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MEASUREMENT AND INSTRUMENTATION

Theory and Application

CHAPTER 1

Fundamentals of Measurement Systems

Chapter Outline

1.1 Introduction

Measurement techniques have been of immense importance ever since the start of human civilization, when measurements were first needed to regulate the transfer of goods in barter trade in order to ensure that exchanges were fair. The industrial revolution during the nineteenth century brought about a rapid development of new instruments and measurement techniques to satisfy the needs of industrialized production techniques. Since that time, there has been a large and rapid growth in new industrial technology. This has been particularly evident during the last part of the twentieth century, because of the many developments in electronics in general and computers in particular. In turn, this has required a parallel growth in new instruments and measurement techniques.

The massive growth in the application of computers to industrial process control and monitoring tasks has greatly expanded the requirement for instruments to measure, record, and control process variables. As modern production techniques dictate working to ever tighter accuracy limits, and as economic forces to reduce production costs become more severe, so the requirement for instruments to be both accurate and cheap becomes ever harder to satisfy. This latter problem is at the focal point of the research and development efforts of all instrument manufacturers. In the past few years, the most cost-effective means of improving instrument accuracy has been found in many cases to be the inclusion of digital computing power within instruments themselves. These intelligent instruments therefore feature prominently in current instrument manufacturers' catalogs.

Measurement and Instrumentation. http://dx.doi.org/10.1016/B978-0-12-800884-3.00001-0

This opening chapter will cover some fundamental aspects of measurement. First, we will look at how standard measurement units have evolved from the early units used in barter trade to the more exact units belonging to the Imperial and metric measurement systems. We will then do on to study the major considerations in designing a measurement system. Finally, we will look at some of the main applications of measurement systems.

1.2 Measurement Units

The very first measurement units were those used in barter trade to quantify the amounts being exchanged and to establish clear rules about the relative values of different commodities. Such early systems of measurement were based on whatever was available as a measuring unit. For purposes of measuring length, the human torso was a convenient tool, and gave us units of the hand, the foot and the cubit. Although generally adequate for barter trade systems, such measurement units are of course imprecise, varying as they do from one person to the next. Therefore, there has been a progressive movement toward measurement units that are defined much more accurately.

The first improved measurement unit was a unit of length (the meter) defined as 10^{-7} times the polar quadrant of the earth. A platinum bar made to this length was established as a standard of length in the early part of the nineteenth century. This was superseded by a superior quality standard bar in 1889, manufactured from a platinum–iridium alloy. Since that time, technological research has enabled further improvements to be made in the standard used for defining length. First, in 1960, a standard meter was redefined in terms of 1.65076373×10^6 wavelengths of the radiation from krypton-86 in vacuum. More recently, in 1983, the meter was redefined yet again as the length of path traveled by light in an interval of 1/299,792,458 s. In a similar fashion, standard units for the measurement of other physical quantities have been defined and progressively improved over the years. The latest standards for defining the units used for measuring a range of physical variables are given in Table 1.1.

The early establishment of standards for the measurement of physical quantities proceeded in several countries at broadly parallel times, and in consequence, several sets of units emerged for measuring the same physical variable. For instance, length can be measured in yards, meters, or several other units. Apart from the major units of length, subdivisions of standard units exist such as feet, inches, centimeters, and millimeters, with a fixed relationship between each fundamental unit and its subdivisions.

Yards, feet, and inches belong to the Imperial System of units, which is characterized by having varying and cumbersome multiplication factors relating fundamental units to subdivisions such as 1760 (miles to yards), 3 (yards to feet), and 12 (feet to inches). The metric system is an alternative set of units, which includes, for instance, the unit of the

Table 1.1: Definitions of standard units

Physical Quantity	Standard Unit	Definition
Length	Meter	The length of path traveled by light in an interval of 1/299,792,458 s
Mass	Kilogram	The mass of a platinum–iridium cylinder kept in the International Bureau of Weights and Measures, Sevres, Paris
Time	Second	9.192631770×10^9 cycles of radiation from vaporized caesium 133 (an accuracy of 1 in 10^{12} or 1 s in 36,000 years)
Temperature	Degrees	The temperature difference between absolute zero Kelvin and the triple point of water is defined as 273.16 K.
Current	Ampere	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross section placed 1 m apart in vacuum and producing a force of 2×10^{-7} N per meter length of conductor
Luminous intensity	Candela	One candela is the luminous intensity in a given direction from a source emitting monochromatic radiation at a frequency of 540 THz (Hz $\times 10^{12}$) and with a radiant density in that direction of 1.4641 mW/steradian (1 steradian is the solid angle which, having its vertex at the center of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	Mole	The number of atoms in a 0.012 kg mass of carbon 12

meter and its centimeter and millimeter subdivisions for measuring length. All multiples and subdivisions of basic metric units are related to the base by factors of 10 and such units are therefore much easier to use than Imperial units. However, in the case of derived units such as velocity, the number of alternative ways in which these can be expressed in the metric system can lead to confusion.

As a result of this, an internationally agreed set of standard units (SI units or Systèmes Internationales d'Unités) has been defined, and strong efforts are being made to encourage the adoption of this system throughout the world. In support of this effort, the SI system of units will be used exclusively in this book. However, it should be noted that the Imperial system is still widely used in the engineering industry, particularly in the United States of America.

The full range of fundamental SI measuring units and the further set of units derived from them are given in Tables 1.2 and 1.3. Conversion tables relating common Imperial and metric units to their equivalent SI units can also be found in Appendix 1.

Table 1.2: Fundamental SI units

Quantity	Standard Unit	Symbol
	(a) Fundamental Units	
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A
Temperature	Kelvin	K
Luminous intensity	Candela	cd
Matter	Mole	mol
	(b) Supplementary Fundamental Units	
Plane angle	Radian	rad
Solid angle	Steradian	sr

1.3 Measurement System Design

In this section, we will look at the main considerations in designing a measurement system. First, we will learn that a measurement system usually consists of several separate components, although only one component might be involved for some very simple measurement tasks. We will then go on to look at how measuring instruments and systems are chosen to satisfy the requirements of particular measurement situations.

1.3.1 Elements of a Measurement System

A *measuring system* exists to provide information about the physical value of some variable being measured. In simple cases, the system can consist of only a single unit that gives an output reading or signal according to the magnitude of the unknown variable applied to it. However, in more complex measurement situations, a measuring system consists of several separate elements as shown in Figure 1.1. These components might be contained within one or more boxes, and the boxes holding individual measurement elements might be either close together or physically separate. The term *measuring instrument* is commonly used to describe a measurement system, whether it contains only one or many elements, and this term will be widely used throughout this text.

The first element in any measuring system is the *primary sensor*: this gives an output that is a function of the measurand (the input applied to it). For most but not all sensors, this function is at least approximately linear. Some examples of primary sensors are a liquid-in-glass thermometer, a thermocouple, and a strain gauge. In the case of the mercury-in-glass thermometer, the output reading is given in terms of the level of the mercury, and so this particular primary sensor is also a complete measurement system in

Table 1.3: Derived SI units

Quantity	Standard Unit	Symbol	Derivation Formula
Area	Square meter	m^2	
Volume	Cubic meter	m^3	
Velocity	Meter per second	m/s	
Acceleration	Meter per second squared	m/s^2	
Angular velocity	Radian per second	rad/s	
Angular acceleration	Radian per second squared	rad/s^2	
Density	Kilogram per cubic meter	kg/m^3	
Specific volume	Cubic meter per kilogram	m^3/kg	
Mass flow rate	Kilogram per second	kg/s	
Volume flow rate	Cubic meter per second	m^3/s	
Force	Newton	N	$kg\text{-}m/s^2$
Pressure	Pascal	Pa	N/m^2
Torque	Newton meter	N-m	
Momentum	Kilogram meter per second	kg-m/s	
Moment of inertia	Kilogram meter squared	$kg\text{-}m^2$	
Kinematic viscosity	Square meter per second	m^2/s	
Dynamic viscosity	Newton second per square meter	$N\text{-}s/m^2$	
Work, energy, heat	Joule	J	N-m
Specific energy	Joule per cubic meter	J/m^3	
Power	Watt	W	J/s
Thermal conductivity	Watt per meter Kelvin	W/m-K	
Electric charge	Coulomb	C	A-s
Voltage, e.m.f., potential difference	Volt	V	W/A
Electric field strength	Volt per meter	V/m	
Electric resistance	Ohm	Ω	V/A
Electric capacitance	Farad	F	A-s/V
Electric inductance	Henry	H	V-s/A
Electric conductance	Siemen	S	A/V
Resistivity	Ohm meter	Ω-m	
Permittivity	Farad per meter	F/m	
Permeability	Henry per meter	H/m	
Current density	Ampere per square meter	A/m^2	
Magnetic flux	Weber	Wb	V-s
Magnetic flux density	Tesla	T	Wb/m^2
Magnetic field strength	Ampere per meter	A/m	
Frequency	Hertz	Hz	s^{-1}
Luminous flux	Lumen	lm	cd-sr
Luminance	Candela per square meter	cd/m^2	
Illumination	Lux	lx	lm/m^2
Molar volume	Cubic meter per mole	m^3/mol	
Molarity	Mole per kilogram	mol/kg	
Molar energy	Joule per mole	J/mol	

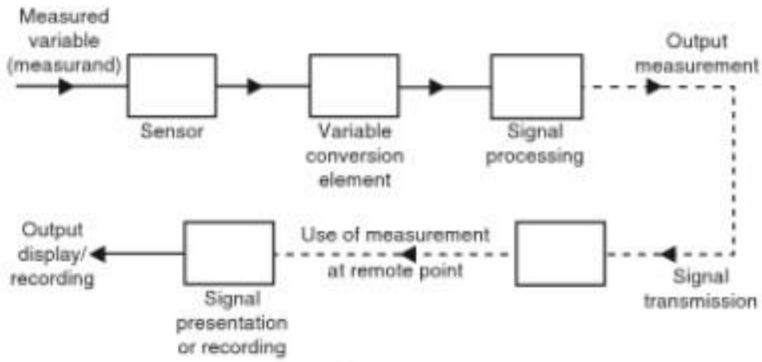

Figure 1.1
Elements of a measuring system.

itself. However, in general, the primary sensor is only part of a measurement system. The types of primary sensors available for measuring a wide range of physical quantities are presented in later chapters.

Intelligent instruments (see Chapters 3 and 10) also have one or more *secondary sensors*. These measure the environmental conditions, particularly temperature and pressure, surrounding a measurement system in order to correct the output of primary sensors affected by the environment conditions (see Chapter 3 for a fuller explanation).

Variable conversion elements are needed where the output variable of a primary transducer is in an inconvenient form and has to be converted to a more convenient form. For instance, the displacement-measuring strain gauge has an output in the form of a varying resistance. The resistance change cannot be easily measured and so it is converted to a change in voltage by a *bridge circuit*, which is a typical example of a variable conversion element. In some cases, the primary sensor and variable conversion element are combined, and the combination is known as a *transducer*.[1]

Signal processing elements exist to improve the quality of the output of a measurement system in some way. However, signal processing is not a magic cure for problems that result from poor measurement system design. Hence, it is important that the measurement system is designed properly such that the output from measurement sensors is of an appropriate amplitude and is as free from noise contamination as possible, as discussed later in Chapter 3. This is the necessary starting point for signal processing to be able to further improve the quality of the measurement system output.

The electronic amplifier is a very common type of signal processing element. This is used to amplify low-amplitude outputs from the primary transducer or variable conversion

[1] In some cases, the word "sensor" is used generically to refer to both transducers and transmitters.

element, thus improving the sensitivity and resolution of measurement. For example, amplification is needed for thermocouples, which have a typical output of only a few millivolts. Other types of signal processing element are those that filter out induced noise and remove mean levels, etc. In some devices, signal processing is incorporated into a transducer, which is then known as a *transmitter*.[1]

In addition to these three components just mentioned, some measurement systems have one or two other components, first to transmit the signal to some remote point and second to display or record the signal if it is not fed automatically into a feedback control system. *Signal transmission* is needed when the observation or application point of the output of a measurement system is some distance away from the site of the primary transducer. Sometimes, this separation is made solely for purposes of convenience, but more often, it follows from the physical inaccessibility or environmental unsuitability of the site of the primary transducer for mounting the signal presentation/recording unit. The signal transmission element has traditionally consisted of single or multicored cable, which is often screened to minimize signal corruption by induced electrical noise. However, fiber-optic cables are being used in ever-increasing numbers in modern installations, in part because of their low transmission loss and imperviousness to the effects of electrical and magnetic fields.

The final optional element in a measurement system is the point where the measured signal is utilized. In some cases, this element is omitted altogether because the measurement is used as part of an automatic control scheme, and the transmitted signal is fed directly into the control system. In other cases, this element in the measurement system takes the form either of a *signal presentation unit* or of a *signal recording unit*. These take many forms according to the requirements of the particular measurement application, and the range of possible units is discussed more fully in Chapter 9.

1.3.2 Choosing Appropriate Measuring Instruments

The starting point in choosing the most suitable instrument to use for measurement of a particular quantity in a manufacturing plant or other system is the specification of the instrument characteristics required, especially parameters like the desired measurement accuracy, resolution, sensitivity, and dynamic performance (see next chapter for definitions of these). It is also essential to know the environmental conditions that the instrument will be subjected to, as some conditions will immediately either eliminate the possibility of using certain types of instrument or else will create a requirement for expensive protection of the instrument. It should also be noted that protection reduces the performance of some instruments, especially in terms of their dynamic characteristics (e.g., sheaths protecting thermocouples and resistance thermometers reduce their speed of response). Provision of this type of information usually requires the expert knowledge of personnel who are intimately acquainted with the operation of the manufacturing plant or system in question. Then, a skilled instrument engineer, having knowledge of all the instruments that are available for measuring the quantity in question, will be able to evaluate the possible list of instruments in terms of their accuracy, cost, and suitability for the environmental conditions and thus choose the most appropriate instrument. As far as possible, measurement systems and instruments should be chosen that are as insensitive as possible to the operating environment, although this requirement is often difficult to meet because of cost and other performance considerations. The extent to which the measured system will be disturbed during the measuring process is another important factor in instrument choice. For example, significant pressure loss can be caused to the measured system in some techniques of flow measurement.

Published literature is of considerable help in the choice of a suitable instrument for a particular measurement situation. Many books are available that give valuable assistance in the necessary evaluation by providing lists and data about all the instruments available for measuring a range of physical quantities (e.g. part B of this text). However, new techniques and instruments are being developed all the time, and therefore a good instrumentation engineer must keep abreast of the latest developments by reading the appropriate technical journals regularly.

The instrument characteristics discussed in the next chapter are the features that form the technical basis for a comparison between the relative merits of different instruments. Generally, the better the characteristics, the higher the cost. However, in comparing the cost and relative suitability of different instruments for a particular measurement situation, considerations of durability, maintainability, and constancy of performance are also very important because the instrument chosen will often have to be capable of operating for long periods without performance degradation and a requirement for costly maintenance. In consequence of this, the initial cost of an instrument often has a low weighting in the evaluation exercise.

Cost is very strongly correlated with the performance of an instrument, as measured by its static characteristics. Increasing the accuracy or resolution of an instrument, for example, can only be done at a penalty of increasing its manufacturing cost. Instrument choice therefore proceeds by specifying the minimum characteristics required by a measurement situation and then searching manufacturers' catalogs to find an instrument whose characteristics match those required. To select an instrument with characteristics superior to those required would only mean paying more than necessary for a level of performance greater than that needed.

As well as purchase cost, other important factors in the assessment exercise are instrument durability and the maintenance requirements. Assuming that one had $20,000 to spend, one would not spend $15,000 on a new motor car whose projected life was 5 years if a car of equivalent specification with a projected life of 10 years was available for \$20,000. Likewise, durability is an important consideration in the choice of instruments. The projected life of instruments often depends on the conditions in that the instrument will have to operate. Maintenance requirements must also be taken into account, as they also have cost implications.

As a general rule, a good assessment criterion is obtained if the total purchase cost and estimated maintenance costs of an instrument over its life are divided by the period of its expected life. The figure obtained is thus a cost per year. However, this rule becomes modified where instruments are being installed on a process whose life is expected to be limited, perhaps in the manufacture of a particular model of car. Then, the total costs can only be divided by the period of time that an instrument is expected to be used for, unless an alternative use for the instrument is envisaged at the end of this period.

To summarize therefore, instrument choice is a compromise between performance characteristics, ruggedness and durability, maintenance requirements, and purchase cost. To carry out such an evaluation properly, the instrument engineer must have a wide knowledge of the range of instruments available for measuring particular physical quantities, and he/she must also have a deep understanding of how instrument characteristics are affected by particular measurement situations and operating conditions.

1.4 Measurement System Applications

Today, the techniques of measurement are of immense importance in most facets of human civilization. Present-day applications of measuring instruments can be classified into three major areas. The first of these is their use in regulating trade, applying instruments that measure physical quantities such as length, volume, and mass in terms of standard units. The particular instruments and transducers employed in such applications are included in the general description of instruments presented in the later chapters of this book.

The second application area of measuring instruments is in monitoring functions. These provide information that enables human beings to take some prescribed action accordingly. The gardener uses a thermometer to determine whether he or she should turn the heat on in his or her greenhouse or open the windows if it is too hot. Regular study of a barometer allows us to decide whether we should take our umbrellas if we are planning to go out for a few hours. While there are thus many uses of instrumentation in our normal domestic lives, the majority of monitoring functions exist to provide the information necessary to allow a human being to control some industrial operation or process. In a chemical process, for instance, the progress of chemical reactions is indicated by the measurement of temperatures and pressures at various points, and such measurements allow the operator to take correct decisions regarding the electrical supply to heaters, cooling water flows,