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Introduction

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1.1 Overview

Scientific and technological advances of recent years allow considering the real-time detection of toxic pollutants or chemical or biological substances in gaseous or liquid environments adequately. It is possible to easily find on the market portable devices that allow, for investments of a few hundred to a few thousand dollars, sensor or diagnostic platforms, or low concentrations of chemical or biological species. A smooth, fast, and cost-effective detection of the presence of a chemical or biological element and the quantification of its concentration in real time are criteria that help to amplify the distribution of these sensors and access to highly sought-after measurements particularly in demanding areas of scientific knowledge at the boundaries between applied mathematics, physics, chemistry, and biology. This enthusiasm is particularly noticeable in applications dedicated to the issues from the environment, food, and health.

Nowadays, the various commercialized systems existing to answer these issues can be presented in two different approaches: the sensors dedicated to the identification of the risks and consequently to alarm the user; and sensors dedicated to the specific detection of target species at very low concentrations in real time.

However, despite these remarkable technological advances, the development of sensors with: (i) high sensitivity, (ii) real selectivity to a biological or chemical species, (iii) low limit of quantification, (iv) energy autonomy, and (v) reasonable cost remain ultimate challenges for manufacturers and academic researchers.

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In recent years based on academic literature, an enormous surge of works has been carried out to develop robust, reliable, accurate, and high-resolution chemical sensing platforms. Also, many efforts have been attempted to convert them into miniaturized, more portable, and cost-effective systems and to study protocols currently used in advanced sensor networks.

A surge of interest, yet an unmet market demand for reliable and high-performance chemical sensors from different perspectives from materials (polymer, metal oxide, carbon material, etc.) and technology (electrochemical, Field Effect Transistor [FET], acoustic, microwave, optic, electronic tongue and nose, etc.) to applications (food spoilage monitoring, odor, medical, environmental, IOT, etc.), and the accurate interpretation of biochemical processes by readily measurable signals still exists. Such biochemical sensors need to provide fast response, high-sensitivity and selectivity, large dynamic range, and low-cost to be considered as viable products. These sensors can serve as various applications such as biothreat detection, epidemic disease control, low-cost home healthcare, and cell-based and environmental monitoring.

This book titled *Smart Sensors for Environmental and Medical Applications* addresses the limitations and challenges in obtaining the state-of-the-art smart biochemical sensors. It includes ten chapters of contributions from leading experts in bio and chemical sensing. We believe that the approaches developed, and the issues raised in this book will enable the reader to identify the requirements, challenges, and future directions related to the burgeoning field of biochemical detection systems. It should be noticed that in this introduction it is important to recall and explain some basic principles and metrological characteristics common to various sensors categories. These basic notions will provide the reader with a foundation and knowledge for understanding the different technologies and issues raised in the presented chapters.

Furthermore, this book will allow the readers to identify new opportunities in this emerging research field.

1.2 Sensors: History and Terminology

Scientific knowledge has developed through a double effort:

- First, the reflection on the mechanisms, that is to say on the nature of interactions between physical and chemical quantities-related phenomena; this thinking is reflected by the mathematical tool by the laws of physics, abstract relationships between physical quantities.
- Second, experimentation based on the measurement of physical and chemical quantities and which, by associating a numerical value allows to quantitatively define the properties of objects, digitally verify the physical laws, or to empirically establish the form.

Whereas science seeks to grasp and then to express coherent mathematical theories and the laws governing the relationships of physical quantities, technology uses these laws and the properties of matter to develop new devices or materials that enable humans to increase their means of action to better support their wellbeing, facilitate their exchanges, and improve their life. Indeed, at first, the technique was a collection of experimental processes, fruits of the observation, random groupings, or successive tests; the knowledge of the laws of nature allowed the technique to rationalize its approach and to become a science of realization. The measure therefore plays a crucial role. In order to be carried out successfully, the measuring operation generally requires that the information be transmitted remotely from the point where it is captured, protected against alteration by parasitic phenomena, and amplified, before being operated in various ways: displayed, saved, and processed by calculator.

In this respect, electronics offer a variety of influential means: to benefit from measurements of all types of physical quantities, such as their processing and exploitation, it is very desirable to transpose each of the physical quantities immediately into the form of an electrical signal. It is the role of the sensor to ensure this duplication of information by transferring it, at the very point where the measurement is made, of the physical quantity (nonelectric) of its own, on an electrical quantity: current, voltage, load, or impedance.

A sensor is first of all the result of the ingenious exploitation of physical law: this is why an important place is given in this book to the physical principles which are at their base. This is the result of specific properties of each type of sensor: performance, field of application, and rules of good use.

The electrical characteristics of the sensor impose on the user the choice of associated electrical circuits that are perfectly adapted. Therefore, the delivered signal is obtained and can be processed under the best conditions. Indeed, physical principles, specific properties, and associated electrical assemblies are the three main aspects under which each type of sensor will be studied.

1.2.1 Definitions and General Characteristics

The physical quantity that is the object of measurement (temperature, pressure, magnetic, humidity, gas molecules, biomarker, deformation, etc.) is designated as the measurand and represented by M; all the experimental operations which contribute to the knowledge of the numerical value of the measurand constitute its measurement [1].

The sensor is a device that is subjected to the action of a physical or chemical phenomenon measurand, which has a characteristic of electrical nature (load, voltage, current, or impedance) designated by R and which is a function of the measurand: $R = F(M)$ (Figure 1.1). R is the response or the output quantity of the sensor. The measurement of R should allow to know the value of M.

The relation $R = F(M)$ results in its theoretical form from the physical laws which govern the operating of the sensor and in the numerical expression of its design (geometry, dimensions), of the materials which constitute it and possibly of its environment, and its mode of use (temperature, power supply).

For any type of sensor, the relation $R = F(M)$ in its numerically exploitable form is explained by calibration: for a set of precisely known values of M, we measure the corresponding values of R which makes it possible to draw the curve of calibration (Figure 1.2a). The calibration curve, at any measured value of R, makes it possible to associate the value of M which determines it (Figure 1.2b).

For reasons of operation ease, efforts are made to make the sensor, or at least to use it, so that it establishes a linear relationship between the variations ΔR of the output quantity and those ΔM of the input quantity: $\Delta R = S\Delta M$. S is the sensitivity of the sensor.

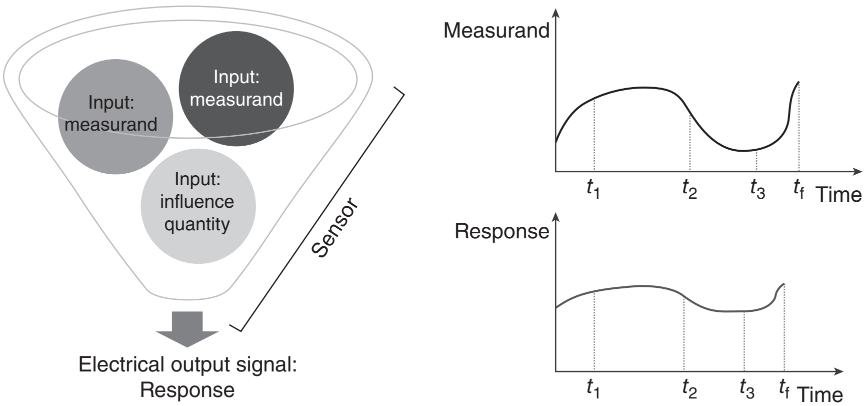

Figure 1.1 Example of evolution of a measurand M and the corresponding response R of the sensor. *Source:* Adapted from [1].

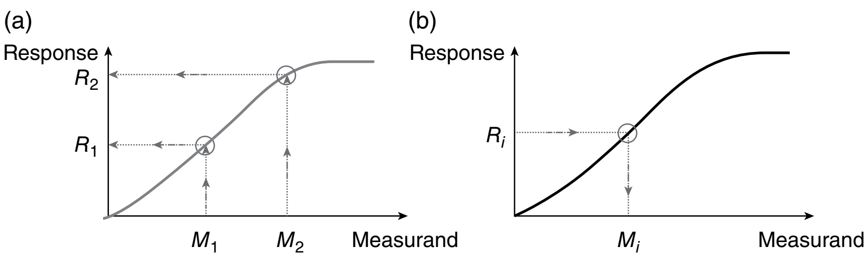

Figure 1.2 Calibration curve of a sensor: (a) its establishment, based on known values of the measurand M; (b) its exploitation, from the measured values of the sensor response R. *Source:* Adapted from [1].

One of the major challenges, in the design and use of a sensor, is the constancy of its sensitivity S which must depend as little as possible on:

- the value of M (linearity) and its frequency of variation (bandwidth);
- time (aging);
- disturbances of other physical quantities of its environment which are not the object of measurement and which are designated as quantities of influence.

As an element of electrical circuit, the sensor is presented, seen from its output:

- either as a generator, R being a load, a voltage, or a current and it is then an active sensor;
- or as an impedance, R then being a resistance, an inductance, or a capacitance: the sensor is then said to be passive.

This distinction between active and passive sensors based on their equivalent electrical circuits reflects a fundamental difference involved in nature of the physical phenomena.

1.2.2 Influence Quantities

The sensor, by its conditions of use, may be subject not only to the measurand but also to other physical quantities whose variations have potential to cause a change in the output electrical magnitude that it is not possible to distinguish from the action of the measurand. These "parasitic" physical quantities to which the response of the sensor can be sensitive are the influence quantities. Thus, we can mention:

- the temperature, which modifies the electrical, mechanical, and dimensional characteristics of the sensor elements;
- the pressure, the acceleration, and vibrations have potential to create in certain sensors parts deformations and constraints that alter the response;
- the humidity at which certain electrical properties such as dielectric constant or resistivity can be sensitive and which may degrade the electrical insulation between sensor components or between the sensor and its environment;
- variable or static magnetic fields: the first create electromotive force and the second can change an electrical property, such as resistivity, when the sensor uses a magnetoresistive material;
- the supply voltage.

In order to be able to deduce the value of M from the measurement of R, it is therefore necessary:

- to reduce the importance of influence quantities on the sensor by protecting it with adequate insulation: antivibration mounts, magnetic shielding;

- either to stabilize the influence quantities to perfectly known values and to calibrate the sensor under these operating conditions: thermostatically controlled, regulated power sources;
- or finally to use circuits that allow to compensate the influence quantities: Wheatstone bridge, differential measurements, etc.

All these notions will be taken up and treated in depth in examples illustrated in the chapters of this book.

1.3 Smart Sensors for Environmental and Medical Applications

Smart sensors in environmental and medical applications are intended for the detection and/or analysis of:

- changes in physical parameters (vibration, temperature, and pressure) and
- the concentration of chemical/biochemical or biological species, gaseous or liquid in general. The field relating to biochemistry and biology is extremely broad and therefore involves a large number of application areas: the chemical industry, fine chemicals, cosmetics, pharmaceuticals, health, agri-food, the environment, home automation, civil security, etc.

In general, it is possible to define a smart sensor in environmental and medical applications by the following elements:

- a medium to be analyzed (temperature, pressure, gases, liquids, tissues, etc.) with its specificities;
- a detection/transduction principle for transforming the analyzed physical/chemical signal into a measurable electrical quantity;
- a measurement and signal processing interface for shaping the useful electrical signal;
- data processing coupled with a calibration system to ensure the reliability of the measurement;
- a source of energy to ensure the autonomy of the whole chain of detection/transduction/data processing.

Different from other types of physical sensors, chemical/biological sensors in environmental and medical applications have had limited commercial success, and this despite the strong demand of many sectors of the economy cited above. This fact is probably linked to the technical difficulty of transforming a quantity such as the concentration of species in a liquid or a gas into an electrical signal, while simultaneously ensuring reproducibility, sensitivity, and selectivity.

The various types of chemical/biological sensors existing and treated in the chapters presented in this book operate according to very varied physicochemical principles in environmental and medical applications.

The term smart or intelligent sensor refers to an instrument in digital technology combining data acquisition and their internal processing and incorporates new features. In general, these sensors integrate an embedded microcontroller to perform internal processing and calculations and have a bidirectional communication capability that means receiving external commands and sending measurements and status information. They are equipped with one or more sensor matrices for measuring the target and influence quantities and other integrated algorithms for the analysis of these measurements and therefore provide decision support.

With the current technological advances in data collection, storage, and processing, it is therefore natural that robust solutions such as combinations of multivariate data analysis and automatic learning methods are associated to biological and chemical sensor arrays to improve their performance in terms of selectivity and identification of target species in complex environments. These methods are widely and successfully utilized for classification in several fields and exhibit high performance.

Human and animals are capable of sensing different types of smell in the vicinity by a natural nose. Scientists investigate "an artificial nose," which had to be trained and then could smartly sense smell like humans; it was called "Electronic Nose" or in short "E-Nose." It has wide applications in the field of smart biological and chemical sensors, of which toxic gas detection is one of the key areas. Another critical application where such sensors will be useful is "healthcare." An E-Nose is an association of advanced algorithms based in multivariate data analysis or machine learning and a variety of transducers dedicated for detection and identification of odorants.

Over the last decade, another kind of biological and chemical sensors has been emerged: Electronic Tongues (e-tongues). E-tongues are promising electroanalytical devices for the quality control of water, beverages, foodstuffs, pharmaceuticals, and complex liquids as they offer simple operation, fast response, low cost, and high sensitivity and selectivity. They comprise an array of sensing units having distinct responses to establish a fingerprint of the samples, being based on the global selectivity concept. In mimicking biological systems, ETs serve to classify large amounts of information into specific patterns. The integration of ETs with microfluidic chips expands potential applications due to miniaturization, and usage of microliters for sampling and discharge, crucial when hazardous reagents or biological materials are studied. The concept of e-tongue was also extended to biosensing, with biomolecules used as sensing units reaching the recognition ability at the molecular level.

The chapters presented in this book provide an in-depth discussion of the necessary definitions of the different transducers associated with these technologies, their metrological performance, associated electronic systems for data processing, and classification methods and associated analyses.

1.4 Outline

We know that only measurements and experiments can drive scientific progress and increase knowledge of what surrounds us; the limits are not reached and never will be. It seems to us, to this day, that the measurement plays a fundamental role in the development or the follow-up of the industrial and human activities and the technologies of the future with the sophistication of automatisms, robotics, the control of the quality, energy, pollution control, disease diagnosis or drug screening, etc. In addition, the measurement, through emerging areas such as artificial intelligence and the Internet of Things and biotechnologies or even neuroscience, is now finding many applications in the design and realization of the systems of the future.

Measurement becomes an essential factor of the economy; it must be treated with special and sustained attention and nothing will be done without the "sensor" at the cornerstone "measure."

This book incorporates different types of smart sensors and discusses each of the chapters in light of a common set of sub-sections so that the readers can be educated about the advantages and disadvantages of the relevant transducers depending on the design, transduction mode, and applications. The book covers all of the major aspects of the primary constituents of the field of smart sensors for environmental and medical applications including working principle and related theory, sensor materials, classification of respective transducer type, relevant fabrication processes, methods for data analysis, and suitable application. In the theory, the book discusses the fundamentals of the sensing phenomena and the relevant equation governing the phenomena based on selected transduction mode. The section on sensor materials not only discusses the promising materials whose properties have been utilized for sensing action but also predicts future innovative materials that have the potential for sensing application. The classification section categorizes the sensor into different sub-types and describes their working, focusing on prominent applications for the readers to realize the benefits of relevant designs and selected methods for data analysis. The application section includes the state-of-the-art update of the developments in the field of the given sensor type and concludes with the challenges in the relevant field of research. Different transduction modes which have been applied in the design and fabrication of various biological and chemical sensors are discussed in the book, as illustrated in Figure 1.3. The massive amounts of data generated in experiments with

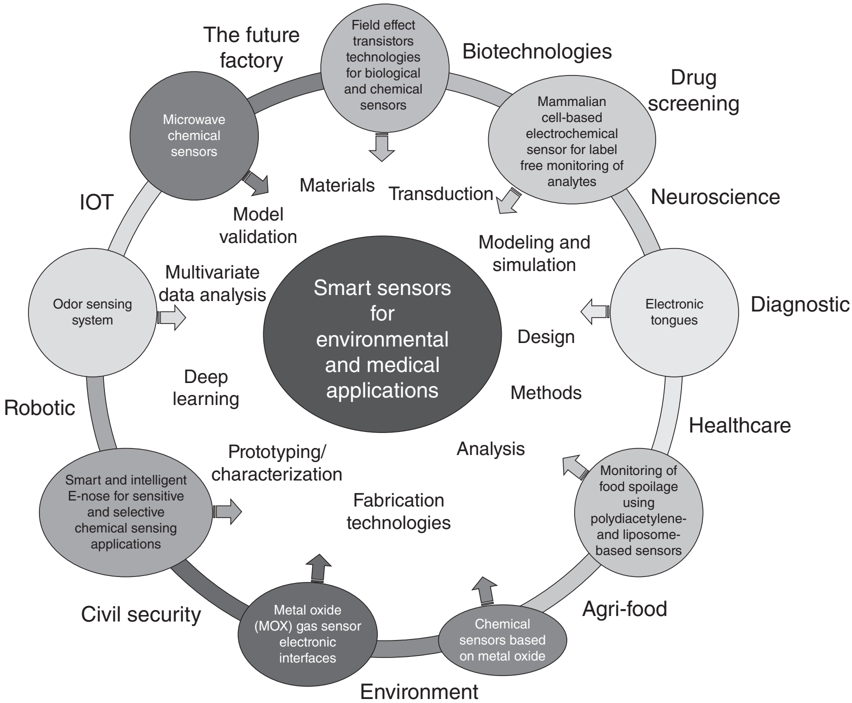

Figure 1.3 Graphical structure of the book.

sensors have motivated studies involving multidimensional projection techniques, feature selection, and machine learning.

The most recently developed state-of-the-art sensors, and still being tested in leading research laboratories, are provided and discussed. The measurement specialists or students will be surprised to discover, on reading, smart chemical sensor novelties that have not yet come to this knowledge. The recent technologies in the smart chemical sensing would fulfil the demand for a book, which has a balance between fundamentals of sensor design, fabrication, characterization, and analysis combined with emerging methods (e.g. machine learning). Furthermore, it should benefit a wide range of students from graduates to undergraduate as well as incorporates recent developments in research that would suit doctoral students, postdoctoral fellows, and industrial engineers.

Reference

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