3.2 Controllers—Electronic

Types:	Analog, digital.
Applications:	Single-loop or multi-loop; single or multi-variable.
Control Modes:	Analog: Manual, two-step (on/off), multi-step, proportional (P, throttling), integral (I, reset), derivative (D, rate), cascade, selective, feed forward, limiting, ratio and adaptive. Digital: all types listed for analog, plus multi-variable interactive, model based, neural and fuzzy logic.
Input Ranges:	4 to 20 mA (most common), 0 to 20 mA, 0 to 10 V, 2 to 10 V.
Typical Output Range:	4 to 20 mA.
Displays:	Set point, controlled (process) variable, manipulated (output) variable, deviation, alarms, limits.
Typical Front Panel Size:	1/32 DIN (1.89 in. × 0.95 in. [48 mm × 24 mm]), 1/16 DIN (1.89 in. × 1.89 in. [48 mm × 48 mm]), 1/8 DIN (1.89 in. × 3.78 in. [48 mm × 96 mm]), 1/4 DIN (3.78 in. × 3.78 in. [96 mm × 96 mm]).
Supply:	AC: 24, 120, 230 V. DC: 12 V.
Inaccuracy:	Analog: 0.5 to 1% of span; Digital: from under 0.1 to 0.5% of span (zero $< 0.2\%$; gain $< 0.1\%$).

INTRODUCTION

Electronic controllers can be analog or digital. Analog controllers are real-time devices that operate on continuous analog signals. The operation of digital controllers is software-based and implements control algorithms, which are very fast but still are intermittent devices in comparison to their analog counterparts. Analog electronic controllers are cheaper than their digital counterparts when the control requirements are small (e.g., single control loop and simple on/off or plain proportional control algorithms).

Digital controllers are more complex because they need (1) to convert analog input signals to digital ones before they can be processed and then to convert the digital output signals back to analog and (2) because digital controls and displays are usually more expensive. In spite of the relative costs favoring analog designs when the control requirements are minimal, the trend is clearly in favor of the digital design, not only because of its flexibility, superior performance, and communications abilities, but also because of its relative economy in case of large control systems.

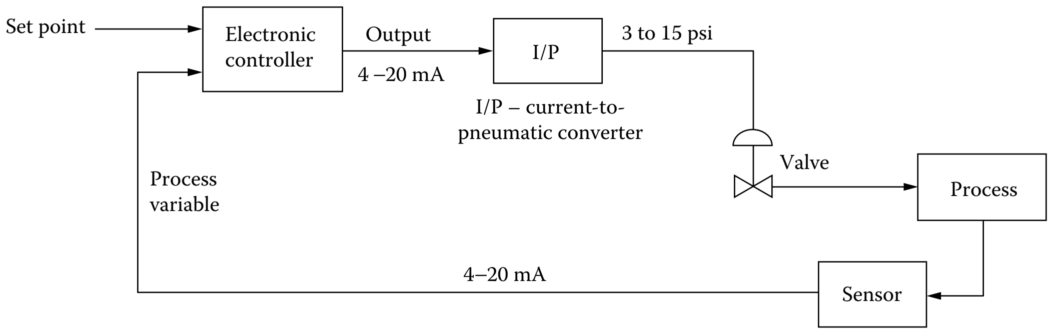

FIG. 3.2a
The main components of an electronic process control loop with a pneumatically operated control valve, which necessitates the use of a current-to-air (I/P) converter.

ANALOG ELECTRONIC CONTROLLERS

Today, analog electronic controllers are solid-state electronic instruments using operational amplifiers. The amplifiers have high gain, high input impedance, very low offset, and high common-mode rejection. When mounted locally, they must be protected against the environment, and they require special care in selecting the controller's components and packaging.

The majority of analog electronic controllers are used to implement the less sophisticated control algorithms (on/off, P, PI, PID, cascade, ratio, etc.) usually in single control loops that are measuring only one process variable. Sometimes, they are also used as backup (for computer failure) of critical loops in systems that are controlled by multi-loop digital controllers.

As shown in Figure 3.2a, an analog electronic controller receives the controlled process variable from a 4- to 20-mA electronic transmitter, compares that signal to its set point and generates a 4- to 20-mA output based on its control algorithm. This signal is converted into a 3- to 15-PSIG pneumatic signal if the manipulated element is an air- operated throttling valve.

Analog On/Off Switch

Figure 3.2b shows the block diagram of an analog based on/off electronic switch. (For a discussion of regular field mounted on/off switches refer to Volume 1 of this handbook and for panel- or console-mounted switches, see Chapter 4 in this volume.)

In Figure 3.2b, the 4- to 20-mA to voltage conversion is achieved by inserting a resistor into the current loop. The isolation amplifier serves to provide the separation between the transmission loop and the on/off controller electronics. The voltage switch provides the means for switching from direct to reverse action. In the direct mode, the in- and outputs move in the same direction, while in the reverse mode an increase in the controlled variable (input) results in a drop in the manipulated variable (output).

In Figure 3.2b, the hysteresis of the voltage comparator (Schmitt trigger type) provides an adjustable dead band to reduce the duty or rate cycle. Voltages at the switch inputs and comparator's output can be used to monitor set point, controlled variable, and manipulated variable values. The set point may be provided either (1) locally using a dc power supply and a voltage divider, or (2) by the output of another controller (cascade control) or (3) by a remote source.

For the manual control of the loop, the input of the voltage to a 4- to 20-mA converter must be disconnected from the comparator output and connected to the remote and adjustable dc supply (e.g., a power supply and a adjustable voltage divider).

Analog PID Controller

PID control algorithms are used on processes with multiple capacities and large and/or fast-changing loads. The output of the PID controller (E_o), which is also called the manipulated variable (m), is a function of the difference between the controlled variable and the set point or error (e). The classical

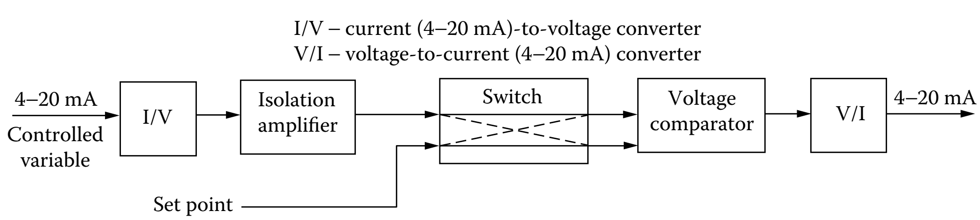

FIG. 3.2b
ON/OFF analog electronic controller.

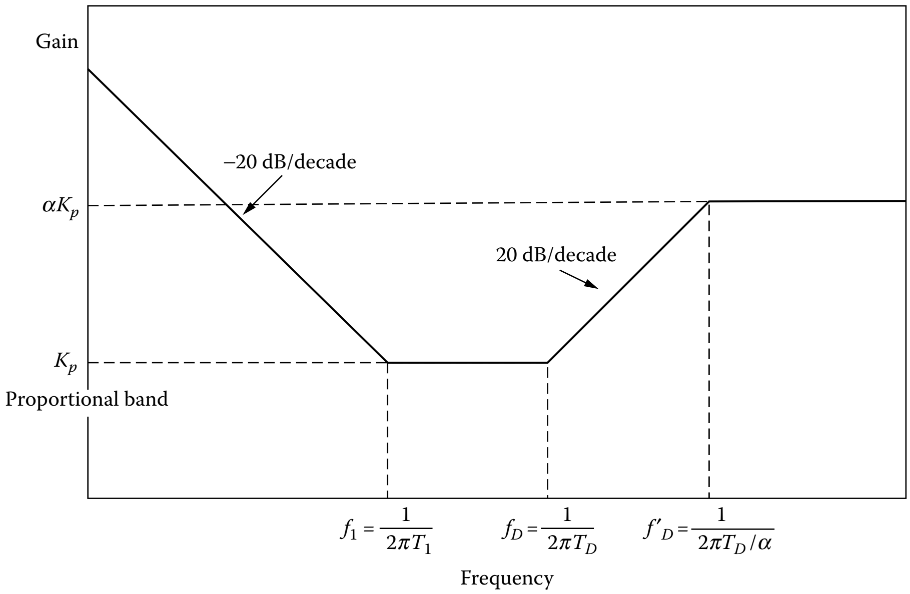

FIG. 3.2c
Bode representation of the PID controller algorithm corresponding to Equation 3.2(3).

differential equation relating the two is:

$$m = E_o = K_P e + K_D \frac{de}{dt} + K_I \int e\,dt \qquad \textbf{3.2(1)}$$

where K_P is the proportional gain, K_D the derivative time, and $1/K_I$ the integral time. The transfer function $G(s)$, which relates E_o with e in the frequency domain, is obtained by Laplace transformation of Equation 3.2(1) yielding:

$$G(s) = K_P\left(1 + T_D s + \frac{1}{T_I s}\right) \qquad \textbf{3.2(2)}$$

where $T_D = K_D/K_P$ and $T_I = K_P/K_I$. Most analog electronic PID algorithms are not this noninteracting variety in the time domain but rather in the frequency domain:

$$G(s) = K_P\left(\frac{1 + T_I s}{T_I s}\right)\left(\frac{1 + T_D s}{1 + (T_D/\alpha)s}\right) \qquad \textbf{3.2(3)}$$

where K_P = 100/PB, (PB is proportional band), $T_D = K_D/K_P$ is a rate (derivative) time, $T_I = K_P/K_I$ is a reset (integral) time, and α is the derivative gain, usually between 5 and 20, that ensures that the output does not change significantly in response to electrical noise (incomplete derivative controller). The Bode frequency-response of this equation is presented in Figure 3.2c.

PID Components Figure 3.2d shows one possible implementation of a PID analog electronic controller. In this figure, IA is a very-high-input impedance amplifier that amplifies the difference between the controlled (process) variable and the set point. If the controlled variable and the set point are equal, the output of the IA (the error, e) is equal to the reference voltage. The same objective can be obtained with an operational amplifier in a difference configuration, but because the voltage that is to be amplified is floating, the

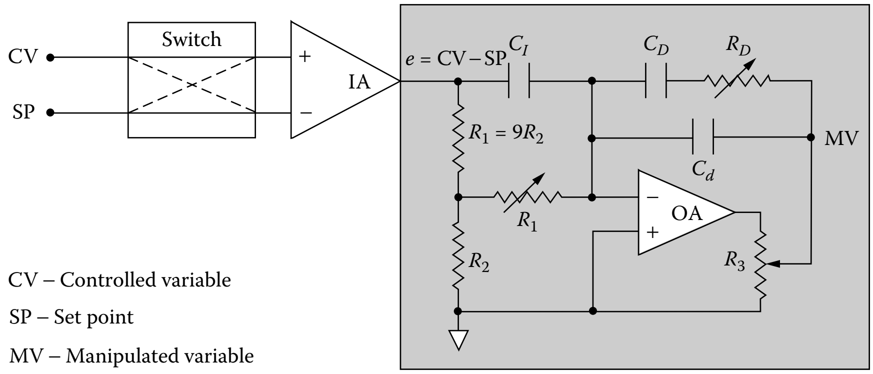

FIG. 3.2d
PID analog electronic controller circuitry including an error amplification stage.

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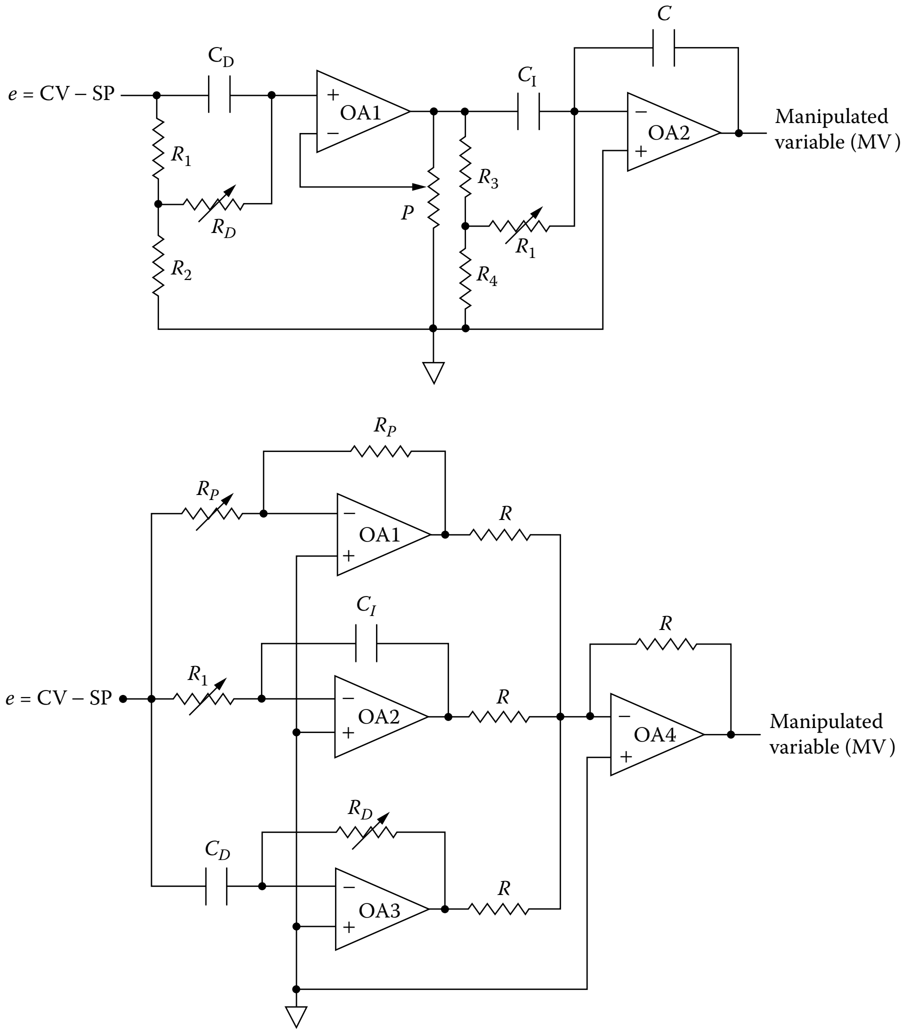

FIG. 3.2e
Operational blocks of two PID controller algorithms corresponding to Equation 3.2(3) (top) and Equation 3.2(1) (bottom).

higher common-mode rejection ratio of instrumentation amplifiers suits this application better.

The switch is in front of the instrumentation amplifier and serves to implement the direct or reverse action of the controller. As shown in Figure 3.2b but not in Figure 3.2d, a current-to-voltage converter and an isolation amplifier would complete the path of the controlled variable to the switch input.

OA is a very high-impedance operational amplifier. The transfer function of this amplifier configuration conforms to Equation 3.2(3). $R_I C_I$ define the reset time constant that determines f_I on the Bode plot of Figure 3.2c. R_1 and R_2 divide the error voltage by 10 so that R_1 is 1/10 of the value required to obtain the same time constant if this voltage divider were not used. The rate time constant of the controller is set by the combination of R_D, C_D, and C_d.

These components determine the lead or lag at f_D and f_d on the Bode diagram of Figure 3.2c. The voltage divider R_3 adjusts the feedback voltage (proportional-band adjustment), the minimum feedback voltage corresponding to the highest gain. Voltage-to-4- to 20-mA conversion, not shown in Figure 3.2d, is usually implemented by feeding the output voltage to a current amplifier.

Figure 3.2e shows two circuits that can also be used instead of the one inside the shaded box of Figure 3.2d for PID analog electronic controller implementation. The top one also implements Equation 3.2(3) while the one on the bottom implements Equation 3.2(1).

Both controllers, which are described in Figures 3.2d and 3.2e, implement PID algorithms that act on the deviation or error. As it is discussed in more detail in Chapter 2, there are several other options as a function of the controlled process. Figure 3.2f shows an algorithm implementation where the derivative mode acts on the measurement (derivative-in-front PID), which tends to speed up the return to set point in some processes.

Displays and Communications In an analog electronic controller the values of set point, controlled variable, deviation, and manipulated variable are represented by the amplitudes of slowly varying electric voltages. Indicating dc analog voltmeters

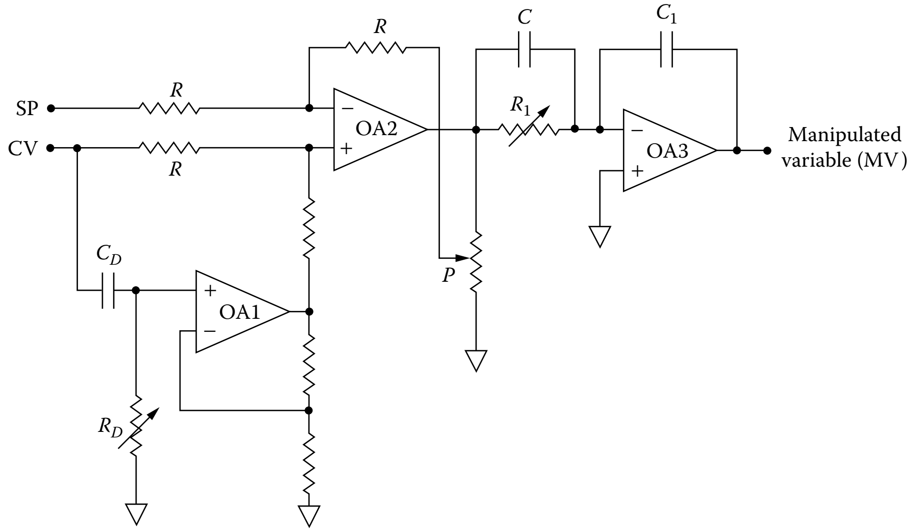

FIG. 3.2f
Operational block of a PID analog electronic controller where the derivative mode acts on the measurement instead of the error.

(e.g., D'Arsonval type) with scales graduated either in units of the process variable or more often in percentage of the span are used for monitoring these values. Abnormal conditions are signaled by voltage- or current-operated sound alarms. Even in analog controllers, the low price of numeric, alphanumeric, and bar graph displays and of their respective circuit drivers favors their use.

One feature that is common in today's analog electronic controllers is the capability for digital interfacing. Interfacing circuits and boards for serial communication, such as RS485, are quite inexpensive, available from different vendors, and fairly easy to incorporate in the controller. As already mentioned, this feature is decisive when the controller is to be integrated into a distributed or supervised control system.

Reset Windup Any controller that has an integral mode will saturate when a deviation between the controlled variable and the set point persists. This is because the reset capacitor in the controller will continue to charge so long as the error exists. This phenomenon is called integral or reset windup and is important in process phases during which the controller is switched to manual. This is the case, for example, after startup, where the controller can saturate its output before it is switched into automatic. Problems resulting from reset windup can be minimized by including circuitry that limits the output voltage of the reset amplifier.

Automatic-to-Manual Switching The manipulated variable (controller output) should stay constant while switching from the automatic to the manual mode of operation and vice versa, because any sudden change in this signal will upset (bump) the process.

One possible way to obtain bumpless transfer is to use a switch that is controlled by voltage transition and is enabled by pressing the front panel button, which commutates only if a comparator circuit detects that the output voltage of the manual operation block crosses the controller output voltage. In this design, if the output of the manual operation block changes very quickly, a bump may still occur.

To avoid this problem, slewing buttons (step-up, step-down) are used for manual adjustment. Controllers provided with automatic commutation means are sometimes called procedureless controllers.

Stability In analog electronic controllers the feedback amplifiers and feedback networks must be carefully designed to ensure that the controller is stable under all operating conditions. Drift due to component leakage is also a problem to overcome. Currents even as low as some nanoamperes can still produce significant output drift due to the extremely large time constants and very high input impedance of the amplifiers. Thus, it is important to carefully select not only the components of the operational amplifier but also the design of the circuit's layout.

DIGITAL ELECTRONIC CONTROLLERS

Computers of medium and large size are used in process control, while local digital controllers are mainly microprocessor based. Initially, microprocessor-based controllers were developed to control more than one loop, which reduced the per-loop cost. Nowadays, however, the price of microprocessors has dropped to a level that allows their usage in both multi-loop and single-loop controllers.

Other processing structures available to support the implementation of digital controllers are programmable logic devices (PLDs), namely, field-programmable gate arrays (FPGAs). Control algorithms such as PID can be implemented in FPGAs.[1] Nevertheless, FPGA-based digital process controllers are still rare because in many aspects they are outperformed by microprocessor-based controllers.

Performance

Digital controllers outperform analog controllers in several aspects. The accuracy of a digital controller is mainly dependent on the performance of the analog-to-digital (A/D) and the digital-to-analog (D/A) converters it incorporates. Thermal, drift, nonlinearity, and hysteresis errors are minimized in digital controllers, which result in errors of 0.1% or less of the span.

The sophistication and number of available control algorithms and number and topology of control loops and special functions (alarm, totalizing, display) that can be implemented with digital controllers, and the low cost or minimal additional hardware required to do so, are factors in favor of this type of controller. Digital controllers with such options are usually less expensive than the equivalent analog controllers.

Communication Capabilities

Digital techniques allow more information to be transmitted faster and with fewer errors than does analog communication. In addition, a digital controller can easily communicate with a digital computer.

The expected lifetime of local electronic controllers is typically 10 years. Integrated circuits (ICs) are the basis of electronic controllers and, due to the fast rate of development in this domain, some ICs become obsolete in a few years or even less. This is particularly true with digital components that support digital controllers. On the other hand, local controllers operate sometimes in harsh environments.

Microprocessor-Based Controllers

For many years, the name microprocessor was associated with a digital system composed of a central processor unit (CPU), memory, and input/output. The term microprocessor was introduced in 1972 by Intel to designate a large-scale integrated (LSI) circuit with the central processor unit functions of a computer implemented by Intel.

Following Intel's terminology, the microprocessor is viewed as central processor unit and the expression *microprocessor-based controller* refers to any digital electronic controller that is implemented around a CPU. This terminology applies to all digital process controllers, programmable logic controllers (PLCs), micro-controllers, and microcomputers. DCS systems are discussed in Chapter 4 and PLCs in Chapter 5 of this handbook. Here we concentrate on microcontroller—and microcomputer-based electronic controllers that can be mounted locally in the plant.

Operation

In contrast to analog controllers, which operate continuously, digital controllers implement their control algorithms in a batch mode. The CPU, which is the heart of the digital controller, operates sequentially in cycles. The cycles include the steps of process data collection and preprocessing (e.g., linearization), if necessary, calculation of the new value of the manipulated variable, and checking for alarm functions and limits before the new value of the manipulated variable is returned to the analog domain.

The displays are also updated during each cycle. This requires the calculation of engineering values of the controlled variable and the set point, the calculation of other process parameters, and the actualization of the display. This cycle of procedures repeats at rates from 0.05 to 0.5 s, typically 0.1 s. In other words, the process is evaluated and the output of the controller is updated 10 times per second.

This means that a digital controller with a single CPU is not in touch with the process except in the instants of sampling. Thus, the controller is not aware of all events that occur during the cycle. Therefore, all events that need to be continuously monitored must be latched by dedicated hardware for later processing. The communications between the controller and other instruments are handled either by using the time when the CPU is idle between the end of one cycle and the beginning of the next or on an interrupt basis.

Hardware

Microprocessor-based process controllers are data acquisition and processing systems with analog output capabilities. Figure 3.2g shows a block diagram of such a controller. It consists of an analog-to-digital conversion block, a digital-to-analog conversion block, a micro-processing block, a display and controls section, and a communications port. The micro-processing block includes not only the processing element (CPU) but also the memory. Memory used for program storage is of the read-only type (ROM); memory for temporary data storage is of the random-access type (RAM). In addition, the controller has two output ports, one of the serial type for communications and another of the parallel type with individually addressable lines.

The conditioning and analog-to-digital conversion block of the controller provides the processor with the set point and controlled variable values for the control algorithm. The conditioning part of the block provides the interfacing between the controller's input signals and the analog-to-digital conversion section and thus its design depends on both.

The remaining components include an analog multiplexer, a programmable-gain amplifier, a sample-and-hold and an analog-to-digital converter (ADC). The CPU controls these components. The ADC must be chosen taking into account the accuracy and resolutions required for the controller and the conversion rate used.

For ADCs, two good choices are the dual-slope and the successive approximation designs. The first is of the averaging type and thus is less influenced by noise while the second can be implemented using the controller's CPU and few additional components.

Sensors with frequency output (e.g., measurand range converted into a 10- to 50-kHz frequency range) are becoming more and more popular, and some microprocessor-based

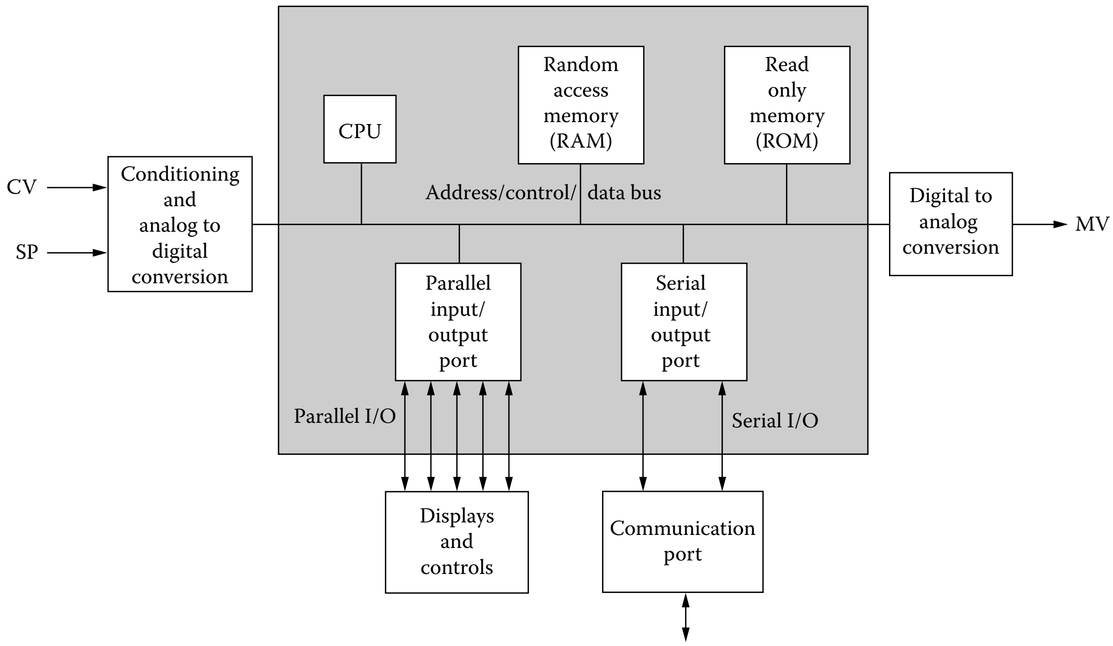

FIG. 3.2g
Typical hardware block diagram of a microprocessor-based process controller.

controllers are able to directly interface with them. In this case, the analog-to-digital conversion is easier because it depends on pulse counting, and thus the analog-to-digital conversion block is not required.

The function of the digital-to-analog conversion (DAC) block is to convert the calculated value of the manipulated variable into a dc voltage or current. DACs use an R-2R resistor ladder network whose natural output is a current. Some manufacturers also offer digital controllers with air pressure output.[2]

Displays and Communications Digital displays with either a bar graph and a digital readout that provide the variable values in engineering units are both good choices since they allow fast reading of values and also fast detection of abnormal conditions.

For adjusting digital controllers, switches, pushbuttons, keyboards, and joysticks are the natural replacements for potentiometers because they are more accurate to input data and easier to read. Figure 3.2h shows the face plates of three microprocessor-based controllers, which all have these types of displays. As a rule, displays and controls are connected to the parallel port of the processing block.

Communication between the controller and other systems is in serial formats to minimize wiring. The serial port of the processing block interfaces the processor buses, but the remaining of the transmission and communication channel can and is implemented in several different ways, some standardized others not, which makes interconnection of equipment from different manufacturers difficult if not impossible.

It is true that several manufacturers offer controllers that are compatible with standard hardware interfaces. Unfortunately, most suppliers provide only the minimum information a user needs to establish communication with other equipment. What is even worse is that in many cases the user has to configure or even has to program the equipment (e.g., computer) to code and decode the commands and data communicated by the controller.

The diversity of solutions is undesirable for users, but to date the definition and general acceptance of a single standard has been resisted by manufacturers. The existence of several fieldbuses is another example of lack of standardization. Nevertheless, some attempts have been made to standardize communications in control systems. The IEEE 1451 series of standards[3] is a good example, but it has had little success to date.

Micro-Controllers and Backup Power In the micro-processing block in Figure 3.2g, the CPU and the other components are separately shown. This corresponds to the architecture of a microcomputer. When the CPU, memory, and I/O are integrated into one circuit chip, the processor unit is called a micro-controller.

Microcomputers and micro-controllers differ also in other aspects. Microcomputers run at higher clock rates, have larger memory blocks, and are easier to program. For these reasons, microcomputers are presently better suited for process control applications. Nevertheless micro-controllers, which were initially designed to operate as embedded systems, are growing in complexity and functionality.

Some micro-controllers today can not only perform as a microcomputer but can also include, in the single chip, a variety of additional functions. These include analog-to-digital and digital-to-analog conversion, memory arrays, both of RAM

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FIG. 3.2h
Front panel view of microprocessor-based controllers: temperature (upper left), general-purpose single-loop or cascade (bottom) and multi-loop (Courtesy of Foxboro Co. and Smar International.)

and of electrical alterable or erasable programmable read only memory (EAPROM, EEPROM), of reasonable sizes and advanced input/output capabilities (e.g., "high" power signal handling). Micro-controllers are inexpensive (less than $10) and thus potentially interesting as hardware support for digital process controllers.

Some processes require control modes and algorithms involving a heavy arithmetic workload and thus fast memory access or heavy data transfer. In those cases, the processing block must use special processors called digital signal processors (DSPs).

The operating parameters of a digital controller are entered by the operator and must be stored in the memory. It is good practice to provide backup power, so that the stored data are not lost and do not need to be reloaded after a power interruption (nonvolatile memory).

Possible solutions are: (1) incorporation of a long-life or rechargeable battery in the controller to maintain power to the RAM during loss of primary power, (2) use of EAPROMs or EEPROMs for parameter storage. Since the number of write/erase cycles in EAPROMs and EEPROMs is limited, the lifetime of this last solution may prove to be incompatible with the expected lifetime of the controller.

Software

The standard control algorithm for process control still is the PID algorithm. Its velocity algorithm is:

$$u_{n\Delta t} = u_{(n-1)\Delta t} + K_P \begin{pmatrix} (e_{n\Delta t} - e_{(n-1)\Delta t}) + \dfrac{\Delta t}{T_I} e_{n\Delta t} \\ + \dfrac{T_D}{\Delta t}(e_{n\Delta t} - 2e_{(n-1)\Delta t} + e_{(n-2)\Delta t}) \end{pmatrix} \qquad \mathbf{3.2(4)}$$

where $u_{n\Delta t}$ is the controller's output in sampling instant $n\Delta t$ (current value); $u_{(n-1)\Delta t}$ is the controller's output value in sampling instant $(n-1)\Delta t$ (previous value); $e_{n\Delta t}$, $e_{(n-1)\Delta t}$, and $e_{(n-2)\Delta t}$ are deviations at sampling instants $n\Delta t$, $(n-1)\Delta t$ and $(n-2)\Delta t$, respectively; K_P, T_I, and T_D are the proportional gain, integral, and derivative times, respectively; and Δt is the time interval between samples.

In the velocity algorithm, integral is replaced by addition, and the simplification leads to a requirement of calculating only the change that has occurred in the error since the last sampling; the change in error is weighted by the appropriate constants.

The performance of a microprocessor-based controller naturally depends on its hardware. Nevertheless, it is the software component that ultimately dictates the controller's capabilities. The controller's cost reflects this. The same hardware may support controllers with different specifications and different prices.

General-purpose digital controllers are designed to meet the expectations of a broad spectrum of users rather than fully exploiting the capabilities of the hardware. Direct signal processor (DSP)-based controllers, for instance, can be programmed for almost anything, including linearization, compensation for valve and actuator characteristics, a variety of control modes (including batch control), and a variety of algorithms, both linear and nonlinear, self-tuning and self-optimization. Many of these features do not require the computation power of a DSP and can be easily implemented with basic processing hardware.

The suitability of a microprocessor-based controller for a specific application depends not only on the algorithms it contains, but also on their implementation and parameter adjustment capabilities. Since most controllers have no or just some extremely restricted reprogramming capabilities, the user should study their capabilities before purchasing. This is particularly the case with batch process control, where the control algorithm is usually dependent on several variables.