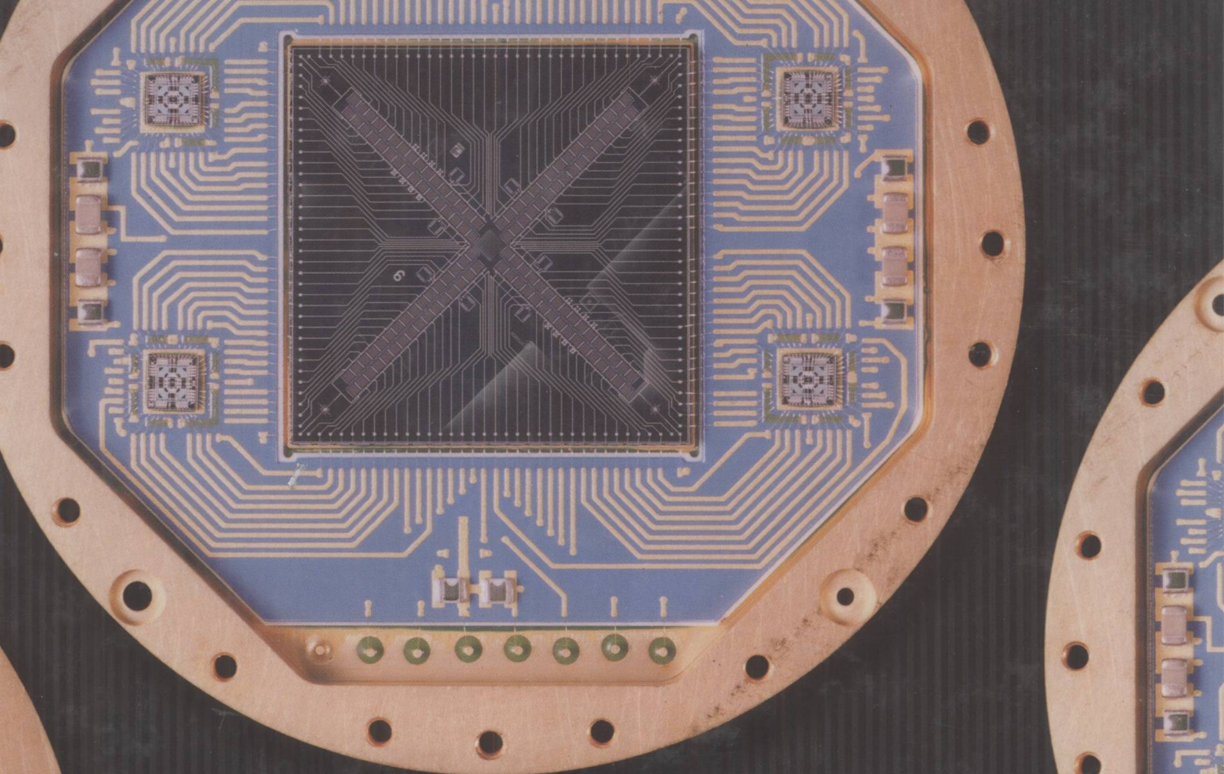

smart sensor systems

EDITED BY GERARD C. M. MEIJER

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SMART SENSOR SYSTEMS

Edited by

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SMART SENSOR SYSTEMS

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Solutions to Problems can be found on the Companion website

Preface

Thanks to the tremendous efforts of numerous scientists and technologists, sensor technology has now arrived in its childhood, which means that we expect that it has started a long period of growth in the intellectual and technological level of sensor systems and that it will reach a level of maturity. It is difficult to predict where this growth will end and what the final stage will look like. For the near future, we expect to see the development of autonomous sensors integrated into distributed systems with intelligent signal processors and smart control of actuators, and powered with a minimum amount of energy. For the longer term, we picture sensor systems as being components of robots in which the system architecture strongly resembles that of animals or human beings.

Of course, such ideas are not new. We can even ask ourselves why it is taking so long for such developments to happen. Is it the difficulty of making a significant step in the level of technology? Could it be possible that the introduction of nanotechnology, in which we can organize technical matter all the way down to the atom level, will bring us the new future we are looking for?

Nobody knows for sure, but it is clear that an important reason for the 'slow' progress in sensor technology can be found in the multidisciplinary character of the required knowledge. It requires the cooperation of physicists, chemists, electrical and mechanical engineers, and ICTers. Moreover, these engineers have to cooperate with medical doctors, agriculturists and horticulturists, and economists.

This book is intended as a reference for designers and users of sensors and sensor systems. It has been written based on material presented in the multidisciplinary courses 'Smart Sensor Systems' that have been organized at Delft University of Technology since 1995. The scope of these courses has been to present the basic principles of advanced sensor systems for a wide, multidisciplinary audience, to develop a common language and scientific background to discuss the problems, and to facilitate mutual cooperation. Thus, we hope to contribute to a continual expansion of the group of people contributing to these world-wide exciting developments.

During the course of writing this text, many people have assisted us. Many people have contributed to this book. We highly appreciate the support of the boards of faculties or heads of our industrial and academic institutes, who have helped us and allowed us to write this book. We have benefited from the suggestions made by our reviewers: Dr. Ferry N. Toth of Exalon, Dr. Michiel Pertijs of National Semiconductors, Ir. Jeroen van der Meer of Xensor Integration, Prof. Albert J.P. Theuwissen of TUDelft, Dr. André Bossche of TUDelft, Ir. Qi Jia of TUDelft, and all of the authors who also acted as reviewers.

At our publisher, John Wiley & Sons, Ltd, we would like to acknowledge the project manager Nicky Skinner for her technical manuscript editing, and executive commissioning editor Simone Taylor for her encouragements and her help in arranging agreements. We would also like to thank Mrs. Trudie (G.) Houweling of TUDelft for her secretarial assistance during the course of this work, and Rob Janse, who made many of the drawings in this book. We wish to extend our appreciation to Sarah von Galambos for her excellent English and linguistic corrections. Furthermore, we want to express our gratitude to the universities, research institutes and companies who allowed us to write this text and helped us with illustrative material and demonstrators to make this book attractive for our readers.

The Companion website for this book is www.wiley.com/go/meijer_smart.

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About the Authors

Gerard C.M. Meijer

Gerard C.M. Meijer was born in Wateringen, the Netherlands, in 1945. He received his M.Sc. and Ph.D. degrees in Electrical Engineering from Delft University of Technology, Delft, the Netherlands, in 1972 and 1982, respectively. Since 1972 he has been a member of the research and teaching staff of Delft University of Technology, where he is a professor of analog electronics and electronic instrumentation. In 1984 and part-time from 1985 to 1987 he was seconded to Delft Instruments Company, Delft, the Netherlands, where he was involved in the development of industrial level gauges and temperature transducers. In 1996 he co-founded the company SensArt, where he is a consultant for the design and development of sensor systems. In 1999 the Dutch Technology Foundation STW awarded Meijer with the honorary degree 'Simon Stevin Meester'. In 2001 he was awarded the Anthony Van Leeuwenhoek Chair at TUDelft. Meijer is chairman of the National STW Platform on Sensor Technology and director of the annual Europractice course 'Smart Sensor Systems'.

Paddy J. French

Paddy J. French received his B.Sc. in mathematics and M.Sc. in electronics from Southampton University, UK, in 1981 and 1982, respectively. In 1986 he obtained his Ph.D., also from Southampton University, for his research on the piezoresistive effect in polysilicon. After 18 months as a post-doc at Delft University of Technology, the Netherlands, he moved to Japan in 1988. For three years he worked on sensors for automotives at Central Engineering Laboratories of Nissan Motor Company. He returned to Delft University of Technology in May 1991 were he has been involved in research on micromachining and process optimization related to sensors. Since 2002 he has chaired the Laboratory for Electronic Instrumentation. In 1999 he was awarded the Anthony van Leeuwenhoek Chair. He has also received the title award of 'Simon Stevin Meester' from the Dutch Technology Foundation.

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Sander van Herwaarden was born in 1957, Rotterdam, the Netherlands. In 1982, he received his B.A. in economics from the Erasmus University in Rotterdam. In 1983 he received his M.Sc. and in 1987 his Ph.D. from Delft University of Technology, both in thermal-sensor subjects. In 1988 he co-founded Xensor Integration and has been managing director since then. His main activities are in the field of thermal sensors and silicon microstructures.

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Johan H. Huijsing was born in Bandung, Indonesia, on May 21, 1938. He received his M.Sc. in Electrical Engineering from Delft University of Technology, Delft, the Netherlands, in 1969, and his Ph.D. from the same University in 1981 for his work on operational amplifiers. Since 1969 he has been a member of the Research and Teaching Staff of the Electronic Instrumentation Laboratory, Department of Electrical Engineering, Delft University of Technology, where he has been a full professor of electronic instrumentation since 1990, and professor emeritus since 2003. He teaches courses on electrical measurement techniques, electronic instrumentation, operational amplifiers, and analog-to-digital converters. His field of research is analog circuit design (operational amplifiers, analog multipliers, etc.) and integrated smart sensors. He is a fellow of the IEEE. He received the title award of 'Simon Stevin Meester' from the Dutch Technology Foundation.

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Ratcho Ivanov was born in v.Razliv, Bulgaria on December 25, 1945. He received his M.Sc. and his Ph.D. in Electronics engineering from the Technical University of Sofia, Bulgaria in 1969 and 1980, respectively. From 1975 to 1977 he specialized on microprocessor-based systems at the Tokyo Institute of Technology, Japan. Since 1970, he has been employed at the Technical University of Sofia, where at present he is a professor specialized in the teaching, design, development and implementation of embedded systems, microcontroller and microprocessor-based industrial systems, smart sensors systems and applications.

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Pavel Kejik was born in the Czech Republic in 1971. He received his university degree in 1994 and Ph.D. degree in 1999 at the Czech Technical University of Prague. In 1999, he joined the Institute of Microelectronics and Microsystems at the EPFL to work on the Institute's circuit design and testing. His research interests include fluxgate magnetometry and micro-Hall sensors combined with mixed-signal IC design and low-noise circuit design for industrial applications.

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Xiujun Li was born in Tianjin, China in 1963. He received his B.Sc. in physics and M.Sc. in electrical engineering from Nankai University, Tianjin, China in 1983 and 1986, respectively. In 1997, he received his Ph.D. degree from the faculty of Electrical Engineering, Delft University of Technology, the Netherlands. Since September 1996, he has been employed as a part-time senior researcher at the Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, where he is involved in research and development of smart capacitive sensors and low-cost interfaces for smart sensors. Since 1997 he has worked part-time for Smartec B.V. on smart temperature sensors and smart sensor interfaces. In 2002 he joined Bradford Engineering B.V., Heerle, the Netherlands, where he conducts research and development of instruments for the space industry.

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Radivoje S. Popović received the Dipl. Ing. degree in engineering physics from the University of Belgrade, Yugoslavia in 1969, and the Mag.Sc and Dr.Sc. degrees in electronics from the University of Nis, Yugoslavia in 1974 and 1978. From 1969 to 1981 he worked for

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Michael J. Vellekoop was born in Amsterdam in 1960. He received his B.Sc. degree in physics in 1982 and his Ph.D. degree in electrical engineering in 1994. In 1988 he co-founded Xensor Integration B.V. where he was managing director until 1996. In that year he initiated a new group on the topic of physical chemosensors at the DIMES Electronic Instrumentation Laboratory of the Delft University of Technology, where in 1997 he became an associated professor. Since 2001 he has been a full professor of industrial sensor systems at the Institute of Sensor and Actuator Systems at the Vienna University of Technology, Austria. In 2002 he became head of this Institute. Since 2005 he has been a corresponding member of the Austrian Academy of Sciences and in the same year he received the Eurosensors Fellow award.

Sergey Y. Yurish
Sergey Y. Yurish was born in Germany in 1963. He received his M.Sc. degree in Automatic and Telemetry from the State University Lviv Polytechnic, Ukraine, in 1985. Since then, he has been involved in the development of microcontroller-based and virtual measuring instruments. In 1997 he received his Ph.D. degree in measurements from the same university. In 1996 he joined the Institute of Computer Technologies for different international joint research projects in the smart sensors area, where he worked as Head of the R&D Department. Since 2006 he has been a professor at the Technical University of Catalonia (UPC-Barcelona). Professor Yurish is the holder of nine patents and he has also published more than 130 articles, papers and four books. He is a founder and President of the International Frequency Sensor Association (IFSA) and Editor-in-Chief of Sensors & Transducers Journal.

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Reinoud F. Wolffenbuttel received his M.Sc. degree in 1984 and his Ph.D. degree in 1988, both from the Delft University of Technology. Since 1986 he has been a member of the research and teaching staff of Delft University of Technology, where he is an associate professor at the Department of Microelectronics. He is involved in research on instrumentation and measurement in general and on-chip functional integration of microelectronic circuits and silicon sensor, fabrication compatibility issues, and micromachining in silicon and microsystems in particular. He was a visiting researcher at the University of Michigan, Ann Arbor, USA in 1992, 1999 and 2001, Tohoku University, Sendai, Japan in 1995 and EPFL Lausanne, Switzerland in 1997. He is the recipient of a 1997 NWO pioneer award. He was general chairman of the Dutch National Sensor Conference in 1996, Eurosensors in 1999 and Micromechanics Europe in 2003.

1

Smart Sensor Systems: Why? Where? How?

Johan H. Huijsing

1.1 Third Industrial Revolution

Automation has three phases:

(1) Mechanization;
(2) Informatization;
(3) Sensorization.

Humans have always tried to extend their capabilities. See Figure 1.1. Firstly, they extended their mechanical powers. They invented the steam engine, the combustion engine, the electric motor, and the jet engine. Mechanization thoroughly changed society. The first industrial revolution was born.

Secondly, they extended their brains, or their ratio. They invented means for artificial logic and communication: the computer and the internet. This informatization phase is changing society again, where we cannot yet fully predict the end result.

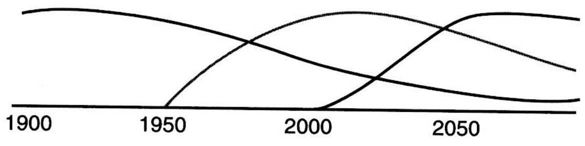

Figure 1.1 Sensorization: the third automation revolution

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