Digital Control of Industrial Processes

CECIL L. SMITH

Louisiana State University, Baton Rouge, Louisiana*

The application of computers for controlling process units is now about ten years old. The applications have progressed from the experimental stages of early development to a well-established (economically speaking) control practice. This has not been without some anxious moments and a few outright failures. These have not been forgotten, but current successes are proving beyond any doubt that digital computers are capable of generating an attractive economic return on the investment required for their installation.

This paper has three objectives: first, to acquaint those outside the process industries of the general process control problem in order that they may appreciate some of the requirements imposed on a control computer; second, to describe the computer hardware normally considered for process control; third, to present the general philosophy of the real-time software systems required for process control.

Key words and phrases: industrial process control, digital control, process control, computer control, real-time systems, control systems, supervisory control, hierarchy control systems, computer-process interface, computer control software, computer control hardware

CR categories: 1.3, 3.22, 3.82

CONTROL

The Process Control Problem

Industrial processes for which successful computer control systems have been reported include blast furnaces, petroleum and petrochemical plants, paper machines, textile mills, etc. Each has its unique problems, so this discussion must be fairly general. In all of these processes, the variables are divided into these four categories, as illustrated in Figure 1:

- Manipulated variables. These are variables such as input raw material flow rate, steam pressure in a vessel, etc., whose values can be adjusted by the control system, whether analog (conventional) or digital.
- Disturbances. These are variables whose values affect the operation of the process but which are not subject to adjustment by the control system. Examples include composition of raw material, ambient air temperature, etc. Some variables in this category can be measured, while others cannot.
- Controlled variables. These are the variables whose values really measure the performance of the plant, and thus are those which the control system must keep at some target value (often called the set point). Examples include production rate, product quality, etc. The general control problem is to adjust the manipulated variables so as to maintain the controlled variables at their target values in face of disturbances. Some controlled variables can be measured directly, but some must be inferred from other measurements, a task at which digital computers far excel their analog counterparts.

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- Intermediates. These variables appear at some intermediate point in the process. The control system can often use them advantageously in determining what control action should be taken. Examples include temperature of a water jacket, composition of an intermediate stream, etc.

As a typical plant has several variables in each of the above categories, it is apparent that the control of process units is no simple matter. This is further complicated by the difficulty in deriving a mathematical model of the process from process characteristics. The problem in this regard is that the process characteristics depend, first, on the level of plant operation (i.e. the plant is usually highly nonlinear), and second, even at a constant operating level the plant's characteristics change with time (i.e. the plant is nonstationary).

Although complicating the job of installing the computer control system, these aspects are really the basic reasons such a sophisticated control system can be justified. The ability of the digital computer to collect large quantities of data, analyze it, and make logical decisions based upon the results makes it attractive for such applications.

Conventional Control Systems

Before delving into the characteristics of digital control systems, an appreciation of the conventional approach to process control is a helpful background [1.3, 1.4, 1.12, 1.15]. The basic control loop in conventional (analog) systems is the simple feedback loop illustrated in Figure 2. The value of the controlled variable is detected by a sensor or transmitter, e.g. a thermocouple for measuring temperature. This value is compared to the desired value or set point to generate the error. The control law generates a change in the manipulated variable so as to drive this error to zero. The controller output is imposed upon the process by an actuator, which is an automatic positioning valve in most cases.

The control law commonly used is the proportional-integral-derivative (PID) relationship or some simplification thereof. That is, the manipulated variable $m(t)$ is related to the error $e(t)$ by the equation

$$m(t) = K_c\left\{e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right\} + m_R, \qquad (1)$$

where

K_c = proportional gain,
T_i = reset or integral time,
T_d = derivative time,
m_R = reference value at which the control action is initialized.

The adjustments K_c, T_i, and T_d appear generally as adjustments on the rear of the controller. The selection of their proper values is normally a trial-and-error procedure called "tuning," although some systematic approaches have been suggested [1.12, 3.13, 3.48, 3.54, 3.64, 3.70–3.72, 3.80, 3.81, 3.83].

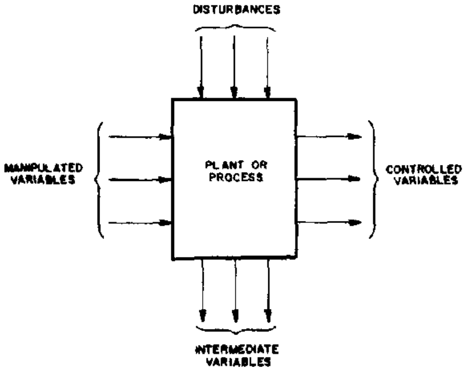


FIG. 1. General representation of a process

In well over 75 percent of the applications, only the proportional-integral (PI) terms are used, primarily because of the difficulty of tuning the general PID (or three-mode) controller.

In a typical plant, there may be anywhere from a few of these devices to upwards of a hundred or more. Until around the late 1950s, these devices were invariably pneumatic (operated on air pressure). Aside from being much more reliable than their vacuum-tube electronic counterparts, they had the added advantage of safety when used in areas in which explosive gases might be encountered. Only with the introduction of solid-state electronic controllers in the late 1950s have pneumatic controllers gradually begun to be replaced.

No matter whether pneumatic or electronic, conventional analog control systems basically suffer from inflexibility. There must be almost a one-to-one correspondence between control loop functions and hardware to perform these functions. This places several burdens upon the designer of the control system: (a) his strategy must be such that it can be implemented with analog hardware; (b) subsequent modifications of the control strategy require modifications of the analog hardware.

In the mid-1950s, control system designers began to look toward the digital computer as a means for circumventing these problems. Virtually any control strategy is

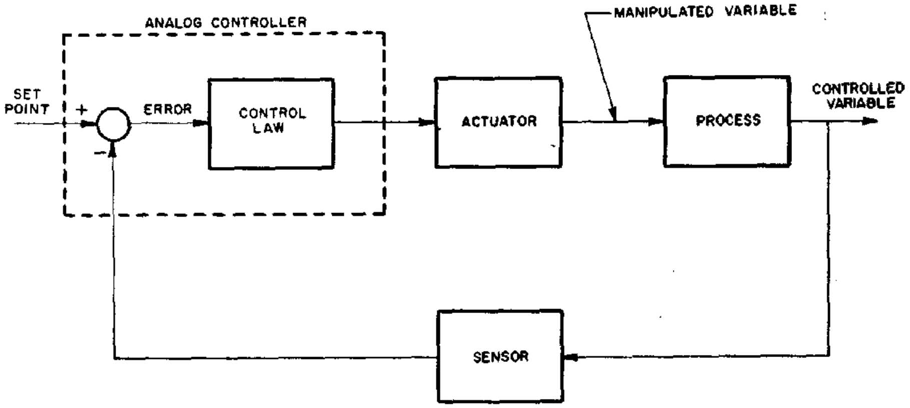


FIG. 2. Basic conventional feedback control loop

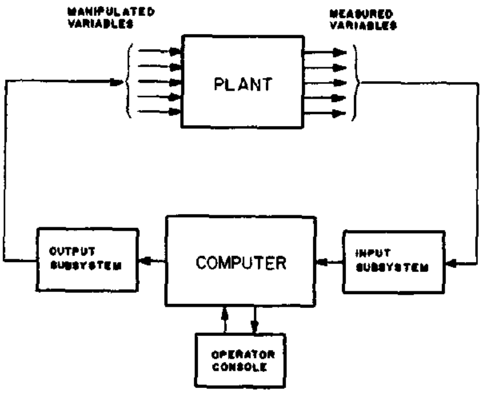


FIG. 3. Direct digital control

programmable, and most modifications in the strategy are simply program changes.

There have been two distinct approaches to digital control—direct digital control versus supervisory digital control [1.7, 1.14, 2.11, 2.19]. Although most control systems are combinations of the two, they shall be treated distinctly here.

Direct Digital Control

In direct digital control [1.14, 2.6–2.8, 2.12, 2.16, 2.20, 2.24, 2.25, 2.28] the computer calculates the values of the manipulated variables (e.g. valve positions) directly from the values of the set points, controlled variables, and other measurements on the process. The decisions of the computer are applied directly to the process, and hence the name direct digital control. This control arrangement is illustrated in Figure 3.

As the values of the manipulated variables are calculated by the computer, the conventional three-mode controllers described above are no longer needed. Their functions are instead performed by the equations, called algorithms, by which the computer calculates the manipulated variable from the set point and controlled variable. An example of a control algorithm is the discrete (finite difference) equivalent to eq. (1) for the continuous controller [3.4, 3.10, 3.12, 3.14, 3.17, 3.19, 3.22, 3.28, 3.65]:

$$m_n = K_c e_n + (K_c T/T_i) \sum_{i=0}^{n} e_i + (T_d K_c/T)(e_n - e_{n-1}) + m_R, \tag{2}$$

where

m_n = value of manipulated variable at the nth sampling instant,

e_n = value of the error at the nth sampling instant,

T = sampling time.

Other parameters are defined as before. This equation is called the position form of the control algorithm, as its result is the actual value of the manipulated variable, typically a valve position. If eq. (2) is written for m_{n-1} and subtracted from eq. (2) as given above, the result is

$$\Delta m_n = K_c(e_n - e_{n-1}) + (K_c T/T_i)\, e_n + (T_d K_c/T)(e_n - 2e_{n-1} + e_{n-2}), \tag{3}$$

where $\Delta m_n = m_n - m_{n-1}$ is equal to the change in the manipulated variable; hence the name "velocity algorithm." The significant difference between eqs. (2) and (3) is that eq. (3), the velocity algorithm, does not contain the term m_R, the value of the manipulated variable when the loop is placed on automatic (i.e. calculations are begun). If eq. (2) is used, the computer must be able to read the valve position to insure a smooth transition from manual to automatic, called "bumpless transfer." Using eq. (3) accomplishes the same objective without having to read m_R.

Being the digital equivalent of the three-mode analog controller, the above algorithms are used in by far the majority of the applications. The adjustment or tuning has been investigated extensively [3.4, 3.15, 3.49, 3.50, 3.57–3.60, 3.74]. There have been other algorithms proposed, some of which exceed the performance of the above algorithms. A field of mathematics known as z-transform theory has been developed especially for digital control systems [1.5, 1.6, 1.8, 1.11, 1.13, 1.16, 1.17, 3.35, 3.43, 3.73]. If the system being controlled can be described reasonably well mathematically, algorithms can be designed to give almost any desired performance.

One of the prime control considerations in DDC is selecting the sampling time. In general, the performance of the system improves as the sampling time is decreased. However, this increases the computational load on the digital processor, eventually limiting the number of control loops a given processor can service. There are no hard-and-fast rules for selecting sampling times, one rule of thumb being one second for flow loops, five seconds for pressure loops, and twenty seconds for temperature loops [2.1].

One of the first incentives suggested for DDC systems was economic savings. The basic idea was that since one computer could provide the same functions as several analog controllers, there must be some point at which the cost of these several analog controllers would equal the cost of the digital system. Some early estimates on the number of loops to be replaced ranged as low as fifty, but this unfortunately was not proven to be correct. Two problems seemed to have been underestimated:

—Programming costs. With no prior experience and without DDC software packages or proven monitors, the programming effort far exceeded that anticipated.

—Backup hardware. This problem stems from the fact that operating personnel must be able to exercise effective control over the plant in event of total computer failure. In many cases this backup was a complete analog system, thus eliminating any hardware savings.

In regard to the question of reliability, the first Users' Workshop on Direct Digital Computer Control [2.1] indicated that a computer availability of 99.95 percent (translates into about four hours downtime per year) would be required for DDC. As this downtime included diagnosis and repair of the problem, it is obvious that the machine should be easily repaired as well as dependable. This consideration has promoted plug-in modules and retarded the trend toward compact machines. In case of computer failure, the system is normally designed so that all outputs are frozen at their most recent valid values. This should occur for a single loop whenever a component fails as well as for the total system when the computer fails.

Current thoughts seem to be that DDC systems simply cannot be justified on the basis of savings in analog hardware. Instead, the justification must come from the application of control techniques that are either impractical or impossible to implement with analog hardware. Such techniques include:

1. *Compensation of process variables.* A prime example is correcting gas flow readings for pressure and temperature changes.

2. *Feedforward control* [1.12, 1.15, 3.9, 3.21, 3.32, 3.52, 3.67]. As illustrated in Figure 4(a), the feedforward control system calculates a change in the manipulated variable to offset the effect of a measured disturbance upon the process. This control strategy is typically used in addition to the usual feedback strategy.

3. *Cascade control* [1.12, 1.15, 3.18, 3.24, 3.30, 3.77]. As illustrated in Figure 4(b), the cascade control system comprises two simple feedback control loops, one of which provides the set point for the other. For example, the outer (master) control loop might calculate the temperature of the water jacket to maintain the reactor temperature at its desired value. The inner (slave) controller then adjusts the water flow to the jacket to give the desired jacket temperature.

4. *Multivariable (noninteracting)* [1.15, 3.6, 3.16, 3.23, 3.82]. In many processes two (or more) variables are to be controlled by adjustig two (or more) manipulated variables. In most cases, adjusting each manipulated variable affects both controlled variables, and the process is said to be coupled. If two separate analog controllers are employed, the two loops affect each other, and are said to be interacting. This interaction can frequently be minimized by using a "decoupler" in conjunction with these feedback loops, as illustrated in Figure 4(c). The decoupler is designed so that adjusting one of its inputs will produce a change in only one of the controlled variables, thus apparently eliminating the interaction.

5. *Adaptive systems* [1.2, 3.1, 3.2, 3.8, 3.26, 3.39, 3.63]. These systems modify the control strategy in response to changing characteristics of the process. They generally attempt to measure one or more parameters in a process model and change the control strategy accordingly.

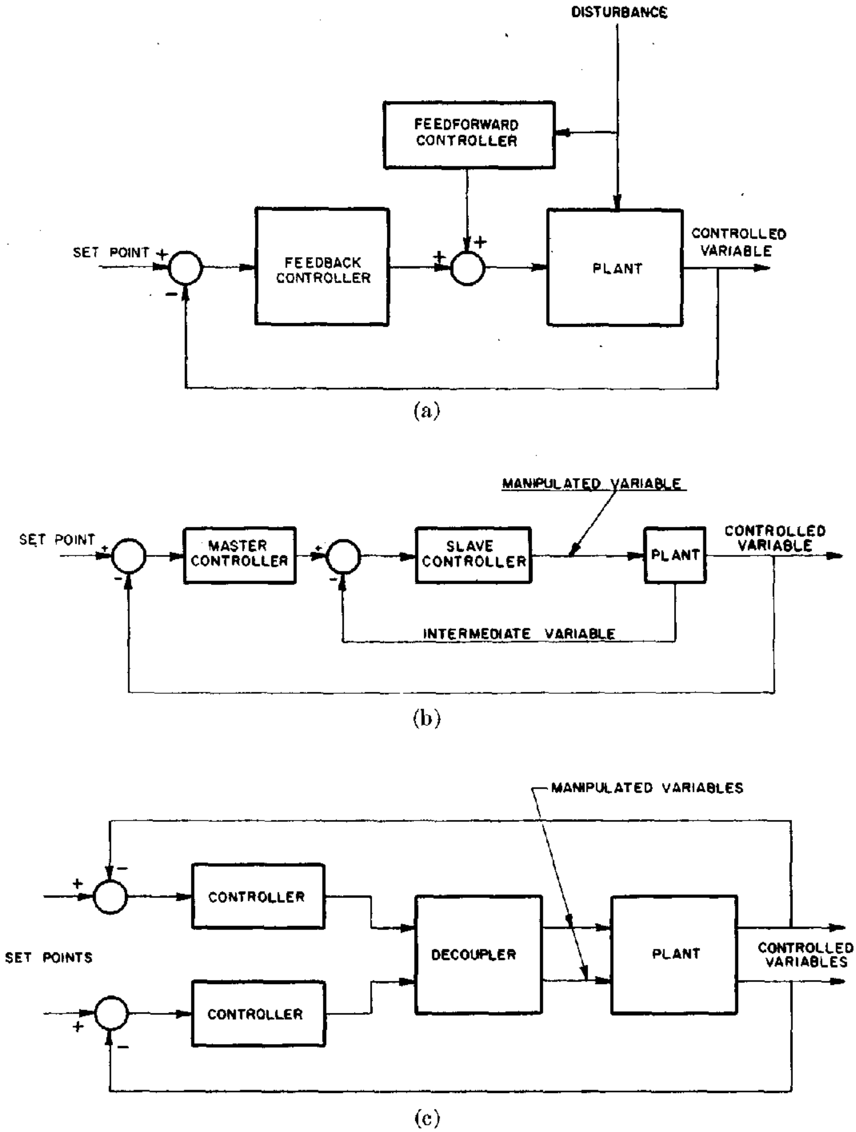


Fig. 4. Advanced control concepts: (a) feedforward, (b) cascade, (c) multivariable

6. *Automatic tuning* [3.25]. As mentioned above, one of the real problems is the tuning of the three-mode controllers. This same problem exists with control algorithms, but progress is being made on procedures that enable the computer to perform the tuning.

7. *Dead-time compensation* [3.2, 3.51]. Most process systems have significant dead-times (time delays or transportation lags, i.e. the time required for material to move from one point to another). Such systems are difficult to control with the conventional three-mode controller or corresponding algorithms, but special compensation techniques are attractive for digital systems.

8. *Optimal control.* Dynamic optimization of process units has not been applied on a widespread basis to date. Several reasons account for this, such as a large number of state variables, the requirement that

the control law be feedback in nature, availability of only relatively poor mathematical models of most processes, etc. Estimation theory may answer the last problem, and at least one investigation has been reported [3.78]. However, the main reason appears to be that there is simply not enough economic incentive in most processes to justify the effort to apply optimal control theory.

One especially promising area for DDC is in the control of batch operations. Control of these units can become quite intricate, especially when one piece of equipment (usually a chemical reactor) is used to manufacture a variety of different products, each of which requires a different operating procedure. The bookkeeping becomes very tedious, resulting in less efficient operation of the unit under manual supervision of a conventional control system. The computer's ability to store operating procedures for all possible batches, to flawlessly progress each batch according to this schedule, and in general provide reproducible and consistent operation gives it a distinct advantage. Standard software designed specifically for batch operations is becoming more widely available.

Supervisory Computer Control

The basic objective of a process operation is to optimize the financial return on investment. The economic return on an operation depends upon a number of factors, one of the significant ones being the day-to-day operating strategy. It is frequently not obvious to the operating personnel what the optimum operating strategy should be. A plant is a complex, interacting entity, and the optimum operating strategy can only be ascertained after considering the combined effect of many different options.

The obvious approach is to use the digital computer to perform just such an analysis. Typical input information needed might include:

- cost of raw materials, utilities, etc.
- value of products;
- composition of raw materials and products;
- current values of variables within the process;
- constraints on the operation, e.g. safety limitations;
- specifications on products.

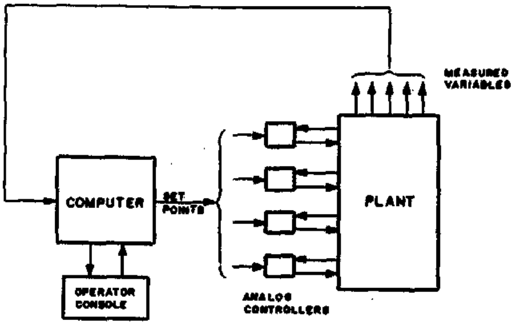


FIG. 5. Supervisory control system

A process model is needed to relate all of these various factors to the economic return on the operation. The optimum operating strategy is that which optimizes this return.

Although the computer determines the optimum operating strategy, the analog control system still implements the decisions. Thus, in many cases, the control computer simply provides the set points for the analog control loops, as illustrated in Figure 5. The computer system does not replace any analog hardware. The backup problem is not as critical, as in the case of computer failure the set points simply remain at their last settings.

The concept of supervisory control actually dates back to the development of autopilots for aircraft. Early development was conducted by the Bunker-Ramo Corporation and by Hughes Aircraft, the latter holding a patent, called the Exner patent [2.2], covering the supervisory concept (specifically, using a digital computer to provide the set point for an analog controller). Bunker-Ramo entered the process computer field and pioneered much of the early development.

The existence of the Exner patent has been of particular importance in supervisory control projects. Although some moves toward litigation have been considered, the current trend appears to be that computer manufacturers are negotiating licensing agreements covering the use of their products in a supervisory environment.

The economics [1.7, 1.14, 4.1–4.14] of supervisory systems are based on the prospect of the system producing sufficient improvement in process operation to justify the financial investment in the computer control system. This is seldom easy to verify beforehand, but processes that are likely to give such a return generally exhibit one or more of the following characteristics:

- high throughput, so small improvements will generate large returns;
- high complexity, thus making it difficult for operating personnel to consistently make correct decisions;
- frequent changes in disturbances, raw materials, or economic market position, requiring frequent changes in the goals of plant operation.

Perhaps the best indication of the acceptance of the supervisory concept lies in the number of repeat orders for such systems.

The main obstacle to the installation of supervisory systems is that mathematical models of plants are seldom available beforehand. Thus, the project must justify the expenditure of funds for this effort, which is by no means minimal. This effort typically requires the work of several engineers for periods of a year or more, plus plant tests and additional laboratory data. In many cases the computer is installed early in order to promote this work. It can easily amount to 25 percent or more of the total project cost.

The Hierarchy Concept

In the immediately preceding sections two distinct approaches toward the application of computer control to process units were presented. In reality the final system is usually a hybrid between the two, containing parts of both. It seems that most applications have been supervisory in nature, but still incorporating a few of the real attractive DDC loops.

The above discussion presents supervisory control as a digital computer providing the set point for analog control loops. However, the same principle applies to the case in which the supervisory digital computer supplies the set points to the DDC computer. In fact, DDC becomes even more attractive in these cases for these reasons:

—Few if any additional analog inputs are required. Thus, this cost only appears once in the total configuration.

—The communication between the two digital computers is considerably superior to the communication between the digital and analog systems.

—The backup problem in DDC can be solved by allowing the supervisory computer to assume control of critical loops in case of failure of the DDC computer.

—The Exner patent apparently does not cover this application.

This concept has certainly been promoted by some of the new features of third-generation computers, such as multiple-ports to memory.

The extension of these concepts to higher and higher levels gives the "hierarchy concept" or the "automated company," as illustrated in Figure 6 [2.15, 2.19, 5.12, 6.7]. The lowest level is occupied by the DDC computer, being responsible for the control of a single plant. On the next step is the supervisory computer, which may be responsible for several individual plants.

The next step up the ladder is to a computer responsible for coordinating an entire complex of several plants. In such a complex the shipping of materials from one plant to another means that the operations in one are highly dependent upon the operations in another. It also follows that what is best for an individual plant in the complex may not be best for the complex as a whole. As the company is only interested in the total return on investment from all the plants, there may be enough incentive to install a computer to ascertain what operating goals in each plant provide the maximum return from the whole complex. These goals are forwarded to the supervisory computer, which in turn calculates the set points for the DDC computer.

At the top of the ladder is the corporate level control computer, which should logically be a part of the management information system. This computer makes available to management an up-to-date status report on the operation of the entire company. On the basis of current market information, it could have the ability to make some policy decisions, which are then communicated to the computers on the lower levels. It could also receive other policy decisions from management, and likewise pass them along. In fact, one of the incentives to install such a system is that decisions at the corporate level could be disseminated to the individual plants in a matter of hours instead of the customary weeks or months. In this way, large companies could be as responsive as small ones to market conditions.

HARDWARE

The Computer System

Now that we have discussed current approaches to implementation of computer systems, we shall examine the computer hardware usually selected. We shall concentrate on the first two levels (i.e. DDC and supervisory) of computer control systems, as that is where most of the effort is being expended at this time. These computers tend to be specialized in one way or another, whereas the computers at the higher levels will probably be very much like those in current scientific data processing centers except for a few real-time features.

For a typical process control application, four approaches could be considered:

1. Use a very large, general purpose computer, for which process control would be only one of its many functions.

2. Use a general purpose computer for which process control would be its primary function, although it could in some cases provide a limited amount of other services.

3. Use a general purpose computer but dedicate it to the sole purpose of process control.

4. Use a small special purpose computer capable of providing only a limited number of control functions.

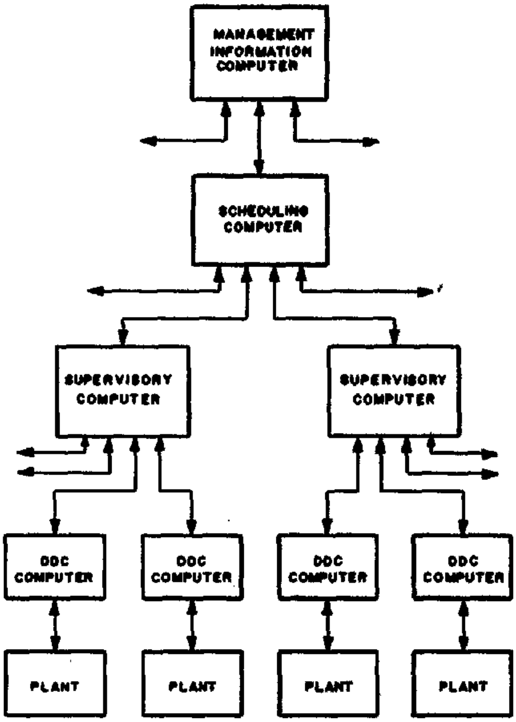


FIG. 6. Hierarchy of control system

As present trends seem to favor the second and third approaches, subsequent discussion will apply only to these. The first is rarely used, but the fourth is becoming more attractive as small computers in the $10,000–$30,000 price range become available. These can be used to capitalize on cases when one or two applications in a plant offer large returns, while all other aspects are marginal.

Virtually all control computers presently being installed are fixed word length, binary machines. The two popular word lengths are 16 bits or 24 bits. Factors that must be considered in choosing between these two are [5.20, 5.40]:

—The maximum resolution of input data from the process is typically 14 bits, and often less. Thus, a 16-bit word length is quite adequate.

—With a 16-bit machine, two words are required to store a floating-point number.

This forces the user to store his data insofar as possible in integer form (one word). With a 24-bit machine, a floating-point number can be stored in one word. Although this word only allows about 4 digits of precision, this is adequate for most process control work.

—A 24-bit machine can direct-address up to at least 16K words of core. This means that indirect addressing will be used much less than for a 16-bit machine. Furthermore, many control computers have 16K or less core storage, which means that 24-bit machines can direct address all of core storage in these cases.

—A 24-bit machine can offer a far more powerful instruction set which leads to more efficient programming and core utilization. Also, most instructions can be single words, while in a 16-bit machine a good many instructions must be double words, i.e. 32 bits versus 24 bits.

—The core storage is more expensive for 24-bit machines.

The proper word size is certainly a function of the specific duty the machine is to perform. For DDC, 16 bits (or even 12) are adequate for most situations. On the other hand, for supervisory control where floating-point numbers are used freely, the 24-bit machines become more attractive.

Other features of the CPU and memory worthy of note are:

- Parity. Parity checking is used with every word in storage.
- Storage protect. In current machines a protect bit is provided with each word in storage to provide the capability of protecting certain areas of core from "runaway programs." Future machines are expected to incorporate paging hardware and fencing schemes.
- Operations monitor. Often called a "watchdog timer," this timer must be frequently reset by the operating programs. If a program gets "hung-up" and the timer is not reset, an alarm is sounded.
- Priority interrupts [5.7, 5.52]. These can divert the CPU's attention from the normal program execution sequence in order to attend to other duties. Upon completion of these, provision is made for the resumption of the normal program execution sequence. Two types of interrupts exist:

a. Interrupts originating within the computer system synchronize various functions, frequently I/O operations.

b. Interrupts originating in the process synchronize the computer system with the outside world, notify the computer of emergency situations, or in general request the computer's immediate attention.

- Real-time clock. This clock's primary function is to coordinate the machine's operation with the real world's time.
- Integral I/O processor, also called "cycle-stealing" I/O. With this feature, the CPU does not have to be devoted to I/O chores.
- Contact closures. Discrete inputs in the form of contact closures can enter directly into the CPU. For a 16-bit machine, 16 of these enter in one word, normally requiring only one instruction cycle to be read. As this is much faster than for analog inputs, these are used to the maximum extent possible.
- Power fail safe. This enables the contents of the working registers to be stored so that operations may be resumed from that point when power is restored.
- Hardware floating point arithmetic. Not available on many computers designed for process control, it is probably not necessary for strictly DDC systems. In supervisory systems where mathematical operations such as linear programming are employed, this item may decrease program execution time significantly.
- Instruction repertoire. This varies considerably from one machine to another, ranging from the twenties to more than a hundred.

The same peripheral devices available for data processing machines are also available for control computers. Considerations in the selection of these devices are:

- Card read/punch versus paper tape read/punch. Card I/O is considerably more expensive than paper tape I/O. However, program changes are much easier to insert into a card deck than into paper tape.

Many early systems were paper tape oriented, but the current trend is toward cards.

- Teletype. Most process control systems have a teletype or a 10- to 15-cps typer for systems messages in the computer room, and often one or more additional units in the field for presenting information or messages to the plant operating personnel.
- Disk or drum storage. Essentially all supervisory systems and some DDC systems use these devices to store programs and data used only intermittently by the control system. Typical mass storage capabilities range from a million words up. Average access times range from on the order of 10 msec for fixed head devices to about a half-second for movable head units. In cases where program excution must begin at once, the access time determines whether the program can reside on disk or must reside in core. The frequency of use of a program is a second factor to consider when deciding where a program is to reside.
- Line printer. Essentially no DDC systems and few supervisory systems produce enough printed output to justify these devices. However, during the initial programming stages, the volume of output is much higher than normal, making it attractive to lease a line printer initially with intention of removing when the volume of output declines.
- Magnetic tapes. Disk or drum storage is virtually always selected over magnetic tape units for control computers, primarily because of the shorter access time with disk or drum.

This list does not include some special output devices such as incremental X-Y plotters found on some systems. Nor are devices such as operator stations or cathode-ray tube devices included, as they will be discussed subsequently.

The Analog Front End

In order to function in a proper manner, it is necessary for the control system to receive an adequate amount of reliable information from the process. The bulk of this information originates in the process in the form of continuous (analog) signals. Before information in this form can be entered into core storage, the continuous signal must be sampled (i.e. read at a discrete instant of time) and quantized (i.e. converted to digital form). These important functions are performed by the analog front end.

The information transfer from process to computer begins with a sensor (or transducer). This device senses a process variable such as temperature, pressure, flow rate, etc., and outputs a voltage signal proportional to its value. The computer control system, whether supervisory or DDC, generally demands more accuracy than does a conventional analog system. The rationale here is quite simple. To justify the expenditure for the digital system, its resulting performance must be superior, which in turn requires better data from the process. In some cases this necessitates better instruments; in others a regular maintenance and calibration effort. In fact, it is often beneficial to incorporate features in the hardware and software systems to aid in calibrating instruments.

Figure 7 gives a schematic diagram of a typical analog front end configuration. Two types of analog signals originate from the sensors:

(a) High level signals. Usually defined as any signal greater than about one volt, these signals originate from transmitters (with process sensing elements) capable of outputting a significant amount of power with the signal.

(b) Low level signals. Typically down in the millivolt range, these signals originate from sensors such as thermocouples or resistance thermometers. These signals are especially prone to distortion, requiring special shielding from noise and careful handling by the analog front end. Although perhaps the majority of the analog signals in present control systems fall into this category, this will surely diminish as integrated circuit amplifiers begin to be incorporated into sensing elements.

Depending upon the type of signal, the analog front end configuration varies, as will be discussed subsequently.

The function of each device in the analog

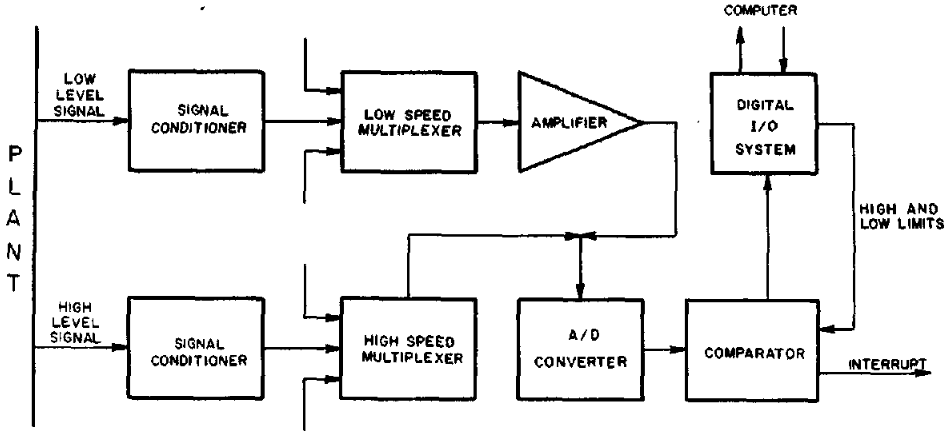


FIG. 7. Analog input system

front end illustrated in Figure 7 is [5.3, 5.11, 5.18, 5.24, 5.25, 5.33, 5.39, 5.41, 5.44, 5.47]:

Signal conditioning. As virtually all signals are to some extent influenced by noise during their transmission, it is usually desirable to remove some of this upon entering the analog front end. This is usually accomplished by a passive network such as an RC circuit.

Multiplexer. This device is effectively the sampler in the digital control loop. It selects the proper signal for conversion to digital form for entry into the computer. The number of inputs to a single multiplexer ranges from about 256 up to about 2048. The switching speed of the multiplexer depends upon the type of analog signal:

(a) For high level signals the switching is accomplished by solid state field effect transistors (FET). Input rates on the order of 10,000 points per second (10 kc) or higher (perhaps 250 kc in the near future) are possible with such devices.

(b) For low level signals, the distortion of field effect transistors cannot be tolerated. Conventional mercury-wetted or reed delays must be used, reducing the input rate to a few hundred points per second or less.

In most cases, all high level inputs are connected to a high speed multiplexer, and all low level inputs connected to a separate low speed multiplexer. Further switching is provided prior to the A/D converter to select the proper multiplexer.

Amplifier. The amplifier converts low level signals to high level prior to the A/D converter. Normally the amplifier follows the multiplexer so that it may be shared to reduce equipment cost. However, if a low level signal is to be sampled rapidly, an amplifier may be inserted in the signal lines prior to the high speed multiplexer.

A/D converter. This device converts the signal from the amplifier or multiplexer into digital form. The multiplexer selects a given signal, which must remain connected to the input of the converter long enough for its output to settle to a constant value. This time can be as low as 20 μsec for 5- to 10-v analog signals.

Comparator. This device compares the input signal with high and low limits stored in the computer's memory. If either is violated, an interrupt to the computer is generated. This comparator is a hardware device external from the CPU, thus freeing the arithmetic unit from this duty.

The control of the analog front end may reside with the CPU, or some of the control may reside with control modules external to the CPU, thus relieving it of some duty. With cycle stealing I/O or multiple ports to memory, it is feasible for the control module to assume all control function, thus freeing the CPU.

Digital Inputs

Two types of digital inputs, namely priority interrupts and discretes, have already been mentioned. Another commonly used digital input is to a pulse counter. This is a hardware device that can operate in either of two fashions:

(a) The register in the counter is initialized to zero, and then incremented at each pulse. At the end of a specified time, the counter is read by the computer.

(b) The register is initialized to a given value, and then "downcounted" (i.e. subtracted by one) at each pulse. When the register reads zero, an interrupt is generated.

These devices are commonly used in conjunction with magnetic flow meters, tachometers, and other similar measuring devices.

Outputs to the Process

Outputs from the computer can generally be classified into three categories: (a) voltage outputs, (b) pulse outputs, and (c) analog outputs [5.15, 5.35, 5.38]. Each of these have their individual uses. The first two types of outputs are found on practically all process control installations, some being able to operate without analog outputs.

Voltage outputs are simply high or low level discrete outputs that can be used to position or operate a relay. These are perhaps the simplest of all the outputs. Uses are typically for controlling on-off devices such as electrical motors, solenoid valves, etc. These are the least expensive, and are utilized whenever possible.

Pulse outputs are typically used for driving stepping motors. These are widely used in the automatic set point stations for the analog loops in a supervisory control system, but are also found on motor-driven potentiometers, valve positioners, and other final control actuators. The pulse generator is normally external to the CPU. A typical unit consists of a register which is loaded by the CPU with the number of pulses to be generated. The pulse generator then generates a pulse at regular intervals of time, down counting the register until it reads zero. The times between pulses and pulse duration is preset in the less expensive units, although some offer a choice of timing sequences. These units may also be shared between several stepper motors by multiplexing the output of the pulse generator.

One of the primary considerations in process control installations is safety in case of computer failure. As the stepper motors maintain their present position until another pulse is received, their positions remain at their last valid settings in case of computer failure. It is also convenient to arrange for a manual station to operate in conjunction with the computer set point station. These considerations frequently make these devices more attractive than digital-to-analog converters.

Analog outputs are obtained from digital-to-analog converters, also commonly called digitally set pots. This device consists of a resistor lattice network with relays or solid-state devices driven by the bit pattern of the input word. These are high impedance devices, providing an accurately proportioned output voltage by dividing a stable reference supply voltage. Although the output of these devices may also be multiplexed, a hold device must be supplied on the output of each channel of the multiplexer to maintain the output voltage between sampling instants, which makes multiplexing economically unattractive.

Operator's Console

One of the most important parts of the computer control system is the operator's console, the device through which the plant operating personnel communicate with the computer [5.23, 5.27, 5.31, 5.49, 5.50]. Human engineering must take the spotlight in designing this device, because information transfer must take place in both directions in a clear, easy-to-use manner. Through this console comes information to the computer such as desired operating conditions, results of laboratory analyses, etc. Similarly, the operating personnel must be able to request information such as values of specific variables in engineering units, current trends, predictions of the effect of a certain proposed action, etc.

The design must everywhere emphasize the convenience of use by the operating personnel. Few of these personnel are engineers, programmers, or equivalent, which increases the burden of designing the console so that the transfer of information is effective in both directions. Extensive coding of information is not readily accepted by these people, nor are intricate mechanisms for obtaining requests or inserting information.

To meet the design objectives of the operator's console, cathode ray tube (CRT) display units are ideally suited. These devices can display trends, present possible choices, and in general present information of all types in a much superior fashion than economically feasible otherwise. For example, a schematic diagram of the entire process could be displayed to the operator. He could then (with a light pen) select a portion to be displayed in greater detail, perhaps showing all sensors and control devices. Those sensors in alarm could perhaps blink to attract his attention. Again, with the light pen he could select specific variables to be displayed or other variables (such as set points) he would like to specify. In general, the future of CRT devices in this area is very promising [5.46, 5.49, 5.50].

SOFTWARE

Software Requirements

One of the main question marks in practically every digital control venture to date has been the software. Costs of user written software have been consistently underestimated; computer configurations have been selected that could not support the software needed (a typical situation is not enough core storage); and users have not always recognized the capabilities and limitations of vendor supplied software.

The record has been so consistent in this area that it has become the focal point in the analysis of every computer control venture (see [4.1–4.14]).

There are several reasons for this. First, every process is unique, requiring a considerable amount of custom software development. Second, the software must be revised as more and more information is learned about the process itself. This has negated the concept of doing a once-for-all programming job. Third, the real-time nature of the computer control task requires software support over and beyond that of conventional software.

At this point it should be understood that the terms software and programming (coding) are not used interchangeably. The coding aspect is indeed quite similar to coding for other applications, as will be discussed briefly in a subsequent section. Although the coding task should not be downgraded, the development of the philosophy and general operating characteristics of the complete set of computer programs is a major and extremely important task. The success of the entire project hinges upon software design and development.

To some extent, the desirable features of the software systems differ between DDC and supervisory systems. In DDC systems, the tasks to be performed are customarily relatively simple, but must be performed at very frequent intervals. Furthermore, while the total number of tasks may be large, many of these are identical or only minor variations of other tasks. On the other hand, a supervisory system usually contains a lesser number of tasks, but each is more complex than a typical task at the DDC level. As the complexity is higher, few of them even approach being similar.

While the demands on the software packages differ between DDC and supervisory systems, both must operate in real-time. In the ensuing discussion, the features of software for supervisory systems will be examined, followed by discussion of the points where DDC systems differ.

Software for Supervisory Control

The heart of a software package for a supervisory control system is a real-time executive or monitor system. This executive must, among other things, be capable of processing interrupts, scheduling program execution, and utilizing auxiliary storage (disk or drum) in an efficient manner. Executive systems of this type are available from several vendors.

For sake of discussion, this executive can be divided into three parts: (1) interrupt servicing, (2) real-time sequencing, and (3) off-line monitor. A simplified flowchart of such a monitor is shown in Figure 8. Note that there are two modes of operation: a normal mode for executing real-time programs and an interrupt mode for servicing interrupts. We shall now discuss briefly the three parts of this monitor.

Interrupts. A typical process control computer could have from two to about sixteen levels of interrupts. With each level of interrupt is associated a priority. That is, an interrupt that occurs on a higher level of priority takes precedent over all others. As real-time programs being executed in the normal mode can be interrupted from any interrupt level, they effectively operate on the lowest priority (aside from off-line work under the off-line monitor). To illustrate the sequence of events under this type of arrangement, consider the sequence of interrupts under the two-level-of-interrupt system illustrated in Figure 9. The first pair of interrupts illustrates an interrupt on the highest level interrupting the servicing of a lower level interrupt. The second pair of interrupts illustrates that when an interrupt on a lower level occurs while a higher level interrupt is being serviced, the lower level interrupt is not serviced until completion of servicing all higher level interrupts. Similarly, the last pair of interrupts illustrates that an interrupt cannot interrupt the servicing of an interrupt on the same level.

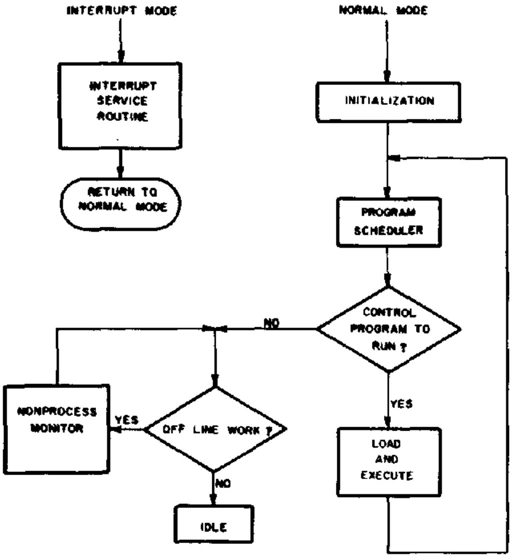


FIG. 8. Abbreviated representation of a real-time executive [1.14]

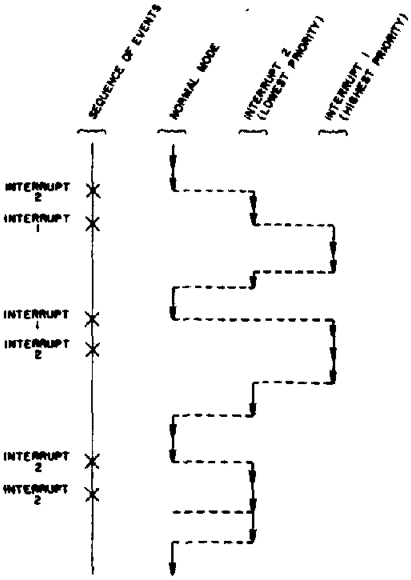


FIG. 9. Typical interrupt sequence

In general, the arrangement of the interrupts and their service routines is not a simple matter. In most cases, interrupts occurring within the computer system occupy the highest levels. Process interrupts may generally be arranged in a variety of ways, and only careful, simultaneous consideration of process characteristics and software development aspects can lead to the most successful operation. The complexity obviously increases as the number of interrupt levels increases. It is conceivable that using fewer levels of interrupts can simplify the software and program logic to the point that a more successful overall operation is obtained. The problem of choosing which interrupts should occupy which levels is also complicated by the fact that, in some systems, the manner in which the interrupts are wired on a given level determines a subpriority for that level. That is, suppose that two interrupts occur on a lower level while a higher priority interrupt is being

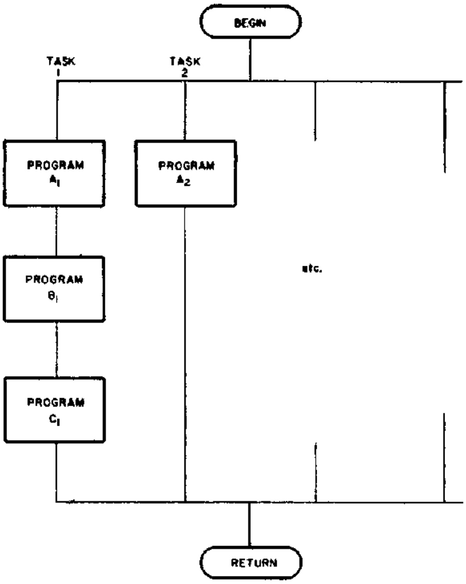


FIG. 10. Organization of tasks

serviced. Which one of the lower level interrupts is serviced first depends upon the manner in which they are wired, not on which occurs first in time.

With each interrupt level, there is set aside sufficient storage in a prespecified location for storing the contents of the working registers so that the program being executed at the time the interrupt occurred can be resumed. If this function is not hardware mechanized, the executive system must accomplish this with software. Program control is then transferred to some designated location in core storage to identify the specfic cause or origin of the interrupt. At this point, a specific program that dictates a specific action to be taken is executed. This action may perform all functions needed, or may simply specify a program to be executed by the real-time monitor. Upon completion of all of these functions, the interrupt is said to have been serviced. Control then reverts back to the program being executed.

It is, of course, conceivable that a certain sequence of events should not be interrupted at all, or perhaps only by extremely urgent interrupts. This condition is obtained by the use of MASK and UNMASK routines. The effect of a MASK is to prohibit the servicing of interrupts on a given level(s) until this condition is removed by an UNMASK routine. This gives the programmer a degree of control over the servicing of interrupts.

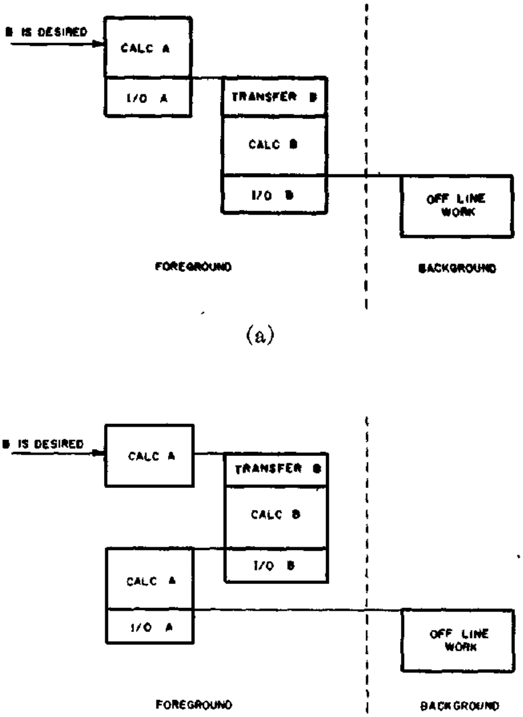
Program sequencing. The execution of programs by the process control computer generally follows no set pattern. Instead it is highly dependent upon process conditions, operator requests, etc., although some programs are executed repetitively at certain intervals of time. To some extent, the operating programs for a process control computer can be organized into groups to perform certain tasks, as illustrated in Figure 10. The completion of a single task may require one or more individual programs. Similarly, the same program may appear in the sequence of programs to perform two different tasks. Each individual program within a given task is assigned its own individual priority, i.e. it is not necessary for all programs within a given task to be assigned the same priority.

In a real-time environment, the executive must be capable of scheduling program execution such that all desired tasks are accomplished. The programmer dictates which individual programs within each task take precedence by assigning them a priority, usually under program control (i.e. not necessarily assigned when the program is written). This sequencing of program execution is accomplished with the aid. of a table called QUEUE. The names of programs to be executed are entered into QUEUE under program control, their priority usually being assigned at this point.

In many cases, servicing an interrupt consists of nothing more than placing the name of some program into QUEUE. This program is usually the first program in a sequence to perform a given task, thus initializing the task. At the completion of this program, the final instructions place the name of its successor in QUEUE, thus propagating the chain. It is also possible for a program in one task to call for another task to be accomplished, thus providing another mechanism for initializing a task.

As all interrupts take priority over programs being executed from QUEUE (unless the program has executed a MASK instruction), it is conceivable that an interrupt service routine could insert into QUEUE the name of a program of higher priority than the program currently being executed. Some process control computer executives, particularly the early ones, do not terminate the execution of a lower priority program that is in progress at the time a higher priority program is inserted into QUEUE. In many applications this is quite satisfactory, although executives are now appearing with the capability of automatic suspension, i.e. the termination of lower priority programs when higher priority entries are made into QUEUE.

In supervisory systems, the executive must also be responsible for effective utilization of mass storage. In most cases, the executive must transfer a program from disk to core before it can be executed. This is illustrated in Figure 11 for executives with and without automatic suspension. In each case, the computing system has cycle stealing I/O, allowing I/O operations (including transfer from mass storage) to be overlapped with program execution. As illustrated in Figure 11(b), the automatic suspension feature reduces the time between the point that the execution of program B is required and the execution actually begins. However, if program A were executing some task that should not be interrupted once in progress (even though the task may be of low priority), the automatic suspension feature may cause some problems unless this was recognized and prevented by the programmer.



(a)

(b)

FIG. 11. Programming sequencing: (a) without automatic suspension; (b) with automatic suspension

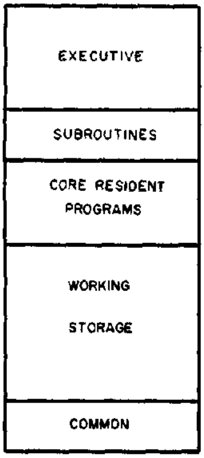


FIG. 12. Allocation of core storage

Allocation of core storage typically resembles that illustrated in Figure 12. The real-time executive typically occupies the lower portion of core storage. Frequently used subroutines, e.g. floating-point subroutines, I/O subroutines, etc., are also located in core storage. Frequently used programs whose execution must proceed quickly are also located in core. These are called core resident programs. All subroutines called by core resident programs must usually be core resident also. A section of core storage is also assigned as a common area for storage of variables whose values are required frequently. Long tables or seldom-required data are stored in files in mass storage. The remaining core storage is called working storage or variable core.

Depending upon the particular executive, this working area may contain only one program or may contain several. Systems that may contain only one program in working storage at any one time usually store these programs on disks as core loads, which include all subroutines not located in permanent core storage. Thus, locating more subroutines in core storage decreases the size of the core loads and, consequently, the time for transfer from mass storage to working storage. Executives with the automatic suspension feature usually permit more than one program to occupy working storage at any given time. If room is not available for the highest priority program, lower priority ones must be removed to the disk to be resumed when space is available.

One desirable feature not always available on real-time executives is the ability to add, modify, or delete core resident programs while the computer is performing its normal control functions. If this capability is not available, control must be transferred to the backup system, and the time required to modify the system is charged as down time against the computer control system. Obviously, this prevents the programmer from inserting frequent changes, although they may be highly desirable, into the control programs. It also impairs the control engineer's freedom to experiment with new control strategies.

Off-line monitor. The free time when the process control computer is not busy with control functions is utilized for off-line (noncontrol) functions under the off-line monitor. Although this is usually referred to as time-sharing by the process control computer manufacturers, this is not time-sharing in the context used for large computer systems. Instead, it is closer to a foreground/background operation, with real-time programs operating in the foreground and off-line work in the background. Except for the cycle stealing I/O, the processor's attention is devoted to a single program at any given time. This was illustrated in Figure 11.

Programs such as the FORTRAN compiler, the assembler, disk utility routines, and other supporting functions to the process control system are operated under the off-line monitor. The core loads for execution in real-time are built under the off-line monitor and stored on disks for subsequent use. Another important program operated under the off-line monitor is the simulator, which allows the testing of a real-time program under a simulated control environment prior to being incorporated into the system. Of course, programs in no way associated with the control system can also be executed under the off-line monitor.

Software for DDC

To some extent, many of the previous comments about software for supervisory systems also apply to DDC systems. But being first level in nature, DDC systems require software packages that emphasize speed, quick response, reliability, and efficiency. To be competitive with analog systems, this must typically be accomplished with a minimum expenditure on computer hardware. This frequently prohibits the addition of mass storage devices such as disks, which often cannot meet the quick response requirements anyway. This simplifies the executive system to some extent, as the disk routines are not required and all programs, subroutines, and data are core resident.

DDC software systems must typically accomplish relatively simple tasks (for example, control algorithms) at frequent intervals of time. To some extent, the duties to be performed vary little from one application to the next. As will be described in a subsequent section, this makes standard software packages in the form of interpreters quite attractive. In fact, perhaps ninety percent of the software required for DDC will be available in standard packages in the near future.

As DDC software is analogous to software for supervisory systems in other aspects, no further discussion seems appropriate.

TABLE I. ASSEMBLY VERSUS COMPILER LANGUAGES*

Language	*Advantage*	*Explanation*
Assembly	Fast object code	Fewer instructions to convert into machine code decreases execution time
	Efficient memory utilization	Assembly code can take advantage of memory-conserving features of modern control computers
	Control over program and data location	Assembly code offers more flexibility in specifying program layout and data storage
	Access to all computer functions and instructions	Programmer can take advantage of his detailed computer knowledge to write more effective control programs
	Efficient program linkage	Calling up subroutines and shifting control parameters is simpler
	Ability to use different classes of codes	Reentrant routines for servicing priority interrupt are facilitated
Compiler	Machine independent and standardized	A limited advantage
	Self-documenting	Yes, but must be supplemented
	Easier to learn	Yes, for a scientist or engineer
	Quicker, less tedious to write or modify	Yes, provided the program writer knows when to provide control alternatives
	Easier to debug—self-checking	Prevents some programmer errors

* From [6.17]; reproduced by permission.

Programming Languages

Assembly. Although used almost exclusively on earlier process control computers, the proportion of control programs written in assembly is decreasing in both supervisory and DDC applications. However, as the assembly language is the most efficient from execution time, it is used more frequently in DDC, where speedy response and fast action are more important than in supervisory systems. The use of assembly language will surely continue to decline, as the high personnel requirements for this type of programming cannot be tolerated in a market where this talent is already in short supply. Instead, the trend will be toward larger, faster systems where programming efficiency is not as critical. Table I gives a summary of the advantages of assembly coding versus use of a compiler such as FORTRAN [6.17].

FORTRAN. The bulk of programming of supervisory systems is currently being done at the FORTRAN level. Although programming in this language is not as efficient as in assembly, it is understood by most engineers graduating today. One solution to permitting FORTRAN to be used most of the time and assembly only when the rewards are high is the provision of a FORTRAN compiler that accepts in-line assembly statements. The FORTRAN compiler converts the FORTRAN statements to assembly, with the assembler taking over from there. This type of operation also permits the programmer to "dress up" the assembly code without having to prepare the entire program in assembly.

FORTRAN compilers available on process control computers are not as general as on larger machines, although they are FORTRAN IV as compared to FORTRAN II. The features generally supported include COMMON, DATA, EQUIVALENCE, DIMEN-

TABLE II. STANDARD LANGUAGE CHARACTERISTICS*

1. Relates to English in defining variable names
2. Defines the solution of problems in the same form as the implementation of the problems
3. Efficiently gathers process data and regulates variables with several algorithmic options
4. Incorporates routine decisions and optimization
5. Data outputting capability and transmission to other computers
6. Free-time calculation capability
7. Formulation capability of the coordinator of all functions
8. System configuration generation
9. Ease of debugging in English
10. Ease of maintenance
11. Self-documentation
12. Machine independent until the machine implementation stage of the project
13. Flexible
14. Must run in a "reasonable" size computer
15. Free formatting
16. Capability of assembly language statement insertion
17. Usable in a management information system
18. Modular flexibility
19. On-line data update capability
20. Easy interface with operator's consoles
21. Interrupt manipulation capability
22. Short execution time and easy modification of programs
23. Reflection of process variable failures throughout the whole system
24. On-line program correction capability
25. Arithmetic instruction capability
26. Program linking
27. Flexible data structures
28. Dynamic storage allocation
29. Time delay capability

* From [6.25]; reproduced by permission.

SION, REAL, INTEGER, DEFINE FILE, READ, WRITE, arithmetic IF, FORMAT, CALL, RETURN, FUNCTION, SUBROUTINE, plus the usual arithmetic operations. Notable omissions are logical IF, double precision, complex, and other special features. Although not selective within a program, double or extended precision can be used for *all* floating-point operations within a program. Similarly, *all* integer variables may be stored in either one word or two words, the former being selected for most cases. Most of these restrictions arise because process control computers are small relative to their large cousins in data processing centers. Similarly, their FORTRAN compilers do not optimize the code as well as their larger cousins. This could potentially be circumvented by the availability of a more general, more efficient compiler that operates on a large system but produces a code executable by the process control computer.

The real-time features are frequently inserted into the FORTRAN programs by callable subroutines, although some compilers accept special statements for real-time functions. Examples of such functions are reading the real-time clock, setting interval timers, masking or unmasking interrupts, placing programs in QUEUE, etc.

Higher level languages. Currently, there is considerable interest in improving and standardizing the programming languages used on process control computers [6.5, 6.25, 6.29, 6.35, 6.36]. Table II gives the characteristics of such a language as they were formulated in a conference held at Purdue [6.5] at which both users and vendors were represented. These characteristics appear to indicate a procedural language such as FORTRAN, but obviously they go far beyond the capability of current FORTRAN'S. There is, however, another school of thought that advocates a problem-oriented or fill-in-the-forms language resembling the interpretive digital simulation languages currently available.

Problem-oriented languages. These are general programs capable of performing many of the control functions common to various applications. They take care of such functions as the analog scan, conversion of input data to engineering units, high and low limit alarm violations, and other common functions. Thus, they can indeed reduce the programming task in many cases.

Of course, there is a penalty. Being general in nature, they will be less efficient than programs written for specific objectives. This means that the computer system will probably need more core and mass storage. If timing is critical, the problem-oriented programming system may not be able to perform as well as custom programs. Further, much of the flexibility of assembly and FORTRAN languages is lost at this level. This disadvantage is minimized when routines specific to a given application can be readily added to the problem-oriented programming package.

Because practically the same basic functions are required of all DDC control systems, the future looks brightest at the DDC level. For example, the block diagram in Figure 13 illustrates the functions required to calculate a control algorithm. The actual calculations or control functions are accomplished within the blocks, their connection pattern dictating the overall task to be accomplished. The input data consists of the connection patterns to the various blocks and the constants or parameters required by each. The problem-oriented programming package consists of routines written to accomplish the task corresponding to each block plus a type of executive to keep track of the interconnection patterns [6.18].

The available blocks are generally sufficient to accomplish all common control functions, such as cascade, feedforward, etc. For functions specific to a given application, special blocks may generally be added. Sections also take care of the analog input scan, the operators console, report writing, and other common requirements of a DDC system so that the programming demands upon the user are minimized.

Although problem-oriented languages are available at the supervisory level [6.4], the differences between individual supervisory systems are such that it is more difficult to provide all the functions required. Again, however, the problem-oriented programming system can at least take care of the analog scan, engineering conversions, operator's console, report writing, and similar functions. (Many computer manufacturers also provide software for these functions, although they may not provide a problem-oriented language as such.)

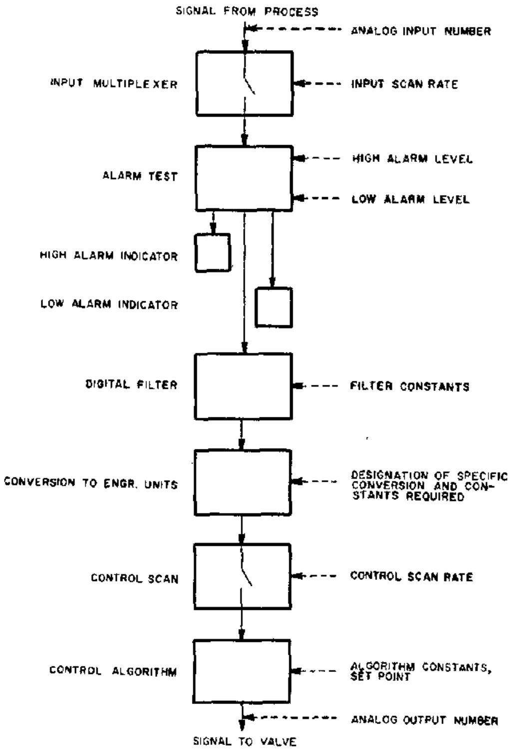


FIG. 13. Typical algorithm calculation

SUMMARY

This article has attempted to familiarize the reader with the current state-of-the-art and requirements for process computer control systems. At the moment, the future of digital computers in this area is especially bright, the rate of installation of new systems being limited primarily by the personnel available. Certainly not all aspects have been covered in this article, and several important ones were mentioned only casually. The following literature references should contain some entries on almost any subject about which additional information is desired [2.19].

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An application of DDC.

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