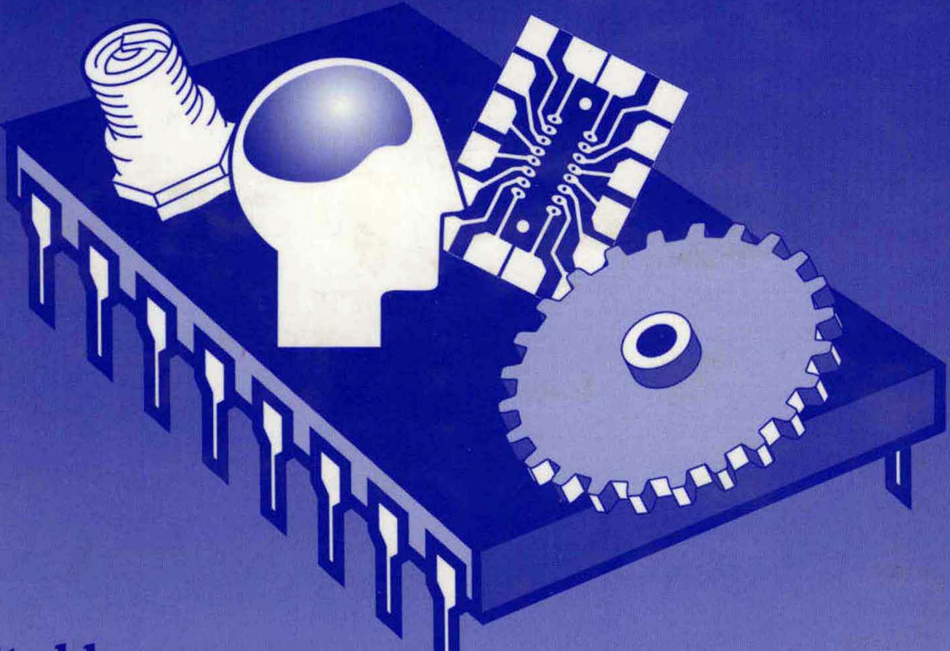
MECHATRONICS IN ENGINEERING DESIGN AND PRODUCT DEVELOPMENT



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Preface

In order to compete in the worldwide marketplace, manufacturers must ensure that their products will fulfill consumers' desired performance and quality requirements. Being at the synergetic intersection of a number of technologies, mechatronics has become the most instrumental tool in facilitating such company goals. Hence, many companies are gathering data on the use of mechatronic processes in engineering design and product development. Our long experience in teaching engineering at the university level and as R&D engineers with industry has led us to the belief that a practical and accessible presentation of mechatronics know-how is both possible and necessary. This book, presenting both theory and practice, is the result of this belief.

A universally accepted definition of the term mechatronics is: the integration of a number of disciplines such as mechanics, electronics, electrical, computer, control, and software engineering using microelectronics to control mechanical devices. In addition to product design, mechatronics as a design philosophy penetrates and is applied to production design, monitoring, and control with the objective of achieving high-quality products at optimal running conditions. To achieve this, mechatronics integrates advanced semiconductor technology, computer and communications technology, robotics, computer vision, and intelligent neuro-fuzzy technology.

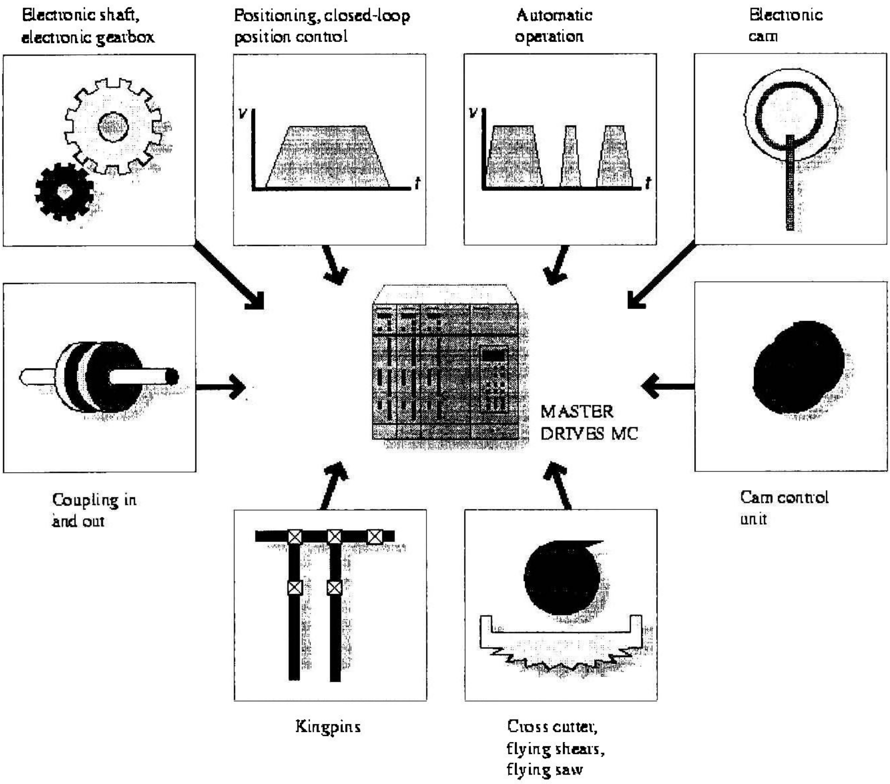
The process of mechatronics and its interdisciplinary synergy is best explained by professionals from all the disciplines involved. This book provides systematic and comprehensive information to practicing engineers in industry and to advanced students. It also helps them to adapt this expert knowledge to their own unique situations and thus become more productive. We therefore expect that this text will serve as a reference book for professionals from the automotive, process, production and aviation industries, robotics, consumer electronics, medicine, manufacturing, and CAD centers. We also expect the text to be used in various pedagogical settings. All who are dedicated to improving engineering design and product development can make use of this book.

The design of a mechatronic product is a challenge for design engineers. It is an exciting and satisfying journey with a specific destination — that of making a product to meet the needs of the customer. While the destination is well defined, the approaches to it are different because each mechatronic product is specific in its design, with a unique composition of the disciplines involved. Having this in mind, this book aims to provide the reader with specific knowledge on how to integrate all pertinent disciplines into a mechatronic product.

Recent progress across all disciplines pertinent to mechatronics has significantly affected future mechatronic product design trends and has fast-forwarded technological enhancement of existing products. It has also led to the design of totally new classes of products such as mechatronic machines. This has been necessary because the conventional approach to machine design has limited further machine improvement due to restrictions imposed upon mechanical components and mechanical subsystems of machines. If a machine is considered to be a mechatronic system then the machine can be designed based on: (a) a minimum number of mechanical and electronic components — those hardware components that are considered absolutely necessary; (b) an intelligent unit to process all information and machine-related functions; and (c) sensors to receive and actuators to respond to this information.

The intelligent SIMOVERT Master Drives Motion Control Servo Converter of Siemens, Germany, is being designed in line with mechatronic machine design principles. As Siemens describes it: "To start with, each mechatronic machine will have its own drive. Mechanical coupling such as cams and kingpins will be eliminated. The electronics will precisely coordinate the various movements. Motion sequences will also be coordinated. Each drive will know what the other drives are doing based on interlinks. Typical applications such as start-up, positioning, synchronous operations and cam can be called upon as standard functional blocks. All these functions, now performed by software, are to be configured to suit a specific machine application. The response so far from the end users of pioneering mechatronic machines is that implementation of the mechatronic approach to machine design has reduced the operating and maintenance costs of the machines and increased their application flexibility."

Mechatronic process is therefore a cross-disciplinary design process which can be properly applied if, and only if, the specialists from all pertinent disciplines work together from very early in the design process. Marketing specialists and production engineers should also participate. This interdisciplinary team-based work is usually called concurrent engineering due to the simultaneous interrelationships of the disciplines and their influence on the final solution. A mechatronic product is therefore not only a simple collection but a synergistic composition of all pertinent disciplinary knowledge.



Frequently used applications are integrated into the drive converter as standard mechatronic functions. (Courtesy of Siemens, Germany.)

It is up to the design team to find and define the composition, harmony and balance of the disciplines involved.

With the above in mind, this book is presented in four parts. Part One of the book addresses the core technologies necessary for the design and development of the mechatronic product. Chapter 1 discusses the transducers (sensors and actuators) most commonly used in mechatronics with the main emphasis on sensors, especially position/displacement sensors. Chapter 2 is dedicated to the advanced solutions recently developed in the area of microsensors and microactuators.

Chapter 3 describes the design philosophy of the microcontroller, a form of microcomputer, which is the intelligent core of a mechatronic system and is responsible for processing information received by the mechatronic product via its sensors. This chapter focuses particularly on designing microcontroller and associated circuits for a target system and discusses prototype implementation techniques. Three prototype design case studies are explained in detail.

The scope of real-time information processing, which is required to be performed by the mechatronic product, may comprise simple measurement and/or control functions but also may consist of complex supervisory, optimization, knowledge-based, and intelligent control functions. The theory behind the machine's ability to be intelligent is explained in Chapter 4.

Part One ends with Chapter 5, an introduction to communications technology. This knowledge is considered essential when integrating the mechatronic product. Some specific bus systems, local area networks, and related inter-networking elements such as network bridges and network gateways are presented and their applications discussed.

Part Two deals with some design approaches, including conceptual design, and relies on the distributed structure of production systems, summarized in Chapter 6. Chapter 7 shows how an automotive engine controller can be developed using computer-aided design tools. A step-by-step explanation of the whole computer-aided design process shows how the design can be coded into the target processor and tested. Chapter 7 also describes the state of the art for automatic code generation, analysis, and synthesis of mechatronic systems that are controlled by computers.

If the controller for a mechatronic product is to be designed, developed, and prototyped in hardware as an Application Specific Integrated Circuit (ASIC), the know-how needed can be found in Chapter 8. The chapter presents an overview of methods, tools, and the latest technology used in the rapid prototyping of mechatronic systems. The main emphasis is on design tools for the rapid prototyping of the mechanical and electronic components of a mechatronic product. Both of these components need to be rapidly prototyped early in the design stage of mechatronic product development in order to evaluate the performance expected to be fulfilled by the target system, to evaluate likely customer response, desired reliability, and so forth.

Related mechatronic product design aspects are grouped in Chapters 9, 10, and 11, which belong to Part Three of the book. In Chapter 9, the design aspect of system integration, optimality, and compatibility of the system elements is presented. Guidelines to the selection and interface of the system elements and the measurement of resulting reliability and robustness of the integrated system are also provided. In Chapter 10, system performance aspects are discussed, with particular attention to production and product quality monitoring, quality assurance, and control. An issue presented within Chapter 11, system software, is the crucial design issue in relation to the real-time application of mechatronic products for which effective interaction between the system and its immediate environment is essential to the performance required of the product.

Part Four, consisting of three chapters, addresses some mechatronic products application-related issues. Chapter 12 describes the versatility of mechatronic system applications. Among the case studies, explained are mechatronic development in gear measuring technology, automatic calibration system for an angular encoder, a construction robot for marking of the ceiling, and, finally, musician robots playing a trio (recorder, violin, and cello) of chamber music. Chapter 13 discusses control and optimization of mechatronic processes describing an operator's model which is applicable to many complex industrial processes that require human intervention. Application examples derived from a pH neutralization process and gear ratio control problems are discussed. These demonstrate applicability of the model to a variety of industrial, manufacturing, and other dynamic large-scale processes where the operator is called upon to exercise corrective actions based upon experience. Chapter 14 is dedicated to the ethics of product design and introduces the reader to the realm of ethical problem solving, emphasizing the similarities between it and the design process with which most engineers are familiar. It shows that ethical considerations can both drive and constrain engineering design and concludes with an examination of a case directly related to the field of mechatronics.

Our profound gratitude goes to all chapter authors. Without their enthusiasm and strong dedication, the manuscript for the book would not have been completed nor its high quality achieved.

Having done our best to review the manuscript carefully, we share the blame for any shortcomings. We give full credit to the authors for the value of their contributions that enabled us to bring this volume to the community of engineers and scientists involved in mechatronic product design and development.

When all is said and done, the book could not have been produced without the able assistance of the production editors, at Marcel Dekker, Inc., Matthew MacIsaac and Brian Black. Their patience and expert guidance were instrumental in converting the manuscript into a book. For this, we are sincerely appreciative.

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Contents

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Sensors and Actuators in Mechatronics

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In the past several decades, partly because of the rapid development of the microelectronics industry and the ever-increasing applications of microcomputers and the automation of various industries, demands for transducers (sensors/actuators) have increased exponentially. This trend is expected to continue as global competition for higher productivity and better quality forces companies in every industry to be constantly looking for ways to reduce cost and improve the quality of their production. In one respect, the revolution in microelectronics and computers has dramatically reduced the cost of automation and control, and has therefore led to broad applications of these technologies in areas where these technologies were not deemed to be economically feasible. On the other hand, the developments in the microelectronics industry and, more recently, the fast development of microelectromechanical systems (MEMS), have generated a wide variety of sensors and actuators at ever-lowering costs, therefore opening up opportunities for applications in some areas not feasible in the past. The fast development of microelectronics has also dramatically improved signal processing and computation capabilities. A signal processing job that might have required a large box of electronic components decades ago can now be carried out by a single IC chip. The availability, the simplicity, and the performance of circuit modules such as active filters, analog dividers, sample/hold devices, function generators, lock-in amplifiers, etc., have made it very convenient to integrate sensors and actuators in a mechanical system and has made the lives of application engineers much easier. As a consequence, integration of sensors and actuators into a system and dealing with signal conditioning, work that was deemed to be the province of an electrical engineer many years ago, can now be done by mechanical, civil, or chemical engineers. This helps expand further the application of advanced sensors in industry.

Nowadays, the application of sensors is so pervasive that it is difficult to find any machines or appliances that do not have integrated sensors. A typical car now has more than 70 sensors and the number grows continuously as efforts towards better performance are made. As the trend towards intelligent vehicles continues, more advanced or smarter sensors will be implemented, for example, ultrasonic sensors for collision prevention, bar-coded intelligent highways and vehicles with optical scanning sensors and computers as well as vehicles with built-in global satellite positioning systems and other sensors for location and guidance. Other common examples of mechatronics products include home appliances such as washing machines and dryers. They are no longer the very simple appliances as they were years ago and have become intelligent machines with many sensors and functions. Go to any toy store, and you will be amazed to find how many of the toys have integrated sensors and are really intelligent toys.

Transducers (sensors and actuators) are to mechatronics systems as the sensing organs and hands and feet are to human beings. As a matter of fact, in most cases the overall performance of a system is set by the performance of the sensors and actuators used. In an instrument, the sensor transforms the physical parameter to be measured into a signal as shown in Figure 1. In most modern instruments, the physical parameter being measured is transduced into an electrical signal. This signal is then processed by a signal conditioning circuit and displayed on a panel or stored for future use or processing. Obviously, the overall sensitivity of the instrument will not be higher than that of the sensor used regardless of the quality of the remaining parts of the system.

The same argument holds for a closed-loop control system. Take a position control system as shown in Figure 2 for example. A target position is set by the operator. Based on the control strategy adopted, a command is generated and sent to the actuators which then drive the plant to the target position. The output position is then measured with a sensing system and compared with the target position. If there is a difference between the measured and the target positions, a correction command is generated and sent out to compensate for the error. This check-correction action continues until the target position is reached. The revolution in microelectronics and microcomputers has made the implementation of advanced control systems and high quality electronic components readily available at ever-lowering costs, and they have therefore become a less vital part of an automatic system. Consequently, researchers and engineers have found that the overall performance of the system is nearly always limited by the performance of the sensors and actuators, especially the sensors. If the sensing system cannot

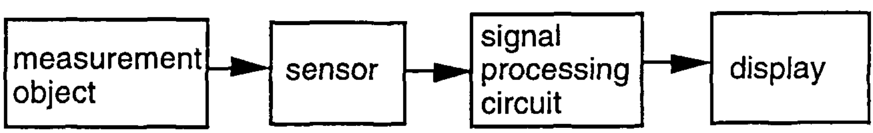

Figure 1 Schematic diagram of an A instrument.

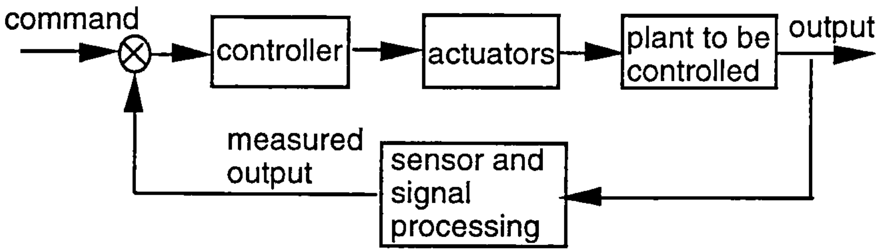

Figure 2 Schematic diagram of an A closed-loop control system.

accurately measure the actual position output, the wrong control command will be generated no matter how fancy the controller is. Similarly, if the actuators are not accurate enough, the correct control commands can still lead to an erroneous output. Also, the dynamic characteristics of the whole system are affected by the characteristics of the transducers used. Therefore it is very important to study the dynamic behavior of the sensors and actuators.

In this chapter, we are going to discuss the transducers (sensors/actuators) most commonly used in mechatronics, with the main emphasis on sensors, especially position/displacement sensors. In the following sections, classification of sensors and actuators will be introduced, followed by the basic concepts and common terms used in sensors and actuators. Then the fundamental principles of several major categories of transducers will be presented. In particular, two of the most commonly used position/displacement sensors, LVDTs and PSDs, will be discussed in detail.

I. CLASSIFICATION OF SENSORS AND ACTUATORS

A. Two Categories of Transducers: Sensors and Actuators

The term *transducer* is widely used in science and engineering. However, there are several different definitions, each having its own advantages and disadvantages, and they are all used in the field. Middlehoek [1] defines a transducer as a device that transforms non-electrical energy into electrical energy or vice versa. Karnopp et al. [2] defines a transducer as a device that transforms energy from one domain to another. The last, and the broadest definition was proposed by Busch-Vishniac [3]: a transducer is a device that transforms energy from one form to another, and it does not matter whether the energy belongs to different domains or the same domains. For example, a load cell, which is commonly used in mechanical measurement, can be classified as a transducer even though both the input energy and output energy are in the mechanical domain. This definition is more general than the one suggested by Middlehoek. If we insist a transducer must have an electrical output, a regular thermostat will not be classified as a transducer because it transforms thermal energy into mechanical energy and no electrical energy is involved. A load cell will not be classified as a transducer using this criterion. Strictly speaking, even a strain gauge, one of the widely used mechanical sensors, cannot be called a transducer (sensor) because it only transforms the mechanical energy (strain) into a change in resistance, not an electrical signal.

Transducers are normally classified using two categories: sensors and actuators. In most cases, they are reciprocal. For example, a capacitive transducer may function as a position sensor that transforms mechanical energy into capacitance change, and therefore electrical signal output (electrical charge or voltage change). It may also function as an actuator when an electrical signal (voltage or charge) is supplied and an electrostatic force or displacement is delivered as output. Both cases have practical applications: for example, the rangefinder of the auto-focusing system for a popular type of Polaroid camera [4]. This camera uses an electrostatic type transducer as both an actuator to generate the ultrasonic pulses and a sensor to receive the acoustic signal echoed back. Similarly, a piezo-electric transducer can either be used as an actuator, transforming an input voltage signal into a controlled displacement (or to deliver a driving force) as commonly used for precision positioning applications such as driving atomic force microscope (AFM) tips. When a force (or pressure) is applied on a piezo-electric disk, a voltage signal is generated across the piezo-electric disk. By measuring the voltage signal, the force or the pressure can be measured. This principle is used for pressure measurement and in accelerometers. Of course, not every type of transducer can be used with equal effectiveness in sensing and actuation. As a matter of fact, optimization of the performances of sensors and actuators often calls for totally different, or most possibly, conflicting requirements in choosing design parameters. In general, the optimization of a sensor requires: (1) a minimum change in the object parameter (called *measurand*) can cause a maximum change in the state of the sensor output; (2) the influence of the sensor on the object being measured is minimal, that is, the status of the object being measured should not be affected by the presentation of the sensor itself; and (3) the output of the sensor is only affected by the desired input, not by any other parameters or environmental conditions. For example, when a thermostat is used to measure the temperature of an object, it is definitely not desired that the temperature of the object is significantly affected by the presence of the thermostat, or that the thermostat readout is influenced by the surrounding magnetic field. Strictly speaking, a thermostat will always change the temperature of the object being measured from the basic principle of the measurement. A thermostat absorbs heat from the measurement object when they come into contact; its temperature goes up as a result of this heat transfer. Therefore a large sized thermostat is always avoided because large physical size almost always means large thermal capacitance, and consequently a significant amount of heat needs to be transferred from the measurement object to the thermostat to bring the thermostat to the same temperature as the object being measured. This significant heat transfer means that the temperature of the object will inevitably be changed by the presentation of the thermostat. The smaller the thermal capacitance of the thermostat, the less significantly the temperature of the object will be changed. This also explains why sensors with smaller physical sizes and weight are always preferred in engineering practice. For an actuator, optimization calls for them being able to impose the desired state on an object regardless of the load applied to them. Taking a DC motor as an example, the ideal performance for the motor means a motor should be able to drive anything connected to it in a specified speed independent of the load it has to overcome. This means an unlimited supply of power is required, a case that can never be achieved. Because actuators are always required to deliver certain power, their physical sizes will be power-limited in most practical cases. In most cases, actuators of extremely small size will not be very useful because of their very limited power capability.

From the foregoing discussions, it is obvious that smaller physical size and lower power requirement is always preferred for sensors while for actuators this is not always true. Partly because of this, progress made in the field of microelectromechanical systems (MEMS) and solid state technologies has greatly advanced the state-of-the-art for sensors while very limited success has been achieved in developing actuators.

B. Classifications of Sensors and Actuators

Because of the great variety of sensors and actuators used in the field of mechatronics, it is very difficult to discuss all of them in detail in the limited space available here. In this section, a very general classification of the most commonly used sensors and actuators in mechatronics will be provided, with emphasis on sensors. The classification of transducers can be done in several different ways. The first approach may be to classify sensors according to their applications, or the physical quantities the sensors can be used to measure. This is probably the most popular method of classification. Using this method, the sensors can be classified as, for example: position or displacement sensing; pressure sensing; temperature sensing; magnetic field sensing; flow measurement; torque sensing; stress or strain sensing; gas sensing; humidity sensing; chemical sensing; biological sensing; velocity or acceleration sensing; acoustic sensing (e.g., sound intensity sensing); radiation sensing. Some representative categories of sensors are shown in Table 1. One major advantage of this classification is that all the sensors for the same application can be introduced as one category and compared by performance and limitations, which can be very convenient for application engineers. There are several major disadvantages in using this classification. First, this method of presentation may become simply a review of what is commercially available today, which is not very useful to engineers who may want to study the fundamentals in sensors and actuators and learn how to develop similar new sensors. Secondly, sensors for same applications may be based on totally different principles, therefore in-depth discussions may lead to unnecessary repetitions and cannot be organized easily into the limited space here.

Another commonly used approach is to classify the sensors according their basic operation principles: optical sensing; capacitive sensing; inductive sensing; acoustic sensing (e.g., ultrasound sensing devices); fiber-optic sensing; Hall-effect

Table 1 Classification of Sensors According to Their Application

Mechanical sensors	Position (linear and rotational), displacement (linear and rotational), velocity (linear and rotational), acceleration (linear and rotational), vibration (linear and rotational), stress and strain, force, torque, pressure, surface topography or roughness and flatness, roundness, etc.
Electrical and magnetic sensors	Voltage, current, resistance, capacitance, inductance, magnetic, radiation, etc.
Acoustic and flow sensors	Sound intensity (pressure), viscosity, flow rate, frequency, ultrasound nondestructive detection, etc.
Chemical and biological sensors	pH, enzymes, ions, gases, concentration, humidity, biological, frequency shift or Doppler, etc.
Optical sensors	Intensity, wavelength, phase, vision and image (e.g., CCD camera), interference, polarization, reflectance, transmittance, scattering, refractive index, spectrum, etc.
Thermal sensors	Temperature, infrared radiation image, etc.

sensing; eddy current; and etc. as shown in Table 2. It should be noted that the list in Table 2 is only representative, not inclusive. There are some sensors not listed because of the limited space here. For example, resonant sensors, magnetoresistive sensors, etc. This method of classification is convenient for in-depth discussions of each category of sensors and is very suitable for efficient presentation of the wide variety of sensors within the confines of this chapter.

We will concentrate our discussions on sensors. Actuators will be discussed only when they are reciprocals of a particular type of sensor. Because of the limited space here, very brief discussion will be provided for each category of sensors. In each category of sensors, only one or two examples will be provided. In addition, because it is estimated that almost 80% of the sensors used in industry are for position measurement, see Luo [5], we will spend most of our efforts on studying position/displacement sensors. In particular, we will discuss in detail two of the best position sensors: linear variable differential transformers (LVDTs) and lateral effect position sensitive detectors (PSDs).

II. PERFORMANCE PARAMETERS OF A SENSOR

In this section, we will briefly discuss the terms commonly used in science and engineering practice to describe the performance of sensors. The databooks of commercial sensor products tend to use different terms to describe the same parameters of products and this makes it quite difficult to compare their performance. To avoid possible confusion, we will first define the fundamental terms used in this chapter. Efforts have been made to define these terms consistently with common usage.

Table 2 Classification of Sensors to Their Fundamental Principles

Capacitive	Position (linear and rotational), displacement (linear and rotational), electrostatic driving and deflection sensing for MEMS devices, chemical sensing, etc.
Inductive	Electric sensors, position/displacement, proximity, magnetic field detection, electromagnetic relay, etc.
Ultrasonic	Range-finders, nondestructive testing, thickness measurement, image scanning, flow measurement (Doppler), etc.
Photoelectric, PSD, CCD	Displacement/position, temperature, vision, and image (e.g., CCD camera), light intensity
Optical and fiber-optic	Optical encoders, gyrator (fiber-optic), temperature, magnetic, fiber-optic interferometer for phase shift measurement and any physical parameters that can modulate the phase shift, proximity sensors, etc.
Eddy current	
Hall effect	Magnetic field detection, proximity sensor
Piezo-electric	Actuators, pressure, force, and torque sensing, etc.

Generally speaking, in choosing sensors we must decide what the sensor is to do and what results we expect. We will discuss some of the criteria that must be considered in selecting and using different kinds of sensors for different kinds of applications in an automation system. The most important parameters are defined and discussed in the following subsections.

A. Sensitivity

Sensitivity is defined as the ratio of change of output to change in input. Suppose the output of a transducer is y for a given input x, that is, $y = f(x)$. This ratio is:

For example, if a 0.01 mm displacement in input gives rise to a 0.5 volt

$$S = \frac{\Delta y}{\Delta x} \tag{1}$$

For example, if an 0.01 mm displacement in input gives rise to an 0.5 volt change in output, then the sensitivity is 50 volt/mm. Some people prefer to use sensitivity to indicate the smallest input that can be detected by the sensor, but in most cases, another term, *resolution*, has been used for this purpose. Normally, the maximum sensitivity is always desired if other parameters such as *linearity* and *accuracy* would not be sacrificed.

B. Linearity

The term *linearity* is used to indicate the constancy of the ratio of output to input. If the output and input of a sensor system have a perfectly linear relationship, it would mean that in the following equation:

$$y = cx \tag{2}$$