Chapter

1

Introduction to Electronic Instruments and Measurements

1.1 Introduction

This chapter provides an overview of both the software and hardware components of instruments and instrument systems. It introduces the principles of electronic instrumentation, the basic building blocks of instruments, and the way that software ties these blocks together to create a solution. This chapter introduces practical aspects of the design and the implementation of instruments and systems.

Instruments and systems participate in environments and topologies that range from the very simple to the extremely complex. These include applications as diverse as:

- Design verification at an engineer's workbench
- Testing components in the expanding semiconductor industry
- Monitoring and testing of multinational telecom networks

1.2 Instrument Software

Hardware and software work in concert to meet these diverse applications. Instrument software includes the firmware or embedded software in instruments

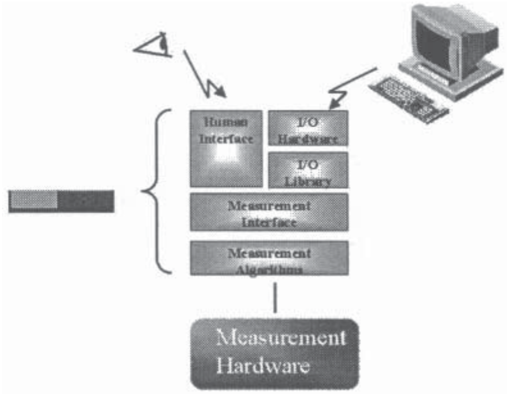

Figure 1.1 Instrument embedded software.

that integrates the internal hardware blocks into a subystem that performs a useful measurement. Instrument software also includes system software that integrates multiple instruments into a single system. These systems are able to perform more extensive analysis than an individual instrument or combine several instruments to perform a task that requires capabilities not included in a single instrument. For example, a particular application might require both a source and a measuring instrument.

1.2.1 Instrument embedded software

Figure 1.1 shows a block diagram of the embedded software layers of an instrument. The I/O hardware provides the physical interface between the computer and the instrument. The I/O software delivers the messages to and from the computer to the instrument interface software. The measurement interface software translates requests from the computer or the human into the fundamental capabilities implemented by the instrument. The measurement algorithms work in conjunction with the instrument hardware to actually sense physical parameters or generate signals.

The embedded software simplifies the instrument design by:

- Orchestrating the discrete hardware components to perform a complete measurement or sourcing function.
- Providing the computer interaction. This includes the I/O protocols, parsing the input, and formatting responses.
- Providing a friendly human interface that allows the user to enter numeric values in whatever units are convenient and generally interface to the instrument in a way that the user naturally expects.
- Performing instrument calibration.

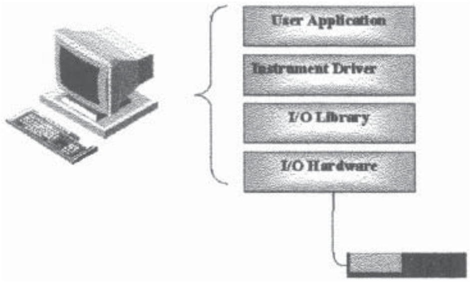

Figure 1.2 Software layers on the host side for instrument to computer connection.

1.2.2 System software

Figure 1.2 shows the key software layers required on the host side for instrument systems. Systems typically take instruments with generic capabilities and provide some specific function. For instance, an oscilloscope and a function generator can be put together in a system to measure transistor gain. The exact same system with different software could be used to test the fuel injector from a diesel engine.

Generally, the system itself:

- Automates a task that would be either complex or repetitive if performed manually.
- Can perform more complex analysis or capture trends that would be impractical with a single instrument.
- Is specific to a particular application.
- Can integrate the results of the test into a broader application. For instance, the system test could run in a manufacturing setting where the system is also responsible for handling the devices being tested as they come off the production line.

Please refer to Part 11 of this handbook for an in-depth discussion of instrument software.

1.3 Instruments

In test and measurement applications, it is commonplace to refer to the part of the real or physical world that is of interest as the *device under test (DUT).* A measurement instrument is used to determine the value or magnitude of a physical variable of the DUT. A source instrument generates some sort of stimulus that is used to stimulate the DUT. Although a tremendous variety of instruments exist, all share some basic principles. This section introduces these basic principles of the function and design of electronic instruments.

1.3.1 Performance attributes of measurements

The essential purpose of instruments is to sense or source things in the physical world. The performance of an instrument can thus be understood and characterized by the following concepts:

- *Connection* to the variable of interest. The inability to make a suitable connection could stem from physical requirements, difficulty of probing a silicon wafer, or from safety considerations (the object of interest or its environment might be hazardous).
- *Sensitivity* refers to the smallest value of the physical property that is detectable. For example, humans can smell sulfur if its concentration in air is a few parts per million. However, even a few parts per billion are sufficient to corrode electronic circuits. Gas chromatographs are sensitive enough to detect such weak concentrations.
- *Resolution* specifies the smallest change in a physical property that causes a change in the measurement or sourced quantity. For example, humans can detect loudness variations of about 1 dB, but a sound level meter may detect changes as small as 0.001 dB.
- *Dynamic Range* refers to the span from the smallest to the largest value of detectable stimuli. For instance, a voltmeter can be capable of registering input from 10 microvolts to 1 kilovolt.
- *Linearity* specifies how the output changes with respect to the input. The output of perfectly linear device will always increase in direct proportion to an increase in its input. For instance, a perfectly linear source would increase its output by exactly 1 millivolt if it were adjusted from 2 to 3 millivolts. Also, its output would increase by exactly 1 millivolt if it were adjusted from 10.000 to 10.001 volts.
- *Accuracy* refers to the degree to which a measurement corresponds to the true value of the physical input.
- *Lag and Settling Time* refer to the amount of time that lapses between requesting measurement or output and the result being achieved.
- *Sample Rate* is the time between successive measurements. The sample rate can be limited by either the acquisition time (the time it takes to determine the magnitude of the physical variable of interest) or the output rate (the amount of time required to report the result).

1.3.2 Ideal instruments

As shown in Fig. 1.3, the role of an instrument is as a transducer, relating properties of the physical world to information. The transducer has two primary interfaces; the input is connected to the physical world (DUT) and the output is information communicated to the operator. (For stimulus instruments, the roles of input and output are reversed—that is, the input is

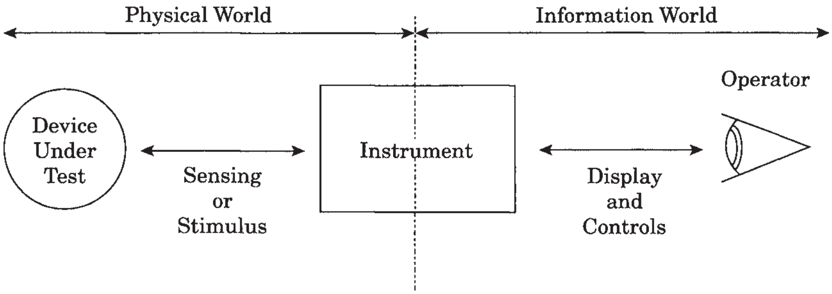

Figure 1.3 Ideal instruments.

the information and the output is the physical stimulus of the DUT.) The behavior of the instrument as a transducer can be characterized in terms of its transfer function—the ratio of the output to the input. Ideally, the transfer function of the instrument would be simply a unit conversion. For example, a voltmeter's transfer function could be "X degrees of movement in the display meter per electrical volt at the DUT."

A simple instrument example. A common example of an instrument is the mercury-bulb thermometer (Fig. 1.4). Since materials expand with increasing temperature, a thermometer can be constructed by bringing a reservoir of mercury into thermal contact with the device under test. The resultant volume of mercury is thus related to the temperature of the DUT. When a small capillary is connected to the mercury reservoir, the volume of mercury can be detected by the height that the mercury rises in the capillary column. Ideally, the length of the mercury in the capillary is directly proportional to the temperature of the reservoir. (The transfer function would be X inches of mercury in the column per degree.) Markings along the length of the column can be calibrated to indicate the temperature of the DUT.

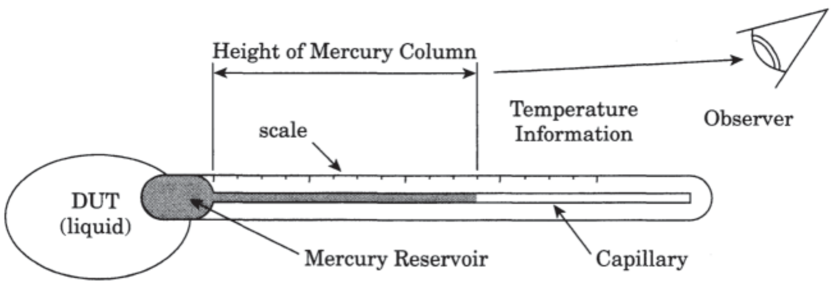

Figure 1.4 A mercury-bulb thermometer.

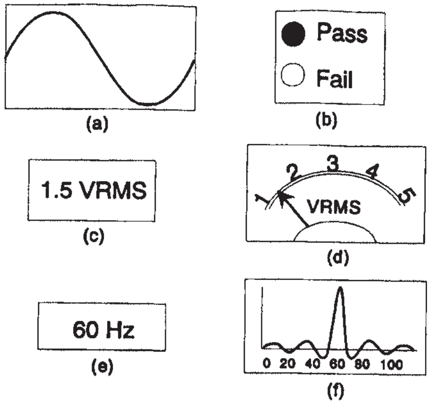

Figure 1.5 Some alternate information displays for an electrical signal.

1.3.3 Types of instruments

Although all instruments share the same basic role, there is a large variety of instruments. As mentioned previously, some instruments are used for measurements, while others are designed to provide stimulus. Figure 1.3 illustrates three primary elements of instruments that can be used to describe variations among instruments.

1. The interface to the DUT depends on the nature of the physical property to be measured (e.g., temperature, pressure, voltage, mass, time) and the type of connection to the instrument. Different instruments are used to measure different things.
2. The operator interface is determined by the kind of information desired about the physical property, and the means by which the information is communicated. For example, the user of an instrument that detects electrical voltage may desire different information about the electrical signal (e.g., rms voltage, peak voltage, waveform shape, frequency, etc.), depending upon the application. The interface to the instrument may be a colorful graphic display for a human, or it may be an interface to a computer. Figure 1.5 illustrates several possible information displays for the same electrical signal.
3. The fidelity of the transformation that takes place within the instrument itself—the extent to which the actual instrument behaves like an ideal instrument—is the third element that differentiates instruments. The same limitations of human perception described in the introduction apply to the behavior of instruments. The degree to which the instrument overcomes these limitations (for example, the accuracy, sensitivity, and sample rate) is the primary differentiator between instruments of similar function.

1.3.4 Electronic instruments

Electronic instruments have several advantages over purely mechanical ones, including:

- Electronic instruments are a natural choice when measuring electrical devices.
- The sophistication of electronics allows for improved signal and information processing within the instrument. Electronic instruments can make sophisticated measurements, incorporate calibration routines within the instrument, and present the information to the user in a variety of formats.
- Electronic instruments enable the use of computers as controllers of the instruments for fully automated measurement systems.

1.4 The Signal Flow of Electronic Instruments

Although the design of individual instruments varies greatly, there are common building blocks. Figure 1.6 illustrates a generic design of a digital electronic instrument. The figure depicts a chain of signal processing elements, each converting information to a form required for input to the next block. In the past, most instruments were purely analog, with analog data being fed directly to analog displays. Currently, however, most instruments being developed contain a digital information processing stage as shown in Fig. 1.6.

1.4.1 Device under Test (DUT) connections

Beginning at the bottom of Fig. 1.6 is the device under test (DUT). As the primary purpose of the instrument is to gain information about some physical property of the DUT, a connection must be made between the instrument and the DUT. This requirement often imposes design constraints on the instrument. For example, the instrument may need to be portable, or the connection to the DUT may require a special probe. The design of the thermometer in the earlier example assumes that the mercury reservoir can be immersed into the DUT that is, presumably, a fluid. It also assumes that the fluid's temperature is considerably lower than the melting point of glass.

1.4.2 Sensor or actuator

Continuing up from the DUT in Fig. 1.6 is the first transducer in the signal flow of the instrument—the sensor. This is the element that is in physical (not necessarily mechanical) contact with the DUT. The sensor must respond to the physical variable of interest and convert the physical information into an electrical signal. Often, the physical variable of interest is itself an electrical

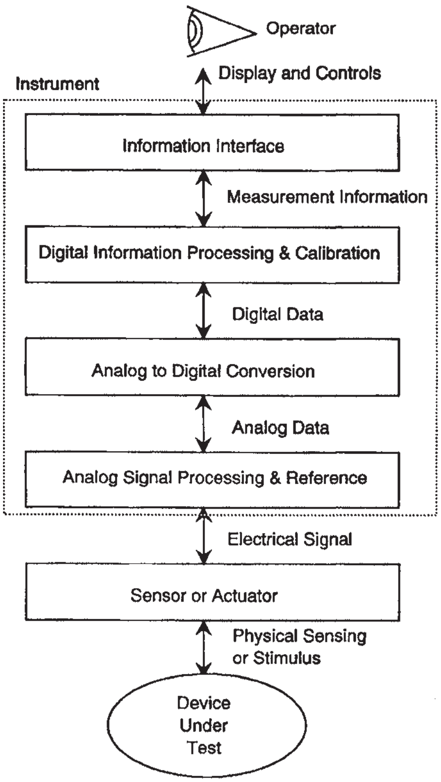

Figure 1.6 The signal flow diagram.

signal. In that case, the "sensor" is simply an electrical connection. In other cases, however, the physical variable of interest is not electrical. Examples of sensors include a piezoelectric crystal that converts pressure to voltage, or a thermocouple that converts temperature into a voltage. The advantage of such sensors is that, by converting the physical phenomenon of interest into an electrical signal, the rest of the signal chain can be implemented with a general-purpose electronic instrument.

An ideal sensor would be unobtrusive to the DUT; that is, its presence would not affect the state or behavior of the device under test. To make a measurement, some energy must flow between the DUT and the instrument. If the act of measurement is to have minimal impact on the property being measured, then the amount of energy that the sensor takes from the DUT must be minimized. In the thermometer example, the introduction of the mercury bulb must not appreciably cool the fluid being tested if an accurate temperature reading is desired. Attempting to measure the temperature of a single snowflake with a mercury-bulb thermometer is hopeless.

The sensor should be sensitive to the physical parameter of interest while remaining unresponsive to other effects. For instance, a pressure transducer should not be affected by the temperature of the DUT. The output of a sensor is usually a voltage, resistance, or electric current that is proportional to the magnitude of the physical variable of interest.

In the case of a stimulus instrument, the role of this stage is to convert an electrical signal into a physical stimulus of the DUT. In this case, some form of actuator is used. Examples of actuators are solenoids and motors to convert electrical signals into mechanical motion, loudspeakers to convert electrical signals into sound, and heaters to convert electrical signals into thermal energy.

1.4.3 Analog signal processing and reference

Analog signal processing. The next stage in the signal flow shown in Fig. 1.6 is the analog signal conditioning within the instrument. This stage often contains circuitry that is quite specific to the particular type of instrument. Functions of this stage may include amplification of very low voltage signals coming from the sensor, filtering of noise, mixing of the sensor's signal with a reference signal (to convert the frequency of the signal, for instance), or special circuitry to detect specific features in the input waveform. A key operation in this stage is the comparison of the analog signal with a reference value.

Analog reference. Ultimately, the value of a measurement depends upon its accuracy, that is, the extent to which the information corresponds to the true value of the property being measured. The information created by a measurement is a comparison of the unknown physical variable of the DUT with a reference, or known value. This requires the use of a physical *standard* or physical quantity whose value is known. A consequence of this is that each instrument must have its own internal reference standard as an integral part of the design if it is to be capable of making a measurement. For example, an instrument designed to measure the time between events or the frequency of a signal must have some form of clock as part of the instrument. Similarly, an instrument that needs to determine the magnitude of an electrical signal must have some form of internal voltage direct reference. The quality of this internal standard imposes limitations on the obtainable precision and accuracy of the measurement.

In the mercury-bulb thermometer example, the internal reference is not a fixed temperature. Rather, the internal reference is a fixed, or known, amount of mercury. In this case, the reference serves as an indirect reference, relying on a well-understood relationship between temperature and volume of mercury. The output of the analog processing section is a voltage or current that is scaled in both amplitude and frequency to be suitable for input to the next stage of the instrument.

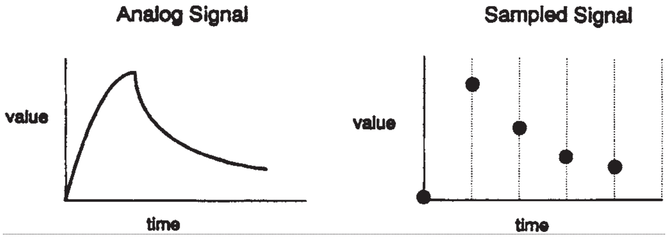

Figure 1.7 A comparison of analog and sampled signals.

1.4.4 Analog-to-digital conversion

For many instruments, the data typically undergo some form of analog-to-digital conversion. The purpose of this stage is to convert the continuously varying analog signal into a series of numbers that can be processed digitally. This is accomplished in two basic steps: (1) the signal is sampled, and (2) the signal is *quantized,* or digitized.

Sampling is the process of converting a signal that is continuously varying over time to a series of values that are representative of the signal at discrete points in time. Figure 1.7 illustrates an analog signal and the resulting sampled signal. The time between samples is the measure of the sample rate of the conversion. In order to represent an analog signal accurately, the sample rate must be high enough that the analog signal does not change appreciably between samples. Put another way: Given a sequence of numbers representing an analog signal, the maximum frequency that can be detected is proportional to the sample rate of the analog-to-digital conversion.

The second step of analog-to-digital conversion, quantization, is illustrated in Fig. 1.8. As shown in the figure, the principal effect of quantization is to round off the signal amplitude to limited precision. While this is not particularly desirable, some amount of quantization is inevitable since digital computation cannot deal with infinite precision arithmetic. The precision of the quantization is usually measured by the number of bits required by a digital representation of the largest possible signal. If N is the number of bits, then the number of output values possible is $2^{**}N$. The output range is from a smallest output of

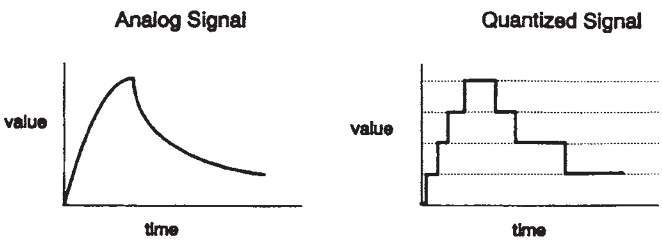

Figure 1.8 A comparison of analog and quantized signals.

zero to a maximum value of 2**N-1. For example, an 8-bit analog-to-digital converter (ADC) could output 2**8, or 256 possible discrete values. The output range would be from 0 to 255. If the input range of the converter is 0 to 10 V, then the precision of the converter would be (10-0)/255, or 0.039 V. This quantization effect imposes a tradeoff between the range and precision of the measurement. In practice, the precision of the quantization is a cost and accuracy tradeoff made by the instrument designer, but the phenomenon must be understood by the user when selecting the most appropriate instrument for a given application.

The output of the analog-to-digital conversion stage is thus a succession of numbers. Numbers appear at the output at the sample rate, and their precision is determined by the design of the ADC. These digital data are fed into the next stage of the instrument, the digital processing stage. [For a stimulus instrument, the flow of information is reversed—a succession of numbers from the digital processing stage is fed into a digital-to-analog converter (DAC) that converts them into a continuous analog voltage. The analog voltage is then fed into the analog signal processing block.]

1.4.5 Digital information processing and calibration

Digital processing. The digital processing stage is essentially a dedicated computer that is optimized for the control and computational requirements of the instrument. It usually contains one or more microprocessors and/or digital-signal-processor circuits that are used to perform calculations on the raw data that come from the ADC. The data are converted into measurement information. Conversions performed by the digital processing stage include:

- Extracting information—for example, calculating the rise time or range of the signal represented by the data.
- Converting them to a more meaningful form—for example, performing a discrete Fourier transform to convert time-domain to frequency-domain data.
- Combining them with other relevant information—for example, an instrument that provides both stimulus of the DUT and response measurements may take the ratio of the response to the stimulus level to determine the transfer function of the DUT.
- Formatting the information for communication via the information interface—for example, three-dimensional data may be illustrated by two dimensions plus color.

Another function of processing at this stage is the application of calibration factors to the data. The sophistication of digital processing and its relatively low cost have allowed instrument designers to incorporate more complete error compensation and calibration factors into the information, thereby improving the accuracy, linearity, and precision of the measurements.

Calibration. External reference standards are used to check the overall accuracy of instruments. When an instrument is used to measure the value of a standard DUT, the instrument's reading can be compared with the known true value, with the difference being a measure of the instrument's error. For example, the thermometer's accuracy may be tested by measuring the temperature of water that is boiling or freezing, since the temperature at which these phase changes occur is defined to be 100°C and 0°C, respectively.

The source of the error may be due to differences between the instrument's internal reference and the standard DUT or may be introduced by other elements of the signal flow of the instrument. Discrepancies in the instrument's internal reference or nonlinearities in the instrument's signal chain may introduce errors that are repeatable, or *systematic*. When systematic errors are understood and predictable, a *calibration* technique can be used to adjust the output of the instrument to more nearly correspond to the true value. For example, if it is known that the markings on the thermometer are off by a fixed distance (determined by measuring the temperature of a reference DUT whose temperature has been accurately determined by independent means), then the indicated temperature can be adjusted by subtracting the known offset before reporting the temperature result. Unknown systematic errors, however, are particularly dangerous, since the erroneous results may be misinterpreted as being correct. These may be minimized by careful experiment design. In critical applications, an attempt is made to duplicate the results via independent experiments.

In many cases the errors are purely random and thus limit the measurement precision of the instrument. In these cases, the measurement results can often be improved by taking multiple readings and performing statistical analysis on the set of results to yield a more accurate estimate of the desired variable's value. The statistical compensation approach assumes that something is known about the nature of the errors. When all understood and repeatable error mechanisms have been compensated, the remaining errors are expressed as a measurement uncertainty in terms of accuracy or precision of the readings.

Besides performing the digital processing of the measurement information, the digital processing stage often controls the analog circuitry, the user interface, and an input/output (I/O) channel to an external computer.

1.4.6 Information interface

When a measurement is made of the DUT, the instrument must communicate that information if it is to be of any real use. The final stage in the signal flow diagram (Fig. 1.6) is the presentation of the measurement results through the information interface. This is usually accomplished by having the microprocessor either control various display transducers to convey information to the instrument's operator or communicate directly with an external computer.

Whether it is to a human operator or a computer, similar considerations apply to the design of the information interface.

Interfaces to human operators. In this case, the displays (e.g., meters and gauges) and controls (e.g., dials and buttons) must be a good match to human sensory capabilities. The readouts must be easy to see and the controls easy to manipulate. This provides an appropriate physical connection to the user. Beyond this, however, the information must be presented in a form that is meaningful to the user. For example, text must be in the appropriate language, and the values must be presented with corresponding units (e.g., volts or degrees) and in an appropriate format (e.g., text or graphics). Finally, if information is to be obtained and communicated accurately, the operator interface should be easy to learn and use properly. Otherwise the interface may lead the operator to make inaccurate measurements or to misinterpret the information obtained from the instrument.

Computer interfaces. The same considerations used for human interfaces apply in an analogous manner to computer interfaces. The interface must be a good match to the computer. This requirement applies to the transmission of signals between the instrument and the computer. This means that both devices must conform to the same interface standards that determine the size and shape of the connectors, the voltage levels on the wires, and the manner in which the signals on the wires are manipulated to transfer information. Common examples of computer interfaces are RS-232 (serial), Centronics (parallel), SCSI, or LAN. Some special instrumentation interfaces (GPIB, VXI, and MMS) are often used in measurement systems. (These are described later in this chapter and in other chapters of this book.)

The communication between the instrument and computer must use a form that is meaningful to each. This consideration applies to the format of the information, the language of commands, and the data structures employed. Again, there are a variety of standards to choose from, including Standard Commands for Programmable Instruments (SCPI) and IEEE standards for communicating text and numbers.

The ease of learning requirement applies primarily to the job of the system developer or programmer. This means that the documentation for the instrument must be complete and comprehensible, and that the developer must have access to the programming tools needed to develop the computer applications that interact with the instrument. Finally, the ease of use requirement relates to the style of interaction between the computer and the instrument. For example, is the computer blocked from doing other tasks while the instrument is making a measurement? Does the instrument need to be able to interrupt the computer while it is doing some other task? If so, the interface and the operating system of the computer must be designed to respond to the interrupt in a timely manner.

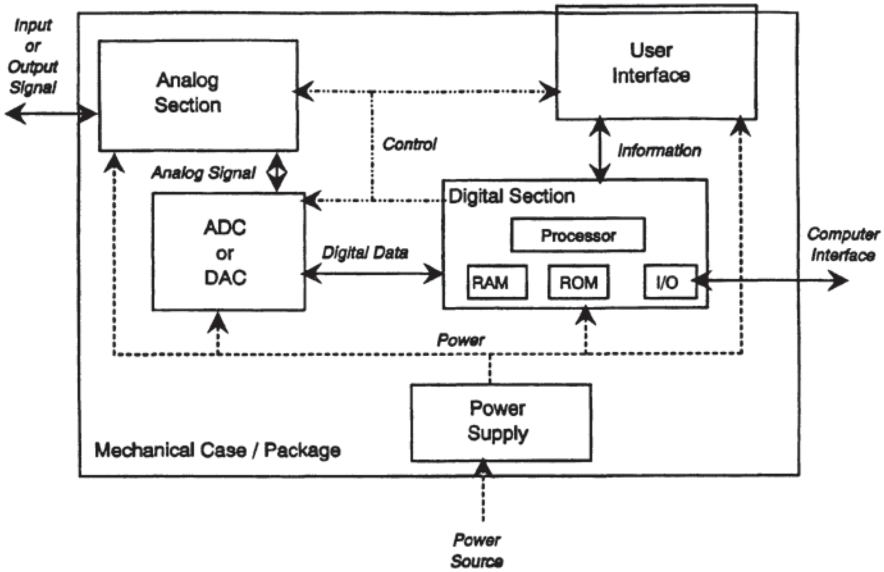

Figure 1.9 An instrument block diagram.

1.5 The Instrument Block Diagram

While the design of the signal flow elements focuses on measurement performance, the physical components chosen and their methods of assembly will determine several important specifications of the instrument, namely, its cost, weight, size, and power consumption. In addition, the instrument designer must consider the compatibility of the instrument with its environment. Environmental specifications include ranges of temperature, humidity, vibration, shock, chemicals, and pressure. These are often specified at two levels: The first is the range over which the instrument can be expected to operate within specifications, and the second (larger) is the range that will not cause permanent damage to the instrument.

In order to build an instrument that implements a signal flow like that of Fig. 1.6, additional elements such as a mechanical case and power supply are required. A common design of an instrument that implements the signal flow path discussed above is illustrated in Fig. 1.9. As shown in the figure, the building blocks of the signal flow path are present as physical devices in the instrument. In addition, there are two additional support elements, the mechanical case and package and the power supply.

1.5.1 Mechanical case and package

The most visible component of instruments is the mechanical package, or case. The case must provide support of the various electronic components, ensuring their electrical, thermal, electromagnetic, and physical containment and protection. The case is often designed to fit into a standard 19-in-wide rack, or it may provide carrying handles if the instrument is designed to be portable. The case supports a number of connectors that are used to interface the instrument with its environment. The connections illustrated in Fig. 1.9 include a power cable, the input connections for the sensor, a computer interface, and the front panel for the user interface. The case must also protect the electrical environment of the instrument. The instrument usually contains a lot of very sensitive circuitry. Thus it is important for the case to protect the circuitry from stray electromagnetic fields (such as radio waves). It is likewise important that electromagnetic emissions created by the instrument itself are not sent into the environment where they could interfere with other electronic devices.

Similarly, the package must provide for adequate cooling of the contents. This may not be a concern if the other elements of the instrument do not generate much heat and are not adversely affected by the external temperature of the instrument's environment within the range of intended use. However, most instruments are cooled by designing some form of natural or forced convection (airflow) through the instrument. This requires careful consideration of the space surrounding the instrument to ensure that adequate airflow is possible and that the heat discharged by the instrument will not adversely affect adjacent devices. Airflow through the case may cause electromagnetic shielding problems by providing a path for radiated energy to enter or leave the instrument. In addition, if a fan is designed into the instrument to increase the amount of cooling airflow, the fan itself may be a source of electromagnetic disturbances.

1.5.2 Power supply

Figure 1.9 also illustrates a power supply within the instrument. The purpose of the power supply is to convert the voltages and frequencies of an external power source (such as 110 V ac, 60 Hz) into the levels required by the other elements of the instrument. Most digital circuitry requires 5 V dc, while analog circuitry has varying voltage requirements (typically, ± 12 V dc, although some elements such as CRTs may have much higher voltage requirements).

The power supply design also plays a major role in providing the proper electrical isolation of various elements, both internal and external to the instrument. Internally, it is necessary to make sure that the power supplied to the analog signal conditioning circuitry, for instance, is not corrupted by spurious signals introduced by the digital processing section. Externally, it is important for the power supply to isolate the instrument from voltage and frequency fluctuations present on the external power grid, and to shield the external power source from conducted emissions that may be generated internal to the instrument.

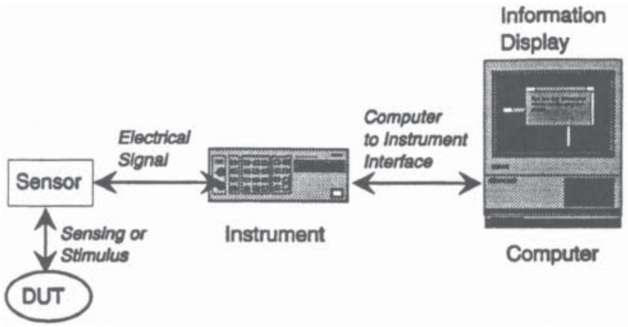

Figure 1.10 A simple measurement system.

1.6 Measurement Systems

One of the advantages of electronic instruments is their suitability for incorporation into measurement systems. A measurement system is built by connecting one or more instruments together, usually with one or more computers. Figure 1.10 illustrates a simple example of such a system.

1.6.1 Distributing the "instrument"

When a measurement system is constructed by connecting an instrument with a computer, the functionality is essentially the same as described in the signal flow diagram (Fig. 1.6), although it is distributed between the two hardware components as illustrated in Fig. 1.11. Comparison of the signal flow diagram for a computer-controlled instrument (Fig. 1.11) with that of a stand-alone instrument (Fig. 1.6) shows the addition of a second stage of digital information processing and an interface connection between the computer and the instrument. These additions constitute the two primary advantages of such a system.

Digital processing in the computer. The digital information processing capabilities of the computer can be used to automate the operation of the instrument. This capability is important when control of the instrument needs to be faster than human capabilities allow, when a sequence of operations is to be repeated accurately, or when unattended operation is desired.

Beyond mere automation of the instrument, the computer can run a special-purpose program to customize the measurements being made to a specific application. One such specific application would be to perform the calculations necessary to compute a value of interest based on indirect measurements. For example, the moisture content of snow is measured indirectly by weighing a known volume of snow. In this case, the instrument makes the weight measurement and the computer can perform the calculation that determines the density of the snow and converts the density information into moisture content.

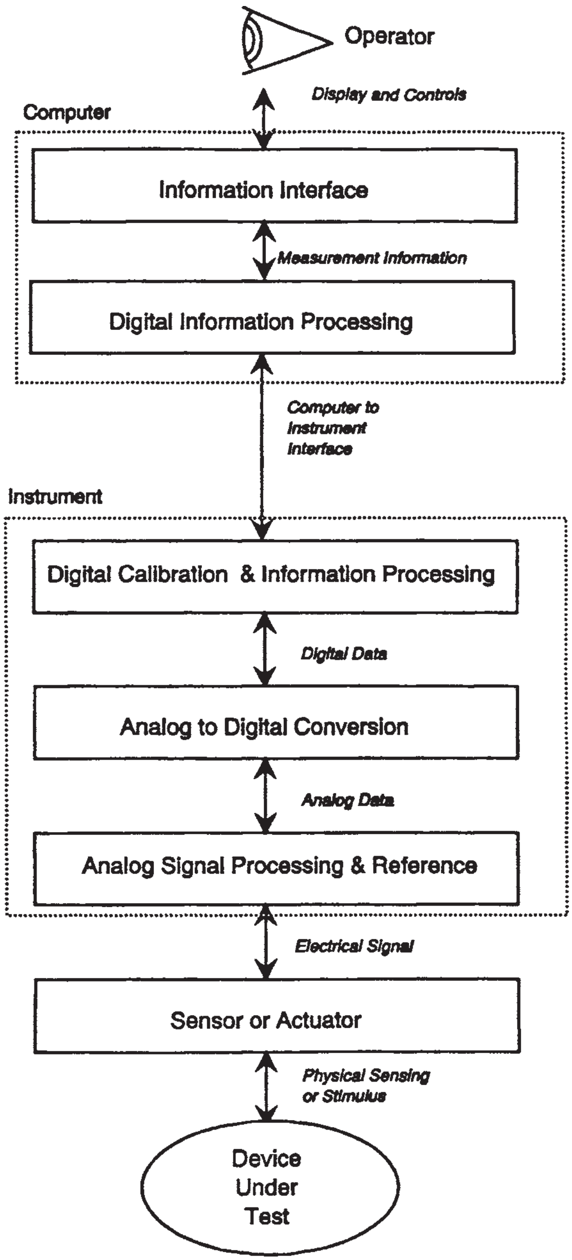

Figure 1.11 The signal flow diagram for a computer-controlled instrument.

Finally, the computer can generate a new interface for the user that displays snow moisture content rather than the raw weight measurement made by the instrument. The software running on the computer in this example is often referred to as a "virtual instrument," since it presents an interface that is equivalent to an instrument—in this case, a "snow moisture content instrument."

Remote instruments. A second use of a computer-controlled instrument is to exploit the distribution of functionality enabled by the computer interface connection to the instrument. The communications between instrument and computer over this interface allow the instrument and computer to be placed in different locations. This is desirable, for example, when the instrument must accompany the DUT in an environment that is inhospitable to the operator. Some examples of this would be instrumentation placed into environmental chambers, wind tunnels, explosive test sites, or satellites.

Computer-instrument interfaces. Although any interface could be used for this purpose, a few standards are most common for measurement systems: computer backplanes, computer interfaces, and instrument buses.

Computer backplanes. These buses are used for internal expansion of a computer. (Buses are interfaces that are designed to connect multiple devices.) The most common of these is the ISA (Industry Standard Architecture) or EISA (Extended Industry Standard Architecture) slots available in personal computers. These buses are typically used to add memory, display controllers, or interface cards to the host computer. However, some instruments are designed to plug directly into computer bus slots. This arrangement is usually the lowest-cost option, but the performance of the instrument is compromised by the physical lack of space, lack of electromagnetic shielding, and the relatively noisy power supply that computer backplanes provide.

Computer interfaces. These interfaces are commonly provided by computer manufacturers to connect computers to peripherals or other computers. The most common of these interfaces are RS-232, SCSI, parallel, and LAN. These interfaces have several advantages for measurement systems over computer buses, including: (1) The instruments are physically independent of the computer, so their design can be optimized for measurement performance. (2) The instruments can be remote from the computer. (3) The interfaces, being standard for the computer, are supported by the computer operating systems and a wide variety of software tools. Despite these advantages, these interfaces have limitations in measurement systems applications, particularly when the application requires tight timing synchronization among multiple instruments.

Instrument buses. These interfaces, developed by instrument manufacturers, have been optimized for measurement applications. The most common of these

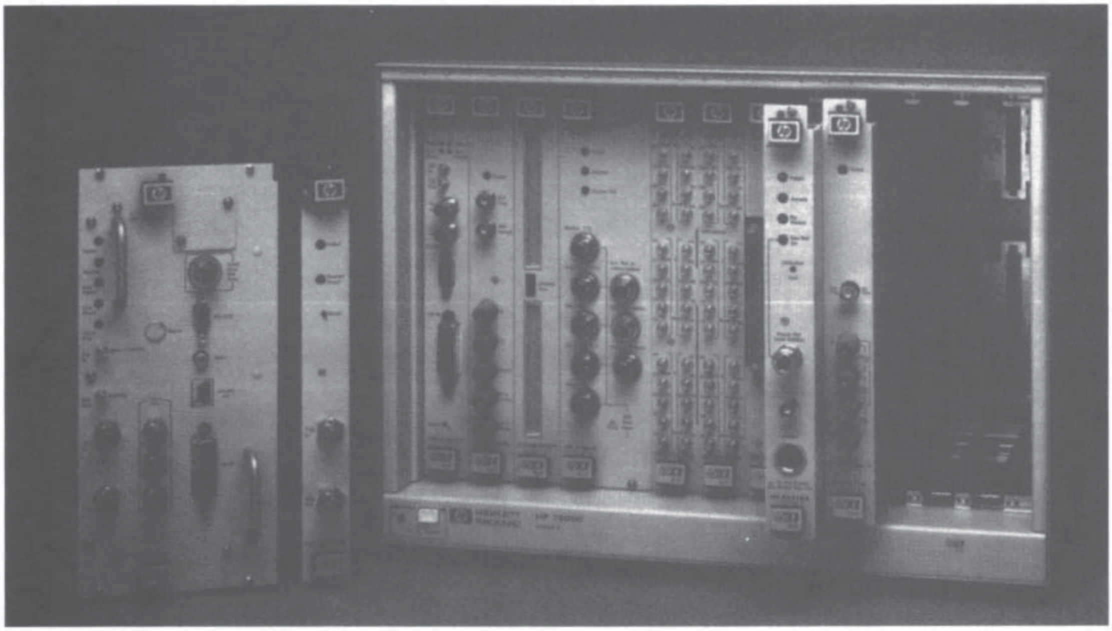

Figure 1.12 VXI instruments.

special instrument interfaces is the General Purpose Interface Bus, GPIB, also known as IEEE-488. GPIB is a parallel bus designed to connect standalone instruments to a computer, as shown in Fig. 1.10. In this case, a GPIB interface is added to the computer, usually by installing an interface card in the computer's expansion bus. Other instrument bus standards are VXI (VMEbus Extended for Instrumentation) and MMS (Modular Measurement System). VXI and MMS are cardcage designs that support the mechanical, electrical, and communication requirements of demanding instrumentation applications. Figure 1.12 is a photograph of VXI instrumentation. Note that in the case of VXI instruments, the instruments themselves have no user interface, as they are designed solely for incorporation into computer-controlled measurement systems.

Cardcage systems use a mainframe that provides a common power supply, cooling, mechanical case, and communication bus. The system developer can then select a variety of instrument modules to be assembled into the mainframe. Figure 1.13 illustrates the block diagram for a cardcage-based instrument system. Comparison with the block diagram for a single instrument (Fig. 1.9) shows that the cardcage system has the same elements but there are multiple signal-flow elements sharing common support blocks such as the power supply, case, and the data and control bus. One additional element is the computer interface adapter. This element serves as a bridge between the control and data buses of the mainframe and an interface to an

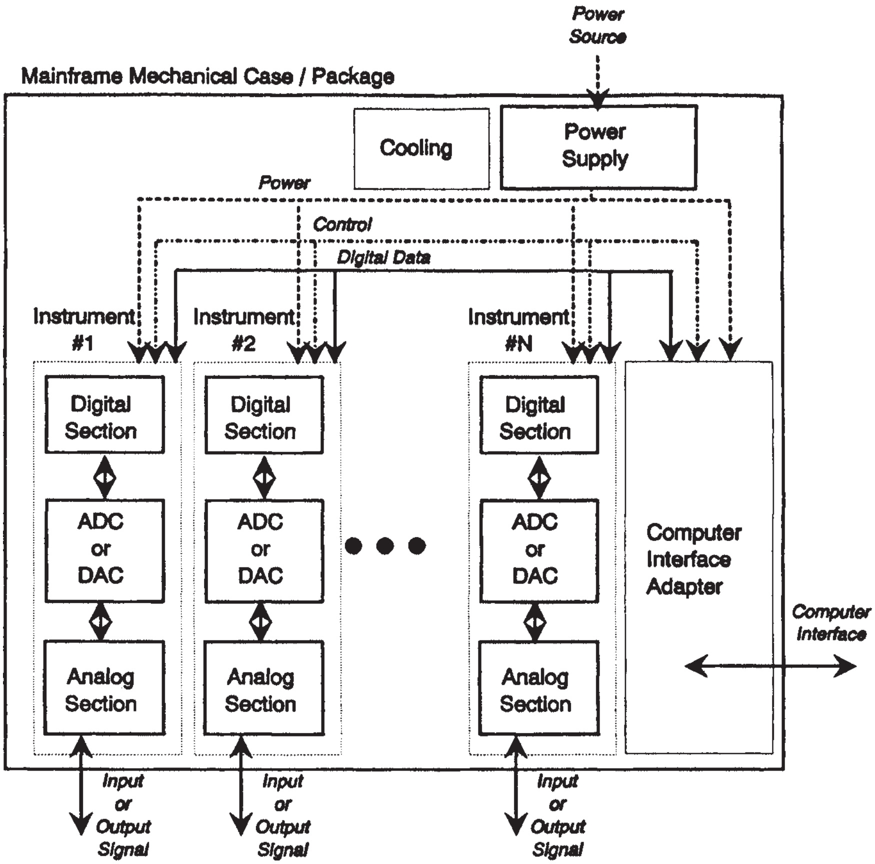

Figure 1.13 The block diagram for a cardcage instrument system.

external computer. (In some cases, the computer may be inserted or embedded in the mainframe next to the instruments where it interfaces directly to the control and data buses of the cardcage.)

1.6.2 Multiple instruments in a measurement system

A common element in the design of each of the instrument buses is the provision to connect multiple instruments together, all controlled by a single computer as shown in Fig. 1.14. A typical example of such a system configuration is composed of several independent instruments all mounted in a 19-in-wide rack, all connected to the computer via GPIB (commonly referred to as a “rack and stack” system).

Multiple instruments may be used when several measurements are required on the same DUT. In some cases, a variety of measurements must be made concurrently on a DUT; for example, a power measurement can be made by

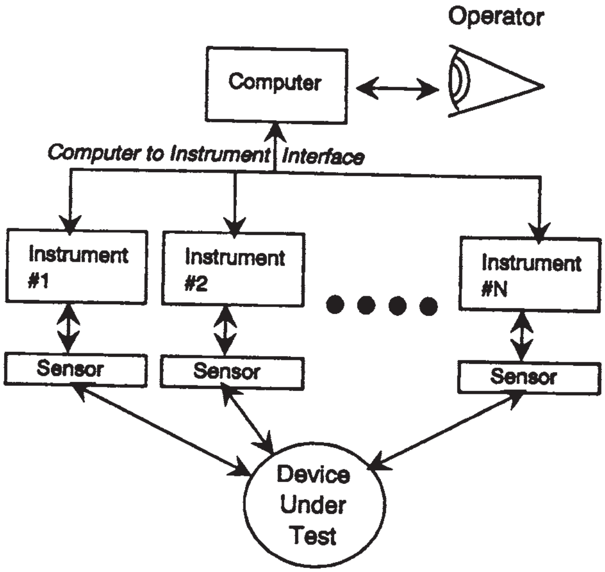

Figure 1.14 A measurement system with multiple instruments.

simultaneously measuring a voltage and a current. In other cases, a large number of similar measurements requires duplication of instruments in the system. This is particularly common when testing complex DUTs such as integrated circuits or printed circuit boards, where hundreds of connections are made to the DUT.

Multiple instruments are also used when making stimulus-response measurements. In this case, one of the instruments does not make a measurement but rather provides a signal that is used to stimulate the DUT in a controlled manner. The other instruments measure the response of the DUT to the applied stimulus. This technique is useful to characterize the behavior of the DUT. A variant of this configuration is the use of instruments as surrogates for the DUT's expected environment. For example, if only part of a device is to be tested, the instruments may be used to simulate the missing pieces, providing the inputs that the part being tested would expect to see in normal operation.

Another use of multiple instruments is to measure several DUTs simultaneously with the information being consolidated by the computer. This allows simultaneous testing (batch testing) of a group of DUTs for greater testing throughput in a production environment. Note that this could also be accomplished by simply duplicating the measurement system used to test a single DUT. However, using multiple instruments connected to a single computer not only saves money on computers, it also provides a mechanism for the centralized control of the tests and the consolidation of test results from the different DUTs.

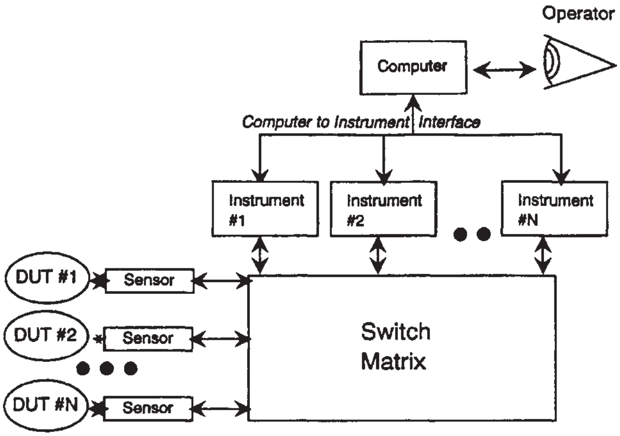

Figure 1.15 Using a switch matrix for batch testing.

Economies can be realized if the various measurements made on multiple DUTs do not need to be made simultaneously. In this case, a single set of instruments can be used to measure several DUTs by connecting all the instruments and DUTs to a switch matrix, as illustrated in Fig. 1.15. Once these connections are made, the instruments may be used to measure any selected DUT by programmatic control of the switch matrix. This approach may be used, for example, when a batch of DUTs is subjected to a long-term test with periodic measurements made on each.

1.6.3 Multiple computers in a measurement system

As the information processing needs increase, the number of computers required in the measurement system also increases. Lower cost and improved networking have improved the cost-effectiveness of multicomputer configurations.

Real time. Some measurement systems add a second computer to handle special real-time requirements. There are several types of real-time needs that may be relevant, depending on the application:

- *Not real time.* The completion of a measurement or calculation can take as long as necessary. Most information processing falls into this category, where the value of the result does not depend on the amount of time that it takes to complete the task. Consequently, most general-purpose computers are developed to take advantage of this characteristic—when the task becomes more difficult, the computer simply spends more time on it.
- *"Soft" real time.* The task must complete within a deadline if the result is to be useful. In this case, any computer will suffice as long as it is fast enough.

However, since most modern operating systems are multitasking, they cannot in general guarantee that each given task will be completed by a specified time or even that any particular task will be completed in the same amount of time if the task is repeated.

- *"Hard" real time.* The result of a task is incorrect if the task is not performed at a specific time. For example, an instrument that is required to sample an input signal 100 times in a second must perform the measurements at rigidly controlled times. It is not satisfactory if the measurements take longer than 1 s or even if all 100 samples are made within 1 s. Each sample must be taken at precisely 1/100-s intervals. Hard real-time requirements may specify the precise start time, stop time, and duration of a task. The results of a poorly timed measurement are not simply late, they're wrong.

Since the physical world (the world of DUTs) operates in real time, the timing requirements of measurement systems become more acute as the elements get closer to the DUT. Usually, the hard real-time requirements of the system are handled completely within the instruments themselves. This requires that the digital processing section of the instrument be designed to handle its firmware tasks in real time.

In some cases, it is important for multiple instruments to be coordinated or for certain information processing tasks to be completed in hard real time. For example, an industrial process control application may have a safety requirement that certain machines be shut down within a specified time after a measurement reaches a predetermined value. Figure 1.16 illustrates a measurement system that has a computer dedicated to real-time instrument control and measurement processing. In this case, the real-time computer is embedded in an instrument mainframe (such as a VXI cardcage) where it interfaces directly with the instrument data and control bus. A second interface on the real-time computer is used to connect to a general-purpose computer that provides for the non-real-time information-processing tasks and the user interface.

A further variant of the system illustrated in Fig. 1.16 is the incorporation of multiple real-time computers. Although each instrument typically performs real-time processing, the system designer may augment the digital processing capabilities of the instruments by adding multiple real-time processors. This would be necessary, in particular, when several additional information processing tasks must be executed simultaneously.

Multiple consumers of measurement results. A more common requirement than the support of real-time processes is simply the need to communicate measurement results to several general-purpose computers. Figure 1.17 illustrates one possible configuration of such a system. As shown in Fig. 1.17,

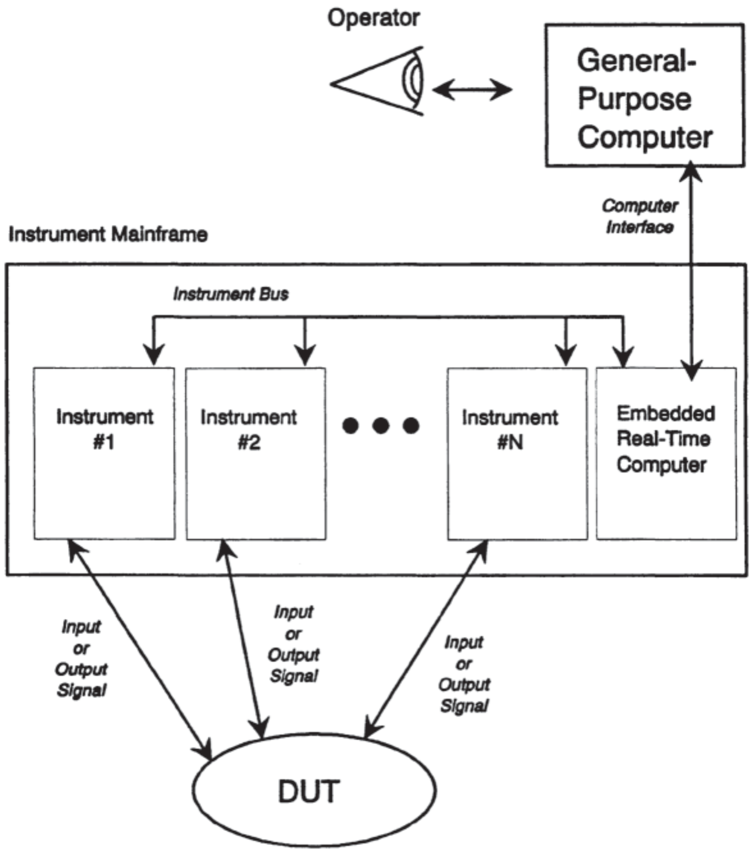

Figure 1.16 A system with an embedded real-time computer for measurement.

several operations may run on different computers yet require interaction with measurements, such as:

- *Analysis and presentation of measurement results.* There may be several different operator interfaces at different locations in the system. For example, a person designing the DUT at a workstation may desire to compare the performance of a DUT with the expected results derived by running a simulation on the model of the DUT.
- *Test coordination.* A single computer may be used to schedule and coordinate the operation of several different instrument subsystems.
- *System development and administration.* A separate computer may be used to develop new test and measurement software routines or to monitor the operation of the system.

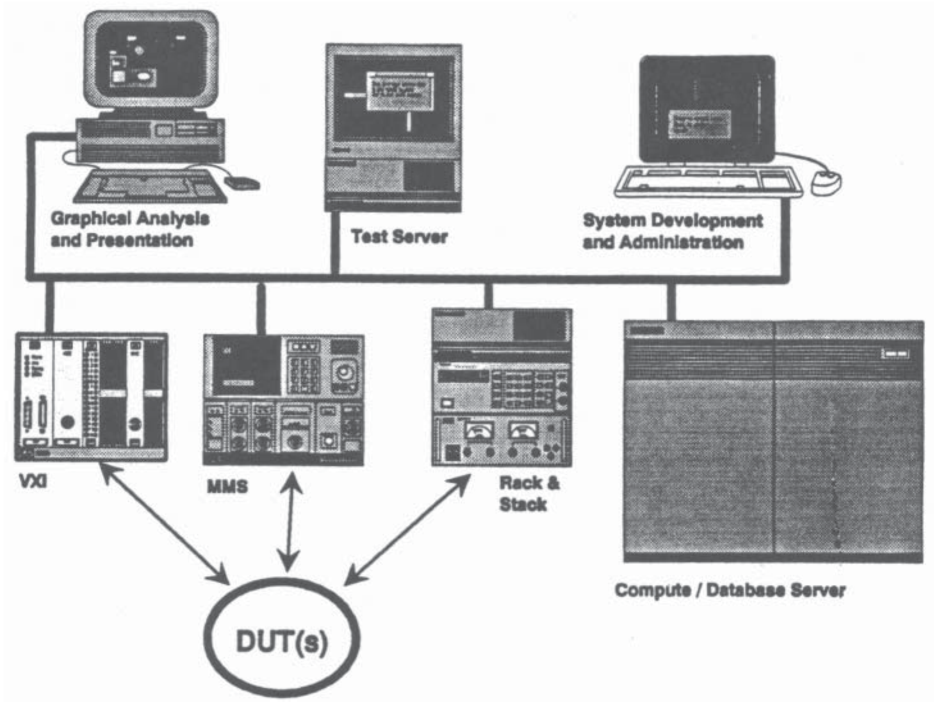

Figure 1.17 A networked measurement system.

- *Database.* Measurement results may be communicated to or retrieved from a centralized database.
- *Other measurement subsystems.* The information from measurements taken at one location may need to be incorporated or integrated with the operation of a measurement subsystem at another location. For example, a manufacturing process control system often requires that measurements taken at one point in the process are used to adjust the stimulus at another location in the process.

1.7 Summary

All instruments and measurement systems share the same basic purpose, namely, the connection of information and the physical world. The variety of physical properties of interest and the diversity of information requirements for different applications give rise to the abundance of available instruments. However, these instruments all share the same basic performance attributes. Given the physical and information interface requirements, the keys to the design of these systems are the creation of suitable basic building blocks and the arrangement and interconnection of these blocks. The design of these basic building blocks and their supporting elements determines the fidelity of the transformation between physical properties and information. The arrangement and connection of these blocks allow the creation of systems that range from a single compact instrument to a measurement and information system that spans the globe.