INSTRUMENTS

Measurement is essential for observing and testing scientific and technological investigations. It is so fundamental and important to science and engineering that the whole science can be said to be dependent on it. Instruments are developed for monitoring the conditions of physical variables and converting them into symbolic output forms. They are designed to maintain prescribed relationships between the parameters being measured and the physical variables under investigation. The physical parameter being measured is known as the *measurand.* The sensors and transducers are the primary sensing elements in the measuring systems that sense the physical parameters to produce an output. The energy output from the sensor is supplied to a transducer, which converts energy from one form to another. Therefore, a transducer is a device capable of transferring energy between two physical systems.

Measurement is a process of gathering information from a physical world and comparing this information with agreed standards. Measurement is carried out with instruments that are designed and manufactured to fulfill given specifications. After the sensor generates the signals, the type of signal processing depends on the information required from it. A diverse range of sensors and transducers may be available to

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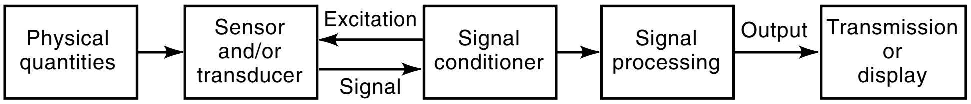

Figure 1. An instrument has a number of relatively independent components that can be described as functional elements. These functional elements are the sensors and transducers, signal conditioners, and output or terminations. In general, if the behavior of the physical system is known, its performance is measured by a suitable arrangement and design of these components.

meet the measurement requirements of a physical system. The sensors and transducers can be categorized in a number of ways depending on the energy input and output, input variables, sensing elements, and electrical or physical principles. For example, from an energy input and output point of view, there are three fundamental types of transducers: modifiers, self-generators, and modulators.

In modifiers, a particular form of energy is modified rather than converted; therefore, the same form of energy exists at the input and the output. In self-generators, electrical signals are produced from nonelectric inputs without the application of external energy. These transducers produce very small signals, which may need additional conditioning. Typical examples are piezoelectric transducers and photovoltaic cells. Modulators, on the other hand, produce electric outputs from nonelectric inputs, but they require an external source of energy. Strain gauges are typical examples of such devices.

The functionality of an instrument can be broken into smaller elements, as illustrated in Fig. 1. Most measurement systems have a sensor or transducer stage, a signal-conditioning stage, and an output or termination stage. All instruments have some or all of these functional blocks. Generally, if the behavior of the physical system under investigation is known, its performance can be assessed by means of a suitable method of sensing, signal conditioning, and termination.

In the applications of instruments, the information about a physical variable is collected, organized, interpreted, and generalized. Experiments are conceived, performed, and repeated; as we acquire confidence in the results, they are expressed as scientific laws. The application of instruments ranges from laboratory conditions to arduous environments such as inside nuclear reactors or on satellite systems and spaceships. In order to meet diverse application requirements of high complexity and capability, many manufacturers have developed a large arsenal of instruments. Some of these manufacturers are listed in Table 1.

In recent years, rapid growth of IC electronics and the availability of cheap analog-to-digital and microprocessors have led to progress in the instrumentation field, with the development of instruments, measuring techniques, distributed architectures, and standards aimed to improve performance.

Instruments are applied for static or dynamic measurements. The static measurements are relatively easy since the physical quantity (e.g., fixed dimensions and weights) does not change in time. If the physical quantity is changing in time, which is often the case, the measurement is said to be dynamic. In this case, steady-state and transient behavior of the physical variable must be analyzed so that it can be matched with the dynamic behavior of the instrument.

DESIGN, TESTING, AND THE USE OF INSTRUMENTS

Instruments are designed on the basis of existing knowledge, which is gained either from the experiences of people about the physical process or from our structured understanding of the process. In any case, ideas conceived about an instrument must be translated into hardware and/or software that can perform well within the expected standards and easily be accepted by the end users.

Usually, the design of instruments requires many multidisciplinary activities. In the wake of rapidly changing technology, instruments are upgraded often to meet the demands of the marketplace. Depending on the complexity of the proposed instrument, it may take many years to produce an instrument for a relatively short commercial lifetime. In the design and production of instruments, we must consider such factors as simplicity, appearance, ease and flexibility of use, maintenance requirements, lower production costs, lead time to product, and positioning strategy in the marketplace.

In order to design and produce instruments, a firm must consider many factors. These include sound business plans, suitable infrastructure, plant, equipment, understanding of technological changes, skilled and trained personnel, adequate finance, marketing and distribution channels, and a clear understanding about worldwide instrument and instrumentation system trends. It is important to choose the right product that is very likely to be in demand in the years to come. Here entrepreneurial management skills may be an important factor.

The design process itself may follow well-ordered procedures from idea to marketing stages. The process may be broken down into smaller tasks such as identifying specifications, developing possible solutions for these specifications, modeling, prototyping, installing and testing, making modifications, manufacturing, planning marketing and distribution, evaluating customer feedback, and making design and technological improvements. Figure 2 illustrates the stages for the design and marketing of an instrument. Each one of these stages can be viewed in detail in the form of subtasks. For example, many different specifications may be considered for particular product. These specifications include but are not limited to operational requirements, functional and technological requirements, quality, installation and maintenance, documentation and servicing, and acceptance level determination by the customers.

In recent years, computers have been used extensively in the instrument manufacturing industry in the form of computer-aided-design (CAD), automated testing, and in other applications. The computer enables rapid access to knowledge-based information and makes design time considerably shorter, thus enabling manufacturers to meet rapid demand.

Table 1. List of Manufacturers

ABB, Inc.
501 Merritt 7, P.O. Box 5308
Norwalk, CT 06856-5308
Tel: 800-626-4999
Fax: 203-750-2263

Allied Signal, Inc.
101 Columbia Road
Morristown, NY 07962
Tel: 800-707-4555
Fax: 608-497-1001

Bailey-Fisher and Porter Company
125 E County Line Road
Wanminster, PA 18974
Tel: 800-268-8520
Fax: 215-674-7183

Consolidated Instrument, Inc.
510 Industrial Avenue
Teterboro, NC 07608
Tel: 800-240-3633
Fax: 201-288-8006

Davies Instrument Manufacturing Company, Inc.
4701 Mt. Hope Drive
Baltimore, MD 21215
Tel: 800-548-0409
Fax: 410-358-0252

Dwyer Instrument, Inc.
P.O. Box 373-T
Michigan City, IN 46361-0373
Tel: 219-879-8000
Fax: 219-872-9057

Fuji Corporation of America
Park 80 West, Plaza Two
Saddlebrook, NJ 07663
Tel: 201-712-0555
Fax: 201-368-8258

Hanna Instrument, Inc.
Highland Industrial Park
584 Park East Drive
Woonscocket, RI 02895-0849
Tel: 800-999-4144
Fax: 401-765-7575

Hewlett-Packard Company
5301 Stevens Creek Boulevard
Santa Clara, CA 95052-8059
Tel: 800-452-6866
Fax: 303-756-6800

Industrial Instruments and Supply, Inc.
P.O. Box 416
12 County Line Industrial Park
Southampton, PA 18966
Tel: 800-523-6079
Fax: 215-396-0833

Instrument and Control Services Company
1351-T Cedar Lake Road
Lake Villa, IL 60046
Tel: 800-747-8367
Fax: 847-356-9007

Keithley Instrument, Inc.
28775-T Aurora Road
Cleveland, OH 44139-1891
Tel: 800-552-1115
Fax: 440-248-6168

MCS Calibration, Inc.
Engineering Division
1533 Lincoln Avenue
Halbrook, NY 11741
Tel: 800-790-0512
Fax: 512-471-6902

MSC Industrial Supply Company
151-T Sunnyside Boulevard
Plainview, NY 11803
Tel: 800-753-7937
Fax: 516-349-0265

National Instruments
6504 Bridge Point Parkway
Austin, TX 78730-7186
Tel: 512-794-0100; 888-217-7186
Fax: 512-794-8411

Omega Engineering, Inc.
P.O. Box 4047
Stamford, CT 06907
Tel: 800-826-6342
Fax: 203-359-7700

Rosemount Analytical
600 S. Harbor Boulevard, Dept TR
La Habra, CA 90631-6166
Tel: 800-338-8099
Fax: 562-690-7127

Scientific Instruments, Inc.
518 W Cherry Street
Milwaukee, WI 53212
Tel: 414-263-1600
Fax: 415-263-5506

Space Age Control, Inc.
38850 20th Street East
Palmdale, CA 93550
Tel: 800-366-3408
Fax: 805-273-4240

Tektronix, Inc.
P.O. Box 500
Beaverton, OR 97077
Tel: 503-627-7111

Texas Instrument, Inc.
34 Forest Street, MS 23-01
P.O. Box 2964
Attleboro, MA 02703
Tel: 508-236-3287
Fax: 508-236-1598

Warren-Knight Instrument Company
2045 Bennett Drive
Philadelphia, PA 19116
Tel: 215-464-9300
Fax: 215-464-9303

Yokogawa Corporation of America
2 Dart Road
Newnon, GA 30265-1040
Tel: 800-258-2552
Fax: 770-251-2088

In CAD systems, mechanical drafting software, electronic circuit design tools, control analysis tools, and mathematical and word processing tools are integrated to assist the design procedure. Design software is available from various manufacturers listed in Table 1.

Testing and Use of Instruments

After the instrument is designed and prototyped, various evaluation tests may be conducted. These tests may be made under reference conditions or under simulated environmental conditions. Some examples of reference condition tests are accuracy, response time, drift, and warm up time. Simulated environmental tests may be compulsory, being regulated by governments and other authorities. Some simulated environment tests include climatic test, drop test, dust test, insulation resistance test, vibration test, electromagnetic compatibility (EMC) tests, and safety and health hazard tests. Many of these tests are strictly regulated by national and international standards.

Adequate testing and proper use of instruments is important to achieve the best results out of them. When the instruments are installed, a regular calibration is necessary to ensure the consistency of the performance over the time period of operation. Incorrect measurements can cost a considerable amount of money or even result in the loss of lives.

For maximum efficiency, an appropriate instrument for the measurement must be selected. Users should be fully aware of their application requirements, since instruments that do not fit their purpose will deliver false data resulting in wasted time and effort. When selecting the instrument, users must evaluate many factors such as accuracy, frequency response, electrical and physical loading effects, sensitivity, response time, calibration intervals, power supply needs, spare parts, technology, and maintenance requirements. They must ensure compatibility with their existing equipment.

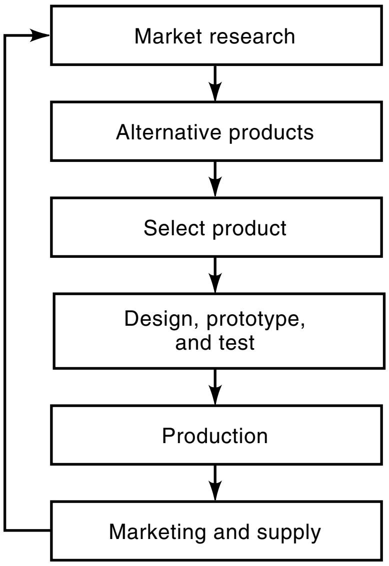

Figure 2. The design process from the conception of ideas to marketing follows carefully considered stages. The proper identification and effective implementation of these stages is important in the success of a specific instrument in the marketplace.

Also, when selecting and implementing instruments, quality becomes an important issue from both quantitative and qualitative perspectives. The quality of an instrument may be viewed differently depending on the people involved. For example, quality as viewed by the designer may be an instrument designed on sound physical principles, whereas from the user's point of view quality may be reliability, maintainability, cost, and availability.

For the accuracy and validity of information collected from the instruments, correct installation and proper use become very important. The instruments must be fully integrated with the overall system. Sufficient background work must be conducted prior to installation to avoid a possible shutdown of the process that is longer than necessary.

Once the system is installed, the reliability of the instrument must be assessed, and its performance must be checked regularly. The *reliability* of the system may be defined as the probability that it will operate at an agreed level of performance for a specified period of time. The reliability of instruments follows a bath tub shape against time. Instruments tend to be unreliable in the early and later stages of their lives. During normal operations, if the process conditions change (e.g., installation of large machinery nearby), calibrations must be conducted to avoid possible performance deterioration of the instrument. Therefore, the correct operations of the instruments must be assured at all times throughout the lifetime of the device.

Once the instruments are installed they may be left alone and expected to operate reliably. They may be communicating with other devices and their performance may affect the performance of the rest of the system, as in the case of the process industry. In some applications, the instruments may be part of a large instrumentation system, taking a critical role in monitoring and/or controlling the process and operations. However, in many applications, instruments are used on a stand-alone basis for laboratory and experimental work, and the success of the experiments may entirely depend on their correct performance. In these cases, the experiments must be designed and conducted carefully by identifying the primary variables, controlling, selecting the correct instruments, assessing the relative performances, validating the results, and using the data effectively by employing comprehensive data analysis techniques. Set procedures for experimental designs can be found in various sources given in the Bibliography (e.g., Sydenham et al., 1989).

After having performed the experiments, the data must be analyzed appropriately. This can be done at various stages by examining the consistency of the data, performing appropriate statistical analyses, estimating the uncertainties of the results, relating the results to the theory, and correlating the data. Details of statistical data analysis can be found in many books; also many computer software programs are available for the purpose analysis including common packages such as Microsoft Excel.

INSTRUMENT RESPONSE AND DRIFT

Instruments respond to physical phenomena by sensing and generating signals. Depending on the type of instrument used and the physical phenomenon observed, the signals may be either slow or fast to change, and may also contain transients.

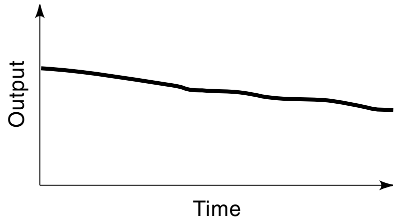

Figure 3. Drift in the output of an instrument. The main causes of the drift are aging, temperature, ambient conditions, and component deterioration. The drift in an instrument may be predicted by performance analysis of components, past experience, environmental tests, and so on.

The response of the instruments to the signals can be analyzed in a number of ways by establishing static and dynamic performance characteristics. Although, the static performances are relatively simple, the dynamic performances may be complex.

Static Response

Instrument are often described by their dynamic ranges and full-scale deflections (span). The *dynamic range* indicates the largest and smallest quantities that can be measured. The *full-scale deflection* of an instrument refers to the maximum permissible value of the input quoted in the units of the particular quantity to be measured.

In instruments, the change in output amplitude resulting from a change in input amplitude is called the *sensitivity.* System sensitivity often is a function of external physical variables such as temperature and humidity. The relative ratio of the output signal to the input signal is the *gain.* Both, the gain and sensitivity are dependent on the amplitude of the signals and the frequency, which will be discussed in the section on dynamic response.

In the design stages or during manufacturing, there might be small differences between the input and output, which is called the *offset.* In other words, when the input is zero the output is not zero or vice versa. The signal output also may change in time, which is known as *drift.* The drift can occur for many reasons including temperature and aging. Fortunately, drift usually occurs in a predictable manner. A typical drift curve of an instrument against time is illustrated in Fig. 3.

During practical applications, readings taken from an instrument under the same conditions may not be repeatable. In this case, a repeatability test may be conducted, and statistical techniques must be employed to evaluate the repeatability of the instrument.

Dynamic Response

The dynamic responses of an instrument is characterized by its natural frequency, amplitude, frequency response, phase shift, linearity and distortions, rise and settling times, slew rate, and the like. These characteristics are a common theme in many instrumentation, control, and electronics books. Although sufficient analysis will be given here, the detailed treatment of the topic can be very lengthy and complex; hence, the full treatment of this topic is not within the scope

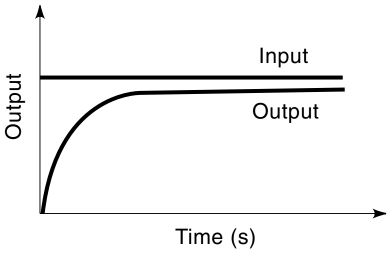

Figure 4. A first-order-hold instrument responds to a step input in an exponential form. For a good response the time delay must be small. Drift is usually expressed in percentage of output.

of this article. Interested readers should refer to the Bibliography (e.g., Doebelin, 1990).

The dynamic response of an instrument can be linear or nonlinear. Fortunately, most instruments exhibit linear characteristics, leading to simple mathematical modeling by using differential equations such as

$$a_n \frac{d^n y}{dt^n} + a_{n-1} \frac{d^{n-1} y}{dt^{n-1}} + \cdots + a_0 y = x(t) \tag{1}$$

where x is the input variable or the forcing function, y is the output variable, and a_n, a_{n-1}, . . ., a_0 are the coefficients or the constants of the system.

The dynamic response of instruments can be categorized as zero-order, first-order, or second-order responses. Although higher-order instruments may exist, their behaviors can be understood adequately in the form of a second-order system. From Eq. (1)

$$a_0 y = x(t) \qquad \text{zero order} \tag{2}$$

$$a_1 \frac{dy}{dt} + a_0 y = x(t) \qquad \text{first order} \tag{3}$$

$$a_2 \frac{d^2 y}{dt^2} + a_1 \frac{dy}{dt} + a_0 y = x(t) \qquad \text{second order} \tag{4}$$

Equations (2)–(4) can be written as Laplace transforms, thus enabling analysis in the frequency domain,

$$\frac{Y(s)}{X(s)} = 1 \tag{5}$$

$$\frac{Y(s)}{X(s)} = \frac{1}{(\tau_1 s + 1)} \tag{6}$$

$$\frac{Y(s)}{X(s)} = \frac{1}{(\tau_1 s + 1)(\tau_2 s + 1)} \tag{7}$$

where s is the Laplace operator and τ is the coefficient also called time constant.

In zero-order instruments, there is no frequency dependence between the input and output. The amplitude change is uniform across the spectrum of all possible frequencies. In practice, such instruments are difficult to obtain, except in a limited range of operations.

In first-order instruments, the relation between the input and the output is frequency dependent. Figure 4 illustrates the response of a first-order instrument for a unit step input in the time domain. Mathematically, the output may be written as

$$y(t) = Ke^{-t/\tau} \tag{8}$$

where K and τ are constants determined by the system parameters. In many cases, the input signals may be a complex rather than a simple step input. In the analysis, we need to multiply the transfer function, the second member of Eq. (6), by the Laplace transform of the input signal and then transform it back to the time domain if we are to understand the nature of transient and steady-state responses. Also, if the first-order systems are cascaded, the relative magnitudes of the time constants become important; some may be dominant, and others may be neglected.

Second-order systems exhibit the laws of simple harmonic motion, which can be described by linear wave equations. Equation (7) may be rearranged as

$$\frac{X(s)}{Y(s)} = \frac{1/a_0}{s^2/\omega_n^2 + 2\zeta s/\omega_n + 1} \tag{9}$$

where ω_n is the natural or undamped frequency (rad/s) and ζ is the damping ratio.

As can be seen, the performance of instruments become a function of natural frequency and the damping ratio of the system. The natural frequency and damping ratios are related to the physical parameters of the devices, such as mass and dimensions. In the design stages, these physical parameters may be selected, tested, and modified to obtain a desired response from the system.

Typical time response of a second-order system to unit step inputs is illustrated in Fig. 5. The response here indicates that a second-order system can either resonate or be unstable. Furthermore, we can deduce that, since the second-order system is dependent on time, wrong readings can be made depending on the time that the results are taken. Clearly, recording the output when the instrument is still under transient conditions will give an inadequate representation of

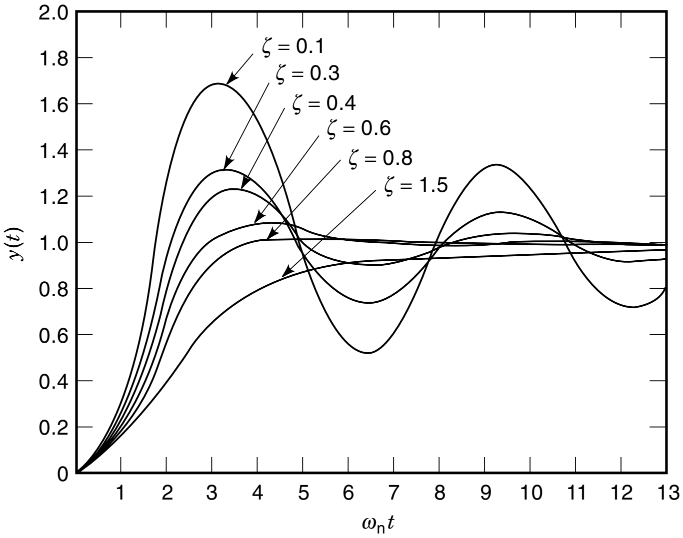

Figure 5. Unit step time responses of a second-order system with various damping ratios. The maximum overshoot, delay, rise, settling times and frequency of oscillation depend on the damping ratio. A smaller damping ratio gives a faster response but larger overshoot. In many applications, a damping ratio of 0.707 is preferred.

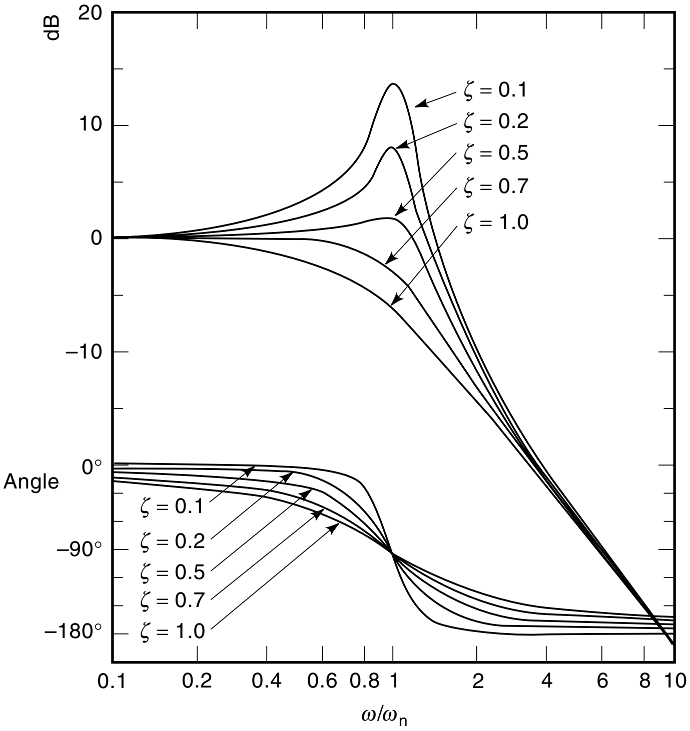

Figure 6. Bode plots of gains and phase angles against frequency of a second-order system. Curves are functions of frequencies as well as damping ratios. These plots can be obtained theoretically or by practical tests conducted in the frequency range.

the physical variable. The frequency compensation, selection of appropriate damping, acceptable time responses, and rise time settling time of instruments may need careful attention in both the design and application stages of an instrument. In these systems, system analysis is essential to ensure that they can measure the input measurand adequately.

A typical frequency dependence of gain and phase angle between input and output is illustrated in Fig. 6 in the form of Bode diagrams. Here, the *bandwidth,* which is the frequencies over which the gain is reasonably constant, is also shown. Usually, half power point (3 dB), which symbolizes 70.7% of the maximum value, is taken as the bandwidth.

An important concept in instruments is *response time,* which can be described as the time required for the instrument to respond to an input signal change. For automatic measurements, the response time is an indication of how many readings can be done per second. Response time is affected by many factors such as analog-to-digital (A/D) conversion time, settling time, delays in electronic components, and delays in sensors.

MEASUREMENT ERRORS AND ERROR CONTROL SYSTEMS

The performance of an instrument depends on its static and dynamic characteristics. The performance may be indicated by its *accuracy,* which may be described as the closeness of measured values to the real values of the variable. The total response is a combination of dynamic and static responses. If the signals generated by the physical variable are changing rapidly, then the dynamic properties of the instrument become important. For slowly-varying systems, the dynamic errors may be neglected. In order to describe the full relationships between the inputs and outputs, differential equations can be used, as discussed previously.

The performance of an instrument may also be decided by other factors, such as the magnitudes of errors; the *repeatability,* which indicates the closeness of sets of measurements made in the short term; and the *reproducibility* of the instrument. The reproducibility is the closeness of sets of measurements when repeated in similar conditions over a long period of time.

The ideal or perfect instrument would have perfect sensitivity, reliability, and repeatability without any spread of values and would be within the applicable standards. However, in many measurements, there will be imprecise and inaccurate results as a result of internal and external factors. The departure from the expected perfection is called the *error.* Often, sensitivity analyses are conducted to evaluate the effect of individual components that are causing these errors. Sensitivity to the affecting parameter can be obtained by varying that one parameter and keeping the others constant. This can be done practically by using the developed instruments or mathematically by means of appropriate models.

When determining the performance of an instrument, it is essential to appreciate how errors arise. There may be many sources of errors; therefore, it is important to identify these sources and draw up an error budget. In the error budget, there may be many factors, such as (1) imperfections in electrical and mechanical components (e.g., high tolerances and noise or offset voltages), (2) changes in component performances (e.g., shift in gains, changes in chemistry, aging, and drifts in offsets), (3) external and ambient influences (e.g., temperature, pressure, and humidity), and (4) inherent physical fundamental laws (e.g., thermal and other electrical noises, Brownian motion in materials, and radiation).

In instrumentation systems, errors can be broadly classified as systematic, random, or gross.

Systematic Errors

Systematic errors remain constant with repeated measurements. They can be divided into two basic groups as instrumental errors and environmental errors. Instrumental errors are inherent within the instrument, arising because of the mechanical structure, electronic design, improper adjustments, wrong applications, and so on. They can also be subclassified as loading error, scale error, zero error, and response time error. The environmental errors are caused by environmental factors such as temperature and humidity. Systematic errors can also be viewed as static or dynamic errors.

Systematic errors can be quantified by mathematical and graphical means. They can be caused by the nonlinear response of the instrument to different inputs as a result of hysteresis. They also emerge from wrong biasing, wear and aging, and other factors such as modifying the effects environment (e.g., interference). Typical systematic error curves are illustrated in Fig. 7.

Because of the predicability of systematic errors, deterministic mathematics can be employed. In the simplest form, the error of a measurement may be expressed as

$$\Delta x(t) = x_{\mathrm{m}}(t) - x_{\mathrm{r}}(t) \tag{10}$$

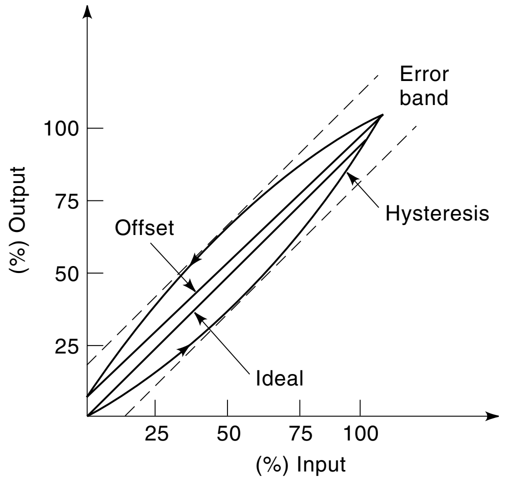

Figure 7. Systematic errors are static errors and they can be quantified theoretically or experimentally. There are many different types, including hysteresis, linearity, and offset. They are contained within an error band typical to particular instrument.

where $\Delta x(t)$ is the absolute error, $x_r(t)$ is the correct reference value, and $x_m(t)$ is the measured value.

From Eq. (10), the relative error $r_e(t)$ may be calculated as

$$r_e(t) = \frac{\Delta x(t)}{x_r(t)} \tag{11}$$

However, in complex situations, correction curves obtained either empirically or theoretically may be used. Manufacturers usually supply correction curves, especially if their products embrace wide ranging and different applications (e.g., slurries with changing characteristics in time).

In many applications, the measurement system is made up of many components that have errors in their own rights. The deterministic approach may be adapted to calculate the overall propagated error of the system, as

$$y = \mathrm{f}(x_1, x_2, x_3, \ldots, x_n) \tag{12}$$

where y is the overall output and x_1, x_2, . . . are the components affecting the output.

Each variable affecting the output will have its own absolute error of Δx_i. The term Δx_i indicates the mathematically or experimentally determined error of each component under specified operating conditions. The overall performance of the overall system with the errors may be expressed as

$$y \pm \Delta y = \mathrm{f}(x_1 \pm \Delta x_1, x_2 \pm \Delta x_2, \ldots, x_n \pm \Delta x_n) \tag{13}$$

For an approximate solution, the Taylor series may be applied to Eq. (13). By neglecting the higher-order terms of the series, the total absolute error Δy of the system may be written as

$$\Delta y = |\Delta x_1 \delta y/\delta x_1| + |\Delta x_2 \delta y/\delta x_2| + \cdots + |\Delta x_n \delta y/\delta x_n| \tag{14}$$

The absolute error is predicted by measuring or calculating the values of the errors of each contributing component.

Slight modification of Eq. (13) leads to uncertainty analysis, where

$$w_y = [(w_1 \delta y/\delta x_1)^2 + (w_2 \delta y/\delta x_2)^2 + \cdots + (w_n \delta y/\delta x_n)^2]^{1/2} \tag{15}$$

where w_y is the uncertainty of the overall system and w_1, w_2, . . ., w_n are the uncertainties of affecting the component.

Uncertainty differs from error in that it involves such human judgemental factors as estimating the possible values of errors. In measurement systems, apart from the uncertainties imposed by the instruments, experimental uncertainties also exist. In evaluating the total uncertainty, several alternative measuring techniques should be considered and assessed, and estimated accuracies must be worked out with care.

Random and Gross Errors

Random errors appear as a result of rounding, noise and interference, backlash and ambient influences, and so on. In experiments, the random errors vary by small amounts around a mean value. Therefore, the future value of any individual measurement cannot be predicted in a deterministic manner. Random errors may not easily be offset electronically; therefore, in the analysis and compensation, stochastic approaches are adapted by using the laws of probability.

Depending on the system, the random error analysis may be made by applying different probability distribution models. But, most instrumentation systems obey normal distribution laws; therefore, the Gaussian model can broadly be applied enabling the determination of the mean values, standard deviations, confidence intervals, and the like, depending on the number of samples being taken. A typical example of a Gaussian curve is given in Fig. 8. The mean value $\overline{x}$ and the standard deviation σ may be found by

$$\overline{x} = \frac{\sum x_{\mathrm{i}}}{n} \tag{16}$$

and

$$\sigma = \frac{\sum (x_{\mathrm{i}} - \overline{x})^2}{n-1} \tag{17}$$

Discussions relating to the application of stochastic theory in error analysis are very lengthy and will not be repeated here. Interested readers should refer to the Bibliography (e.g., Holman, 1989).

Gross errors are the result of human mistakes, equipment fault, and the like. Human errors may occur in the process of observations or during the recording and interpretation of

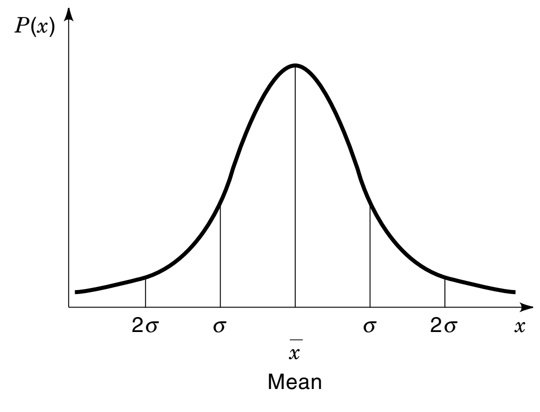

Figure 8. Random errors of instruments can be analyzed by using probability methods. In many instruments, the errors can be described by a Gaussian distribution curve.

experimental results. A large number of errors can be attributed to carelessness, the improper adjustment of instruments, the lack of knowledge about the instrument and the process, and so on. These errors cannot be treated mathematically and eliminated completely, but they can be minimized by having different observers repeat the experiments.

Error Reduction Techniques

Controlling errors is an essential part of instruments and instrumentation systems. Various techniques are available to achieve this objective. The error control begins in the design stages by choosing the appropriate components, filtering, and bandwidth selection, by reducing the noise, and by eliminating the errors generated by the individual subunits of the complete system. In a good design, the errors of the previous group may be compensated adequately by the following groups.

The accuracy of instruments can be increased by postmeasurement corrections. Various calibration methods may be employed to alter parameters slightly to give correct results. In many cases, calibration graphs, mathematical equations, tables, the experiences of the operators, and the like are used to reduce measurement errors. In recent years, with the application of digital techniques and intelligent instruments, error corrections are made automatically by computers or the devices themselves.

In many instrumentation systems, the application of compensation strategy is used to increase static and dynamic performances. In the case of static characteristics, compensations can be made by many methods including the introducing opposing nonlinear elements in the system, using isolation and zero environmental sensitivity, opposing compensating environmental inputs, using differential systems, and employing feedback systems. On the other hand, the dynamic compensation can be achieved by applying these techniques as well as by reducing harmonics, using filters, adjusting bandwidth, using feedback compensation techniques, and the like.

Open loop and close loop dynamic compensations are popular methods employed in both static and dynamic error corrections. For example, using high-gain negative feedback can reduce the nonlinearity generated by the system. A recent and fast-developing trend is the use of computers for estimating measured values and providing compensation during the operations if any deviations occur from the estimated values.

STANDARDS AND REFERENCE MATERIALS

Standards of fundamental units of length, time, weight, temperature, and electrical quantities have been developed for measurements to be consistent all over the world. The length and weight standards—the meter and the kilogram—are kept in the International Bureau of Weights and Measures in Sèvres, France. Nevertheless, in 1983 the meter was defined as the length of the path traveled by light in vacuum in the fraction 1/299,792,458 of a second, which was adopted as the standard meter. The standard unit of time—second—is established in terms of known oscillation frequencies of certain devices, such as the radiation of the cesium-133 atom. The standards of electrical quantities are derived from mechanical units of force, mass, length, and time. Temperature standards are established as international scale by taking eleven primary fixed points. If different units are involved, the relationship between different units are defined in fixed terms. For example, 1 lbm = 453.59237 g.

Table 2. Basic SI Units

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd
Plane angle	radian	rad
Solid angle	steradian	sr

Based on these standards, primary international units, SI (Système International d'Unités), are established for mass, length, time, electric current, luminous intensity, and temperature, as illustrated in Table 2. From these units, SI units of all physical quantities can be derived as exemplified in Table 3. The standard multiplier prefixes are illustrated in Table 4.

In addition to primary international standards, standard instruments are available having stable and precisely defined characteristics that are used as references for other instruments that are performing the same function. Hence, the performance of an instrument can be cross-checked against a known device. At a global level, checking is done by using an international network of national and international laboratories, such as the National Bureau of Standards (NBS), the National Physical Laboratory (NPL), and the Physikalisch-Technische Bundesanstalt of Germany. A treaty between the world's national laboratories regulates the international activity and coordinates development, acceptance, and intercomparisons. Basically, standards are kept in four stages:

1. *International standards* represent certain units of measurement with maximum accuracy possible within today's available technology. These standards are under the responsibility of an international advisory committee and are not available to ordinary users for comparison or calibration purposes.
2. *Primary standards* are the national standards maintained by national laboratories in different parts of the world for verification of secondary standards. These standards are independently calibrated by absolute measurements that are periodically made against the international standards. The primary standards are compared against each other.
3. *Secondary standards* are maintained in the laboratories of industry and other organizations. They are periodically checked against primary standards and certified.
4. *Working standards* are used to calibrate general laboratory and field instruments.

Another type of standard is published and maintained by the IEEE in New York. These standards are for test procedures, safety rules, definitions, nomenclature, and so on. The IEEE standards are adopted by many organizations around the world. Many nations also have their own standards for test procedures, instrument usage procedures, safety, and the like.

Table 3. Fundamental, Supplementary, and Derived Units

Quantity	Symbol	Unit Name	Unit Symbol
		Mechanical Units	
Acceleration	a	Meter/second^2	m/s^2
Angular acceleration	α	Radian/second^2	rad/s^2
Angular frequency	ω	Radian/second	rad/s
Angular velocity	ω	Radian/second	rad/s
Area	A	Square meter	m^2
Energy	E	Joule	J(kg · m^2/s^2)
Force	F	Newton	N(kg · m/s^2)
Frequency	f	Hertz	Hz
Gravitational field strength	g	Newton/kilogram	N/kg
Moment of force	M	Newton · meter	N · m
Plane angle	$\alpha, \beta, \theta, \phi$	Radian	Rad
Power	P	Watt	W(J/s)
Pressure	p	Newton/meter^3	N/m^3
Solid angle	ω	Steradian	Sr
Torque	T	Newton meter	N · m
Velocity	v	Meter/second	m/s
Volume	V	Cubic meter	m^3
Volume density	ρ	Kilogram/meter^3	kg/m^3
Wavelength	λ	Meter	M
Weight	W	Newton	N
Weight density	γ	Newton/cubic meter	N/m^3
Work	w	Joule	J
		Electrical Units	
Admittance	Y	Mho (siemen)	mho (S)
Capacitance	C	Farad	F(A · s/V)
Conductance	G	Mho(siemen)	mho(S)
Conductivity	γ	Mho/meter	mho/m(S/m)
Current density	J	Ampere/meter^2	A/m^2
Electric potential	V	Volt	V
Electric field intensity	E	Volt/meter	V/m
Electrical energy	W	Joule	J
Electrical power	P	Watt	W
Impedance	Z	Ohm	Ω
Permittivity of free space	ϵ	Farad/meter	F/m
Quantity of electricity	Q	Coulomb	C(A · s)
Reactance	X	Ohm	Ω
Resistance	R	Ohm	Ω
Resistivity	ρ	Ohm · meter	Ω · m
		Magnetic Units	
Magnetic field intensity	H	Ampere/meter	A/m
Magnetic flux	Φ	Weber	Wb
Magnetic flux density	B	Tesla (weber/meter^2)	T (Wb/m^2)
Magnetic permeability	μ	Henry/meter	H/m
Mutual inductance	M	Henry	H
Permeability of free space	μ_o	Henry/meter	H/m
Permeance	P	Henry	H
Relative permeability	μ_r	—	—
Reluctance	R	Henry^{-1}	H^{-1}
Self inductance	L	Henry	H
		Optical Units	
Illumination	lx	Lux	cd · sr/m^2
Luminous flux	lm	Lumen	cd · sr
Luminance	cd	Candela/meter^2	cd/m^2
Radiance	L_e	Watt/steradian · meter^3	W/sr · m^3
Radiant energy	W	Joule	J
Radiant flux	P	Watt	W
Radiant intensity	I_e	Watt/steradian	W/sr

Table 4. Decimal Multiples

Name	Symbol	Equivalent
Exa	E	10^{18}
Peta	P	10^{15}
Tera	T	10^{12}
Giga	g	10^{9}
Mega	M	10^{6}
Kilo	k	10^{3}
Hecto	h	10^{2}
Deca	da	10
Deci	d	10^{-1}
Centi	c	10^{-2}
Milli	m	10^{-3}
Micro	μ	10^{-6}
Nano	n	10^{-9}
Pico	p	10^{-12}
Femto	f	10^{-15}
Atto	a	10^{-18}

CALIBRATION, CALIBRATION CONDITIONS, AND THE LINEAR CALIBRATION MODEL

The calibration of all instruments is essential for checking their performances against known standards. This provides consistency in readings and reduces errors, thus validating the measurements to be valid universally. After an instrument is calibrated, future operation is deemed to be error-bounded for a given period of time for similar operational conditions. The calibration procedure involves comparison of the instrument against primary or secondary standards. In some cases, it may be sufficient to calibrate a device against another one with a known accuracy.

Many nations and organizations maintain laboratories with the primary functions of calibrating instruments and field measuring systems that are used in everyday operations. Examples of these laboratories are National Association of Testing Authorities (NATA) of Australia and the British Calibration Services (BCS).

Calibrations may be made under static or dynamic conditions. A typical calibration procedure of a complex process involving many instruments is illustrated in Fig. 9. In an ideal situation, for an instrument that responds to a multitude of physical variables, a commonly employed method is to keep all inputs constant except one. The input is varied in increments in increasing and decreasing directions over a specified range. The observed output then becomes a function of that single input. The calibration is continued in a similar manner until all other inputs are covered. For better results, this procedure may be repeated by varying the sequences of inputs thus developing a family of relationships between the inputs and outputs. As a result of these calibration readings, the input and output relation usually demonstrates statistical characteristics. From these characteristics, appropriate calibration curves can be obtained, and other statistical techniques can be applied.

In many instruments, the effect of a single input may not represent the true output values when one input is varied and all others are kept constant. In these cases, calibration is conducted by varying several inputs simultaneously. Throughout the calibration procedure, the n number of variables of the system are monitored by appropriate standard instruments. The rule of thumb is that each calibrated variable must have a traceable ladder starting from laboratory standards and secondary standards leading to primary standards. This is known as the linear calibration model or traceability.

Most instrument manufacturers supply calibrated instruments and reliable information about their products. But their claims of accuracy and reliability must be taken at face value. Therefore, in many cases, application-specific calibrations must be made periodically within the recommended calibration intervals. Usually, manufacturers supply calibration programs. In the absence of such programs, it is advisable to conduct frequent calibrations in the early stages of installation and lengthen the period between calibrations as the confidence builds based on satisfactory performance. Recently, with the wide applications of digital systems, computers can make automatic and self calibrations as in the case of many intelligent instruments. In these cases, post measurement corrections are made, and the magnitudes of various errors are stored in the memory to be recalled and used in laboratory and field applications.

ANALOG AND DIGITAL INSTRUMENTS

Instruments can be analog or digital or a combination of the two. Nowadays, most instruments are produced to be digital because of the advantages that they offer. However, the front end of majority of instruments are still analog; that is, the majority of sensors and transducers generate analog signals. Initially, the signals are conditioned by analog circuits before they are put into digital form for signal processing. It is important to mention that digital instruments operating purely on digital principles are developing fast. For instance, today's smart sensors contain the complete signal condition circuits in a single chip integrated with the sensor itself. The output of smart sensors can be interfaced directly with other digital devices.

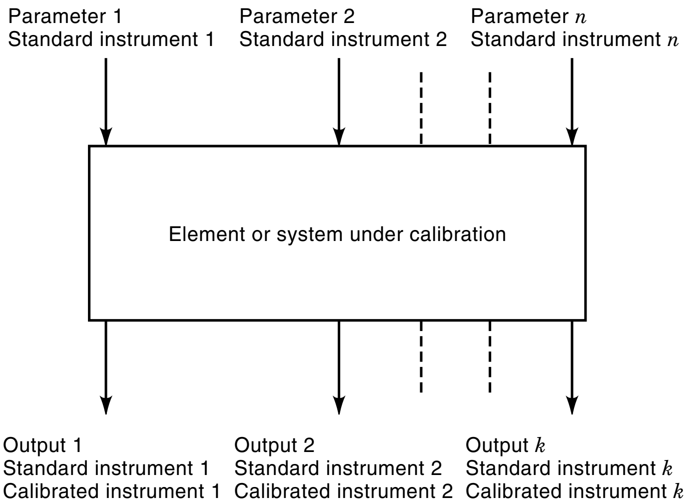

Figure 9. Instruments are frequently calibrated sequentially for all affected inputs. Calibrations are made under static or dynamic conditions, usually keeping all inputs constant and varying only one and observing the output. The calibration continues until all other inputs are covered.

In analog instruments, the useful information is conveyed by changes in amplitudes, phases, or frequencies or a combination of the three. These signals can be deterministic or nondeterministic. In all analog or digital instruments, as in the case with all signal-bearing systems, there are useful signals that respond to the physical phenomena and unwanted signal resulting from various forms of noise. In the case of digital instruments, additional noise is generated in the process of A/D conversion.

Analog signals can also be nondeterministic; that is, the future state of the signal cannot be determined. If the signal varies in a probabilistic manner, its future can be foreseen only by statistical methods. The mathematical and practical treatment of analog and digital signals having deterministic, stochastic, and nondeterministic properties is a very lengthy subject and a vast body of information can be found in literature; therefore, they will not be treated here.

As is true of all instruments, when connecting electronic building blocks, it is necessary to minimize the loading effects of each block by ensuring that the signal is passed without attenuation, loss, or magnitude and phase alterations. It is also important to ensure maximum power transfer between blocks by appropriate impedance-matching techniques. Impedance matching is very important in all instruments but particularly at a frequency of 1 MHz and above. As a rule of thumb, output impedances of the blocks are usually kept low and input impedances are kept high so that the loading effects can be minimized.

Analog Instruments

Analog instruments are characterized by continuous signals. A purely analog system measures, transmits, displays, and stores data in analog form. The signal conditioning is usually made by integrating many functional blocks such as bridges, amplifiers, filters, oscillators, modulators, offsets and level converters, buffers, and the like, as illustrated Fig. 10. Generally, in the initial stages, the signals produced by the sensors and transducers are conditioned mainly by analog electronics, even if they are configured as digital instruments later. Therefore, we pay more attention to analog instruments, keeping in mind that much of the information given here also may be used in various stages of the digital instruments.

Instrument bridges are commonly used to measure such basic electrical quantities as resistance, capacitance, inductance, impedance, and admittance. Basically, they are two-port networks in which the component to be measured is connected to one of the branches of the network. There are two basic groups, ac and dc bridges. Also, there are many different types in each group, such as Wheatstone and Kelvin dc bridges and Schering, Maxwell, Hay, and Owen ac bridges. In a particular instrument, the selection of the bridge to be employed and the determination of values and tolerances of its components is very important. It is not our intent to cover all bridges here; however, as typical example of an ac bridge, a series *RC* bridge is given in Fig. 11. We also offer some analysis to illustrate briefly their typical operational principles. At balance,

$$Z_1 Z_3 = Z_x Z_z \tag{18}$$

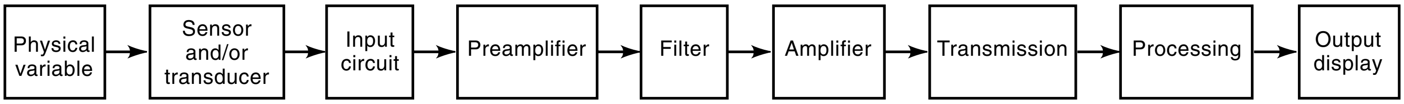

Figure 10. Analog instruments measure, transmit, display, and store data in analog form. The signal conditioning usually involves such components as bridges, amplifiers, filters, oscillators, modulators, offsets and level converters, buffers, and so on. These components are designed and tested carefully to suit the characteristics of particular instruments.

Substitution of impedance values gives

$$R_3(R_1 - j/\omega C_1) = (R_x - j/\omega C_x)R_2 \tag{19}$$

Equating the real and imaginary terms gives the values of unknown components as

$$R_x = \frac{R_1 R_3}{R_2} \tag{20}$$

and

$$C_x = \frac{C_1 R_2}{R_3} \tag{21}$$

In instruments, the selection and use of amplifiers and filters are also very important since many transducers generate extremely weak signals in comparison to the noise existing in the device. Today, operational amplifiers and high-precision instrumentation amplifiers are the building blocks of modern instruments.

The operation amplifiers may be used as inverting and noninverting amplifiers, and by connecting suitable external components, they can be configured to perform many other functions, such as multipliers, adders, limiters, and filters. Instrumentation amplifiers are used in situations where operational amplifiers do not meet the requirements. They are essentially high-performance differential amplifiers consisting of several closed-loop operational amplifiers. The instrumentation amplifiers have improved common mode rejection ratios (CMRR) (up to 160 dB), high input impedances (up to 500 MΩ), low output impedance, low offset currents and voltages and better temperature characteristics. To illustrate amplifiers in instrumentation systems, a typical current amplifier used in charge amplification is illustrated in Fig. 12. In this circuit, if the input impedance of the operational amplifier is high, output is not saturated, and the differential input voltage is small, it is possible to write

$$\frac{1}{C_\mathrm{f}} \int i_\mathrm{f}\, dt = e_\mathrm{ex} - e_\mathrm{ai} = e_\mathrm{ex} \tag{22}$$

$$\frac{1}{C_\mathrm{x}} \int i_\mathrm{x}\, dt = e_0 - e_\mathrm{ai} = e_0 \tag{23}$$

$$i_\mathrm{f} + i_\mathrm{x} - i_\mathrm{ai} = 0 = i_\mathrm{f} + i_\mathrm{x} \tag{24}$$

Manipulation of these equations gives

$$e_0 = \frac{-C_\mathrm{f}\, e_\mathrm{ex}}{C_\mathrm{x}} \tag{25}$$

However, a practical circuit requires a resistance across C_f to limit output drift. The value of this resistance must be greater than the impedance of C_f at the lowest frequency of interest.

Filtering is used to reject unwanted components of signals. For example, by using a filter that narrows the bandwidth, the broadband noise energy is reduced, and unwanted signals outside the passband are rejected. Analog filters can be designed by using various techniques, such as Butterworth, Chebyshev, and Bessel-Thomson filters etc. They can be lowpass, highpass, bandpass, bandstop, and notch filters. Filters can be classified as active and passive. Active filters involve active components such as operational or instrumentation amplifiers, whereas passive filters are configured completely by inductive, capacitive, and resistive components. The choice of active or passive filters depends on the available components, the precision required, and the frequency of operations. A typical filter used in instrument is given in Fig. 13.

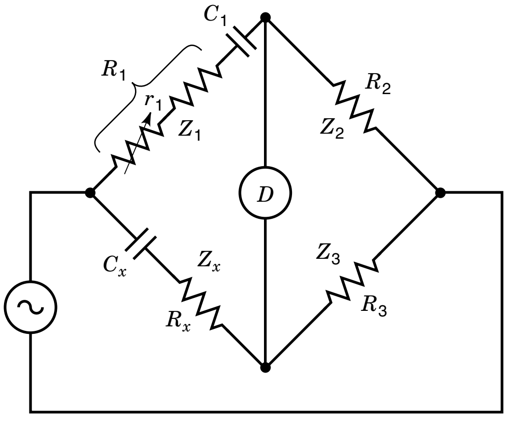

Figure 11. A series *RC* bridge wherein the unknown capacitance is compared with a known capacitance. The voltage drop across R_1 balances the resistive voltage drop in branch Z_2. The bridge balance is achieved relatively easily when capacitive branches have substantial resistive components. The resistors R_1 and either R_2 or R_3 are adjusted alternately to obtain the balance.

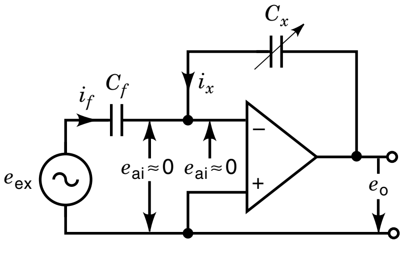

Figure 12. Using an operational amplifier signal processor is useful to eliminate the nonlinearity in the signals generated by capacitive sensors. With this type of arrangement, the output voltage can be made to be directly proportional to variations in the signal representing the nonlinear operation of the device.

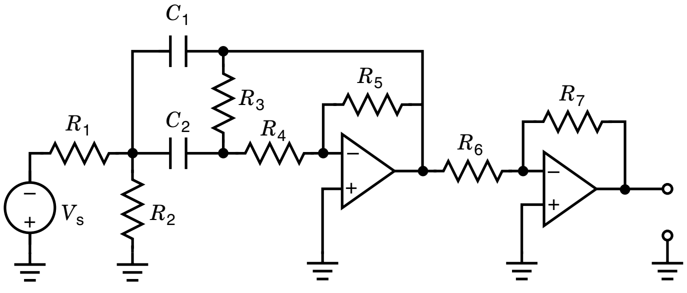

Figure 13. Filtering is used in various stages of signal processing to eliminate unwanted components of signals. They can be designed and constructed to eliminate or pass signals at certain frequency ranges. Suitable arrangements of components yield to bandpass, highpass, bandpass, bandstop and notch filters. Filters can be classified as active and passive.

Digital Instruments

In modern instruments, the original data acquired from the physical variables are usually in analog form. This analog signal is converted to digital before being passed on to the other parts of the system. For conversion purposes, analog-to-digital converters are used together with appropriate sample-and-hold devices. In addition, analog multiplexers enable the connection of a number of transducers to the same signal-processing media. The typical components of a digital instrument are illustrated in Fig. 14. The digital systems are particularly useful in performing mathematical operations and storing and transmitting data.

Analog-to-digital conversion involves three stages: sampling, quantization, and encoding. The Nyquist sampling theorem must be observed during sampling; that is, "the number of samples per second must be at least twice the highest frequency present in the continuous signal." As a rule of thumb, depending on the significance of the high frequencies, the sampling must be about five to ten times the highest frequency of the signal. The next stage is the quantization, which determines the resolution of the sampled signals. The quantization error decreases as the number of bits increases. In the encoding stage, the quantized values are converted to binary numbers to be processed digitally. Figure 15 illustrates a typical A/D sampling process of an analog signal.

After the signals are converted to digital form, the data can be further processed by employing such various techniques as FFT analysis, digital filtering, sequential or logical decision making, correlation methods, spectrum analysis, and so on.

Virtual Instruments (VIs)

Traditional instruments have three basic components—acquisition and control, data analysis, and data presentation. In VIs, the use of digital techniques, software, and computers replace the display and processing capabilities of most traditional instruments. In this technology, plug-in data acquisition (DAQ) boards, PC cards (PCMCIA), and parallel port I/O devices are used to interface sensors and transducers of the system under investigation to computers. There are standard interface buses such as VXIbus, which stands for VMEbus Extensions for Instrumentation (also known as the IEEE Standard 1155-1992).

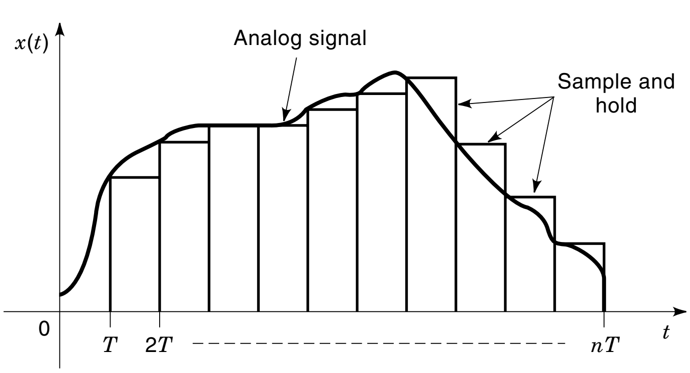

Figure 15. Analog-to-digital converters involve three stages: sampling, quantization, and encoding. However, the digitization introduces a number of predictable errors. After the conversion, the data can be processed by techniques such as FFT analysis, DFT analysis, digital filtering, sequential or logical decision making, correlation methods, spectrum analysis, and so on.

Once the system is interfaced, the computer can be programmed to act just like a stand-alone instrument, but offering additional benefits of flexibility of the processing, display, and storage. In VIs, the data can be saved or loaded in memory to be processed in popular spreadsheet programs and word processors, and a report generation capability complements the raw data storage by adding timestamps, measurements, user names, and comments.

VI technology allows the user to build test systems that fit specific applications. The VI software can be programmed to resemble familiar instrument panels, including buttons and dials. The user interface tools include knobs, meters, gauges, dials, tank displays, thermometers, graphs, strip charts, and the like to simulate the appearance of traditional instruments. Computer displays can show more colors, and allow users to quickly change the way they display test data and controls as required. The software also contains analysis libraries with high-powered statistics, curve fitting, signal processing, and filtering to standard dynamic link libraries (DLLs).

Designing a VI system is similar to designing a test system with stand-alone instruments. The first step is to determine

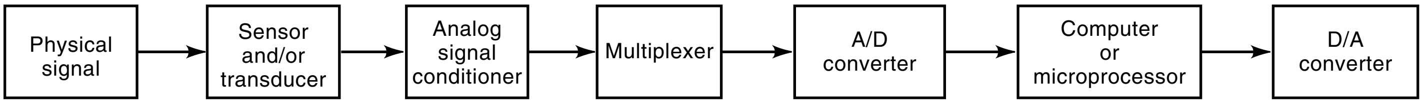

Figure 14. Digital instruments have more signal-processing components than analog instruments. Usually, analog signals are converted to digital form by analog-to-digital (A/D) converters. The digital instruments have the advantage of processing, storing, and transmitting signals more easily than their analog counterparts.

what types of signals are needed to measure, including their frequencies, amplitudes, and other signal characteristics together with the level of accuracy expected from these signals. To develop the software for the test application, a programming language or test-development software package needs to be selected such as C or Microsoft Visual Basic. Since the display is not fixed, as on a stand-alone instrument, it can be as complex or as simple as the application requires.

Nowadays, users can configure their VIs to update front panels and display real-time, animated VIs over the Internet. The toolkits let applications be published over the Web and viewed with a standard Web browser with little additional programming. With these tools, developers can monitor VIs running in remote locations, publish experiment results on the Web, and automatically notify operators of alarm conditions or status information.

CONTROL OF INSTRUMENTS

Instruments can be manual, semiautomatic, or fully automatic. Manual instruments need human intervention for adjustment, parameter setting, and interpreting readings. Semiautomatic instruments need limited intervention such as the selection of operating conditions and so on. In the fully automatic instruments, however, the variables are measured either periodically or continuously without human intervention. The information is either stored or transmitted to other devices automatically. Some of these instruments can also measure the values of process variables and regulate their deviations from preset points.

It is often necessary to measure many parameters of a process by using two or more instruments. The resulting arrangement for performing the overall measurement function is called the measurement system. In measurement systems, instruments operate in an autonomously but coordinated manner. The information generated by each device is communicated between instruments themselves, or between the instrument and other devices such as recorders, display units, and computers. The coordination of instruments can be done in three ways: analog-to-analog, analog-to-digital, and digital-to-digital.

Analog systems consist of instruments that generate continuous current and voltage waveforms in response to the physical variations. The signals are processed by using analog electronics; therefore, signal transmission between the instruments and other devices is also done in the analog form. In assembling these devices, the following characteristics must be considered:

Signal transmission and conditioning
Loading effects and buffering
Proper grounding and shielding
Inherent and imposed noises
Ambient conditions
Signal level compatibility
Impedance matching
Proper display units
Proper data storage media

Offset and level conversion is used to convert the output signal of an instrument from one level to another, compatible with the transmission medium in use. In analog systems, signals are usually transmitted at suitable current levels (4–20 mA). In this way, change in impedance does not affect the signal levels, and standard current signal levels can easily be exchanged.

In digital instrumentation systems, analog data are converted and transmitted in digital form. The transmission of data between digital devices can be done relatively easily, by using serial or parallel transmission techniques. However, as the measurement system becomes large by the inclusion of many instruments, the communication becomes complex. To avoid this complexity, message interchange standards are used for digital signal transmission such as RS-232 and IEEE-488 VXIbus.

Many instruments are manufactured with output ports to pass measurement data and various control signals. The IEEE-488 (also known as the GPIB) bus is one of the established industry standard instrumentation interfacings. It enables simultaneous measurements by interfacing up to 15 instruments together at the same time. It has 16 signal lines distributed as 8 data lines, 3 control lines, and 5 general interface management lines. The line configuration of an IEEE-488 bus is given in Fig. 16. Once connected, any one device can transfer data to one or more other devices on the bus. All devices must be able to perform at least one of the following roles: talker, listener, controller. The minimum device consists of one talker and one listener without a controller. The length of cables connected to the bus cannot exceed 20 m, and the maximum data rate is restricted to 250 kilobytes per second.

RS-232 is issued by the Electronic Industries Association (EIA). It uses serial binary data interchange and applies specifically to the interconnection of data communication equipment (DCE) and data terminal equipment (DTM). Data communications equipment may include modems, which are the devices that convert digital signals suitable for transmission through telephone lines. The RS-232 uses standard DB-25 connectors, the pin connection is given in Table 5. Although 25 pins are assigned, a complete data transmission is possible by using only three pins—2, 3 and 7. The transmission speed can be set to certain baud rates such as 19200 bits per second and can be used for synchronous or nonsynchronous communication purposes. The signal voltage levels are very flexible, with any voltage between -3 V to -25 V representing logic 1 and any voltage between $+3$ V to $+25$ V representing logic 0.

In many industrial applications, the current loop digital communication is used. This communication is similar to analog current loop systems, but the signal is transmitted in digital form, with 20 mA signifying logic 1 and 0 mA representing logic 0. Depending on the external noise sources in the installation environment, the current loop can be extended up to 2 km.

When data are transmitted distances greater than those permitted by the RS-232 or current loop, the modem, microwave, or radiofrequency (RF) transmissions are used. In this case, various signal modulation techniques are necessary to convert digital signals to suitable formats. For example, most modems, with medium-speed asynchronous data transmission, use frequency-shift keyed (FSK) modulation. The digital interface with modems uses various protocols such as MIL-STD-188C to transmit signals in simplex, half-duplex, or full duplex forms depending on the directions of the data flow. The simplex interface transmits data in one direction,

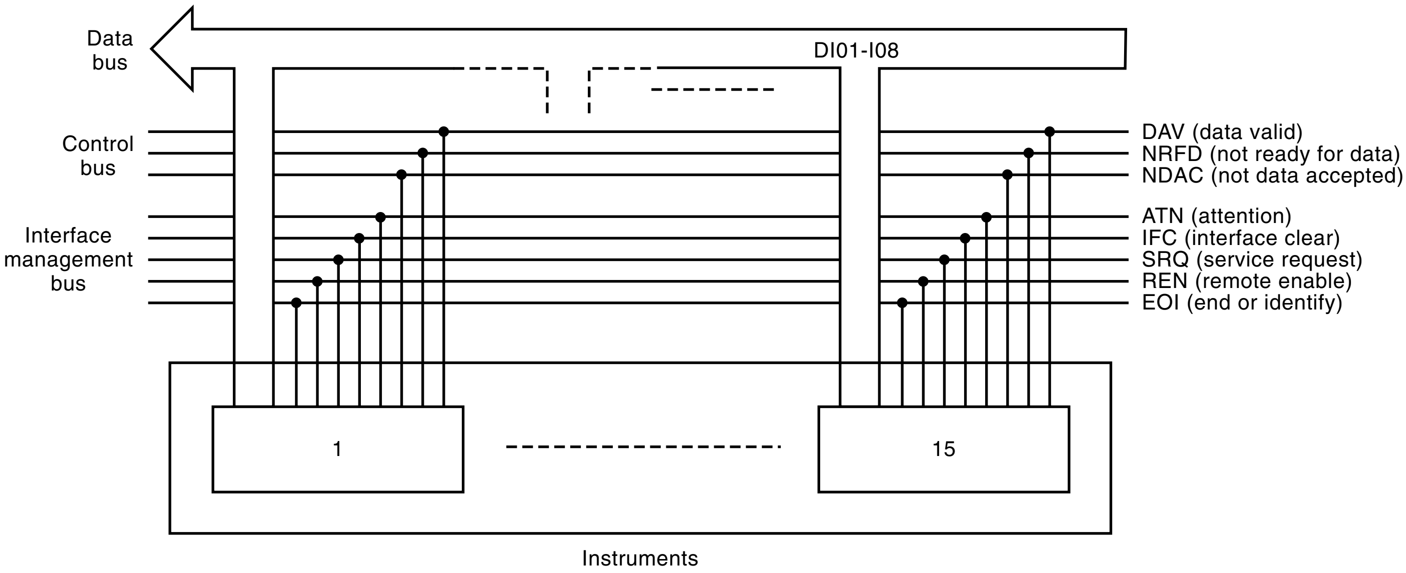

Figure 16. The IEEE-488 or the GPIB bus is an industry standard for interface medium. It has 8 data lines, 3 control lines, and 5 general interface management lines. In noisy environments the maximum length of cable is recommended to be not more than 20 m.

whereas full-duplex transmits it in two directions simultaneously.

As far as industrial applications are concerned, several standards for digital data transmission are available, commonly known as *fieldbuses* in the engineering literature. For example, WordFIP and Profibus have been developed and Foundation Fieldbus is under development to increase the performance of the 20 mA current loop. New devices allow for an increase in the data rates (e.g., National Instruments chips and boards operating with high-speed protocol HS488 for 8 Mbytes/s transfer rate). A new standard is under discussion at the IEEE by the working group for higher performance IEEE Std. 488.1, with a very high increase in the data rate.

Concerning the design software, there are important tools that help implement control (application) software for automatic measuring equipment, such as LabWindows and LabVIEW from National Instruments and VEE from Hewlett-Packard.

Table 5. RS-232 Pin Connections

Pin Number	Direction	Function
1	—	Frame ground
2	Out	Transmitted data (−TxD)
3	In	Received data (−RxD)
4	Out	Request to send (RTS)
5	In	Clear to send (CTS)
6	In	Data set ready (DSR)
7	—	Signal ground (SG)
8	In	Received line signal detector (DCD)
9	Out	+ Transmit current loop data
11	Out	−Transmit current loop data
18	In	+ Receive current loop data
20	Out	Data terminal ready (DTR)
22	In	Ring indicator (RI)
25	In	− Receive current loop return

In many applications, many instruments (say over a thousand) may be used to monitor and control the process as in the case of computer integrated manufacturing (CIM). In these cases, instruments are networked either in groups or as whole via a center computer or group of computers. Appropriate network topologies (e.g., star, ring, field bus) may be employed to enable the signal flow between the instruments and computers, among the instruments themselves, or between instruments and control panels.

INDUSTRIAL MEASURING INSTRUMENTS

In industry, instruments are used to sense and maintain the functions of the process. Because the requirements of diverse industries are different, the instruments are made quite differently to suit applicational differences from one industry to another. Here, instruments specific to some industries will be discussed briefly.

The process industry uses instruments extensively for on-line monitoring and off-line analysis. Specific instruments are used commonly for sensing variables such as temperature, pressure, volumetric and mass flow rate, density, weight, displacement, pH levels, color, absorbency, viscosity, material flow, dew point, organic and inorganic components, turbidity, solid and liquid level, humidity, and particle size distribution. The selection and use of these instruments constitute an important part of process engineering, which is a discipline in its own right. Additional information can be found in the Bibliography (e.g., Sydenham et al., 1989).

In medical technology, there are three basic types of instruments—imaging, physiological measurements, and laboratory analysis. In imaging and physiological measurements, the instruments are closely linked with patients. Some examples of these instruments are X-ray tomography, nuclear magnetic resonance (NMR) and nuclear spin tomography, ultrasound imaging, thermography, brain and nervous system sensors, and respiratory sensors. Many instruments are based on the radiation and sound, force and tactile sensing, electromagnetic sensing, and chemical and bioanalytical sensors.

Power plants are instrumented for maximum availability, operational safety, and environmental planning. Therefore, their measurements must be as accurate as possible and reliable. Instruments are used for temperature, pressure, flow, level, vibration measurements, and water, steam, and gas analysis. For example, gas analysis requires instruments to measure carbon compounds, sulfur and nitrogen compounds, and dust and ash contents.

Environmental monitoring requires a diverse range of instruments for air, water, and biological monitoring. Instruments are used for measuring various forms of radiation, chemicals hazards, air pollutants, and organic solvents. Many sophisticated instruments are also developed for remote monitoring via satellites, and they operate on optical, microwave, and RF electromagnetic radiation principles.

In automobiles, instruments are used to assist drivers by sensing variables such as cooling, braking, fuel consumption, humidity control, speed, travel route monitoring, and position sensing. Instruments also find applications for safety and security purposes, such as passenger protection and locking and antitheft systems. Recently, with the advent of micromachined sensors, many diverse instruments such as engine control, fuel injection, air regulation, and torque sensing are developed.

The manufacturing industry, especially automated manufacturing, requires a diverse range of instruments. Machine diagnosis and process parameters are made by instruments based on force, torque, pressure, speed, temperature, and electrical parameter-sensing instruments. Optics, tactile arrays, and acoustic scanning instruments are used for pattern recognition. Distance and displacement measurements are made by many methods (e.g., inductive, capacitive, optical, and acoustic techniques).

Aerospace instrumentation requires an accurate indication of physical variables and the changes in these variables. Instruments are designed to suit specific conditions of operations. Some of the measurements are gas temperature and pressure, fluid flow, aircraft velocity, aircraft icing, thrust and acceleration, load, strain and force, position, altitude sensing, and direction finding.

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INSTRUMENTS, MUSICAL. See MUSICAL INSTRUMENTS.

INSTRUMENTS, SOUND-INTENSITY. See LEVEL METERS.

INSTRUMENTS, SOUND-LEVEL. See LEVEL METERS.