DISTRIBUTED CONTROL SYSTEMS

Introduction

Generally, the concept of automatic control includes accomplishing two major operations; the transmission of signals (information flow) back and forth and the calculation of control actions (decision making). Carrying out these operations in real plant requires a set of hardware and instrumentation that serve as the platform for these tasks. Distributed control system (DCS) is the most modern control platform. It stands as the infrastructure not only for all advanced control strategies but also for the lowliest control system. The idea of control infrastructure is old. The next section discusses how the control platform progressed through time to follow the advancement in control algorithms and instrumentation technologies.

1. Historical Review

To fully appreciate and select the current status of affairs in industrial practice it is of interest to understand the historical perspective on the evolution of control systems implementation philosophy and hardware elements. The evolution concerns the heart of any control system which is how information flow and decision making advanced.

1. Pneumatic Implementation: In the early implementation of automatic control systems, information flow was accomplished by pneumatic transmission, and computation was done by mechanical devices using bellows, spring etc. The pneumatic controller has high margin for safety since they are explosion proof. However, There are two fundamental problems associated with pneumatic implementation:

    - *Transmission*: the signals transmitted pneumatically (via air pressure) are slow responding and susceptible to interference.
    - *Calculation*: Mechanical computation devices must be relatively simple and tend to wear out quickly.

2. Electron analog implementation: Electrons are used as the medium of transmission in his type of implementation mode. Computation devices are still the same as before. Electrical signals to pressure signals converter (E/P transducers) and vice verse (P/E transducers) are used to communicate between the mechanical devices and electron flow. The primary problems associated with electronic analog implementation are:

    - *Transmission*: analog signals are susceptible to contamination from stray fields, and signal quality tends to degrade over long transmission line.
    - *Calculation*: the type of computations possible with electronic analog devices is still limited.

3. Digital Implementation: the transmission medium is still electron, but the signals are transmitted as binary numbers. Such digital signals are far less sensitive to noise. The computational devices are digital computers. Digital computers are more flexible because they are programmable. They are more versatile because there is virtually no limitation to the complexity of the computations it can carry out. Moreover, it is possible to carry out computation with a single computing device, or with a network of such devices.

Many field sensors naturally produce analog voltage or current signals. For this reason transducers that convert analog signals to digital signals (A/D) and vice verse (D/A) are used as interface between the analog and digital elements of the modern control system. With the development of digital implementation systems, which DCS are based on, it is possible to implement many sophisticated control strategies on a very fast timescale.

2. Modes of Computer control

Computer control is usually carried out in two modes: *supervisory control* or *direct digital control*. Both are shown in Figure 1. Supervisory control involves resetting the set point for a local controller according to some computer calculation. Direct digital control, by contrast, requires that all control actions be carried out by the digital computer. Both modes are in wide use in industrial applications, and both allow incorporating modern control technologies. Measurements are transmitted to computer and control signals are sent from computer to control valves at specific time interval known as sampling time. The latter should be chosen with care.

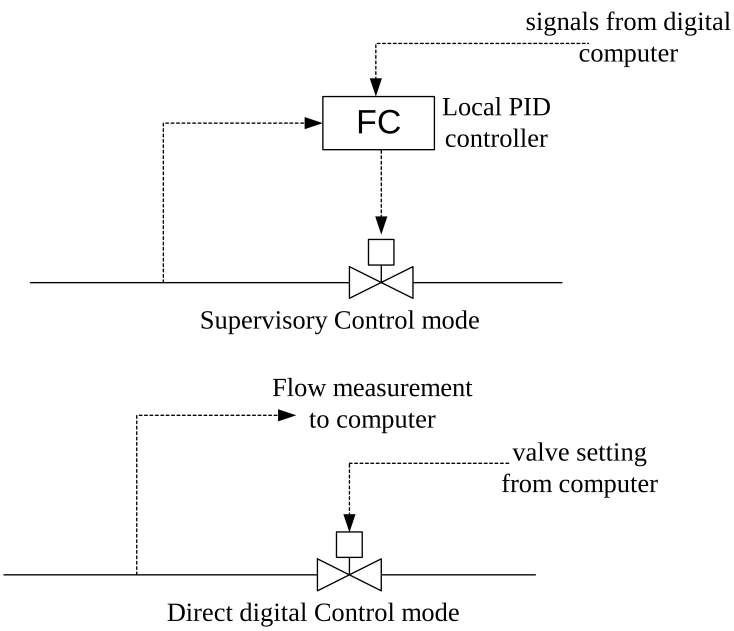

Figure 1: Computer control modes.

4. Computer Control Networks

The computer control network performs a wide variety of tasks: data acquisition, servicing of video display units in various laboratories and control rooms, data logging from analytical laboratories, control of plant processes or pilot plant, etc. The computer network can be as simple as an array of inexpensive PC's or it could be a large commercial distributed control system (DCS).

4.1 Small Computer Network

In small processes such as laboratory prototype or pilot plants, the number of control loops is relatively small. An inexpensive and straightforward way to deal with the systems is to configure a network of personal computers for data acquisition and control. An example configuration of a PC network control system is depicted in Figure 2. The network consists of a main computer linked directly to the process in two-way channels. Other local computers are linked to the main computer and are also connected to the process through one-way or two-way links. Some of these local computers can be interconnected. Each of the local computers has a video display and a specific function. For example, some local computers are dedicated for data acquisition only, some for local control only and some other for both data acquisition and local control. The main computer could have a multiple displays.

All computers operate with a multitasking operating system. They would be normally configured with local memory, local disk storage, and often have shared disk storage with a server.

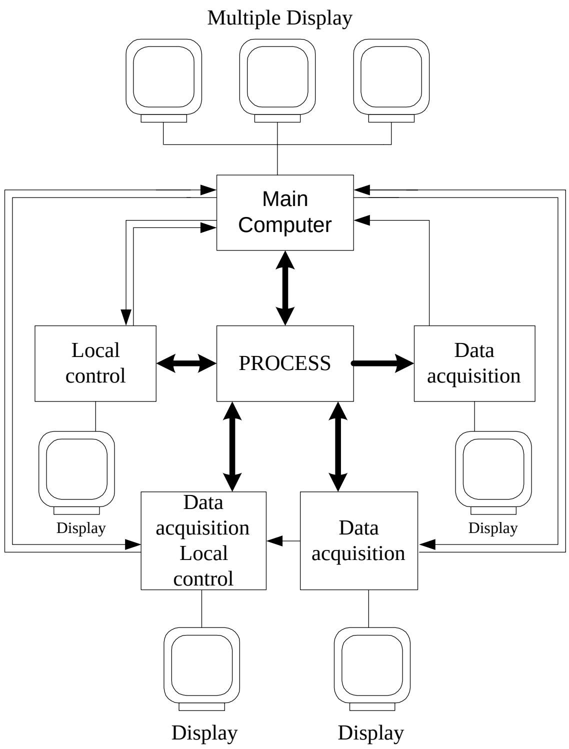

Figure 2: PC network

4.2 Programmable Logic Controllers

Programmable logic controller (PLC) is another type of digital technology used in process control. It is exclusively specialized for non-continuous systems such as batch processes or that contains equipment or control elements that operate discontinuously. It can also be used for many instants where interlocks are required; for example, a flow control loop cannot be actuated unless a pump has been turned on. Similarly, during startup or shutdown of continuous processes many elements must be correctly sequenced; that is, upstream flows and levels must be established before downstream pumps can be turned on.

The PLC concept is based on designing a sequence of logical decisions to implement the control for the above mentioned cases. Such a system uses a special purpose computer called *programmable logic controllers* because the computer is programmed to execute the desired Boolean logic and to implement the desired sequencing. In this case, the inputs to the computer are a set of relay contacts representing the state of various process elements. Various operator inputs are also provided. The outputs from the computer are a set of relays energized (activated) by the computer that can turn a pump on or off, activate lights on a display panel, operate solenoid valve, and so on.

PLCs can handle thousands of digital I/O and hundreds of analog I/O and continuous PID control. PLC has many features besides the digital system capabilities. However, PLC lacks the flexibility for expansion and reconfiguration. The operator interface in PLC systems is also limited. Moreover, programming PLC by a higher-level languages and/or capability of implementing advanced control algorithms is also limited.

PLCs are not typical in a traditional process plant, but there some operations, such as sequencing, and interlock operations, that can use the powerful capabilities of a PLC. They are also quite frequently a cost-effective alternative to DCSs (discussed next) where sophisticated process control strategies are not needed. Nevertheless, PLCs and DCSs can be combined in a hybrid system where PLC connected through link to a controller, or connected directly to network.

4.3 Commercial Distributed Control Systems

In more complex pilot plants and full-scale plants, the control loops are of the order of hundreds. For such large processes, the commercial distributed control system is more appropriate. There are many vendors who provide these DCS systems such as Baily, Foxboro, Honeywell, Rosemont, Yokogawa, etc. In the following only an overview of the role of DCS is outlined.

Conceptually, the DCS is similar to the simple PC network. However, there are some differences. First, the hardware and software of the DCS is made more flexible, i.e. easy to modify and configure, and to be able to handle a large number of loops. Secondly, the modern DCS are equipped with optimization, high-performance model-building and control software as options. Therefore, an imaginative engineer who has theoretical background on modern control systems can quickly configure the DCS network to implement high performance controllers.

A schematic of the DCS network is shown in figure 3. Basically, various parts of the plant processes and several parts of the DCS network elements are connected to each others via the data highway (fieldbus). Although figure 3 shows one data highway, in practice there could be several levels of data highways. A large number of local data acquisition, video display and computers can be found distributed around the plant. They all communicate to each others through the data highway. These distributed elements may vary in their responsibilities. For example, those closest to the process handle high raw data traffic to the local computers while those farther away from the process deal only with processed data but for a wider audience.

The data highway is thus the backbone for the DCS system. It provides information to the multi-displays on various operator control panels sends new data and retrieve historical data from archival storage, and serves as a data link between the main control computer and other parts of the network.

On the top of the hierarchy, a supervisory (host) computer is set. The host computer is responsible for performing many higher level functions. These could include optimization of the process operation over varying time horizons (days, weeks, or months), carrying out special control procedure such as plant start up or product grade transition, and providing feedback on economic performance.

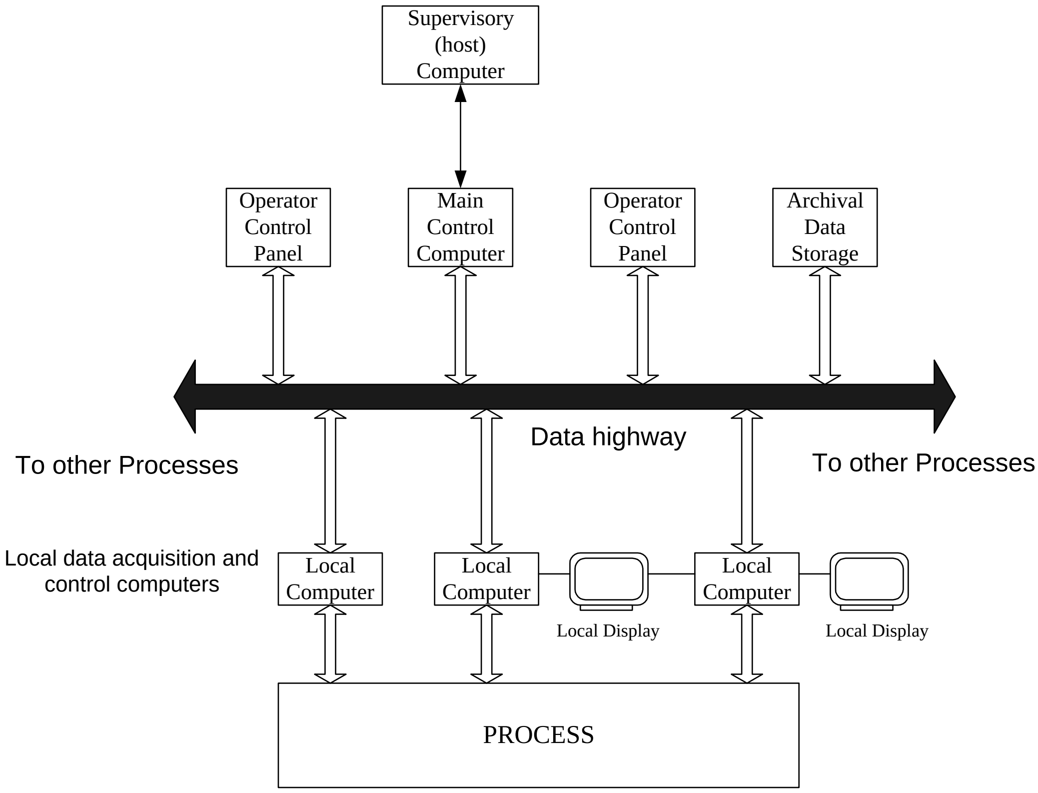

Figure 3: The elements of a commercial distributed control system network

A DCS is then a powerful tool for any large commercial plant. The engineer or operator can immediately utilize such a system to:

- Access a large amount of current information from the data highway.

- See trends of past process conditions by calling archival data storage.

- Readily install new on-line measurements together with local computers for data acquisition and then use the new data immediately for controlling all loops of the process.

- Alternate quickly among standard control strategies and readjust controller parameters in software.

- A sight full engineer can use the flexibility of the framework to implement his latest controller design ideas on the host computer or on the main control computer.

In the common DCS architecture, the microcomputer attached to the process are known as front-end computers and are usually less sophisticated equipment employed for low level functions. Typically such equipment would acquire process data from the measuring devices and convert them to standard engineering units. The results at this level are passed upward to the larger computers that are responsible for more complex operations. These upper-level computers can be programmed to perform more advanced calculations.

5. Description of the DCS elements

The typical DCS system shown in Figure 3 can consists of one or more of the following elements:

- *Local Control Unit* (LCU). This is denoted as local computer in Figure 3. This unit can handle 8 to 16 individual PID loops, with 16 to 32 analog input lines, 8 to 16 analog output signals and some a limited number of digital inputs and outputs.
- *Data Acquisition Unit*. This unit may contain 2 to 16 times as many analog input/output channels as the LCU. Digital (discrete) and analog I/O can be handled. Typically, no control functions are available.
- *Batch Sequencing Unit*. Typically, this unit contains a number of external events, timing counters, arbitrary function generators, and internal logic.
- *Local Display*. This device usually provides analog display stations, analog trend recorder, and sometime video display for readout.
- *Bulk Memory Unit*. This unit is used to store and recall process data. Usually mass storage disks or magnetic tape are used.

- *General Purpose Computer*. This unit is programmed by a customer or third party to perform sophisticated functions such as optimization, advance control, expert system, etc.
- *Central Operator Display*. This unit typically will contain one or more consoles for operator communication with the system, and multiple video color graphics display units.
- *Data Highway*. A serial digital data transmission link connecting all other components in the system may consist of coaxial cable. Most commercial DCS allow for redundant data highway to reduce the risk of data loss.
- *Local area Network (LAN).* Many manufacturers supply a port device to allow connection to remote devices through a standard local area network.

6. The advantages of DCS systems

The major advantages of functional hardware distribution are flexibility in system design, ease of expansion, reliability, and ease of maintenance. A big advantage compared to a single-computer system is that the user can start out at a low level of investment. Another obvious advantage of this type of distributed architecture is that complete loss of the data highway will not cause complete loss of system capability. Often local units can continue operation with no significant loss of function over moderate or extended periods of time.

Moreover, the DCS network allows different modes of control implementation such as manual/auto/supervisory/computer operation for each local control loop. In the manual mode, the operator manipulates the final control element directly. In the auto mode, the final control element is manipulated automatically through a low-level controller usually a PID. The set point for this control loop is entered by the operator. In the supervisory mode, an advanced digital controller is placed on the top of the low-level controller (Figure 1). The advanced controller sets the set point for the low-level controller. The set point for the advanced controller can be set either by the operator or a steady state optimization. In the computer mode, the control system operates in the direct digital mode shown in Figure 1.

One of the main goals of using DCS system is allowing the implementation of digital control algorithms. The benefit of digital control application can include:

- Digital systems are more precise.
- Digital systems are more flexible. This means that control algorithms can be changed and control configuration can be modified without having rewiring the system.
- Digital system cost less to install and maintain.
- Digital data in electronic files are easier to deal with. Operating results can be printed out, displayed on color terminals, stored in highly compressed form.

7. Important consideration regarding DCS systems.

7.1 The control loop

The control loop remains the same as the conventional feedback control loop, but with the addition of some digital components. Figure 4 shows a typical single direct digital control-loop. Digital computer is used to take care of all control calculations. Since the computer is a digital (binary) machine and the information coming out of the process in an analog for, they had to be digitized before entering the computer. Similarly the commands issued by the computer are in binary, they should be converted to analog (continuous) signals before implemented on the final control element. This is the philosophy behind installing the A/D and D/A converter on the control loop. Signal conditioning is used to remove noise and smooth transmitted data. Amplifier can also be used to scale the transmitted data if the signals gain is small. Signal generators (transducer) are used to convert the process measurements into analog signals. The most common analog signals used are 0-5 Volts and 4-20mA. Some of the process variables are represented in millivolts such as those form thermocouples, strain gauges, pH meters, etc. Multiplexers are often used to switch selectively a number of analog signals.

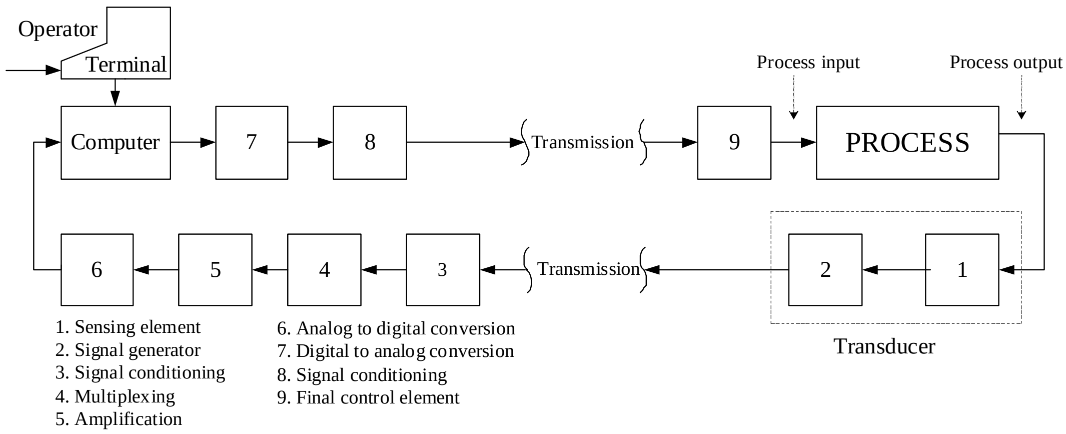

Figure 4: The component of a digital control loop

All instrumentation hardware (1-9) is designed, selected, installed and maintained by an instrumentation engineer. The computer is responsible for making decisions (control actions). It can host a simple control algorithm or a more advanced one. The latter can either purchased from a commercial vendor or developed in-house by a process/control engineer (See section 7.3). The terminal is the main operator interface with the control system. The operator can use the terminal to monitor the control performance, adjust the set points and tune the controller parameters.

7.2 The basic units of a digital computer

The digital computer used in DCS systems is a regular microcomputer with the simplified components shown in Figure 5. It includes the *arithmetic unit*, which carry out arithmetic and logic commands. The *control unit* is the part of the computer responsible for reading program statements from memory, interpreting them, and causing the appropriate action to take place. The *memory unit* is used for storing data and programs. Typical computers have Random-Access-Memory (RAM) and Read-Only-Memory (ROM). The final unit is the input/output interface. The I/O interface is necessary for the computer to communicate with the external world. This interface is the most important in the control implementation. The process information is fed to the computer through the I/O interface and the commands made by the computer are sent to the final control element through the I/O interface.

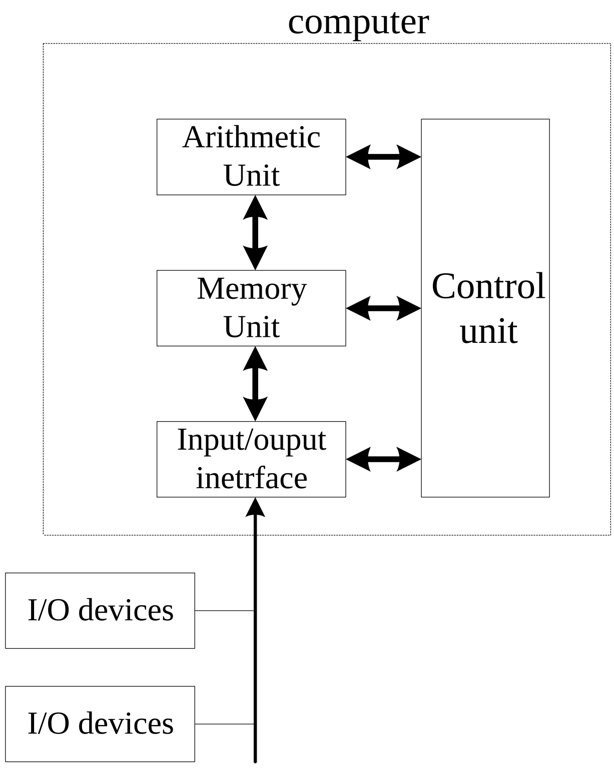

Figure 5: A general purpose digital computer

In control application, the design of the I/O devices and interface is an important part of the overall digital control philosophy. The following subsections discuss some of these issues.

7.2.1 *Information presentation and accuracy*.

The modern digital computer is a binary machine. This means that internal data and arithmetic and logic must be represented in binary format. Therefore all process information flowing into and out of the computer must also be converted to that form. Traditionally, the computer memory location is made up of a collection of bits called a word (register). A typical computer word consists of 16 bits (new computers carry 32-bits word). Consider, for example, the following machine number:

16-bit computer word: 1011001100010100

The base for this word is 2. Therefore, each bit has the following decimal equivalent:

	Bit 1	Bit 2	Bit 3	Bit 4	…	Bit 16
Machine number	0	0	0	0	…	0
Decimal equivalent	2^0	2^1	2^2	2^3	…	2^{16}

Each single bit consists of binary elements, i.e. 0 or 1. Therefore, any integer number from 0 to 7 can be represented by a three-bit word as follows:

Contents of a 3-bit word	Digital Equivalent
0 0 0	$0(2^0)+0(2^1)+0(2^2) = 0$
0 0 1	$1(2^0)+0(2^1)+0(2^2) = 1$
0 1 0	$0(2^0)+1(2^1)+0(2^2) = 2$
0 1 1	$1(2^0)+1(2^1)+0(2^2) = 3$
1 0 0	$0(2^0)+0(2^1)+1(2^2) = 4$
1 0 1	$1(2^0)+0(2^1)+1(2^2) = 5$
1 1 0	$0(2^0)+1(2^1)+1(2^2) = 6$
1 1 1	$1(2^0)+1(2^1)+1(2^2) = 7$

In this case, analog process information should be first changed to voltage or current as mentioned earlier. Then it is converted to digital form by an electronic device called analog to digital converter (A/D). Similarly, digital information is converted to analog form (Voltage or current) by a digital to analog converter (D/A). The accuracy (resolution) of such digitization process depends on the number of bits used to for representation. The degree of resolution is given by:

$$resolution = [\,full\ \text{scale range}] \times \frac{1}{2^m - 1}$$

where m is the number of bits in the representation. Obviously, higher resolution can be obtained at higher number of bits. For example, consider a sensor sends an analog signal between 0 and 1 volt and assume only a three-bit computer word is available, and then the full range of the signal can be recognized as follows:

This means that eight specific values for the analog signal can be exactly recognized. Any values interim values will be approximated according to the covered analog range shown in the fourth column of Table 1. In this way, the error in resolution is said to be in the order of 1/14. Assume now a 4-bit word is available for the same analog signal. Then the full range will be divided over 15 points, i.e. sixteen equally spaced values between 0 and 1 can be recognized, and the error in resolution will be in the order of 1/30. Most current control-oriented ADC and DAC utilize a 10 to 12 bit representation (resolution better than 0.1%). Since most micro- and minicomputers utilize at least a 16-bit word, the value of an analog variable can be stored in one memory word. New computers are capable of using 32-bit word. Therefore, new generation of ADC and DAC with higher resolution (up to 16 to 20 bit) are emerging.

Table 1: Representation of a 0 to 1 volt analog variable using a 3-bit word

Binary representation	Digital Equivalent	Analog equivalent	Analog range covered
0 0 0	0	0	0 to 1/14
0 0 1	1	1/7	1/14 to 3/14
0 1 0	2	2/7	3/14 to 5/14
0 1 1	3	3/7	5/14 to 7/14
1 0 0	4	4/7	7/14 to 9/14
1 0 1	5	5/7	9/14 to 11/14
1 1 0	6	6/7	11/14 to 13/14
1 1 1	7	1	13/14 to 14/14

7.2.2 *Process interface*

A typical plant with large number of variables contains abundance of process information (data). Therefore, process information can be classified under several classes (groups). Then a specialized device can be used to transfer all information of a specific class into and out of the computer. This way designing different I/O interface for each I/O device to be connected to the computer is avoided. In fact, most process data can be grouped into four major categories as listed in Table 2.

Table 2: Categories of process information

Type	*Example*
1. Digital	Relay Switch Solenoid valve Motor drive
2. Generalized digital	Laboratory instrument output Alphanumerical displays
3. Pulse or pulse train	Turbine flow meter Stepping motor
4. Analog	Thermocouple or strain gauge (millivolt) Process instrumentation (4 – 20 mA) Other sensors (0 -5 Volt)

The *digital input/output signals* can be easily handled because the match the computer representation format. The digital interface can be designed to have multiple registers, each with the same number of bits as the basic computer word. In this way a full word of 16-bit can represent 16 separate process binary variables and can be transmitted to the computer at one time and stored. Each bit will determine the state of a specific process input lie. For example, a state of 1 means the input is on and 0 means off or vice verse.

The *generalized digital* information usually uses binary coded decimal and ranges from 0000 to 9999. Hence, a 16-bit register can be used as interface device to transmit 4 digits of result because four-bits are necessary to represent one digit (0-9) of binary coded decimal.

In the *input pulse information* case, a single register (interface device) is designed for each input line. The register ordinarily consists of pulse counter. The accumulated pulses over a specified length of time are transferred to the computer in binary or BCD count. The *output pulse* interface consists of a device to generate a continuous train of pulses followed by a gate. The gate is turned on and off by the computer.

The *analog input* information must be digitized by ADC before fed to the computer. Since the process has a large number of analog sensing devices, a multiplexer is used to switch selectively among various analog signals. The main purpose of a multiplexer is to avoid the necessity of using a single ADC for each input line. The DAC devise performs the reverse operation. Each *analog output* line from the computer has its own dedicated DAC. The DAC is designed such that it holds (freeze) a previous output signal until another command is issued by the computer.

7.2.3 *Timing*

The control computer must be able to keep track of time (real time) in order to be able to initiate data acquisition operations and calculate control outputs or to initiate supervisory optimization on a desired schedule. Hence, all control computers will contain at least one hardware timing device. The so-called *real-time clock* represents one technique. This device is nothing more than a pulse generator that interrupts the computer on a periodic basis and identifies itself as interrupting device.

7.2.4 *Operator interface*.

The operator interface is generally a terminal upon which the operator can communicate with the system. Such terminals usually permit displaying graphical information. Often these display consoles are color terminals for better visibility and recognition of key variables. The operator will use the keyboard portion of the terminal to perform specific tasks. For example, the operator can type in requests for information or displaying trends, changing controller parameters or set points, adding new control loop, and so on.

7.3 Digital control software

To make the best use of a DCS system, an advance control strategy or supervisory optimization can be incorporated in the main host computer. In the past, computer control projects are written in assembly language, an extremely tedious procedure. Nowadays most user software is written in higher-level languages such as BASIC, FORTRAN, C etc. In many cases, the user is able to utilize the template routines supplied by the vendor, and is required only to duplicate these routines and interconnect them to fit his own application purposes. Another way is to write his own complete control program and implement it.

Other software in the form of control-oriented programming languages is supplied by the vendor of process control computers. A simpler approach for the user is to utilize vendor-supplied firmware or software to avoid writing programs. Currently, most DCS manufacturers develop their own advance control and optimization software, which can included in the package as options. Similarly, many control algorithm developers; (DMC, ASPEN, etc) design a special interface to allow incorporating their own control programs into most of the commercial DCS network.

8. Conclusion

Digitally-based control instrumentation represents a revolutionary change in the process control paradigm. With digital systems the control engineer has the opportunity to go beyond the narrow limitation of standard analog control components to construct a system that is optimum for the information processing and control requirements of large processes or even of entire plants. This is why many industrial plants are updating their hardware and instrumentation systems bearing in mind that the payout times for installation and commissioning costs is as a low as three to four months.

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