## Electronic Sensor Design Principles

Get up to speed with the fundamentals of electronic sensor design with this comprehensive guide and discover powerful techniques to reduce the overall design timeline for your specific applications.

It includes:

- A step-by-step introduction to a generalized information-centric approach for designing electronic sensors, demonstrating universally applicable practical approaches to speed up the design process.
- Detailed coverage of all the tools necessary for effective characterization and organization of the design process, improving overall process efficiency.
- A coherent and rigorous theoretical framework for understanding the fundamentals of sensor design, to encourage an intuitive understanding of sensor design requirements.

Emphasizing an integrated interdisciplinary approach throughout, this is an essential tool for professional engineers and graduate students keen to improve their understanding of cutting-edge electronic sensor design.

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**To Marianna my grandmother**

**and my daughter Ottavia,**

**for teaching me how to feel,**

**what artificial sensors do not, love**

# Contents



 

# Preface

One question I have constantly pondered in the course of my professional life is whether there are general principles in the sensing process that can be applied to the designing of electronic sensors. The aim of this book is to guide the reader along a train of argument leading to an affirmative answer to that question, which provided the title.

Textbooks outlining techniques of sensor design often follow one of two quite contrasting approaches. The first is to focus on one highly specific context linked to a single application. The second hangs the treatment on a broad classification of transduction and architecture techniques. The latter approach leads to the false idea that sensor design boils down to a series of separate cases classified according to their specific application. Such a view may be erroneously encapsulated in the idea that the highly interdisciplinary nature of this field consists in a reasoned assembly of various points geared only to enhance the design efficiency. In actual fact, interdisciplinarity in this domain (which calls for highly different techniques and models ranging from the mathematics of random processes to the science of measurements, signal conversion and processing, information theory, and transduction physics) reveals that the various different subjects are nothing but contextualizations of a few general principles. This book thus sets out to define a general methodology behind the designing of electronic sensors, regardless of the individual application: this will markedly reduce design time and enable the essential design variables to be swiftly identified.

One basic line of inquiry that the book pursues is the role of *information* in the sensing process. This led to a broader definition of *sensor*, focusing on its ability to extract information from the environment. Whereas information theory stemmed from the area of electric communications in which codes may be optimized so as to maximize the amount of data transmitted on the channel, with sensing, the perspective has to be reversed. Here, since the source of information pertains to observed nature, it cannot, as a rule, be altered, and design optimization can be seen as the maximizing of information conveyed by the process. It is in this context that certain basic definitions of sensor physics have been revised. By way of example, we will describe the concept of resolution not just in its original accepted meaning, but highlighting its connections to the amount of information conveyed in the sensing process: an aspect that will enable us to find effective methods of optimizing electronic sensor design.

Writing a textbook is a complex process in which the author is often torn between opposing courses of action. On the one hand, he or she will tend to go for formal rigor of presentation vis-à-vis the scientific community above all. On the other, the desire is to outline the subject as clearly as possible for the beginner, if possible, favoring an intuitive approach based on solving certain conceptual problems, sometimes at the expense of formal rigor. Depending on the target audience, the author will juggle between these two opposing approaches.

Yet if I consider my own teaching experience more closely, it has shown some surprising features. In many (though not all) cases, students to begin with prefer a formal approach to the discipline since that confers an apparent security; they are suspicious about the kind of treatment that starts from concrete examples and ends up in abstract concepts. On the other hand, those already familiar with the discipline will tend to focus more on the principles of the subject, picking out points that had previously eluded them. This accounts for the reaction to certain seminal scientific textbooks that favor a bottom-up approach to the subject. For all their conceptual rigor, they are unlikely to be popular as student course books, since by definition the abstracting process calls for a long period of maturation in the mind of a student. With this book, I have hence adopted a style that mixes the two: the intuitive approach is designed not around abstract hypotheses, but concrete numerical examples, concluding with a due degree of formalism suitable for the task of summing up.

The text is based on two courses I have taught for several years at the Cesena Campus of Bologna University. I must thank my past and present undergraduate, graduate, and Ph.D. students, first and foremost, for their responsiveness and dialogue that enabled me to correct and hone this experience of tuition. I find it hard to imagine writing a textbook without the critical backing of a course dealing with the subject. In drafting the book, I adopted a number of different approaches: trying them out on the course helped me choose among them. My thanks go to many people with whom it has been a pleasure to exchange notes. First of all, Alessandro Piovaccari for his friendship, constant support and encouragement, and above all for firing my imagination about basic principles of the subject. I must also thank Victor Zhirnov for points to do with the limits of sensing, Marco Chiani for information theory, Davide Dardari for the theory of estimation, Aldo Romani for piezoelectric transduction, Alberto Corigliano for mechanical transduction, Hywel Morgan for ionic transduction and biosensor physics, and Marco Crescentini for our many discussions on electronic noise and measurement science. Also, a special thanks to my colleagues Alessandra Costanzo, Alessandro Talamelli, Emanuele Giordano, Luigi Ragni, Elena Babini, Annachiara Berardinelli, Mauro Ursino, and Enrico Sangiorgi for scientific collaboration, friendship, and constant and effective support in this work. My thanks, too, to Roberto Trolli for various points to do with the philosophy of science, raised by him over many years of fraternal friendship and endless and engaging discussions. A special thanks to my older brother Flavio Tartagni for intriguing me into experimental science when I was a child. Last, and definitely not least, my sincere thanks to my publishers, Cambridge University Press, and in particular to Julie Lancashire, for the unreserved confidence they passed on to me from the outset. My thanks to all the editorial staff for their patience, constant assistance, and suggestions over these past years.

One important restriction must be noted in the range of subjects covered by the book. It analyzes sensors whose resolution is constrained by thermal noise – the area often referred to as “thermal noise limited sensors” - and by sensors limited by shot noise . Such an approach is suited to most sensors used at room temperature and for general applications. Analysis of the origin of the noise is thus briefly introduced from the angle of classical statistical mechanics. Of course, it is evident that in sensing and measurement science, the extreme outer limits are dictated by the uncertainty principle, the restraints of which are felt in far less usual cases than those here described. For this reason, sensors based on quantum mechanics principles will not figure in here.

The book falls into three parts. The first one contextualizes general concepts by definitions of design variables, characterization parameters, signals, and errors. This framework will discuss the design tradeoffs under the information theory viewpoint.

The second part focuses on the physical origin of the noise and its role in electronic interfaces design. Here, general design optimization approaches, techniques, and architectures are analyzed, also covering the time-domain sensing techniques.

Finally, the third part deals with selected topics on three different aspects of transduction physics: optical, ionic, and mechanical. The section makes no claim to cover all sides to transduction but only gives examples of typical applications. However, the latter part is not a bare addition to this book since physical transduction is an essential step of the overall sensor acquisition chain, and it should be considered a processing block like all the others in the design process. Therefore, I considered it necessary to show transduction examples to practice the overall sensor design optimization.

Chapter 1 introduces various concepts concerning information and signals, which will be dealt with in later chapters but meanwhile yield a definition of the artificial sensor. Chapter 2 introduces a number of basic parameters characterizing sensor physics, including precision/accuracy and respective tradeoffs, along with relevant figures of merits. Chapter 3 analyzes the main sensor design tradeoffs under the information theory perspective. Chapter 4 lists certain important features of the mathematical methods used in analyzing and synthesizing sensor systems. Chapter 5, by M. Chiani (Alma Mater, University of Bologna), introduces the compressive sensing approach.

Chapter 6 deals with the origins and models of noise in various contexts, including the time domain, such as phase noise. Chapter 7 provides models for calculating and optimizing noise in the case of devices and simple electronic circuits. Chapter 8 covers more complex electronic systems of extracting information that operates in signal and time-space.

Chapter 9 introduces a number of concepts of photonic transduction with particular reference to the photodiode and its configurations in area sensors. Chapter 10 deals with the ionic-electronic transduction that underlies biosensing. That chapter also provides an opportunity to cover some noise issues in biosensors, especially in biopotential sensing. Lastly, Chapter 11 tackles mechanical transduction with particular attention to piezoresistivity and piezoelectricity. The chapter also considers some examples in which resistive mechanical sensors are applied. Finally, Chapter 12 by M. Crescentini (Alma Mater, University of Bologna) offers a collection of electronic sensor design problems and related solutions.

The book is dedicated to the memory of Professors Silvio Cavalcanti and Claudio Canali.