

smart sensor systems

EDITED BY GERARD C. M. MEIJER

Companion Website

 WILEY

TP212.6
S636

SMART SENSOR SYSTEMS

Edited by

Gerard C.M. Meijer

Delft University of Technology, the Netherlands

SensArt, Delft, the Netherlands



 **WILEY**

A John Wiley and Sons, Ltd, Publication



E2009002665

This edition first published 2008

© 2008 John Wiley & Sons, Ltd, except for:

Chapter 4 © 2008 Reinoud Wolffenbuttel. Printed by John Wiley & Sons, Ltd

Chapter 5 © 2008 Michael Vellekoop. Printed by John Wiley & Sons, Ltd

Chapter 6 © 2008 Sander van Herwaarden. Printed by John Wiley & Sons, Ltd

Registered office

John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Cover picture: copyright Sodern. The sensor on the cover picture was developed by Xensor Integration for Sodern (subsidiary of EADS)

Library of Congress Cataloging-in-Publication Data

Smart sensor systems/ edited by Gerard C.M. Meijer.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-86691-7 (cloth)

1. Detectors—Design and construction. 2. Detectors—Industrial applications. 3. Microcontrollers.

I. Meijer, G. C. M. (Gerard C. M.)

TA165.S55 2008

681'.25—dc22

2008017675

A catalogue record for this book is available from the British Library.

ISBN: 9780470866917

Set in 10/12pt Times by Aptara Inc., New Delhi, India

Printed in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire

SMART SENSOR SYSTEMS

Contents

Preface	xiii
About the Authors	xv
1 Smart Sensor Systems: Why? Where? How?	1
<i>Johan H. Huijsing</i>	
1.1 Third Industrial Revolution	1
1.2 Definitions for Several Kinds of Sensors	3
1.2.1 Definition of Sensors	3
1.2.2 Definition of Smart Sensors	9
1.2.3 Definition of Integrated Smart Sensors	9
1.2.4 Definition of Integrated Smart Sensor Systems	11
1.3 Automated Production Machines	12
1.4 Automated Consumer Products	16
1.4.1 Smart Cars	16
1.4.2 Smart Homes	16
1.4.3 Smart Domestic Appliances	17
1.4.4 Smart Toys	19
1.5 Conclusion	21
References	21
2 Interface Electronics and Measurement Techniques for Smart Sensor Systems	23
<i>Gerard C.M. Meijer</i>	
2.1 Introduction	23
2.2 Object-oriented Design of Sensor Systems	24
2.3 Sensing Elements and Their Parasitic Effects	25
2.3.1 Compatibility of Packaging	25
2.3.2 Effect of Cable and Wire Impedances	26
2.3.3 Parasitic and Cross-effects in Sensing Elements	27
2.3.4 Excitation Signals for Sensing Elements	29
2.4 Analog-to-digital Conversion	30
2.5 High Accuracy Over a Wide Dynamic Range	33
2.5.1 Systematic, Random and Multi-path Errors	33
2.5.2 Advanced Chopping Techniques	34
2.5.3 Autocalibration	36

2.5.4 <i>Dynamic Amplification</i>	37
2.5.5 <i>Dynamic Division and Other Dynamic Signal-processing Techniques</i>	40
2.6 <i>A Universal Transducer Interface</i>	41
2.6.1 <i>Description of the Interface Chip and the Applied Measurement Techniques</i>	41
2.6.2 <i>Realization and Experimental Results</i>	47
2.7 <i>Summary and Future Trends</i>	50
2.7.1 <i>Summary</i>	50
2.7.2 <i>Future Trends</i>	51
Problems	51
References	54
3 Silicon Sensors: An Introduction	55
<i>Paddy J. French</i>	
3.1 <i>Introduction</i>	55
3.2 <i>Measurement and Control Systems</i>	55
3.3 <i>Transducers</i>	57
3.3.1 <i>Form of Signal-carrying Energy</i>	57
3.3.2 <i>Signal Conversion in Transducers</i>	59
3.3.3 <i>Smart Silicon Sensors</i>	60
3.3.4 <i>Self-generating and Modulating Transducers</i>	63
3.4 <i>Transducer Technologies</i>	63
3.4.1 <i>Introduction</i>	63
3.4.2 <i>Generic Nonsilicon Technologies</i>	64
3.4.3 <i>Silicon</i>	66
3.5 <i>Examples of Silicon Sensors</i>	68
3.5.1 <i>Radiation Domain</i>	68
3.5.2 <i>Mechanical Domain</i>	70
3.5.3 <i>Thermal Domain</i>	70
3.5.4 <i>Magnetic Domain</i>	72
3.5.5 <i>Chemical Domain</i>	74
3.6 <i>Summary and Future Trends</i>	75
3.6.1 <i>Summary</i>	75
3.6.2 <i>Future Trends</i>	75
References	76
4 Optical Sensors Based on Photon Detection	79
<i>Reinoud F. Wolffenbuttel</i>	
4.1 <i>Introduction</i>	79
4.2 <i>Photon Absorption in Silicon</i>	81
4.3 <i>The Interface: Photon Transmission Into Silicon</i>	84
4.4 <i>Photon Detection in Silicon Photoconductors</i>	87
4.4.1 <i>Photoconductors in Silicon: Operation and Static Performance</i>	89
4.4.2 <i>Photoconductors in Silicon: Dynamic Performance</i>	93
4.5 <i>Photon Detection in Silicon pn Junctions</i>	93
4.5.1 <i>Defining the Depletion Layer at a pn Junction</i>	94
4.5.2 <i>Electron-hole Collection in the Depletion Layer</i>	97

4.5.3	<i>Electron-hole Collection in the Substrate</i>	97
4.5.4	<i>Electron-hole Collection Close to the Surface</i>	99
4.5.5	<i>Backside-illuminated Pin Photodiode</i>	100
4.5.6	<i>Electron-hole Collection in Two Stacked pn Junctions</i>	102
4.6	Detection Limit	103
4.6.1	<i>Noise in the Optical Signal</i>	104
4.6.2	<i>Photon Detector Noise</i>	105
4.6.3	<i>Photon Detector Readout</i>	106
4.7	Photon Detectors with Gain	108
4.7.1	<i>The Phototransistor</i>	108
4.7.2	<i>The Avalanche Photodiode</i>	109
4.7.3	<i>Time Integration of Photon-generated Charge</i>	112
4.8	Application Examples	113
4.8.1	<i>Color Sensor in CMOS</i>	113
4.8.2	<i>Optical Microspectrometer in CMOS</i>	115
4.9	Summary and Future Trends	117
4.9.1	<i>Summary</i>	117
4.9.2	<i>Future Trends</i>	118
	Problems	119
	References	119
5	Physical Chemosensors	121
	<i>Michael J. Vellekoop</i>	
5.1	Introduction	121
5.1.1	<i>Thin-film Chemical Interfaces</i>	122
5.1.2	<i>Total Analysis Systems</i>	122
5.2	Physical Chemosensing	123
5.3	Energy Domains	124
5.4	Examples and Applications	126
5.5	Examples of <i>in situ</i> Applications	127
5.5.1	<i>Blood Oximeter</i>	127
5.5.2	<i>Thermal Conductivity Detector</i>	127
5.5.3	<i>Engine Oil Monitoring System</i>	129
5.5.4	<i>Oil-condition Sensor Based on Infrared Measurements</i>	130
5.5.5	<i>Electronic Nose</i>	130
5.6	Microfluidics Devices	131
5.6.1	<i>Projection Cytometer</i>	135
5.6.2	<i>Coulter Counter</i>	138
5.6.3	<i>Dielectrophoresis-based Devices</i>	140
5.6.4	<i>High-throughput Screening Arrays</i>	144
5.6.5	<i>Contactless Conductivity Detection in CE</i>	145
5.7	Conclusions	146
	Problems	147
	References	147

6 Thermal Sensors	151
<i>Sander (A.W.) van Herwaarden</i>	
6.1 The Functional Principle of Thermal Sensors	151
6.1.1 Self-generating Thermal-power Sensors	151
6.1.2 Modulating Thermal-conductance Sensors	152
6.2 Heat Transfer Mechanisms	153
6.3 Thermal Structures	155
6.3.1 Modeling	155
6.3.2 Floating Membranes	160
6.3.3 Cantilever Beams and Bridges	161
6.3.4 Closed Membranes	163
6.4 Temperature-Difference Sensing Elements	165
6.4.1 Introduction	165
6.4.2 Thermocouples	165
6.4.3 Other Elements	168
6.5 Sensors Based on Thermal Measurements	168
6.5.1 Microcalorimeter	169
6.5.2 Psychrometer	170
6.5.3 Infrared Sensor	171
6.5.4 RMS Converter	172
6.5.5 EM Field Sensor	173
6.5.6 Flow Sensor	174
6.5.7 Vacuum Sensor	174
6.5.8 Thermal Conductivity Gauge	176
6.5.9 Acceleration Sensors	177
6.5.10 Nanocalorimeter	177
6.6 Summary and Future Trends	179
6.6.1 Summary	179
6.6.2 Future Trends	179
Problems	180
References	182
 7 Smart Temperature Sensors and Temperature-Sensor Systems	 185
<i>Gerard C.M. Meijer</i>	
7.1 Introduction	185
7.2 Application-related Requirements and Problems of Temperature Sensors	188
7.2.1 Accuracy	189
7.2.2 Short-term and Long-term Stability	189
7.2.3 Noise and Resolution	190
7.2.4 Self-heating	192
7.2.5 Heat Leakage along the Connecting Wires	194
7.2.6 Dynamic Behavior	194
7.3 Resistive Temperature-sensing Elements	196
7.3.1 Practical Mathematical Models	196
7.3.2 Linearity and Linearization	198

7.4	Temperature-sensor Features of Transistors	200
7.4.1	<i>General Considerations</i>	200
7.4.2	<i>Physical and Mathematical Models</i>	201
7.4.3	<i>PTAT Temperature Sensors</i>	203
7.4.4	<i>Temperature Sensors with an Intrinsic Voltage Reference</i>	207
7.4.5	<i>Calibration and Trimming of Transistor Temperature Sensors</i>	208
7.5	Smart Temperature Sensors and Systems	208
7.5.1	<i>A Smart Temperature Sensor with a Duty-cycle-modulated Output Signal</i>	209
7.5.2	<i>Smart Temperature-sensor Systems with Discrete Elements</i>	212
7.6	Case Studies of Smart-sensor Applications	212
7.6.1	<i>Thermal Detection of Micro-organisms with Smart Sensors</i>	213
7.6.2	<i>Control of Substrate Temperature</i>	217
7.7	Summary and Future Trends	220
7.7.1	<i>Summary</i>	220
7.7.2	<i>Future Trends</i>	221
	Problems	222
	References	223
8	Capacitive Sensors	225
	<i>Xiujun Li and Gerard C.M. Meijer</i>	
8.1	Introduction	225
8.2	Basics of Capacitive Sensors	226
8.2.1	<i>Principles</i>	226
8.2.2	<i>Precision of Capacitive Sensors</i>	226
8.3	Examples of Capacitive Sensors	227
8.3.1	<i>Angular Encoders</i>	228
8.3.2	<i>Humidity Sensors</i>	229
8.3.3	<i>Liquid-level Gauges</i>	230
8.4	The Design of Electrode Configurations	231
8.4.1	<i>EMI Effects</i>	231
8.4.2	<i>Electric-field-bending Effects</i>	232
8.4.3	<i>Active-guard Electrodes</i>	232
8.4.4	<i>Floating Electrodes</i>	233
8.4.5	<i>Contamination and Condensation</i>	234
8.5	Reduction of Field-bending Effects: Segmentation	234
8.5.1	<i>Three-layered Electrode Structures</i>	235
8.5.2	<i>A Model for the Electrostatic Field in Electrode Structures</i>	236
8.5.3	<i>Influence of the Electric-field-bending Effects on Linearity</i>	237
8.6	Selectivity for Electrical Signals and Electrical Parameters	237
8.6.1	<i>Selective Detection of Band-limited Frequencies</i>	238
8.6.2	<i>Selective Detection of a Selected Parameter</i>	239
8.6.3	<i>Measurement Techniques to Reduce the Effects of Shunting Conductances</i>	240
8.7	Summary and Future Trends	246
	Problems	246
	References	247

9	Integrated Hall Magnetic Sensors	249
	<i>Radivoje S. Popović and Pavel Kejik</i>	
9.1	Introduction	249
9.2	Hall Effect and Hall Elements	250
	9.2.1 <i>The Hall Effect</i>	250
	9.2.2 <i>Hall Elements</i>	253
	9.2.3 <i>Characteristics of Hall Elements</i>	253
	9.2.4 <i>Integrated Horizontal Hall Plates</i>	256
	9.2.5 <i>Integrated Vertical Hall Plates</i>	258
9.3	Integrated Hall Sensor Systems	259
	9.3.1 <i>Biasing a Hall Device</i>	260
	9.3.2 <i>Reducing Offset and 1/f noise</i>	260
	9.3.3 <i>Amplifying the Hall Voltage</i>	262
	9.3.4 <i>Integrating Magnetic Functions</i>	265
9.4	Examples of Integrated Hall Magnetic Sensors	267
	9.4.1 <i>Magnetic Angular Position Sensor</i>	267
	9.4.2 <i>Fully Integrated Three-axis Hall Probe</i>	269
	9.4.3 <i>Integrated Hall Probe for Magnetic Microscopy</i>	271
	Problems	276
	References	276
10	Universal Asynchronous Sensor Interfaces	279
	<i>Gerard C.M. Meijer and Xiujun Li</i>	
10.1	Introduction	279
10.2	Universal Sensor Interfaces	280
10.3	Asynchronous Converters	283
	10.3.1 <i>Conversion of Sensor Signals to the Time Domain</i>	284
	10.3.2 <i>Wide-range Conversion of Sensor Signals to the Time Domain for Very Small or Very Large Signals</i>	287
	10.3.3 <i>Output Signals</i>	288
	10.3.4 <i>Quantization Noise of Sampled Time-modulated Signals</i>	290
	10.3.5 <i>A Comparison between Asynchronous Converters and Sigma–delta Converters</i>	294
10.4	Dealing with Problems of Low-cost Design of Universal Interface ICs	296
10.5	Front-end Circuits	297
	10.5.1 <i>Cross-effects and Interaction</i>	297
	10.5.2 <i>Interference</i>	298
	10.5.3 <i>Optimization of Components, Circuits and Wiring</i>	298
10.6	Case Studies	299
	10.6.1 <i>Front-end Circuits for Capacitive Sensors</i>	299
	10.6.2 <i>Front-end Circuits for Resistive Bridges</i>	302
	10.6.3 <i>A Front-end Circuit for a Thermocouple-voltage Processor</i>	305
10.7	Summary and Future Trends	307
	10.7.1 <i>Summary</i>	307
	10.7.2 <i>Future Trends</i>	307
	Problems	308
	References	311

11	Data Acquisition for Frequency- and Time-domain Sensors	313
	<i>Sergey Y. Yurish</i>	
11.1	Introduction	313
11.2	DAQ Boards: State of the Art	314
11.3	DAQ Board Design for Quasi-digital Sensors	316
	11.3.1 <i>Advanced Methods for Frequency-to-digital Conversion</i>	316
	11.3.2 <i>Examples</i>	322
	11.3.3 <i>Methods for Duty-cycle-to-digital Conversion</i>	324
	11.3.4 <i>Methods for Phase-shift-to-digital Conversion</i>	326
11.4	Universal Frequency-to-digital Converters (UFDC)	330
	11.4.1 <i>ICs for Frequency-to-digital Conversion: State of the Art</i>	332
	11.4.2 <i>UFDC: Features and Performances</i>	333
11.5	Applications and Examples	335
11.6	Summary and Future Trends	338
	Problems	339
	References	340
12	Microcontrollers and Digital Signal Processors for Smart Sensor Systems	343
	<i>Ratcho M. Ivanov</i>	
12.1	Introduction	343
12.2	MCU and DSP Architectures, Organization, Structures, and Peripherals	344
12.3	Choosing a Low-Power MCU or DSP	347
	12.3.1 <i>Average Current Consumption</i>	348
	12.3.2 <i>Oscillator and System Clocks</i>	349
	12.3.3 <i>Interrupts</i>	350
	12.3.4 <i>Peripherals</i>	350
	12.3.5 <i>Summary</i>	350
12.4	Timer Modules	351
	12.4.1 <i>Introduction to Timer Modules</i>	351
	12.4.2 <i>Examples of Timer Module Applications for Various Microcontrollers</i>	355
12.5	Analog Comparators, ADCs, and DACs as Modules of Microcontrollers	370
	12.5.1 <i>Introduction</i>	370
	12.5.2 <i>Application Examples of Analog Modules</i>	370
12.6	Embedded Networks and LCD Interfacing	373
12.7	Development Tools and Support	374
12.8	Conclusions	374
	References Sites	374
Appendix A	Material Data	375
Appendix B	Conversion for non-SI Units	377
Index		379

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.

Gerard C.M. Meijer
Delft, the Netherlands

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 automobiles at Central Engineering Laboratories of Nissan Motor Company. He returned to Delft University of Technology in May 1991 where 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.

Sander (A.W.) van Herwaarden

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.

Johan H. Huijsing

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.

Ratcho M. Ivanov

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.

Pavel Kejik

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.

Xiujun Li

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.

Radivoje S. Popović

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

Elektronska Industrija, Nis, Yugoslavia; and from 1982 to 1993 for Landis & Gyr AG, Central R&D, Zug, Switzerland. Since 1994, he has been a professor at the Swiss Federal Institute of Technology at Lausanne (EPFL), Switzerland. His current research interests include sensors for magnetic and optical signals, interface electronics, and noise phenomena. Dr Popovic is author or co-author of about 250 publications and 100 patent applications. He is the founder of the start-up companies Sentron AG, Sentronis AD, Senis GmbH, and Ametes AG. He is a member of the Swiss Academy of Engineering Sciences and of the Serbian Academy of Engineering Sciences.

Michael J. Vellekoop

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.

Reinoud F. Wolffenbuttel

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.

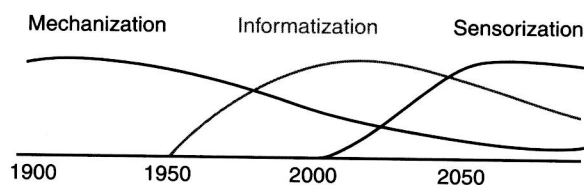


Figure 1.1 Sensorization: the third automation revolution