

smart sensor systems

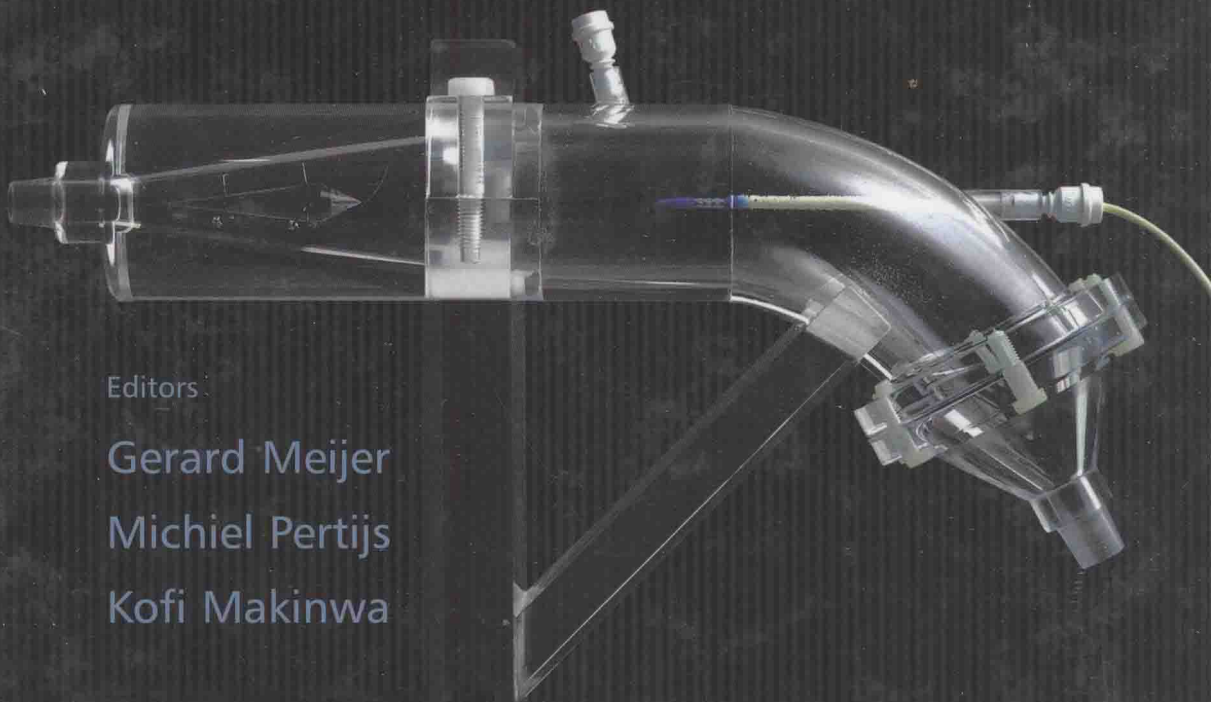
Emerging Technologies and Applications

Editors

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SMART SENSOR SYSTEMS: EMERGING TECHNOLOGIES AND APPLICATIONS

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SMART SENSOR SYSTEMS

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Preface

This book is intended as a reference for designers and users of sensors and sensor systems, and as a source of inspiration and a trigger for new ideas. For a major part, it is based on material used in the multidisciplinary “Smart Sensor Systems” course, which has been held annually at Delft University of Technology since 1995. The goals of this course are to present the basic principles of smart sensor systems to a broad, multidisciplinary audience, to develop a common language and scientific background to discuss the challenges associated with the design of such systems, and to facilitate mutual cooperation. In this way, we hope to contribute to the continuous expansion of the community of people advancing the exciting field of smart sensor systems.

As diverse and widespread as smart sensors may be today, research and development in this field is far from complete. It is driven by the continuous demand for lower cost, size and power consumption, and for higher performance and greater reliability. Moreover, new sensing principles and technologies are continuously emerging, and so significant effort is required to bring them to maturity. Often, this process involves more than just improving the performance of the transducer concerned. The *system* around the transducer plays an equally important, if not a more important, role. This system includes the electronics that interface with the transducer, the package that protects the transducer from the environment, and the calibration procedure that ensures that a certain performance specification is met.

This book focuses on these important system aspects, and, in particular, on the design of *smart* sensor systems, in which sensors and electronics are combined in a single package or even on a single chip to provide improved functionality, performance and reliability. In a previous book entitled “Smart Sensor Systems,” the basics of such systems were covered. This book complements this prior publication by covering a number of emerging sensing technologies and applications, as well as discussing, in more detail, the system aspects of smart sensor design.

The book opens by discussing the exciting possibilities afforded by the combination of sensors and electronics: the accurate processing of small sensor signals (Chapter 1), the adoption of self-calibration techniques (Chapter 2), and the integration of precision instrumentation amplifiers (Chapter 3). This is followed by a discussion of a number of sensor systems in which system aspects play a key role: sensing of physical and chemical parameters by means of impedance measurement (Chapter 4); low-power angular-rate sensing using feedback and background-calibration techniques (Chapter 5); sensor systems for the detection of biomolecules, such as DNA (Chapter 6); optical sensor systems-on-a-chip in the form of CMOS image sensors (Chapter 7); and smart sensors capable of interfacing with the human

nervous system (Chapter 8). Finally, the book also describes emerging technologies for the generation and storage of energy, since these are the key to realizing truly autonomous sensor systems (Chapter 9).

During the course of writing this text, we have been assisted by many people. We gratefully acknowledge the feedback and suggestions provided by our reviewers: Reinoud Wolffenbuttel of Delft University of Technology, Michael Kraft of the Fraunhofer Institute for Microelectronic Circuits and Systems, Michiel Vellekoop of the University of Bremen, Jan Bosiers of Teledyne DALSA, Firat Yazicioglu of imec, and the authors who also acted as reviewers. At our publisher, John Wiley & Sons, Ltd., we would like to acknowledge the Project Editors Richard Davies, Liz Wingett, and Laura Bell, for their support, encouragement and help in arranging agreements as well as to Production Editor Genna Manaog and Sangeetha Parthasarathy of Laserwords for help throughout the production of this book. Furthermore, we want to express our gratitude to the universities, research institutes and companies who permitted the use of figures and illustrations to make this book attractive for our readers. Finally, we would like to thank our spouses, Rumiana, Hannah and Abi, for their love and support.

Gerard Meijer, Michiel Pertijs and Kofi Makinwa
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1

Smart Sensor Design*

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1.1 Introduction

Sensors have become a ubiquitous part of today's world. Modern cars employ tens of sensors, ranging from simple position sensors to multi-axis MEMS accelerometers and gyroscopes. These sensors enhance engine performance and reliability, ensure compliance with environmental standards, and increase occupant comfort and safety. In another example, modern homes contain several sensors, ranging from simple thermostats to infrared motion sensors and thermal gas flow sensors. However, the best example of the ubiquity of sensors is probably the mobile phone, which has evolved from a simple communications device into a veritable sensor platform. A modern mobile phone will typically contain several sensors: a touch sensor, a microphone, one or two image sensors, inertial sensors, magnetic sensors, and environmental sensors for temperature, pressure and even humidity. Together with a GPS receiver for position location, these sensors greatly enhance ease of use and have extended the utility of mobile phones far beyond their original role as portable telephones.

Today, most of the sensors in a mobile phone, as well as most sensors intended for consumer applications, are made from silicon. This is mainly because silicon sensors can be mass-produced at low cost by exploiting the large manufacturing base established by the semiconductor industry. Another important motivation is the fact that the electronic circuitry required to bias a sensor and condition its output can be readily realized on the same substrate or, at least, in the same package. It also helps that semiconductor-grade silicon is a highly pure material with well-defined physical properties, some of which can be tuned by doping, and which can be precisely machined at the nanometer scale.

Silicon is a versatile material, one that exhibits a wide range of physical phenomena and so can be used to realize many different kinds of sensors [1]. For example, magnetic fields can

* This chapter is an expanded and updated version of [7].

be sensed via the Hall effect, temperature differences can be sensed via the Seebeck effect, mechanical strain can be sensed via the piezo-resistive effect and light can be sensed via the photo-electric effect. In addition, measurands that do not directly interact with silicon can often be indirectly sensed with the help of silicon-compatible materials. For example, humidity can be sensed by measuring the dielectric constant of a hygroscopic polymer [2], while gas concentration can be sensed by measuring the resistance of a suitably adsorbing metal oxide [3]. It should be noted that although silicon sensors may not achieve best-in-class performance, their utility and increasing popularity stems from their small size, low cost and the ease-of-use conferred by their co-integrated electronic circuitry.

Sensors are most useful when they are part of a larger system that is capable of processing and acting upon the information that they provide. This information must therefore be transmitted to the rest of the system in a robust and standardized manner. However, since sensors typically output weak analog signals, this task must be performed by additional electronic circuitry. Such *interface electronics* is best located close to the sensor, to minimize interference and avoid transmission losses. When they are both located in the same package, the combination of sensor and interface electronics is what we shall refer to as a *smart sensor* [4].

In addition to providing a robust signal to the outside world, the interface electronics of a smart sensor can be used to perform traditional signal processing functions such as filtering, linearization and compression. But it can also be used to increase the sensor's reliability by implementing self-test and even self-calibration functionality (as will be discussed in Chapter 2). A recent trend is towards sensor fusion, in which the outputs of multiple sensors in a package are combined to generate a more reliable output. For example, the outputs of gyroscopes, accelerometers and magnetic sensors can be combined to obtain robust position estimates, thus enabling mobile devices with indoor navigational capability.

This chapter discusses the design of smart sensor systems, in general, and the design of smart sensors in standard integrated circuit (CMOS) technology, in particular. Examples will be given of the design of state-of-the-art CMOS smart sensors for the measurement of temperature, wind velocity and magnetic field. Although the use of standard CMOS technology constrains the performance of the actual sensors, it minimizes cost, and as will be shown, the performance of the overall sensor *system* can often be significantly improved with the help of the co-integrated interface electronics.

1.2 Smart Sensors

A smart sensor is a system-in-package in which a sensor and dedicated interface electronics are realized. It may consist of a single chip, as is the case with smart temperature sensors, image sensors and magnetic field sensors. However, in cases when the sensor cannot be implemented in the same technology as the interface electronics, a two-chip solution is required. Since this also decouples the production yield of the circuit from that of the sensor, a two-chip solution is often more cost effective, even in cases where the sensor could be co-integrated with the electronics. Examples of two-chip sensors are mechanical sensors, such as MEMS accelerometers, gyroscopes and microphones, whose manufacture requires the use of micro-machining technology.

Since silicon chips, and especially their connections to the outside world, are rather fragile, smart sensors must be protected by some kind of packaging. The design of an appropriate