DIGITAL INSTRUMENTS

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Summary

In the field of process control and supervision, the design of devices to carry out the monitoring and control of processes is of primary importance. Monitoring and control

functions require the use of instruments to measure process variables. Once the process variables have been monitored, they can be presented to computers or other supervisory systems to take the necessary actions to control the process. The design of monitoring and control systems can be achieved in two different ways:

- using analog instruments which deal directly with analog signals, and
- converting the analog signals into digital forms and then implementing the systems using digital instruments.

In this article all the relevant aspects related to the second approach are presented.

The key feature of digital instruments is the conversion of signals from analog into digital forms and *vice versa*. This article begins by explaining the basic concepts related to signal conversions and the associated circuits that carry out operations. Nevertheless, in addition to analog-to-digital and digital-to-analog conversion, other operations (such as sampling) are essential to make the use of digital instruments feasible. The whole system that carries out all these operations is known as the *data-acquisition system*. The basic functions of these systems and the theoretical foundations of their operation are presented in this article.

One crucial advantage of digital information is that it can be managed and communicated much more easily and reliably than analog information. The main protocols and standards utilized in the communication of digital instruments are reviewed here.

In the last part of the article two examples of digital instruments are described: the digital oscilloscope and the digital power recorder. The use of computers in the testing and development of digital instruments is also analyzed. This topic is known as *virtual instrumentation*. The article concludes by indicating some relevant future research directions with regard to this subject matter.

1. Introduction

In the field of process control and supervision, the design of devices to carry out the monitoring and control of processes is an activity of primary importance. In this field two types of devices can be found:

- *Monitoring devices* to display and record the values of process variables. The display of the variables is carried out on-line. The objective of this exercise is to inform the process supervisor about the state of the process at all times. Variable recording is oriented towards storing the information about the process in order to analyze its behavior off-line when necessary.
- *Control devices* to act on processes in order to control their variables.

On many occasions, however, monitoring and control functions are both combined in the same device.

Monitoring and control functions require the use of instruments to measure the process variables, to present them to the supervisor, and to carry out the necessary actions to control these variables. In Figure 1 the main instruments utilized in monitoring and control of a process are shown. *Sensors* are used for sensing the variables of the process, and are essential to both monitoring and control. The *display* and *recorder* instruments carry out monitoring functions: the display is used for visualizing the values of process variables, while the recorder stores these values. The *controllers* carry out the control functions, calculating the degree and order of control strategy for the *actuators.* The actuators set and control the process variables. Actuators can be many different types: for example valves, thermostats, stepping motors, and other devices.

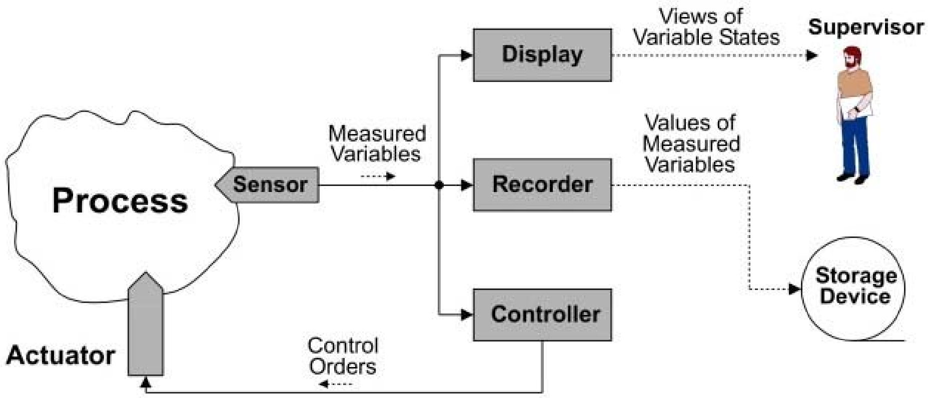

Figure 1. Instruments for monitoring and controlling a process

The sensors used for measuring process variables normally produce analog voltage or current signals. These signals therefore become the input for any control or monitoring system. However, the control and monitoring systems can be designed in two ways:

- by using analog instruments to deal directly with the analog signals, or
- by converting the analog signals into the digital signals, and implementing them by means of digital instruments.

The second approach offers crucial advantages, particularly if the system is complex. The main reason for this is that digital systems are based on digital processors, and these devices provide powerful capabilities for signal processing and handling. In addition, using only one processor many different functions can be carried out by suitable software implementation. Another important advantage of digital systems is that a signal, once has been converted to digital format, can be managed by all kinds of digital computers. This provides a wide range of possibilities for signal communication, storage, and visualization, as well as the scope for distributed operation in large systems. In Figure 2 the monitoring and control of a process using digital instruments is illustrated. Sensors measure process variables producing analog signals. Then an electronic circuit, termed the *analog-to-digital converter* (ADC), converts the analog signals into digital forms that can be stored in the memory of the computer. The computer also carries out the monitoring and control functions. For example, it can store the signal for off-line analysis or display the values on-line, and use these values to calculate the control actions for the process. The computer determines the control actions in digital formats. Many actuators are analog devices, however, in which case the control actions must be converted from digital to analog format. This operation is carried out by another electronic circuit called the *digital-to-analog converter* (DAC).

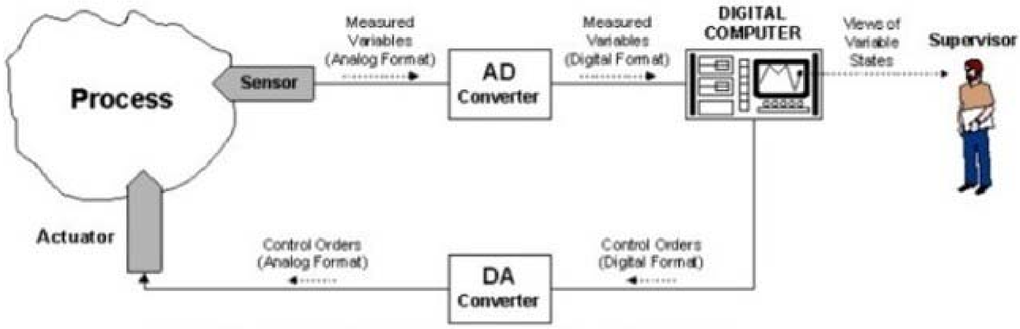

Figure 2. Process monitoring and control using a digital computer

In summary, the most important beneficial aspects of digital instrumentation are:

- conversion between analog and digital signals is possible in both directions, that is, analog-to-digital and digital-to-analog; and
- digital computers offer greatest flexibility in managing the signals in digital format.

These basic aspects of digital instrumentation will be discussed in the rest of this article.

2. AD and DA Signal Conversions

The conversion of the analog signals into digital forms involves representing the analog values in digital numbers as a sequence of n bits. The conversion is carried out in two steps: quantization and coding. *Quantisation* means representing the continuous analog signals using a set of discrete values, while *coding* involves representing these discrete values using bit sequences. The number of bits in these sequences determines the number of possible values of the conversion: 2^n for n bits. The quantization and coding processes are carried out by an ADC device. An ADC operates on signals with determined amplitudes, for example between –V and V volts. Therefore, if the ADC uses n bits to carry out the conversions, the continuous values of the analog signal must be converted using a set of 2^n discrete steps, and the step size will be $2V/2^n$.

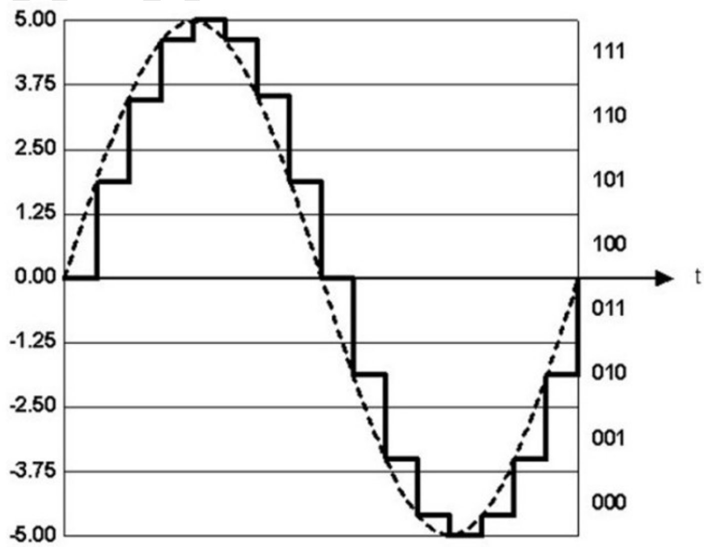

Figure 3. Sinusoidal signal and its digital version using a conversion of three bits

In Figure 3, a sinusoidal analog signal and its digital version generated by an ADC are shown. The ADC of the figure operates between –5 V and 5 V and uses three bits for the conversions: the output of the ADC will have eight possible output values, represented by the codes from 000 to 111. As the range of operation of the ADC is 10 V, each code will represent an interval of amplitudes of 10 V/8 = 1.25 V. Thus, for example, any value in the interval [–5, –3.75] is assigned the code 000, as shown in the figure.

The conversion from digital into analog signals is carried out by a DAC. This device converts digital codes of n bits into a signal of 2^n discrete levels of voltages or currents.

Both DA and AD converters can be implemented using different design principles. In the following subsections examples of both types of converters are presented.

2.1. DA (Digital-to-Analog) Converters

Figure 4 shows a typical design of an n-bit DAC. It is made up of four main elements: a set of n latches, a resistor network, a voltage reference, and an operational amplifier. The set of latches holds the binary number to be converted to an analog voltage signal. The output of each latch controls a transistor switch that is associated with a determined resistor in the resistor network. The voltage reference, connected to the resistor network, controls the range of the output voltage. The operational amplifier works as an additional circuit. For each one of the resistors in the network, when the corresponding switch is on the operational amplifier adds a voltage to V_{out} inversely proportional to the value of the resistor and directly proportional to the reference voltage and the feedback resistor (R). For example, for the $2R$ resistor the operational amplifier adds the following value to V_{out}:

$$V_{out} = V_{ref}\ \frac{R}{2R} = \frac{V_{ref}}{2} \qquad (1)$$

The total value of V_{out} can be calculated by the following formula:

$$V_{out} = V_{ref}\left(\frac{D_{n-1}}{2} + \frac{D_{n-2}}{4} + ... + \frac{D_1}{2^{n-1}} + \frac{D_0}{2^n}\right) \qquad (2)$$

where D_{n-1}, D_{n-2}, and so on, represent the values of the bits of the binary number to be converted. In this formula, each active bit contributes to V_{out} with a value proportional to its weight in the binary number, and thus the output voltage generated by the DAC is proportional to the value of the input binary number.

The main drawback presented by the DAC shown in Figure 4 is the wide range of resistors with precise values that are required to give the correct weights, leading to difficulties in manufacturing. A solution may be found by using an alternative circuit requiring fewer resistors, and by using standard resistances with set values. One solution is based on substituting the resistor network in Figure 4 by an R-2R network that only uses two resistor values (R and 2R). This solution is fully equivalent to that represented in Figure 4, but is easier to make.

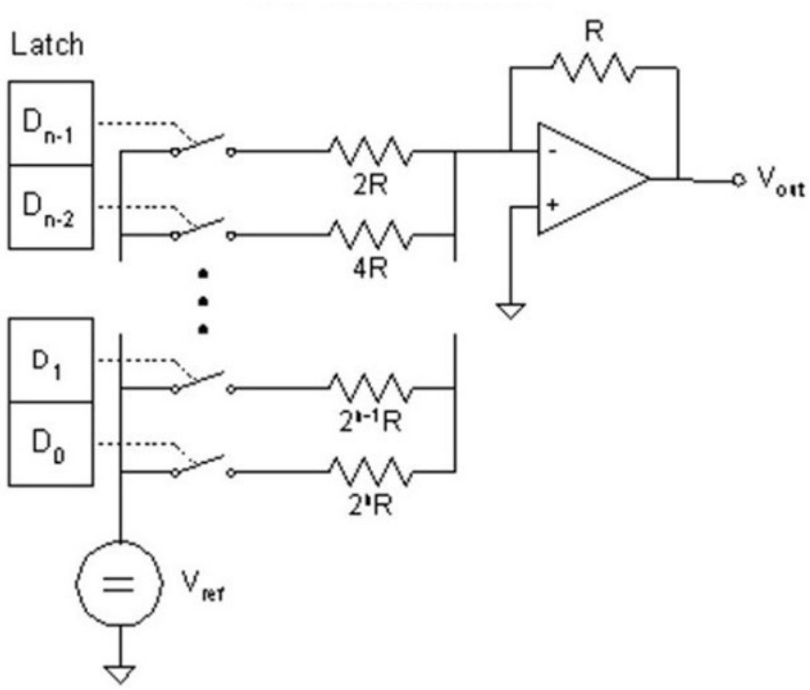

Figure 4. Basic DAC design

2.2. AD (Analog-to-Digital) Converters

A variety of circuits and techniques are available for use in AD conversion. The most common application in ADCs is the integration technique to carry out the conversion function. However, there are also other types based on different approaches, such as the parallel or flash converters.

The widely utilized *successive approximation* technique is used by one ADC design. Figure 5a shows the basic design of a successive approximation ADC. The analog input to this system is successively compared with the voltage generated by a DAC. The digital input to the DAC, which is stored in the *successive approximation register* (SAR), is adjusted according to the result of each comparison. If the converter is of *n* bits, the conversion process requires *n* comparisons, and the result of the final conversion value is stored in the SAR.

Figure 5b shows the conversion process involving a value of an analog input. Only the calculation of the five most significant bits of the digital output is shown. The first comparison is carried out with the binary number 10 … 00, which is stored in the SAR. Then, as the analog input is greater than the voltage generated by the DAC with this number, the most significant bit of the SAR is held in “1.” Once the first step is finished, a new comparison is carried out. Then the following bit (the second) of the SAR is set to “1.” At that moment the binary number in the SAR is 1100 … 00. Consequently, the value of the analog input is greater than the voltage generated by the DAC, so the second bit of the output is set to “0.” This process continues until the *n* bits of the output are calculated.

Other types of converters are:

- the *counter* or *tracking ADC*, based on the use of a DAC and a counter to generate the conversion;
- the *dual-slope integrating ADC*, based on integration techniques; and
- the *parallel or flash ADC*, which is used when very high speed conversion is required, as in the case of video, radar and digital oscilloscope applications.

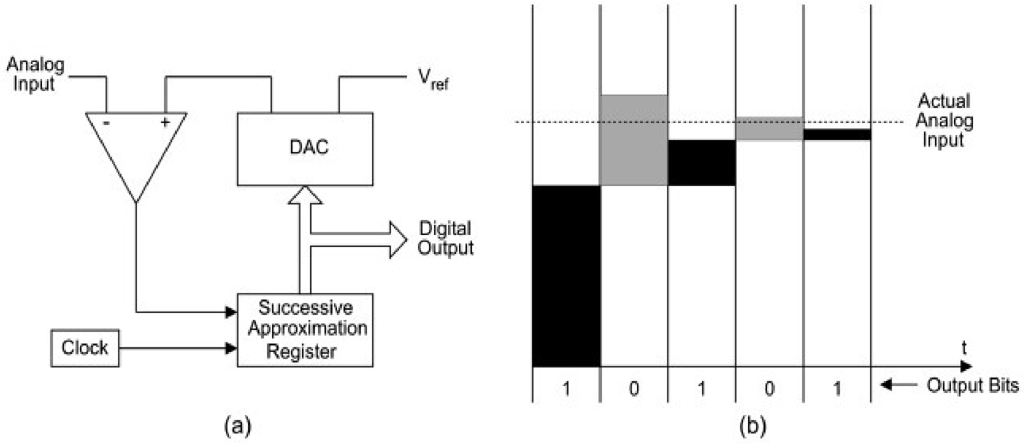

Figure 5. (a) Scheme of a successive approximation ADC. (b) Output bit generation in the approximation process.

3. Theory of Signal Acquisition

This section presents the theoretical foundations for the representation of analog information in the digital format. The transformation between analog and digital information is carried out during AD conversion.

The conversion process can be analyzed as three separate processes: sampling, quantization, and coding. In the following subsections each of these processes is briefly described.

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Biographical Sketches

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