Sensors Applications
Volume 4

Sensors for Automotive Applications

Edited by
J. Marek, H.-P. Trah, Y. Suzuki, I. Yokomori

Series Editors:
J. Hesse, J.W. Gardner, W. Göpel †

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Sensors Applications
Volume 4
Sensors for Automotive Applications

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Preface to the Series

As the use of microelectronics became increasingly indispensable in measurement and control technology, so there was an increasing need for suitable sensors. From the mid-Seventies onwards sensors technology developed by leaps and bounds and within ten years had reached the point where it seemed desirable to publish a survey of what had been achieved so far. At the request of publishers WILEY-VCH, the task of editing was taken on by Wolfgang Göpel of the University of Tübingen (Germany), Joachim Hesse of Carl Zeiss (Germany) and Jay Zemel of the University of Philadelphia (USA), and between 1989 and 1995 a series called *Sensors* was published in 8 volumes covering the field to date. The material was grouped and presented according to the underlying physical principles and reflected the degree of maturity of the respective methods and products. It was written primarily with researchers and design engineers in mind, and new developments have been published each year in one or two supplementary volumes called *Sensors Update*.

Both the publishers and the series editors, however, were agreed from the start that eventually sensor users would want to see publications only dealing with their own specific technical or scientific fields. Sure enough, during the Nineties we saw significant developments in applications for sensor technology, and it is now an indispensable part of many industrial processes and systems. It is timely, therefore, to launch a new series, *Sensors Applications*. WILEY-VCH again commissioned Wolfgang Göpel and Joachim Hesse to plan the series, but sadly Wolfgang Göpel suffered a fatal accident in June 1999 and did not live to see publication. We are fortunate that Julian Gardner of the University of Warwick has been able to take his place, but Wolfgang Göpel remains a co-editor posthumously and will not be forgotten.

The series of *Sensors Applications* will deal with the use of sensors in the key technical and economic sectors and systems: *Sensors in Manufacturing, Intelligent Buildings, Medicine and Health Care, Automotive Technology, Aerospace Technology, Environmental Technology* and *Household Appliances*. Each volume will be edited by specialists in the field. Individual volumes may differ in certain respects as dictated by the topic, but the emphasis in each case will be on the process or system in question: which sensor is used, where, how and why, and exactly what the benefits are to the user. The process or system itself will of course be outlined and the volume will close with a look ahead to likely developments and applications in the future. Actual sensor functions will only be described where it seems necessary for an understanding of how they relate to the process or system. The basic principles can always be found in the earlier series of *Sensors* and *Sensors Update*.

The series editors would like to express their warm appreciation in the colleagues who have contributed their expertise as volume editors or authors. We are deeply indebted to the publisher and would like to thank in particular Dr. Peter Gregory, Dr. Jörn Ritterbusch and Dr. Claudia Barzen for their constructive assistance both with the editorial detail and the publishing venture in general. We trust that our endeavors will meet with the reader's approval.

Oberkochen and Coventry, November 2000

Joachim Hesse
Julian W. Gardner

Foreword

H.-J. Queisser

Little sensors make great sense! Biological systems can survive sudden external changes only if their sensory organs can speedily detect the altered environment and thus trigger the necessary responses. Technical systems are now beginning to behave in a similar quick, efficient mode. Distributed intelligence has become available and affordable and is making remarkable inroads into many applications. This voluminous tome is a most impressive example of current trends in utilizing modern materials, novel simulation techniques, and, in particular, the new and commanding technology of microminiaturization.

Richard Feynman, that imaginative and farsighted theorist, presented the after-dinner speech at the Pasadena meeting of the American Physical Society in 1959; its memorable title was “There is plenty of room at the bottom!” I consider myself most fortunate to have been a witness to this fascinating speech. Feynman showed, profoundly but amusingly, that no basic laws of physics prohibit technical systems from being reduced to very small sizes, even to atomic dimensions. Neither thermodynamics nor quantum mechanics forbid such ventures into smallness, although economic considerations might be limiting. This speech encouraged and motivated me enormously in my own work on semiconductors. I had just joined Shockley’s laboratory in Mountain View, California to work on silicon, the material that was later to lend its name to the Santa Clara Valley. Shockley’s lab was housed in an old apricot barn on San Antonio Avenue, now recognized as the ‘cradle’ of Silicon Valley.

Microminiaturization of semiconductors had been the driving motivation all along; it began in seriousness in the 1960s.

The success in size reduction that we have attained today was unimaginable in the beginning. Submicron control of design rules seemed hopeless and far too expensive. But the economics of the integrated circuit overcame all obstacles. Expensive new tools and methods were developed, and they paid off. Later on, in the 1980s, the remarkable tools in the arsenal of semiconductor processing gave birth to the new technology of micromechanics, with its small sensors of high speed and sensitivity, yet low cost and wide applicability. Silicon is now extremely well understood and under control. This material is therefore the mainstay for sensors and actuators of microscopic dimensions. Recent developments, however, clearly show that new materials and new technologies with specific applications in micro-mechanical sensors are still evolving. Technologies like thin-film technology, thick-film technology, and ceramics technology also turn out to be of essential importance in automotive sensors. The right choice of technology always depends on the special application, but all these innovative technologies are driven by common challenges: high-volume batch fabrication, miniaturization, functional improvements, high reliability, and low cost.

This book covers one aspect of sensors: automotive applications. Here lies a steady, huge market with many millions of end consumers. And those consumers are willing to pay for the novel features of these microdevices, although they will never actually see the devices. The tiny chips are well hidden within and distributed throughout the vehicle. Yet it is obvious to everybody that two essential properties can be enhanced by sensor technology: safety and environmental protection. Antiskid systems and the air bag would be unthinkable without highly sophisticated sensors. The well-controlled management of engine combustion has been a blessing for reducing exhaust reductions; legal authorities recognized the technical capabilities and responded by making stringent requirements, thus reinforcing the development and mass production of sensors.

Modern sensors are remarkable in many ways. Their small dimensions open up new areas of mechanics, flow control, friction, and oscillation. Force measurements are just one example. The once somewhat obscure classical Coriolis force is now the principle means of sensing rotation. And the even more obscure miniscale quantum-mechanical Casimir force, arising between two close interfaces, is now also accessible to sensor structures. Sensitivities are astonishing even now, but will most probably continue to be enhanced. Very many external parameters, such as temperature, pressure, and electromagnetic fields, can be accurately and quickly measured. What a wonderful area of activity for physicists, chemists, engineers – and salespeople alike! The prospect of protecting humankind as well as the environment is gratifying.

This volume contains a wealth of information on all facets of sensors in the automobile. I feel privileged and proud to have been approached by the two editors, Jiri Marek and Hans-Peter Trah, both former doctoral students of mine, to contribute this preface. Thanks to the entire international team of contributors and hopes for the successful use of its information by all its readers!

Stuttgart, April 2003 Hans-Joachim Queisser

Contents

Abbreviations

A/D	analogue to digital
ABC	active body control
ABS	antilock braking system
ac	alternating current
ACC	adaptive cruise control
AFS	active front & rear steering
APS	active pixel sensor
ASIC	application-specific integrated circuit
ASC	anti skid control
AQS	air-quality sensor
BBP	bridge base potential
BCD	body control damping
BITE	built-in test
BSI	bit synchronous interface
CAN	control area network
CCD	charge coupled device
CEA-LETI	le Commissariat à l'Energie Atomique – le Laboratoire d'Electronique, de Technologie et d'Instrumentation
CMOS	complementary metal-oxide semiconductor
C-V	capacitance to voltage conversion
CW	continuous wave
dB	decibel
dc	direct current
DLI	distributor-less ignition
DR	dynamic range
DRL	daylight running lamp
DSP	digital signal processing
ECU	electronic control unit
EHB	electrohydraulic braking
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EPROM	erasable programmable read-only memory
EPS	electric power steering

ESD	electrostatic discharge
ESP	electronic stability program
FEM	finite element method
FIR	far infrared
FMCW	frequency modulated continuous wave
FSD	full-scale deflection
GDI	gasoline direct-injection
GMR	giant magnetoresistance
GPS	global positioning system
HUD	head-up display
IC	integrated circuit
L	litres
LDW	lane-departure warning
LIN	local interconnect network
LPCVD	low-pressure chemical vapor deposition
LRR	long-range radar
MEMS	microelectrical mechanical systems
µC	microcontroller
MI	magnetoimpedance
MOS	metal-oxide semiconductor
MPU	magnetic pick-up coil
MR	magnetoresistive effect
MRE	ferromagnetoresistive element
MST	micro system technology
NIR	near infrared
OBD	on-board diagnosis
PAS	peripheral acceleration sensor connection
PD	photodiode
PID	proportional integral differential
PLCC	plastic leadless chip carrier
ppm	parts per million
PROM	programmable read-only memory
RIE	reactive ion etching
RME	rapeseed oil methyl ester
rms	root mean square
ROSE	roll-over sensing
SAS	steering-angle sensor
SbW	steer-by-wire
SMD	surface mounted device
SNR	signal-to-noise ratio
SOI	silicon on insulator
SPI	serial peripheral interface
SRR	short-range radar
TCM	top (of steering) column module
TCO	temperature coefficient of offset

TCS	temperature coefficient of sensitivity
TFA	thin film on ASIC
TMR	tunnel magnetoresistance
TWC	three-way catalyst
VDC	vehicle dynamics control
WSS	wheel-speed sensors

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1 Overview

Jiri Marek and Hans-Peter Trah

According to market studies, the automotive market is the largest segment for sensors. At the same time, sensors are playing an important role in the performance of modern electronic systems in the automobile. In this book we would like to give you an overview of this field.

First (Chapter 1) we explain the automotive sensor market: the market size, important technical issues, business models, and major players are discussed. Current trends and the outlook for new sensors and market opportunities are reviewed.

The production of automotive sensors in high quantities at very low failure rates requires elaborate design methods and simulation tools, as well as improvements in production processes. The second part (Chapters 2–6) focuses on these design and manufacturing issues.

In the third part of the book (Chapter 7) we present the different sensor types and show the various fields of application, ranging from engine management to safety systems and all the way to comfort systems.

The purpose of the book is to give you an overview of the various sensors used in the car today, as well as of the technologies required to manufacture these components. We hope to give interesting insights into this exciting field.

1.1 Introduction

The use of electronic control systems in automobiles has grown rapidly in recent decades. Fifty years ago, most systems were based on (electro-)mechanical principles; today almost all systems are electronic. Without these systems, today's cars simply would not be operational.

The first electronic systems to enter the car were for engine management. In the 1960s electronic ignition systems became widespread, followed soon after by electronic fuel injection. To meet emission regulations, electronic engine management was implemented in the 1970s. Due to these systems' complexity, analog control was replaced by digital electronics soon after. On-board diagnostics are now required to assure the functionality of these complex systems over a car's lifetime. Today's developments focus on the creation of ULEV (ultra low-emission vehicles).

After power train control, the area of safety received a strong market push. In the 1980s airbag passenger-protection systems achieved high market penetration in response to legislation in the USA; Japan and Europe followed soon after. In European cars, the use of both side and front airbags has led to further improvements in passenger protection. Vehicle stability was first improved with ABS (antilock braking system) systems in the 1980s. ABS brakes dramatically improve vehicle performance on slippery or icy roads. In 1995, the electronic stability program (ESP) began to be produced in volume; by comparing the steering wheel's angle with the vehicle rotation rate, vehicle stability is improved due to individual braking of the four wheels. Driver-assistance systems using ultrasound, RADAR, LIDAR, video the will further improve passive and active safety in the future.

The third major area for automotive sensors is in comfort systems. Besides entertainment (radios, CD-players, cassette-players), climate-control systems, adaptive cruise control, electronic positioning of mirrors, seats, etc., as well as navigation systems, are gaining in popularity. Figure 1.1 shows the development of automotive electronics from an historical perspective.

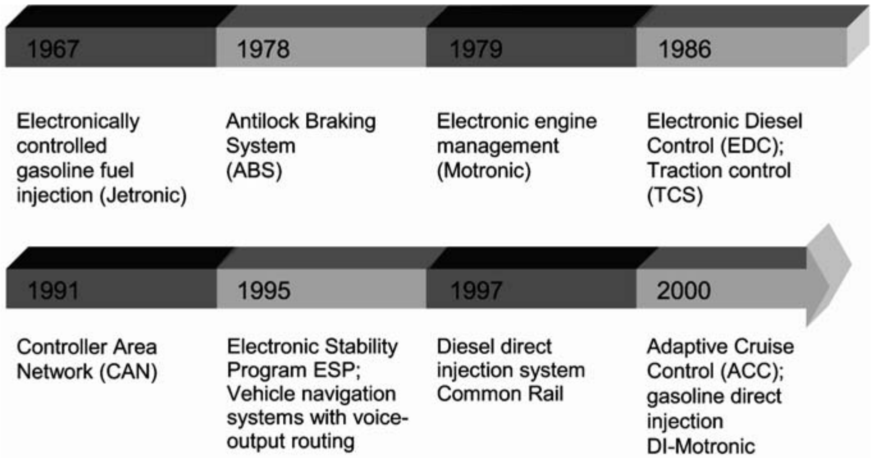

Fig. 1.1 Milestones in automotive electronic control systems

Electronic monitoring and control systems follow the same basic concept (Figure 1.2): environmental and engine parameters such as

- temperature of air intake
- pressure at air intake
- pressure of brake fluid
- air mass intake at the manifold
- fuel tank pressure
- chemical composition of the exhaust
- wheel speed

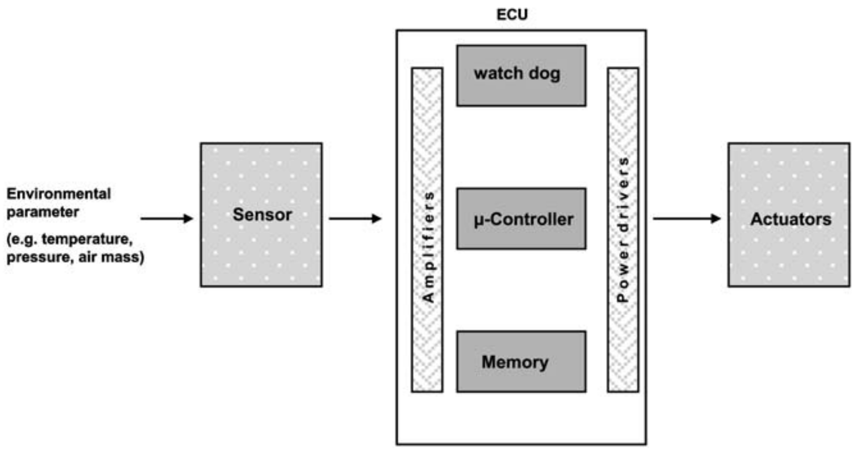

Fig. 1.2 Schematic principle of electronic control systems

are needed as input values for the control system. The appropriate sensor converts the mechanical or chemical parameter to an electrical signal. The electronic control unit (ECU) takes this value and performs the appropriate calculations using the software and algorithm embedded within the microcontroller. The output of the ECU then drives the actuators of the system, for example:

- injector valves for fuel injection
- spark ignition
- valves of the braking system
- motors for climate control

Automotive sensors need to work in a very demanding environment. Depending on the application, the sensor has to function in a temperature range of –40 °C to 85 °C (passenger compartment) or 125 °C (engine compartment). Exhaust sensors must withstand temperatures up to 800 °C. The vibration levels affecting sensors mounted on the engine can reach 100 time the gravitational force. Sensors also have to withstand exposure to gasoline, salt, detergents, and other chemicals. All these requirements have to be met at a very low price, as well as with a reliability of a few ppm!

The development of sensors for automobiles has generally followed progress in electronics. The first sensors used electromechanical working principles. In the past two decades, semiconductor-based technologies, like micro-machining, thin film technology, and hall/AMR (anisotropic magnetic resistance), took over. However, the second important type of sensors – chemical transducers – are still dominated by ceramic technologies, due to the high temperature requirements.

Major achievements in the development of automotive sensors are following the system roadmap. Often, however, innovations in sensor technology have been the enabling technology for making an automotive system economically feasible, and on several occasions a breakthrough on the sensor side decreased system costs significantly, leading to a high market penetration. Therefore, the question of whether sensor technology has pulled or pushed improvements in automotive sys-

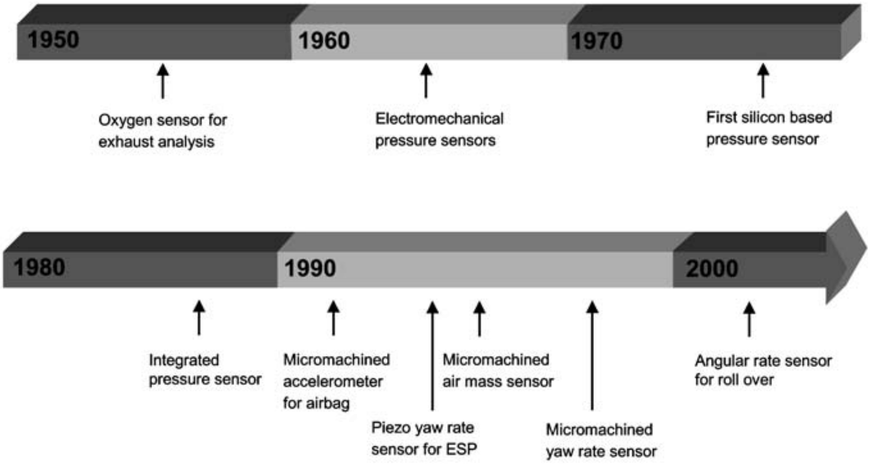

Fig. 1.3 Important milestones in automotive sensor development

tems has to be discussed case by case. Figure 1.3 shows the history of important developments in the field of sensors.

The first market pull came in the 1960s, when the demand for emission control necessitated sensors for measuring engine load. This measurement task was performed first with vortex air-flow meters and then with hot wire air-mass sensors. Micromachining technology was applied in this field fairly late; in 1995 a micromachined air-mass sensor began being produced in volume. The other sensing alternative, measuring the pressure at the manifold air intake, was also implemented. These pressure sensors were first based on an electromechanical principle and were later realized using silicon micromachining. The next step was the integration of the sensing element and the associated evaluation and trimming circuit into one device.

Airbag systems, first developed in the 1980s, have a critical need for accurate measurement of acceleration during a collision. In 1984 the first electromechanical accelerometer started in volume production; it used a spring-mass system and piezoresistive signal transformation. About five years later, the piezoelectric principle was applied using PZT (Pb-Zr-Ti) ceramics. In the beginning of the 1990s, the first micromachined accelerometer came to market.

The next safety system having very demanding sensor requirements was the electronic stability program. In 1995, development of the electromechanical yaw-rate sensor using piezoelectric excitation and pickup made the ESP possible. Only three years later, a micromachined yaw-rate sensor came to market; it both reduced manufacturing costs and enabled high market penetration of ESP. In 2001, the angular rate sensor started volume production, enabling passenger protection in rollover accidents.

The above sensors enabled the automotive industry to implement the very demanding systems of today's vehicles. Many more innovative automotive systems are being developed, and sensors will contribute significantly to the development and performance of these systems in the future.

2
Automotive Sensor Market

Karl-Franz Reinhart and Matthias Illing

2.1
Introduction

According to the association of the German automotive industry (VDA), 55.6 million cars and trucks were manufactured worldwide in 2001 [1]. This figure will not change significantly in the coming years. The automotive market is rather mature – if not saturated – in most countries; average growth rates on the order of just 2% per year can be expected.

However, the picture is different with automotive components. Since the late 1970s, electronic systems have been increasingly used in the automobile. The relative value of electronic components in cars has increased from near zero in the 1970s to almost 20% in a 2000-model-year midclass car and even higher in luxury cars. In addition, electronics are responsible for the majority of innovations and thus contribute strongly to differentiating a car brand from its competitors.

Essentially all electronics systems in use – be it for engine management, in safety systems, or as convenience features – need one or more sensors as input to their signal processing. An overview by Fleming [2] counted 107 different sensor applications in the car; a luxury car typically contains 100 or more sensors. Therefore the automotive sensor market has grown at least as well as the electronics market over the past two decades and will continue to do so for the foreseeable future.

This article gives an overview of the automotive sensor market. It starts with a general overview of market size and growth and puts it into perspective with other relevant markets, such as the general sensor market and the electronics market. The major distinctive features of the automotive market are explained. Another section details some of the major trends in technologies and products and within geographical regions. Finally, various market segments are highlighted in more detail. The conclusion includes an outlook on possible future developments.

2.2
Automotive Sensor Market Overview

2.2.1
Market Size

Sensors are used in a multitude of markets and applications and perform an innumerable variety of monitoring and control functions. To put the automotive sensor market into perspective, we briefly mention other sensor markets here. According to a study from Intechno Consulting [3], sensor markets can be categorized as follows:

- machinery manufacturers and suppliers
- processing industries
- aircraft and ship building
- construction sector
- consumer and other electronics
- automotive
- others

According to the same study, in 2003 the overall sensor market will be $42.2 billion, and the automotive sensor market will be about $10.5 billion, or 25% of the overall sensor market. This is by far the largest of the market segments mentioned above. Taking into account the tendency of automotive sensors to be lower in cost than sensors in other segments (with the possible exception of the consumer electronics market), the large share of the automotive sensor market is even more pronounced if one looks at production volumes.

The relative importance of the automotive sensor market will continue to grow in the future. The average annual growth rate (CAGR) of the total sensor market from now until 2010 is estimated as 4–5%, and expectations for the automotive sensor market range from 5.1% [4] to 7.5% [3].

It is also interesting to compare the automotive sensor market with the automotive electronics market, since they share the same driving forces and thus have similar dynamics. In comparing market figures, we should be aware that sensors do contain a significant and increasing amount of electronics, so some double counting may occur in the literature.

According to a report of the German association of electrical engineers ZVEI, the automotive electronics market had a volume of $14.9 billion in 2000 and should grow to $23.9 billion in 2005. This is equivalent to a growth rate of 10% per year [5].

2.2.2
Technical Issues

As indicated before, about 55.6 million cars and light trucks are manufactured each year. In consequence, each broadly distributed sensor type has a market of