SMART SENSOR SYSTEMS

Edited by

Gerard C.M. Meijer

Delft University of Technology, the Netherlands
SensArt, Delft, the Netherlands

WILEY

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Contents

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

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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'.

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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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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.

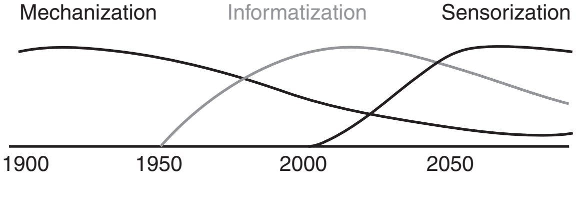

Figure 1.1 Sensorization: the third automation revolution

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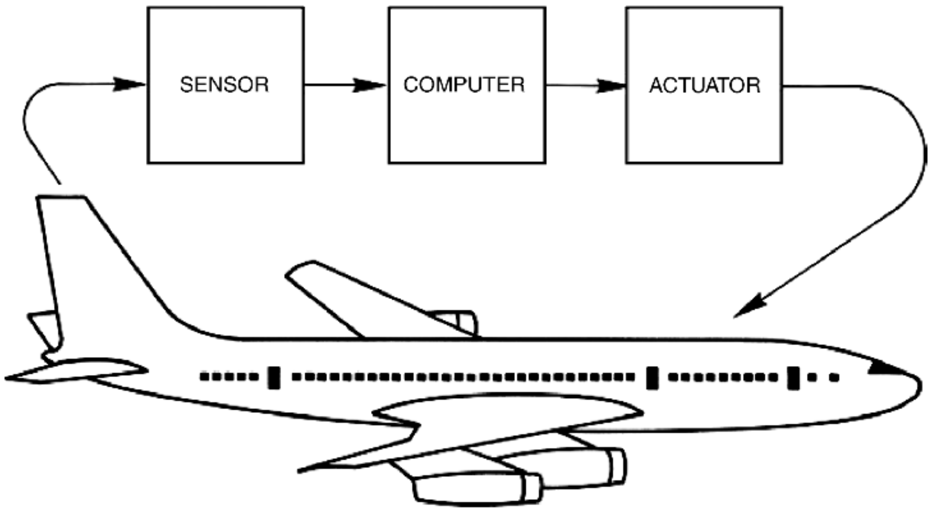

Figure 1.2 A fully automated airplane showing the triplet of mechanization, informatization and sensorization

However, this is not all. By inventing sensors, humans are now learning to artificially expand their senses. Sensorization together with mechanization and informatization will bring about the third industrial revolution of full automation or robotization.

A good example is the automated flight control system of a modern airplane (Figure 1.2). It includes many sensors to monitor the flight. The computers process the signals, compare them with the designed values, and provide control signals for the engines, rudders, and flaps that move the plane. This triptych of mechanics, computers, and sensors allows the plane to fly on autopilot.

If aircraft can fly automatically, why then can we still not have our car drive us to work by simply telling it to do so? Because the sensor system for an autodriver still weighs too much, is too bulky, and too costly to manufacture. So before we can apply sensorization to smart cars, smart homes, and industrial production machines, we must reduce the costs, size, and weight of the sensor system. This effort is the subject of our present challenge to develop Integrated Smart Sensors, as shown in Table 1.1.

Table 1.1 Integrated smart sensors

Challenge:	enabling the measurement of many physical and (bio)chemical signals
Requirements:	low cost, low size, low weight, low power, self-test, bus or wireless communication
HOW:	integrating sensors, actuators and smart interface electronics, preferably in one IC-package

1.2 Definitions for Several Kinds of Sensors

We will now provide definitions for several kinds of sensors as follows:

- Sensors
- Smart Sensors
- Integrated Smart Sensors
- Smart Sensors Systems

1.2.1 Definition of Sensors

Sensors transform signals from different energy domains to the electrical domain. Figure 1.3 classifies signals in six domains.

The uppermost domain in Figure 1.3 contains all signals of the radiant or optical domain. Optical sensors are able to translate these signals into electrical signals, which are depicted in the lowest domain. An example is an image sensor that translates a picture into an electrical signal. The next domain, to the right is the mechanical signal domain. For example, an accelerometer or airbag sensor is able to translate mechanical acceleration into an electrical signal. Similarly, a temperature sensor translates the temperature into an electrical signal. Even electrical sensors exist. They translate electrical signals into other electrical signals, for instance to measure accurately the voltage difference between two skin electrodes on the chest of a patient. To the lower left is the magnetic domain. A Hall plate is able to convert a magnetic signal into an electrical signal. And finally, from the chemical and biochemical domain sensors are able to translate these signals into electrical ones. Examples are pH sensors and DNA sensors.

The physical effects of sensors can be described by differential equations on energy or power containment [1]. Parameters of cross-effects between different energy domains describe the cross-sensitivities of a sensor between these signal domains. These effects are shown in Table 1.2, which places the physical sensor effects in a system. On the left-hand side, we find the sensor input signal domains. At the top there are the output signal domains. All effects on the left/upper-right/lower diagonal refer to effects within one signal domain. An example is photoluminescence within the radiation domain. All effects in the column with electrical output signals describe sensor effects, for example photoconductivity. All effects in the row with an electrical signal as input describe actuator effects.

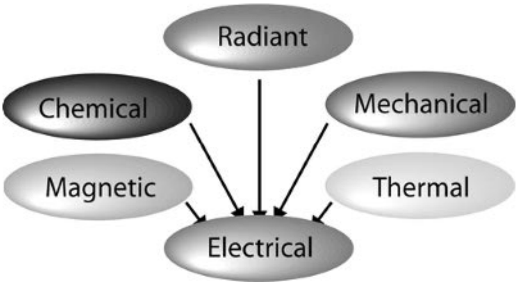

Figure 1.3 Sensor classification according to six signal domains

Table 1.2 Physical sensor effects [1]

In/Out	Radiant	Mechan.	Thermal	Electrical	Magnetic	Chemical
Rad	Photo-luminan.	Radiant pressure	Radiant heating	Photo-cond.	Photo-magn.	Photo-chem.
Mech.	Photo-elastic effect	Conservation of moment	Friction heat	Piezo-electricity	magneto-striction	Pressure-induced explos.
Therm.	Incan-descence	Thermal expansion	Heat conduction	Seebeck effect	Curie-Weiss law	Endotherm raction
Electr.	Inject. Luminan.	Piezo-electr.	Peltier effect	PNjunction effect	Ampere's law	Electrolysis
Magn.	Faraday effect	Magneto-striction	Ettinghausing effect	Hall effect	Magnetic induction	
Chem.	Chemo-lumin.	Explosion reaction	Exothermal reaction	Volta effect		Chem. reaction

Sensors can be further divided into passive (self-generating) and active (modulating) types. This is depicted in Figure 1.4. Passive sensors such as the electrodynamic microphone obtain their output energy from the input signal; active sensors on the other hand, such as the condenser microphone, obtain it from an internal power source. Active sensors can achieve a large power gain between the input and output signals. The sensor cube in Figure 1.5 shows a three-dimensional space of input, output, and power-source signals for sensors. A further classification of sensors is shown in Figure 1.6. Two classes can be distinguished: open systems, in which there is no feedback, and closed-loop systems, with feedback. A spring balance is a good mechanical example of the first; a chemical balance is a good example of the second.

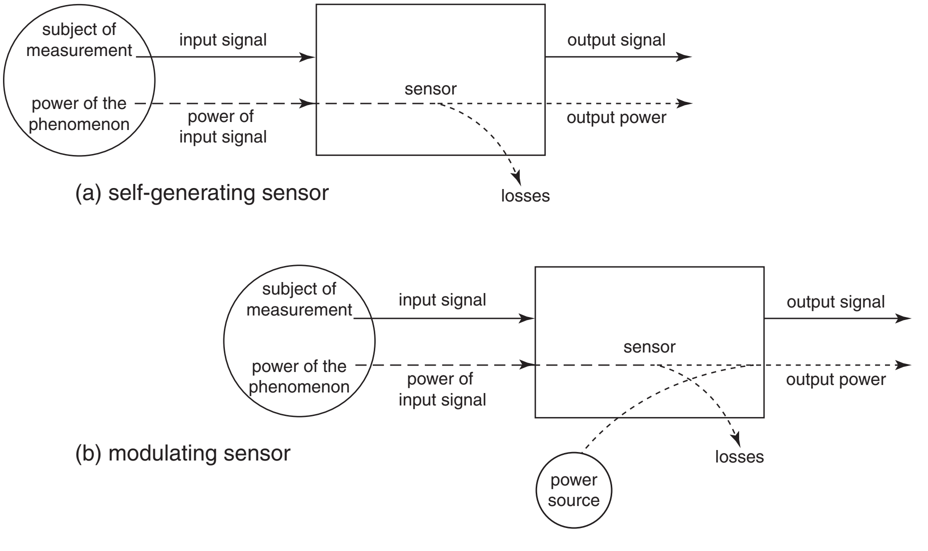

Figure 1.4 Self-generation and modulating sensors [2]

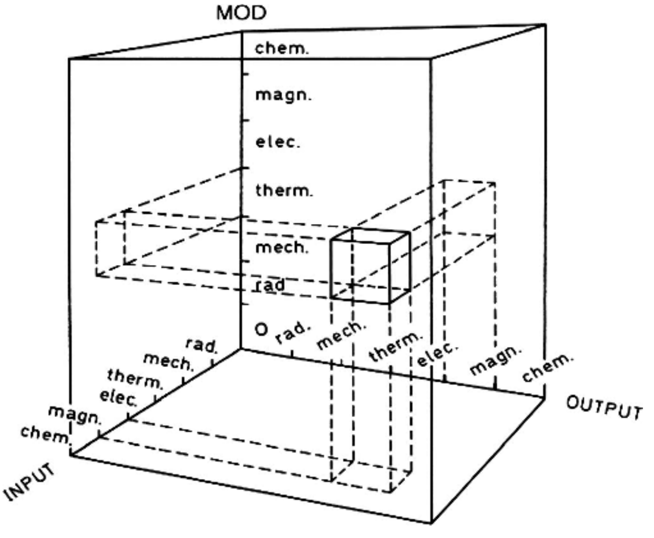

Figure 1.5 Sensor cube [1]

To measure with a chemical balance, weights have to be placed on the balance scale in order to bring the pointer to zero. The advantage of this system is that the actual sensor only needs to sense accurately around the zero point. The feedback placing of weights determines the value. In an open sensor system, the sensor has to provide the linearity and accuracy of the signal transfer all by itself.

Figures 1.7 and 1.8 depict the multitude of materials that can be chosen for sensors. Semiconductors are becoming increasingly popular as a sensor material because of their stable

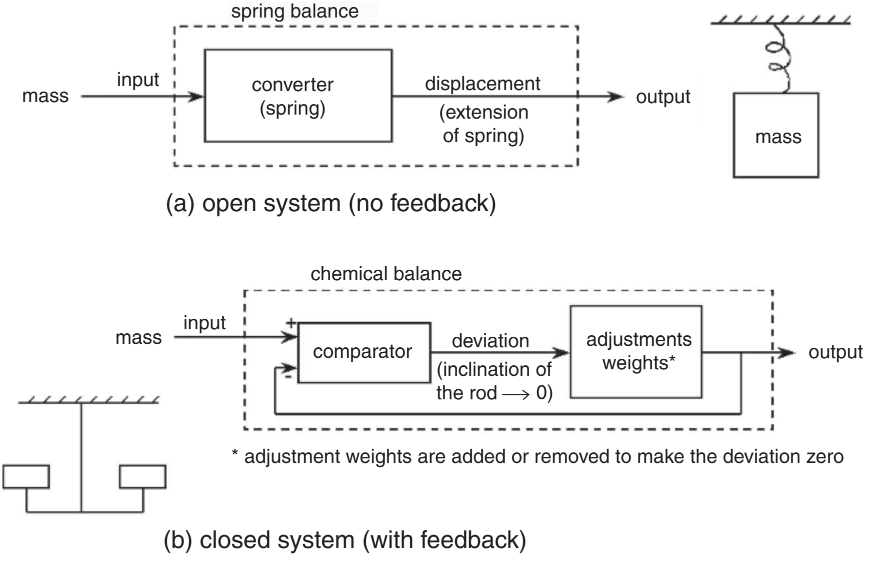

Figure 1.6 Open and closed loop sensor systems [2]

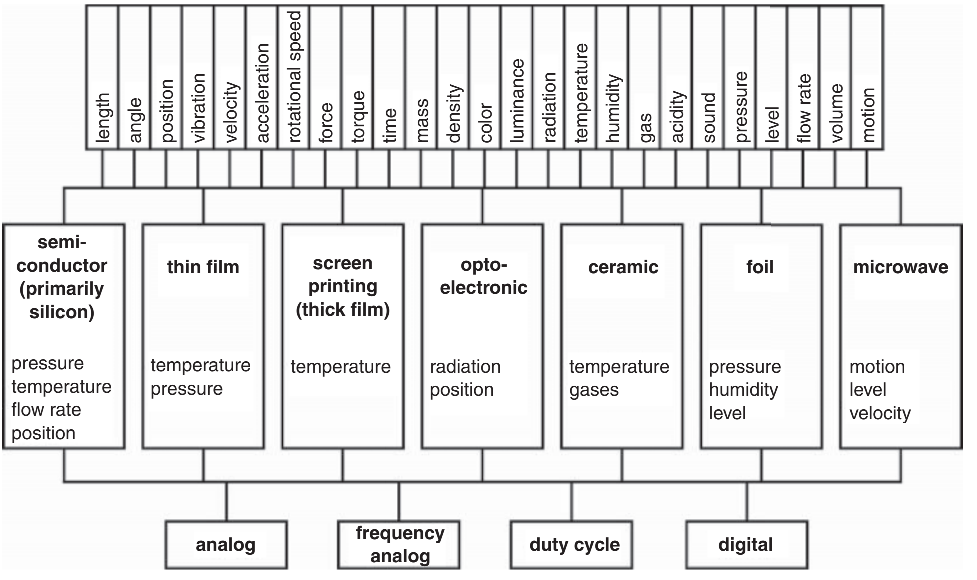

Figure 1.7 Sensor materials [3]

Figure 1.8 Which one? [2]

crystalline structure and because its standardization in mass fabrication is being improved; and because of their low price.

The production economics of sensors is often hampered by the multitude of sensor parameters to be measured. This is illustrated in Table 1.3.

Even for one parameter, such as pressure, there are many specifications: accuracy, sensitivity, noise, resolution, dynamic range, and environmental requirements. For this reason there are thousands of different pressure sensors on the market (see Figure 1.9).

Another complicating factor is the many output signal types of sensors. Some are listed in Table 1.4.

Further standardization and compacting is needed. The smart sensor is the solution (see Figure 1.10).

Table 1.3 Sensor parameters [3]

1. mechanical parameters of solids
   - acceleration
   - angle
   - area
   - diameter
   - distance
   - elasticity
   - expansion
   - filling level
   - force
   - form
   - gradient
   - hardness
   - height
   - length
   - mass
   - mass flow rate
   - moment
   - movement
   - orientation
   - pitch
   - position
   - pressure
   - proximity
   - revolutions per minute
   - rotating velocity
   - roughness
   - tension
   - torque
   - torsion
   - velocity
   - vibration
   - way
   - weight

2. mechanical parameters of fluids and gases
   - density
   - flow direction
   - flow velocity
   - level
   - pressure
   - rate of flow
   - vacuum
   - viscosity
   - volume

3. thermal parameters
   - enthalpy
   - entropy
   - temperature
   - thermal capacity
   - thermal conduction
   - thermal expansion
   - thermal radiation
   - thermal radiation temperature

4. optical parameters
   - color
   - image
   - light polarization
   - light wave-length
   - luminance
   - luminous intensity
   - reflection
   - refractive index

5. acoustic parameters
   - sound frequency
   - sound intensity
   - sound polarization
   - sound pressure
   - sound velocity
   - time of travel

6. nuclear radiation
   - ionization degree
   - mass absorption
   - radiation dose
   - radiation energy
   - radiation flux
   - radiation type

7. magnetic & electrical parameters
   - capacity
   - charge
   - current
   - dielectric constant
   - electric field
   - electric power
   - electric resistance
   - frequency
   - inductivity
   - magnetic field
   - phase

8. chemical parameters
   - cloudiness
   - composition
   - concentration
   - dust concentration
   - electrical conductivity
   - humidity
   - ice
   - impurities
   - ionization degree
   - molar weight
   - particle form
   - particle size
   - percentage of foreign matter
   - pH-value
   - polymerization degree
   - reaction rate
   - rendox potential
   - thermal conductivity
   - water content

9. other significant parameters
   - frequency
   - pulse duration
   - quantity
   - time

Figure 1.9 Sensitivity? Accuracy? [2]

Table 1.4 Non-standard sensor signals

Voltage:	Thermo Couple, Bandgap Voltage
Current:	Bip. trans., P.S.D., Radiation Detector
Resistance:	Strain-Gauge Bridge, Hall Sensor
Capacitance:	Humidity, Tactile, Accelerometer
Inductance:	(difficult on-chip)

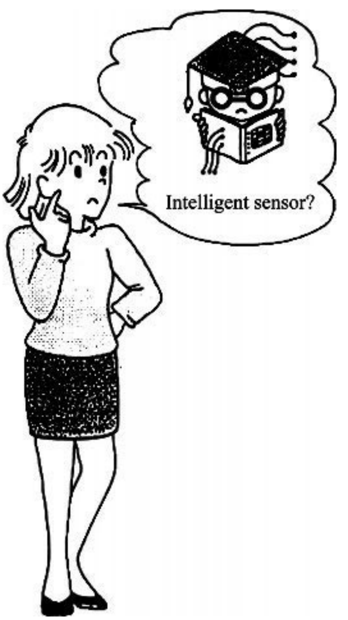

Figure 1.10 Smart sensor? [2]

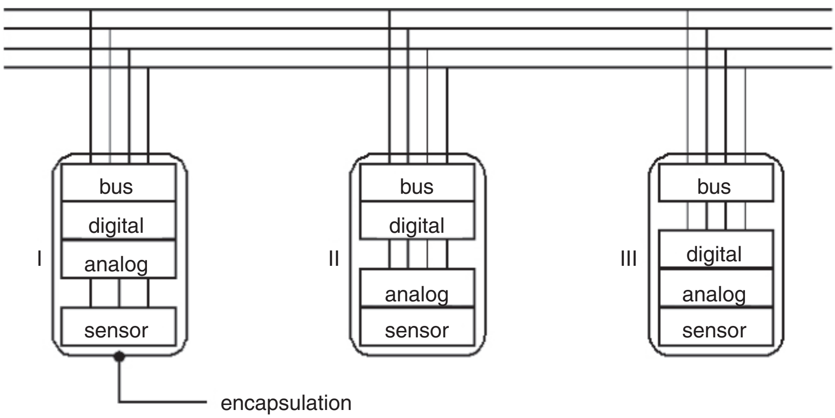

Figure 1.11 Hybrid smart sensors

1.2.2 Definition of Smart Sensors

If we combine a sensor, an analog interface circuit, an analog to digital converter (ADC) and a bus interface in one housing, we get a smart sensor. Three hybrid smart sensors are shown in Figure 1.11, which differ in the degree to which they are already integrated on the sensor chip. This calls for standardization. And hence the sensor must become smarter.

In the first hybrid smart sensor, a universal sensor interface (USI) can be used to connect the sensor with the digital bus. In the second one, the sensor and signal conditioner have been integrated. However, the ADC and bus interface are still outside. In the third hybrid, the sensor is already combined with an interface circuit on one chip that provides a duty cycle or bit stream. Just the bus interface is still needed separately.

At this level, still many output formats exist, as shown in Table 1.5.

1.2.3 Definition of Integrated Smart Sensors

If we integrate all functions from sensor to bus interface in one chip, we get an integrated smart sensor, as depicted in Figure 1.12.

Table 1.5 Standard sensor interface signals

Sign. Cond.:	Analog Voltage	0.5 V to 4.5 V
	Analog Current	4 mA to 20 mA
Sign. Conversion:	Frequency	2 kHz to 22 kHz
	Duty Cycle	10 % to 90 %
	Bit Stream	
	Bites	
Bus Output:	IS^2, I^2C	
	D^2B, Field, CAN	

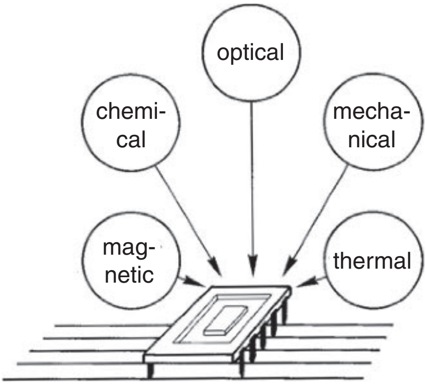

Figure 1.12 Integrated smart sensor

An integrated smart sensor should contain all elements necessary per node: one or more sensors, amplifiers, a chopper and multiplexers, an AD converter, buffers, a bus interface, addresses, and control and power management. This is shown in Figure 1.13.

Although fully integrating all functions will be expensive, mass-production of the resulting sensor can keep the cost per integrated smart sensor reasonable. Another upside is that the

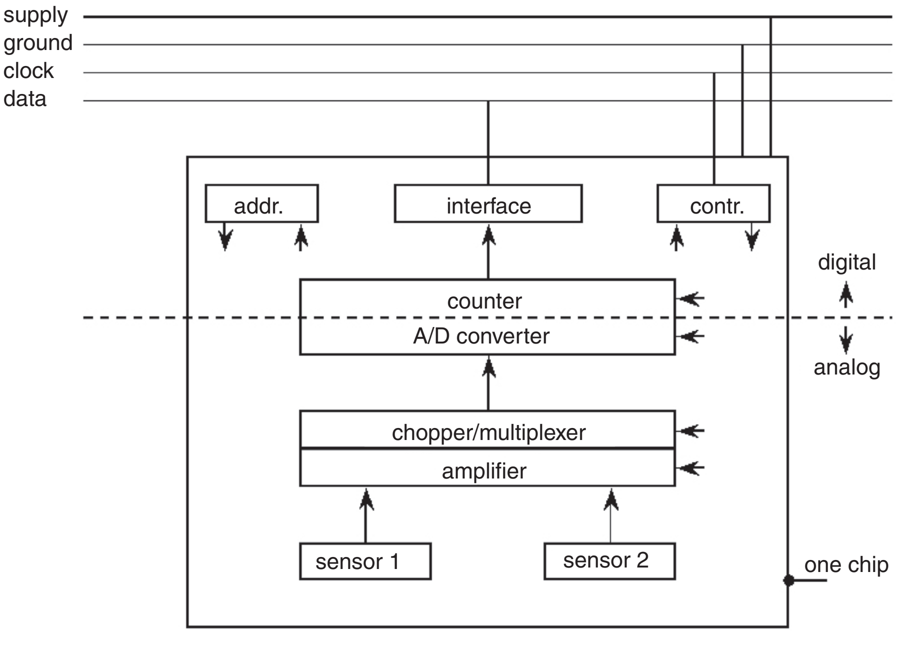

Figure 1.13 Functions of an integrated smart sensor