very delicate matter, for a solution that might optimize it might at the same time affect other processes in an adverse way.

2. Define process objectives. Process objectives must be expressed initially in economic terms. One usual objective is to produce the maximum amount of a product having specified characteristics from certain raw materials at the minimum processing cost. It is necessary, therefore, to examine and place values on all of the materials and energies that enter and leave the previously established process boundaries, and to determine other operating costs (e.g., maintenance costs) that cannot be expressed in terms of inputs.

The process economics are not always easily evaluated. For example, it may be very difficult to assign a value to improved product quality. It may be necessary in one instance to improve quality in order to meet the quality characteristics of a competitive product, or in another instance, to use it in advertising as a means of increasing sales. In either case, the designer will have to place some arbitrary value upon improved quality.

The process objectives in the control-system design should be expressed explicitly so that control actions taken by the digital control system can be based continuously on their calculated effects on process economics. On the other hand, it may be that process economics are so straightforward that certain simplifications can be made and subsidiary operating objectives may be set up, such as maximizing process throughput or minimizing raw material costs. Further, a quick appraisal of the economics may disclose that the potential payoff for improved control of a given process is so small that there is no point in proceeding further with digital-system design.

3. Study process variables. These variables may be divided into three groups: (1) the independent variables, such as the raw material chemical properties and amounts available; (2) the operating and intermediate variables that serve to measure and control the state of the process or operation: temperatures, pressures, liquid levels, flow rates, chemical compositions, etc., at points in the process between the raw material and the end product; (3) the product variables, which determine the character of the end-product and must be controlled: octane number, density, viscosity, chemical composition, etc.

The general problem is to manipulate the intermediate variables so as to compensate for variations in the independent variables and still produce a product whose characteristics lie in a certain range as measured by the product variables. It is therefore very important to gather all available data on each of the process variables. Some of these data will be in the form of specifications, but most will be in the form of historical records showing past variability in operation of the process under study. It is also important to find out which process variables may be controlled directly by existing equipment or by the installation of new equipment, and to determine the range over which control may be exercised. If it develops that some critical control variable has a range too limited for optimum control, it may be necessary to explore the cost of increasing the control range.

4. Analyze equipment and operating procedures. The layout of the plant, maximum allowable temperatures and pressures, capacities of conveyor belts and pipes, nominal ratings of compressors, generators, etc., are all important. Their description serves, among other things, to delineate the process bottlenecks, and to indicate where excess capacity is available. Furthermore, a study of the existing control system will disclose what correlations between the intermediate and the product variables are presently employed to meet product and process specifications in the face of variations in the independent variables. A complete analysis will also reveal what actions should be taken under emergency conditions.

5. Determine process dynamics. The speed with which the process responds to changes in the independent and the intermediate variables subject to direct control is a very important aspect of any control-system analysis. Knowing this speed, it is possible to predict how the system will react to process changes. Data on system dynamics may be gathered from theoretical studies, from manufacturers' data, from analysis of operating records, and from plant experiments. The interaction between computer speed and process dynamics will be less severe if the computer output adjusts the set-point of a conventional controller rather than controlling a process variable directly.

6. Analyze plant instrumentation. Finally, the system designer must collect information on measurements and measuring equipment. He should determine, if possible, the accuracy of the equipment that supplied him with the operating records so that he can judge whether a variability in a parameter recorded on a certain day, for example, is a significant variation or one which may be ascribed to an error in the measurement. An investigation must also be made of the accuracy and dynamic characteristics of whatever new instruments may be employed in a new control system. In the beginning, it is of course not apparent which of the many process variables should be measured, and therefore what new instruments will be necessary and should be investigated. This part of the investigation will be guided as time goes on partly by the parameters that appear to be important, and partly by the ease or difficulty with which various parameters can be measured.

System design

When the system analysis is complete, the designer should have in mind a complete picture of the economics, physical and chemical characteristics, and existing control of the process. He must now organize and analyze his data, and synthesize or invent a control system. Some of the steps in organizing and analyzing data will now be described.

1. *THEORETICAL ANALYSIS OF PROCESS.* A theoretical and fundamental approach to the process under study often makes it possible for the designer to derive approximate relationships among some of the important variables. Such a derivation may necessarily be based on a very much simplified model of the process, in which the effects of many variables are completely ignored.

2. *CORRELATION OF VARIABLES.* Unfortunately, most processes are so complex as to defy complete theoretical analysis. Therefore, when analysis and approximation have yielded as much information as possible, it is necessary to return to the operating data and records that have been collected and to try to derive from these data relationships between the independent and intermediate variables and the product variables. The methods and procedures of mathematical statistics must be brought to bear upon the data, and some correlations between various operating variables must be established. Often, because of the errors in measuring devices, the large number of variables that actually affect the process, and the incompleteness of process data available, it is not possible to obtain a very good fit between the data and an analytic curve. Nevertheless, any correlation at all will serve as a basis for control, and will in general provide a better basis than the rules of thumb employed by human operators. Furthermore, after the digital-control system is installed, it may be used to gather more accurate and more detailed data that may serve as a basis for improved correlations.

3. *INVENTION.* At some point along the way, when the process is fairly well understood and the importance of the various process variables has been established, the designer must invent a control system. This consists of choosing an appropriate set of variables to be measured and controlled, and determining the relationships and rules connecting these variables, provided that:

a. Process objectives are met.
b. The chosen variables can be measured and controlled with existing equipment.
c. The operation of the control system and the process results in a total system that is dynamically stable.
d. None of the limitations on equipment capacity is exceeded.

The designer will often be able to suggest several ways (conventional, digital, or both) of improving control over the process, all varying in degree of complexity and expense. It will be necessary to evaluate the costs and payoffs for each of these prospective solutions to the control problem.

4. *SPECIFICATION OF SYSTEM COMPONENTS.* When the general plan for the control system has been laid out, the designer is in a position to fill in details and to examine, evaluate, and overcome the obstacles that stand between his initial idea and the completed system.

Assuming that a digital control system is found to be the most economical solution to the control problem, the designer must specify computer speed, accuracy, number and kind of input and output channels, and the functions that the computer must perform. If the computer is to be connected directly to input analog-to-digital transducers, the transducers and analog-to-digital converters must be specified and the details of their connection to the computer worked out. If the computer is to control the set-point of a conventional pneumatic controller, the necessary components must be described. If it is to read numerical data entered by an operator, and print out data for monitoring by supervisor, the type and operating speed of input and output devices must be shown.

5. *SYSTEM OPERATION.* The system synthesis is complete only when the designer has described in detail exactly how the various system components operate together, and what procedures (if any) the human operator must follow. For a digital-control system, the designer must specify both the computer program and the operator functions for four different modes of operation: start-up, shutdown, normal operating conditions, and emergency operating conditions. The computer program determines the sequence in which input data are read; the methods used to interpret input data; the calculations employed to relate input and controlled variables; the sequence of adjustments made in controlled variables; the kind and amount of information printed out; the methods and procedures employed by the computer to check the calibration of an output device; and the methods used by the computer to check its own operations.

For the operator, the designer must specify a reaction for each anticipated computer output. Ordinarily, the operator may do nothing more than survey process operation by keeping an eye on instruments and computer output. Under certain conditions, the computer will print out data which require special action to be taken by the operator. Under other circumstances, the computer may detect an error in itself or in some instrument associated with it and may print out an alarm to the operator together with some indication of what has gone wrong. Depending on what the trouble is, the operator may then override computer operation and take charge of the process himself, or request maintenance for instrument or computer, or both. In addition to preparing for these anticipated difficulties and situations, the designer must state some general rules indicating under what conditions the operator should override the computer control on his own initiative.

DESIGN CASE HISTORY

A simplified and idealized application will illustrate some of the problems that arise in system analysis and design and will show the results that digital control can provide. A chemical process, Figure 1, consists of a reactor, a heat exchanger, a catalyst-separating system, and a fractionating tower. The raw material enters at point 1 with flow rate f_1 and proceeds through a heat exchanger which increases its temperature. The material at point 1 contains x_1 percent of the primary reactant, and $(1 - x_1)$ percent of an inert material that does not enter into the reaction. After the heat exchanger, the mixture enters the reactor where a catalyst is added at flow rate f_2. The reaction is exothermic.

The hot product leaves the reactor, passes through a heat exchanger where it is cooled and the reactor feed is heated, and enters the catalyst separator. After removal of the catalyst, the remaining material, consisting of inert substance, the product, and that part of the reactant not converted to product, passes point 2 and enters a fractionating tower. Here the product is separated from the other components. The product leaves the process at rate f_3.

The graphs of Figure 2 indicate the relative amounts of the various components at the two process points. The process boundaries will be taken to be those indicated in Figure 1. A study of the relationship between this process and the rest of the operation of the plant discloses the following boundary conditions for the study: (1) Incoming material is available at instantaneous flow rate f_a, and contains x_1 percent of reactant. Both of these quantities are independent variables that may vary over wide ranges. Often there is more of this incoming material than the reactor can use, and whatever is not used will be employed elsewhere in the plant. (2) Product-flow rate f_3 can vary over a wide range without effect on the rest of the plant.

The objective is to obtain maximum operating profit from the operation of the unit. It will be assumed that maintenance costs are constant, unaffected by operation of the process. For this reason and because in general

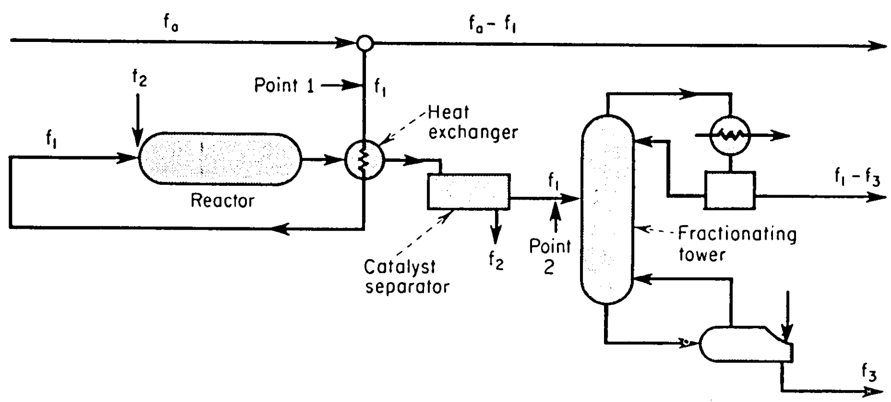
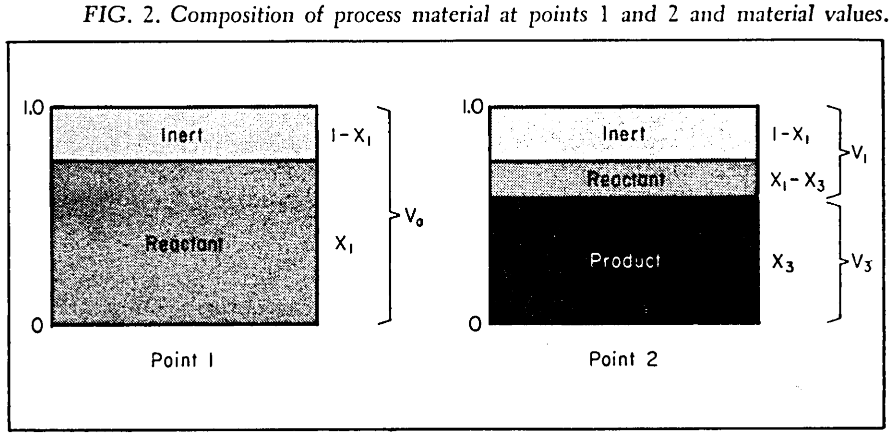


FIG. 1. Block diagram of chemical process on which example problem is based.

FIG. 2. Composition of process material at points 1 and 2 and material values.



the operation of the unit from one minute to the next does not affect its operation in the future, the act of maximizing total operating profit is equivalent to maximizing the instantaneous profit derived from the unit. An expression for the profit follows:

$$P = f_1x_3v_3 + f_1(1-x_3)\,v_1 + (f_a-f_1)\,v_a - f_av_a - f_2v_2 - b$$
$$= f_1x_3(v_3-v_1) - f_1(v_a-v_1) - f_2v_2 - b \quad (1)$$

where x_3 = weight percentage of desired product at point 2
f_a = flow rate of incoming material
f_1 = flow rate of material at points 1 and 2
f_1x_3 = flow rate of product at point 1

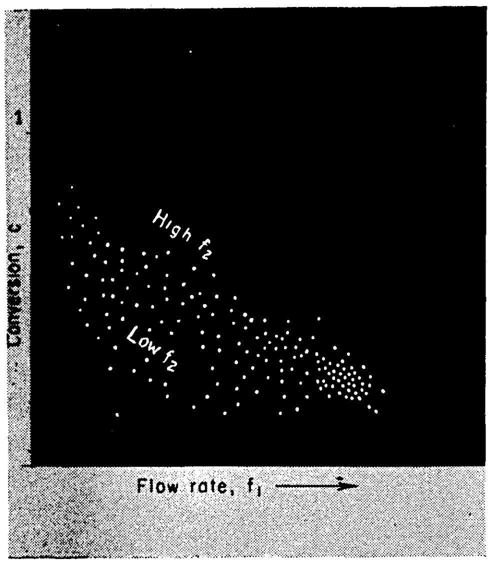


FIG. 3. Conversion as a function of flow rate f_1, shows effects of catalyst flow rate f_2.

v_3 = value of desired product at point 2
v_1 = value of that material at point 2 which is not product
v_a = value of raw material, if not processed in this unit
f_2 = flow rate of catalyst
v_2 = loss in value of catalyst in process
b = constant operating costs

The effect of heat losses on cost is negligible. The catalyst, on the other hand, is very expensive and is one of the major costs of operation.

The independent variables are the incoming flow rate f_a and x_1, not susceptible to control. The only product variable is x_3, the concentration of the desirable product in the output of the catalyst separator. The intermediate variables are f_1 and f_2, the flow rates of raw material and catalyst into the reactor, respectively. Other important intermediate variables are reactor temperature and pressure, catalyst-separator level, and fractionating-tower operating conditions. In the existing installation, the catalyst separator provides the bottleneck on unit capacity and determines the upper limits on the intermediate variables f_1 and f_2. The total flow into the separator may not exceed f_{max}, and the catalyst flow rate may not exceed f_{2max}. Or,

$$f_1 + f_2 \leq f_{max}$$
$$f_2 \leq f_{2max} \quad (2)$$

The operation of the reactor is generally specified by quoting a "conversion" for the reactor, defined as the ratio of the amount of desired product at point 2 to the amount of that raw material at point 1 which theoretically could have been converted entirely to desired product. If this is expressed as $c = x_3/x_1$, x_3 can be replaced in Equation 1 by cx_1, obtaining

$$P = f_1cx_1(v_3-v_1) - f_1(v_a-v_1) - f_2v_2 - k \quad (3)$$

In Figure 3, conversion c is plotted as a function of f_1 from data collected in past operating experience with this unit. Each point represents a daily average of conversion and input flow, which may fluctuate widely over the period of a day.

Conversion is known to be a function of reactor temperature and pressure, catalyst flow, and feed flow. The temperature and pressure variations are such that ideal operation is clearly at the maximum safe temperature and pressure ratings of the process equipment. Conversion is also known to increase with catalyst-flow rate, as indicated in Figure 3.

In the existing system, reactor temperature and pressure are controlled at their desired maximums by conventional recorders and controllers. The separation of feedstock flow into reactor feed and by-pass feed, and the ratio of catalyst-feed rate to reactor-feed rate is controlled by an operator, who adjusts the two flow rates compatible with process limitations and with the established boundary conditions.

The dynamics of the process (the variation in output parameters as a function of time with variations on the independent and operating variables) are largely unknown. Experience indicates that a change in flow at the input to the reactor reaches its final value at the fractionating-tower feed about 15 min later, and at the fractionating-tower output about 45 min later.

The data collected and plotted in Figure 3 are based on a laboratory analysis of samples collected three times a day at the process. The flow f_1 in Figure 3 is an average value of flow over the same time interval for which the average conversion was calculated. To each point in Figure 3 there is also assigned a value of catalyst flow rate f_2 and this is also obtained by averaging that flow over the entire day. An investigation of available equipment for analyzing continuously the streams at points 1 and 2 indicates that an instrument can be found to measure x_1 at point 1. However, no instrument is available to continuously and accurately measure product percentage x_3 at point 2, and the presence of the product makes it impossible to measure the reactant percentage at point 2.

System synthesis

A theoretical analysis of the kinetics of the reaction and of the relationship between all process variables proves impossible. However, a careful study of the available operating data on conversion and on the relationship between feed-flow rate, catalyst-flow rate, and conversion makes it possible to establish certain correlations between these variables and to write a mathematical expression relating them that provides the best possible fit to available operating data. In the equation below expressing this mathematical relationship, constants k_1, k_2, and k_3 are chosen to make this curve best fit the data of Figure 3:

$$c = \frac{k_2f_2}{1 + k_3f_2}\, e^{-k_1f_1} \quad (4)$$

This equation for c is plotted in Figure 4, wherein the maximum values for catalyst-flow rate and for combined catalyst- and feed-flow rates are also indicated.

Unfortunately, Equation 4 does not exactly describe the effect of all variables on conversion. In particular, there is reason to believe that unpredictable and unidentifiable factors tend to shift the conversion curves from one day to another and even from one eight-hour period to another. A typical set of operating points taken on two different days is shown in Figure 5, and the curve of Equation 4 is fitted to each set of points by suitably choosing parameters k_1, k_2, and k_3.

Reviewing his collection of data at this point, the system designer can make the following statements: the objective of any control system is to maximize the operating profit function P of Equation 3; in Equation 3 the initial percentage of reactant in the feed (x_1) is an independent variable beyond control; the conversion c is a function of f_1 and f_2 whose general form is indicated by Equation 4; the two flow rates f_1 and f_2 are the intermediate variables subject to control; the physical characteristics of the process equipment set upper limits on these flow rates, Equation 2.

The control problem is now specified in enough detail so that the designer can see how it might operate. The data of Figure 3 must be used

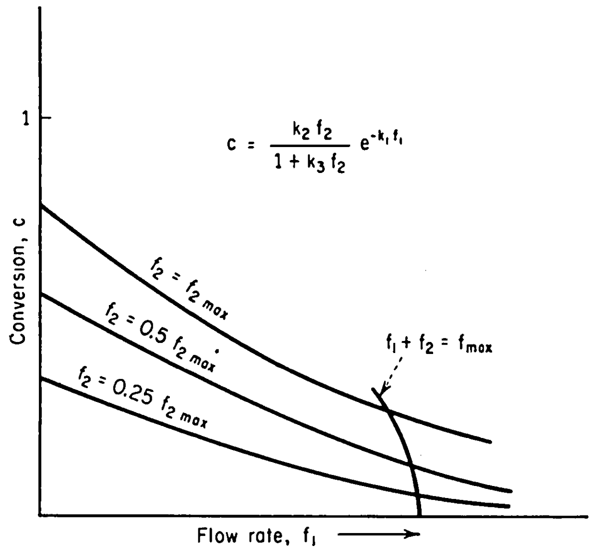


FIG. 4. Curves of conversion vs. flow rate f_1 for three specific catalyst flow rates f_2.

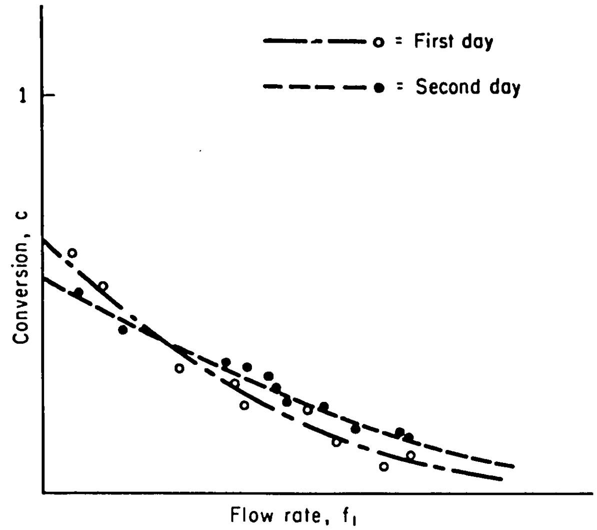


FIG. 5. Relationship of conversion and flow rate on two different days for constant f_2.

to evaluate constants k_1, k_2, and k_3 of Equation 4 and provide a good fit of the curves to that data. With these constants determined, there are particular values of f_1 and f_2 which maximize the profit of Equation 3 for every value of reactant concentration x_1 (see Equations 5 and 6 below). In its simplest form, the control system must therefore measure x_1; must calculate the appropriate values of f_1 and f_2; and must adjust the corresponding flow-control valves in the process.

The control system will, however, be complicated by several other factors. First, it may be that there is not enough feed available to obtain maximum theoretical profit from the operation. Second, the optimum values of f_1 and f_2 may be such that the capacity of process equipment is exceeded. Finally, the control system must continually make sure that the functional relationship it uses to relate conversion with catalyst and feed flow rates, Equation 4, accurately represents plant conditions at the time.

Computer control. To control the process, a computer must first find the maximum value for P of Equation 3, subject to the restriction that conversion c is a function of f_1 and f_2 as shown in Equation 4. Substituting Equation 4 in Equation 3, then taking the partial derivative of P with respect to f_1, and setting it equal to zero,

$$c\,(1 - k_1 f_1) = \frac{v_a - v_1}{x_1\,(v_3 - v_1)} \qquad (5)$$

Similarly, setting the partial derivative of P with respect to f_2 equal to zero,

$$\frac{f_1 c}{f_2(1 + k_3 f_2)} = \frac{v_2}{x_1(v_3 - v_1)} \qquad (6)$$

The reactant feed concentration x_1 of Equations 5 and 6 is measured every time new values for f_1 and f_2 are to be determined. All of the other constants in Equations 5 and 6, and Equation 4 (which relates conversion to the unknown quantities) are known. Therefore, the computer must solve Equations 5 and 6 simultaneously for the flow rates f_1 and f_2, after substituting c from Equation 4. The result will be the optimal values for flow, which will be called f_{10} and f_{20}.

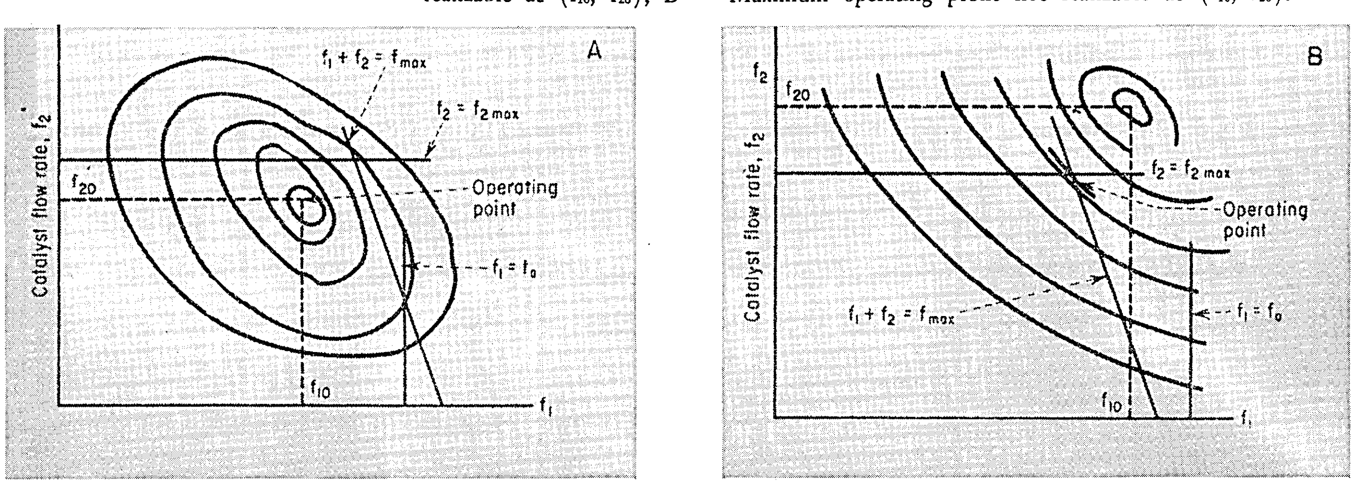
The computer must now determine whether the optimal flow rates are obtainable in practice, and must determine what flow rates should actually be used if they are not. The effect of process limitations is most easily understood with reference to Figure 6, wherein contours representing equal values of P in the f_1 f_2 plane are plotted. Because of the nature of Equations 3 and 4, there is only one point of maximum profit, represented by the coordinates (f_{10}, f_{20}). Equipment limitations are represented by the straight lines,

$$f_2 = f_{2\max} \qquad (7)$$

$$f_1 + f_2 = f_{\max} \qquad (8)$$

and the feed-availability limitation is

FIG. 6. Plots of constant profit in the f_1 f_2 plane. A — Maximum operating profit realizable at (f_{10}, f_{20}); B — Maximum operating profit not realizable at (f_{10}, f_{20}).



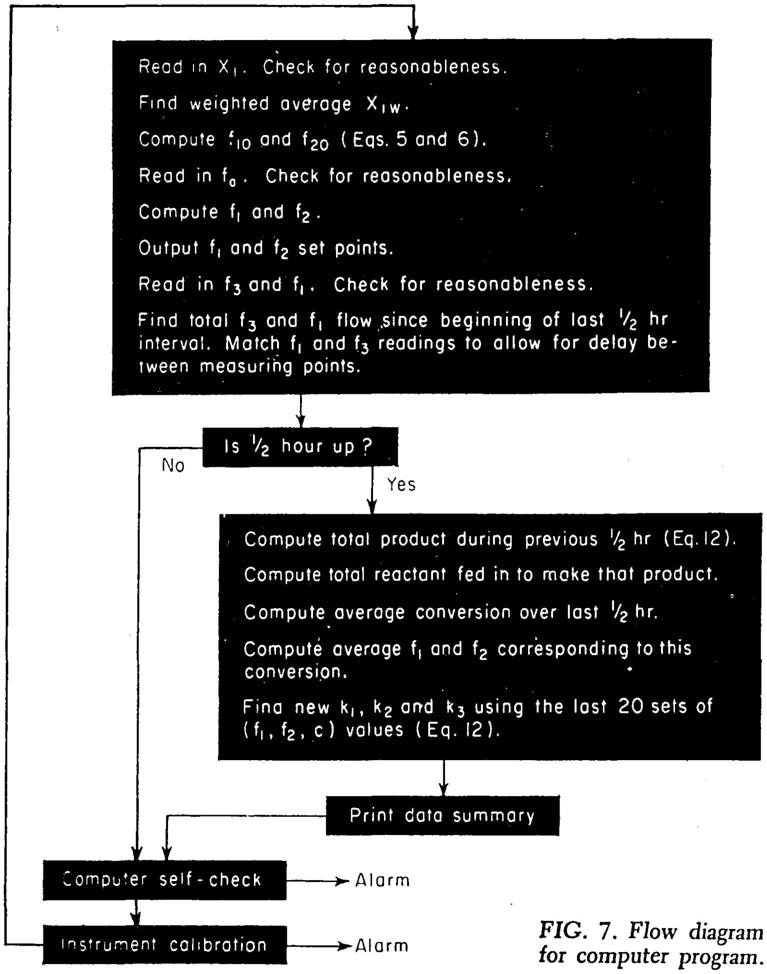


FIG. 7. Flow diagram for computer program.

represented by the single straight line

$$f_1 = f_a \quad (9)$$

As long as the coordinates of the maximum-profit point lie to the left of and below the lines defined by Equations 7, 8, and 9, the process flow rates f_1 and f_2 should be set at the optimum values f_{10} and f_{20}, Figure 6A. However, if any one of the three inequalities of Equations 2 and 10, namely:

$$f_2 \leqq f_{2max} \quad (2)$$

$$f_1 + f_2 \leqq f_{max}$$

$$f_1 \leqq f_a \quad (10)$$

is not satisfied, the optimum flow rates cannot always be used. Note that the lines defined by Equations 7 and 8 are fixed, but that the line defined by Equation 9 shifts from time to time as feed availability varies. Furthermore, the coordinates of the optimum point will also shift as x_1 and conversion equation constants k_1, k_2, and k_3 vary.

Some procedure must be specified for enabling the computer-control system to find the best settings for f_1 and f_2 when one or more of the inequalities of Equations 2 and 10 are not satisfied, as in Figure 6B. The procedure to be followed may be based on the fact that, for the simple profit function of Equation 3, the realizable maximum profit will always lie on one of the lines, Equations 7, 8, or 9, if one or more of Equations 2 and 10 are not satisfied. With this in mind, the following procedure may be recognized for finding the proper operating point when the optimum operating point cannot be reached.

(1) If $f_a \geqq f_{max}$:
Find the maximum value of P from Equation 3 along the line $f_1 + f_2 = f_{max}$, with $O \leqq f_2 \leqq f_{2max}$.
Find the maximum value of P along the line $f_2 = f_{2max}$ with $O \leqq f_1 \leqq f_{max} - f_{2max}$.
Compare these two values of P. The process flow rates should be set at the f_1 and f_2 coordinates corresponding to the larger P.

(2) If $f_{max} - f_{2max} < f_a < f_{max}$:
Find the maximum value of P along the line $f_1 = f_a$ with $O \leqq f_2 \leqq f_{max} - f_a$.
Find the maximum value of P along the line $f_1 + f_2 = f_{max}$ with $f_{max} - f_a < f_2 \leqq f_{2max}$.
Find the maximum value of P along the line $f_2 = f_{2max}$ with $O \leqq f_1 < f_{max} - f_{2max}$.
Compare these three values of P. The process-flow rates should be set at the f_1 and f_2 coordinates corresponding to the largest P.

(3) If $f_a \leqq f_{max} - f_{2max}$:
Find the maximum value of P along the line $f_1 = f_a$ with $O \leqq f_2 \leqq f_{2max}$.
Find the maximum value of P along the line $f_2 = f_{2max}$ with $O \leqq f_1 \leqq f_a$.
Compare these two values of P. The process flow rates should be set at the f_1 and f_2 coordinates corresponding to the larger P.

When the digital control system has calculated the appropriate best values for f_1 and f_2, and has taken action to assure that the chosen flow rates are adjusted to the process, it must modify the constants of Equation 4 so as to make sure that the resulting curve is as accurate a prediction as possible of the relationships between conversion, f_1 and f_2. The digital control system does this by taking a measurement of conversion periodically, and relating the measured value to previously set values for f_1 and f_2, taking into account whatever delay exists in the process between the time a flow-rate adjustment is made at the reactor input, and the time the resulting change in conversion is measured. The digital-control system will be required to keep a record of the average of such measurements over the past 10 hours. The computer thus has a list of 20 sets of three numbers each (f_1, f_2, and c) and it must find k_1, k_2, and k_3 such that these 20 points provide a best fit for the resulting curve. If the 20 points are labeled c_i, f_{1i}, f_{2i}, ($i = 1, 2, 3, \ldots 20$) then k_1, k_2, and k_3 may be evaluated by minimizing the following function with respect to the three variables.

$$D = \sum_{i=1}^{i=20} \left[c_i - \frac{k_2 f_{2i}}{1 + k_3 f_{2i}} e^{-k_1 f_{1i}} \right]^2 \quad (11)$$

This is closely related to the self-checking procedure proposed by Case Institute*.

It will be observed that the curve-fitting operation of Equation 11, which is designed to take into account slow and unpredictable changes in the conversion-flow relationship, will be most effective only if fairly wide variations in f_1, f_2, and c occur over a period of 10 hours. Putting it another way, it is meaningless to fit the curve of

* Described in "Process Automation", Report. 1, 1954-56, Case Institute of Technology, September 1956; "Integration of the Computer In Process Control", D. P. Eckman, 11th Annual Instrument-Automation Conference, September 1956.

Equation 4 to a set of 20 points all clustered together in a small area of Figure 3. Such a cluster would occur if, over a period of 10 hours or more, there was little or no variation in x_1, and f_a did not get lower than f_{10}.

One way to avoid this cluster is to require the control system to perturb the process occasionally, if process conditions do not themselves cause a perturbation. In other words, the variables f_1 and f_2 may be set at arbitrary points some distance from their ideal values long enough for the conversion corresponding to those flow rates to be measured. A probably better way is to let the curve-fitting operation depend not only on the 20 most recent process points, but also on previous values of k_1, k_2, and k_3.

The control system whose rough characteristics are now emerging clearly meets process objectives and no limitations on equipment capacity are exceeded. It now must be explained how the necessary process variables are to be measured and controlled, and how the dynamics of the process are to be taken into account.

Specification of components

The principal process variables which must be measured are f_a, the available feed rate; x_1, the percentage of the reactant in the feed; and conversion, which may be computed if x_1 and x_3 are known. There is no difficulty involved in measuring f_a. Flow measuring devices are widely used and are cheap and reliable. The measurement of stream composition is more difficult. There is a continuous analytical instrument available which can measure the concentration of the reactant in the feed stream, but no instrument is available to measure product concentration in the fractionating-tower feed (point 2) or to measure the remaining reactant concentration in that feed.

Product concentration x_3 can be found by measuring the flow rate of material into the fractionating tower and the flow rate at the tower bottom, and dividing the second by the first. This rough value for x_3 may be refined somewhat by noting that the fractionating tower is normally operated so that some fixed percentage of the product appears at the tower top, regardless of tower-feed composition. If, for example, this particular tower is operated so that 5 percent of the distillate-flow rate is product, while approximately 90 percent of the residue is product, then x_0 can be found as follows:

$$f_1 x_3 = 0.05\,(f_1 - f_3) + 0.9 f_3$$

$$x_3 = 0.9 \frac{f_3}{f_1} + 0.05 \qquad (12)$$

where f_3 = flow rate of product from fractionating system, and

$$f_1 = \text{tower-feed rate}$$

So far, no mention has been made of the frequency with which measurements and computations are to take place. It is now necessary to specify these frequencies and to discuss how they will react on the control system and on the process. First, adjustments will be made in f_1 and f_2, as often as it is possible to measure the reactant concentration, and to carry out the calculations necessary to find f_1 and f_2. These calculations are not dependent upon measurements made later in the process, and there can therefore be no instability due to feedback. The modifications to Equation 4, on the other hand, will be carried out much more infrequently and will be based upon data accumulated over a long period of time. Specifically, one value of conversion will be obtained every half-hour by averaging instantaneous samples of flow rates and of reactant percentages over that period of time. To each value of conversion so obtained, appropriate average value of f_1 and f_2 will be determined. These three numbers, together with the corresponding numbers for the 19 previous half-hourly intervals, are employed in Equation 11 to determine k_1, k_2, and k_3. Adjustments in these k values thus take place very slowly, being affected only by data obtained over a long period of time. It is at this point that feedback is introduced into the control system. However, the feedback is smoothed and delayed to such an extent that it will not upset the dynamic equilibrium of the process.

With the control system thus roughly outlined, it is possible to evaluate cost and potential payoff. The cost depends upon the cost of the computer, analog-digital converters, and associated instrumentation, and the payoff depends entirely on a comparison of the control actions taken by operators in the past with the results which would have been obtained if the digital-control system had been operating on the same feeds, or on the feeds expected after the installation of such a control system. For large flow rates and valuable materials, a deviation from optimum control for one hour may result in \$100 of lost profits. The exact dollar loss depends, of course, on how peaked the profit curve is at its optimum point and how far away from that point the process operates. Depending on the parameters involved, the profit curve may have a very flat peak, so that the system is fairly insensitive to variation in f_1 and f_2. This sensitivity must be evaluated in determining payoff.

The principal control system components required are a new instrument for the measurement of x_1, the reactant composition, and the digital control computer itself. The system designer's study of the required computer program must be extensive enough to allow him to specify computer precision, speed, and memory

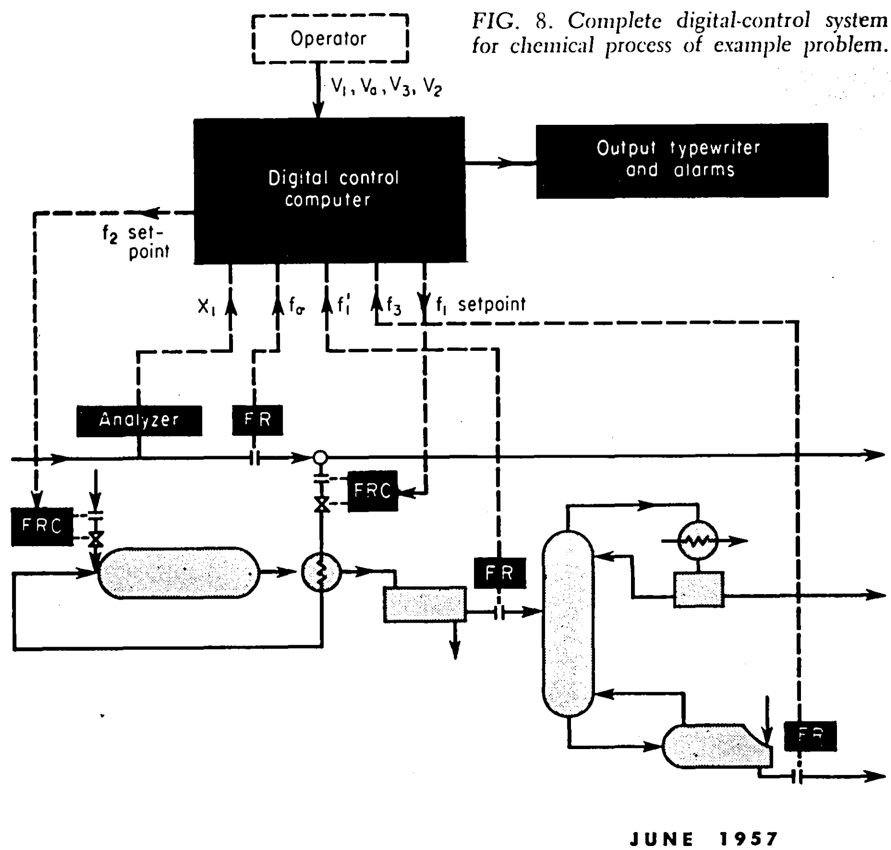


FIG. 8. Complete digital-control system for chemical process of example problem.

capacity required. The number and type of input and output transducers and lines must also be specified.

System operation

A flow diagram for the computer program is shown in Figure 7, and the entire control system is displayed in Figure 8. Note that care must be taken in evaluating measurements made on the process to take the process delays into account. For example, the product concentration x_3 of Equation 12 is evaluated by employing two readings, f_3 and f_1, which occur 45 min apart. This means that every time this quantity is evaluated, the latest reading of f_3 is compared with the value of f_1 measured 45 min earlier and stored in the computer. At that same time, the latest measurement of f_1 is stored away for use 45 min later. Note that the computer checks itself and calibrates the continuous analytical instrument used to measure x_1 during every computer cycle. Furthermore, it prints a summary of the pertinent operating data every half-hour. This summary includes the average values for x_1, f_1, f_2, x_3 c, and f_a. In addition, it may be desirable to print out the maximum and minimum of values for f_a during the previous half-hour.

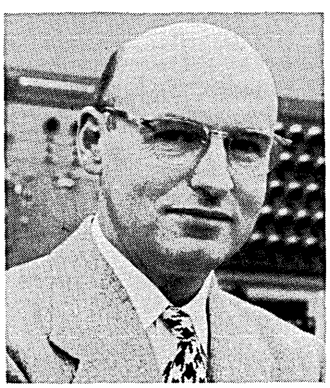
The instrument readings taken at various points in the process are important to the correct control of the process, and instrument malfunctions can and do cause serious troubles in process control. In a conventional process, the operators are told what to look for on the control panel in the way of instrument failures. These same instructions can be given to the computer, which will print an alarm warning the operator when some failure occurs.

The rules for detecting a failure depend on the characteristics of the instrument being checked and upon the characteristics of the quantity being measured. For example, it may be that the feed for the unit is varying in composition almost continuously, but that reactant concentration never is less than 40 percent or greater than 60 percent. To check the operation of the continuous analytical instrument, then, the computer might compare each reading for x_1 with the previous two readings, and print out an alarm if all three of them are the same, since it would be very unlikely that three sequential readings would be identical. The computer might also check each reading to see that it lies within the range of 40 to 60 percent, and print out an alarm when this range is exceeded. The alarm would identify the suspect instrument, and would indicate what seemed to be the trouble with it. These instrument checks are indicated in Figure 7 as "checks for reasonableness"

Computer malfunctions detected by the program also cause an alarm to be given. The operator must then disconnect the computer outputs so that controller set-points are set manually; the operation of the process then deteriorates to the conditions which existed before the introduction of a digital-control system. The operator must also be on the lookout for computer errors which are not detected by the computer itself. The computer may, for example, print out nonsense; it may try to adjust process variables to impossible values; it may try to read information through the input device for no reason; or it may stop unexpectedly. Each of the possibilities must be anticipated, and their possible effect on the control system evaluated and compensated for by the system designer.

Several additional comments must be made about the proposed control system. A practical control system would probably control variables other than the flows f_1 and f_2. There might, in general, be some advantage to be gained from controlling reactor temperature and pressure, or fractionating-tower conditions, and the effect of these variables can be reflected in a profit equation similar to Equation 3.

The control system should be arranged so that the effect of other process variables on conversion can be analyzed and logged as time goes on. If the effect of some other variable—the character of the catalyst or the content of the inert part of the feed—does have an effect, that effect can be incorporated into the control system by providing the appropriate input data and rewriting the computer program to use that data.

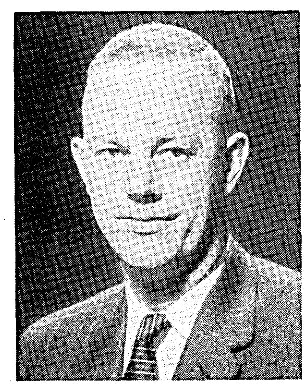


Eugene M. Grabbe

We rank one of the authors in the "needs no introduction" category. He is Gene Grabbe, senior staff consultant on automation in the Computer Systems Div. of The Ramo-Wooldridge Corp. The editor of a brand new Wiley book (*Automation in Business and Industry*), Gene is both a CtE contributor and one of our consulting editors. Just a few months back, we sketched his life and career in a *Control Personality* (CtE, February '57, p. 23).

Gene's co-author Montgomery Phister Jr. is head of the Industrial Control Systems Section of R-W's Computer Systems Div. His work has centered about digital computers including logical design, maintenance techniques, scientific and business applications, and systems planning and analysis. The latter has prompted Monty to encourage the use of electronics in the automatic control of industrial processes.

Well-qualified scholastically for his field with BS and MS degrees in electrical engineering from Stamford University and a PhD in physics from Cambridge University, Monty has often been seen on the campus of UCLA in the role of a visiting assistant professor of engineering.



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Computer Control Systems

Data-Logging and Scanning Systems

Systems Engineering

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