Automotive sensors

The term sensor has become common, as in the past 20 to 40 years measuring gages have also come into use in consumer applications (e.g. motor vehicle and domestic appliance technology). Sensors – another term for measuring detectors or measuring sensors – convert a physical or chemical (generally non-electrical) variable Φ into an electrical variable E; this process often also takes place over further, non-electrical intermediate stages.

Table 1 summarizes and compares the various fields of application for sensors. Figure 1 provides an overview of the abundance of electronic vehicle systems already on the market. Undoubtedly, this number will increase immensely in the years to come.

Basics and overview

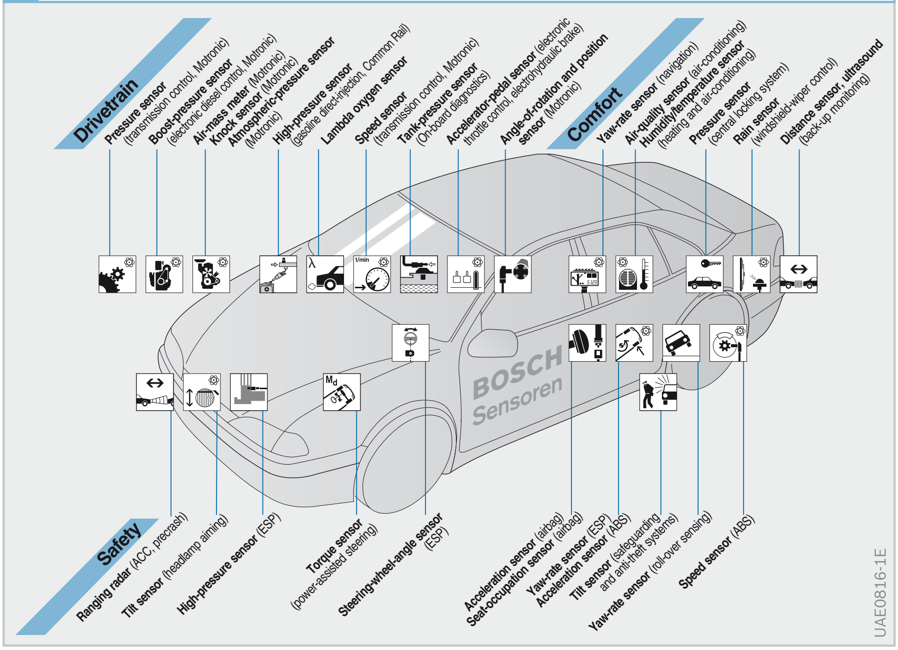
Sensor, term/definition

The electrical sensor outputs are not only provided in the form of current and voltage, but are also available as current or voltage amplitudes, frequency, phases, pulse widths, and cycles or periods of an electrical oscillation, or as the electrical parameters, resistance, capacitance, and inductance. A sensor can be defined using the following equation:

(1) $E = f(\Phi, Y_1, Y_2 \ldots)$
Sensor output signal
(2) $\Phi = g(E, Y_1, Y_2 \ldots)$
Required measured variable

If the functions f or g are known, then they represent a sensor model with the help of which the measured variable sought may be mathematically calculated from output

1 Automotive systems and their sensors



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1 Areas in which sensors are used

Typical features	**Primary standards**	**Precision measurement**	**Industrial measurement**	**Consumer technology**
Accuracy	10^{-11} to 10^{-7}	2 to $5 \cdot 10^{-4}$	2 to $5 \cdot 10^{-3}$	2 to $5 \cdot 10^{-2}$
Costs	€ 100 k to € 1 m	€ thousands	€ hundreds	€ 1 to 10
Units/year	single figures	approximately 10	100 to 1 k	10 k to 10 m
Use	– Research – Testing of secondary normals	– Calibration	– Process instrumentation – In-process measurement	– Auto electronics – Building services

Table 1

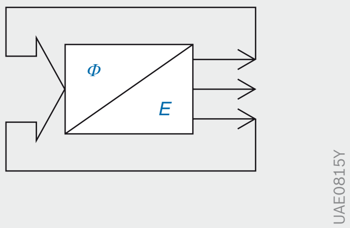
signal E and the influencing variables Y_i practically without error (intelligent or smart sensors).

Adjustment

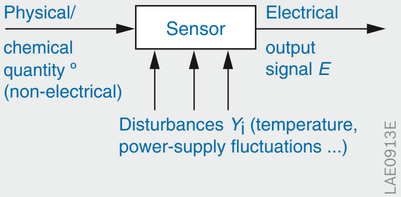
In the real world, the sensor model always includes some free parameters, with which the model can be adapted to the actual properties of the individual sensor type in a kind of calibration process (Fig. 4a).

These model parameters are generally stored in a programmable, nonvolatile memory component (PROM) in the digital processes for conditioning sensor signals, which have come to dominate. By contrast with the conventional analog compensation of influencing variables, it is not only roughly linearly acting influences that may be corrected, but also strongly nonlinear processes that can be corrected successfully. Another significant advantage of this type of calibration, which takes place over a purely electrical connection, is that each sensor may easily be maintained under operating conditions during the calibration phase.

2 Sensor symbol



3 Basic sensor function



▶ Concept of the smart sensor

In a somewhat more general form, intelligent sensors (smart sensors) may be defined as follows:
Intelligent sensors, sometimes also known as integrated sensors or sensors with specific local electronics, allow the (static or dynamic) accuracy inherent in a sensor to be exploited by means of (generally digital) microelectronics to a far greater degree than conventional sensors. The sensor information, in particular the complex information from multisensor structures, can be compressed here by local further processing, that is to say, it is brought to a higher level (than the sensor alone is capable of providing), without a multiplicity of external connections being required for this.

There is no clear determination as to whether sensors can already incorporate a part of the signal processing or not; it is, however, recommended, for example, that no distinction be made between elementary sensor, sensor cell, or the like and an integrated sensor.

Calibration process

A smart sensor is generally programmed or calibrated, in a procedure corresponding to the calibration of conventional analog sensors, in three steps with the help of an external computer (host) (Fig. 4):

Recording the actual value

The host computer systematically varies both the measured variable x_e and the influencing variable(s) y, thus setting a specific number of relevant and representative operating points. The smart sensor here passes the, still uncorrected, raw signals x_a^* to it. The host, however, is simultaneously also receiving the "true" values x_e and y from substantially more accurate reference sensors. The host computes the correction values necessary by comparing these two values, and interpolates these corrections over the full measuring range.

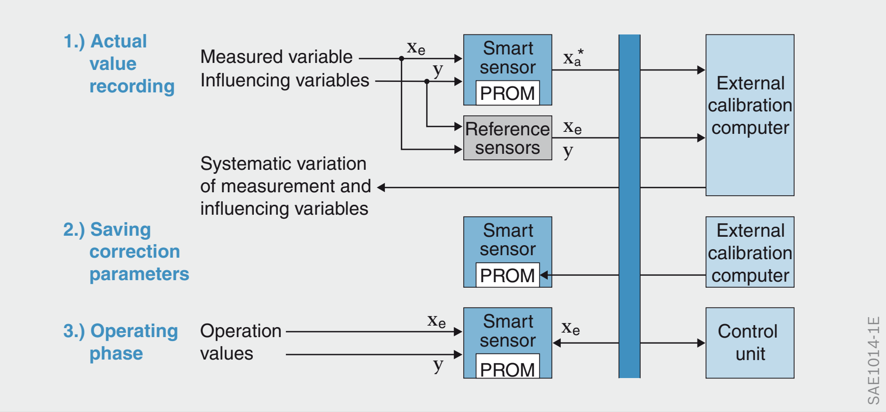
Saving the correction parameters

The host computer calculates the model parameters for the specific sensor from the data previously obtained, e.g. for a linear characteristic curve course and saves these to the smart sensor's PROM. In a check process, these parameters may also first be emulated in the host computer's RAM before they are finally burnt to the nonvolatile memory of the smart sensor. If characteristic curves are approximated with higher order polynomials, program maps (look-up tables) may also be stored in the smart sensor to avoid protracted computing processes. The solution of saving a coarse-grid program map in conjunction with a simple linear interpolation between the data points (example shown in Fig. 5) has also proved very useful.

Operating phase

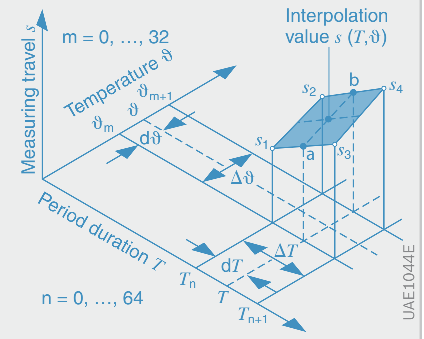
The smart sensor is now disconnected from the host computer and is in a position itself to calculate the measured variable x_e with very low error thanks to the stored model data. It is able to pass the value to a connected control unit in digital, bit-serial or even analog form (e.g. pulse-width modulated), for instance. The measured variable can also be distributed digitally to further control units via a bus interface.

4 Trimming/calibration of a smart sensor



This process can, unlike conventional laser calibration, in principle also be repeated if an erasable PROM is used. This is a particular advantage in the development phase of sensors.

5 Interpolation of measured values using a data point program map



Example: two-dimensional data point-program map s (T_n, ϑ_m) of a smart sensor for the measurement of a travel s:

For a highly precise evaluation of the sensor, which operates using variable inductance, its natural characteristic curve and its temperature sensitivity are each approximated using 5th order polynomials. As a frequency-determining element of a very simple oscillator circuit, it outputs the period duration T as an uncorrected output signal. As a sensor model for the measuring travel s, an outline program map embracing only 32 x 64 = 2,048 example-specific values $s_{n,m}$ is stored (in the PROM) along with a simple interpolation algorithm (in the ROM), instead of a total of 36 polynomial coefficents and a protracted polynomial evaluation. Should a signal T occur between these data points T_n and T_{n+1} in conjunction with a temperature ϑ between data points ϑ_m and ϑ_{m+1}, the sensor interpolates in two dimensions in accordance with the mapping between the benchmark figures stored "error-free" s_1,...s_4 and thus the measured value $s(T, \vartheta)$ sought is determined as the result of interpolation.

Automotive applications

With increasing demands on all functions in the vehicle, the control and regulation functions that were previously implemented by mechanical means have, in the last 40 years, successively been replaced by electronic devices (ECU, Electronic Control Unit). This has necessarily caused high demand for sensors and actuators with which these electronic control units can, on the one hand determine the relevant states of the vehicle, and on the other hand, actually influence these states. Over this period, the vehicle industry has become one of the, previously unprecedented, drivers of the development of sensors that could be manufactured in large numbers.

Whereas at the outset they still were of electromechanical or macromechanical form of some sort, the trend beginning in the 80s was for miniaturization, with

6 Milestones in the development of sensors for automotive applications

1950	Lambda oxygen sensor
1960	Electromechanical pressure sensor Piezoelectric knock sensor
1970	First integrated Hall sensor Strain-gage acceleration sensor for airbag First pressure sensor on silicone base
1980	Hot-wire air mass meter Thick-film air mass meter Integrated pressure sensor
1990	Micromechanical acceleration sensor for airbag Piezoelectric yaw-rate sensor for ESP Micromechanical air-mass meter Micromechanical yaw-rate sensor
2000	Yaw-rate sensor for roll-over sensing

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semiconductor methods (batch processing) for the manufacture of high use sensors. For a while, sensors originating in hybrid technology using thick-film techniques also played a not insubstantial role. These are still used in isolated applications today, e.g. in the wafer-shaped Lambda oxygen sensors and high temperature sensors for the exhaust line.

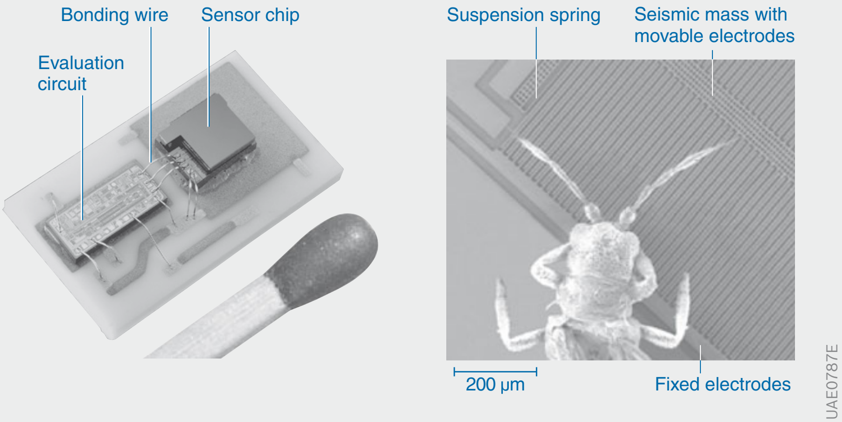
Where temperature and magnetic field sensors could initially still be designed in circuit-like structures and be produced in batches, this trend increased as it became possible also to micromachine silicon in many various ways in two or three dimensions, and also to connect them, even in multiple layers, very soundly by very efficient methods.

Where the technologies of the electronic semiconductor circuits were practically exclusively based on silicon as the base material, quite different materials and technologies played a not insignificant role in sensors. Thus, for instance, quartz can also be micromachined using anisotropic etching techniques, and unlike silicon also has very advantageous piezoelectric properties. III-V semiconductors such as gallium arsenide (GaAs) have a substantially greater operating temperature range than silicon, which can be very advantageous, particularly at some points in the vehicle. Thin metallic layers are very well suited to the manufacture of precise strain-gage resistors, accurate temperature sensors and magnetic field-dependent resistors.

With silicon it is possible also to integrate the electronics monolithically with the sensor. This technique has lost its importance – with a few exceptions (e.g. Hall-effect ICs) – because of the generally very different number and type of process steps and also because of the inflexibility associated with this. Hybrid integration technologies in the tightest of spaces as a rule lead to substantially more cost effective, but functionally equivalent solutions (Fig. 7).

While the development of sensors was initially concentrated almost exclusively on systems inside the detail in the drivetrain, the suspension and the body and driving safety, the direction of sensing of newer developments is increasingly named to the outside and to the area close to and further from the vehicle:

7 Hybrid integration of sensor and electronics: surface micromechanical acceleration sensor on a microhybrid circuit



- Ultrasound sensors detect obstacles on parking and will even allow automatic parking in the foreseeable future, perhaps in combination with other sensors.
- Near-range radar scans the area around the vehicle to detect objects that probably could cause a collision, to gain time and to prime safety systems before a collision occurs (precrash sensors).
- Imaging sensors can not only detect traffic signs and send them to the driver's display, but also detect the edge of the carriageway, warn the driver of any hazardous deviation and, where required, in the long term also permit automatic driving. In combination with infrared beams and a screen in the driver's field of vision, IR-sensitive imaging sensors could permit long distance observation of the carriageway, even at night (night vision) or in foggy conditions.
- Long-range radar sensors observe the carriageway for 150 m in front of the vehicle, even in poor visibility, to adapt the driving speed to vehicles ahead and, in the longer term, also to support automatic driving.

As part of the vehicle's peripheral equipment, the sensors and actuators form the vehicle's interface to its complex drive, braking, chassis, and bodywork functions, as well as to the vehicle guidance and navigation functions and the (usually digital) ECUs which operate as the processing units (Fig. 8). An adapter circuit is generally used to convert the sensor's signals into the standardized form (measuring chain, measured-data registration system) required by the control unit.

8 Sensors in the multilayered process that is the motor vehicle

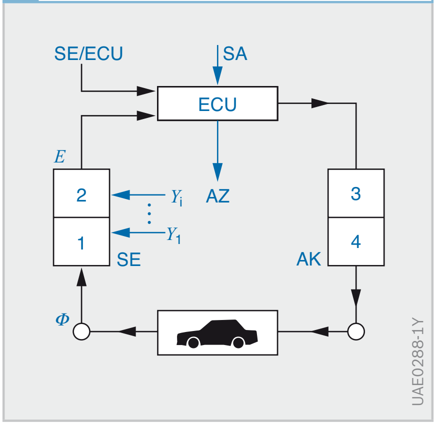


Fig. 8

1	Measuring sensors
2	Adapter circuit
3	Driver circuit
4	Actuators
AK	Actuator
AZ	Display
SA	Operating switch
SE	Sensors
ECU	Control unit
Φ	Physical variable
E	Electrical variable
Y_i	Disturbances

These customer-specific adapter circuits are tailor-made for specific sensors and are available in integrated design and in a wide variety of versions. They represent a quite substantial and very valuable addition to the sensors described here, without which their use would not be possible, and the measuring accuracy of which is, properly said, only defined in conjunction with these.

The vehicle can be regarded as a highly complex process, or control loop, which can be influenced by the sensor information from other processing units (control units), as well as from the driver using his/her controls. Display units keep the driver informed about the status and the process as a whole.

Details of the sensor market

The proportion of value added in the vehicle by the electrical and electronics systems is currently around 26 %. Nowadays, practically every second sensor is fitted into a vehicle, with annual growth rates that are, in some cases, still in double digits. Since the start of the 90s, micromechanical and microsystem-technical sensors have taken a rapidly increasing share, which amounted to about a third in 2005.

Unlike in the general sensor market, Europe has a current market share of 41 % of the vehicle sensors sector and Bosch is the world market leader; this has clearly surpassed America with a share of just 34 %. The total market for sensors for vehicle applications is expected to grow from US$ 8.88 billion in 2005 to around US$ 11.35 billion in 2010, that is by a total of 28 % (Fig. 9).

There are typically three groups of companies offering sensors for use in the vehicle:

- The semiconductor industry: sensors from semiconductor manufacturing originated here with the application of a few process steps. They serve the entire sensor market including the automotive industry and have an efficiently-operating sales and distribution system. Micromechanical processes for the production of sensors are continually being further developed in tandem with the semiconductor processes. These companies do not, however, have any specific know-how in the area of specification, testing and packaging appropriately for the vehicle.
- Special, generally medium-sized manufacturers of sensors, who do not produce semiconductor circuits, but have generally chosen just a few sensor types as their product to supply the sensor market overall or just preferred branches such as the vehicle market.
- Large vehicle suppliers and system manufacturers (e.g. Bosch) or large subsidiaries of vehicle manufacturer who have specialized in the needs and support of their mother groups. Here too, since the introduction of electronics in the vehicle, experience has been gained with the production of semiconductor and hybrid circuits in close collaboration with semiconductor manufacturers (process development, licensing). Thanks to system knowledge, it has been possible to build up comprehensive know-how in the field of specification, testing and packaging techniques appropriate for the vehicle.

9 Sensor market for automotive applications

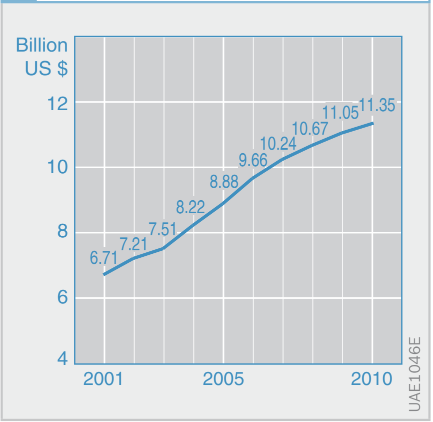


Fig. 9
Source: Bosch

Features of vehicle sensors

While general sensors are being developed for as broad a user group as possible and in multilevel measuring ranges, often without the manufacturer being aware of the application, vehicle sensors are generally specified and optimized for a special application. They are a part of a system and are often not freely available in the trade. Their development generally takes longer than that of commercial sensors, not just because of the enhanced demands. It is more associated with the development of the system and generally lasts as long as this does, as the sensor specification can still change until system development is concluded.

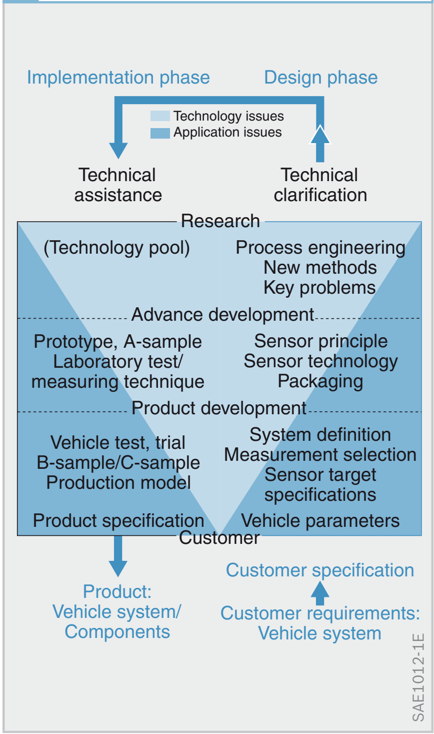
The high thrust for innovation in systems for the automobile sector very often compels the development of new sensor technologies or significant extensions of their specifications. Figure 10 shows the typical development phases that vehicle sensors pass through at the supplier's works.

The development process begins naturally with the system idea originating with the vehicle manufacturer or the supplier. The initial task is to make a selection of the measured variables required, whether or not this is feasible. At this stage, the sensors' function is simulated as part of the systems engineers' usual system simulation and a first specification is drawn up. If it is possible to use a sensor technology that has already been introduced, the wishes in respect of the sensors are passed directly to product development or the producing area. If no technology is immediately available, sensor and technology experts are gradually increasingly included in research and advanced development. Here, the first laboratory prototypes can be created using known technologies and often with the help of external partners. These prototypes can then be passed to product development for initial tests.

If no sensor principles are known for the requirements set, research will be started into new procedures and methods for the measurement of the variables required. This phase is one of fundamental research which ultimately also supplies new initial technology prototypes. This procedure can repeat itself recursively until a promising solution which can then be sent to product development is found. It is not unusual for this development loop to be repeated again in full or for a different measured variable to be selected.

Five distinct phases are generally identified in the development of a completely new sensor, just as with other electronic products (Table 2). While prototypes and A-samples mostly still come from advance development or research, B- and C-samples

10 Genesis of a functional Bosch sensor



are products of product development. If recursions are necessary in difficult developments, there can easily also be a number of B- or C-sample phases (B1, B2, C1, C2).

Table 2

2 Sensor prototyping phases leading to series production

Prototype phase	Function/ specifications	Manufacture
Prototype	restricted	Prototype construction without tools
A	restricted	Prototype construction without tools
B (possibly B1, B2)	full	Prototype construction without tools (construction identical to C)
C (possibly C1, C2)	full	Prototype construction with series production tools
D	full	Pilot series, partially manual
Series production	full	Automated

11 Characteristic curve types

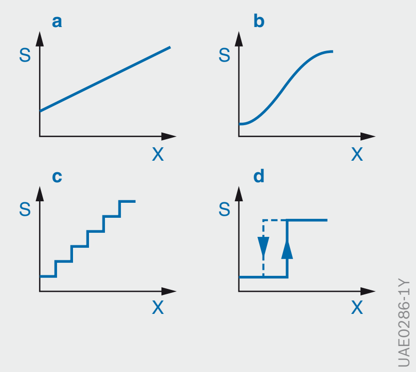


Fig. 11

S Output signal
X Measured variable

a Continuous, linear
b Continuous, nonlinear
c Discontinuous, multi-step
d Discontinuous, two-step (with hysteresis)

Sensor classification

Sensors can be classified and grouped according to very different points of view. They can be classified with regard to their use in the vehicle as follows:

Assignment and application

- Functional sensors (pressure, air-mass flow) mainly used for open and closed-loop control assignments
- Sensors for safety (passenger protection: airbag, ESP) and security (theft-deterrence feature)
- Sensors for vehicle monitoring (on-board diagnosis (OBD), fuel-consumption and wear parameters) and for driver/passenger information

Characteristic curve type

- Continuous linear curves (Fig. 11a) are used mainly for control assignments covering a wide measuring range. Linear curves are also distinguished by uncomplicated testing and calibration.
- Continuous nonlinear curves (Fig. 11b) are often used for the closed-loop control of a measured variable across a very restricted measuring range (e.g. exhaust-gas control to $\lambda = 1$, vehicle spring-deflection level). When, for instance, a constant permissible deviation relative to the measured value is demanded throughout the complete measuring range (e.g. HFM air-mass meter), curves which feature both pronounced non-linearity and a special shape (e.g. logarithmic) are at an advantage.
- Such two-step curves (possibly even featuring hysteresis, Fig. 11d) are used for limit-value monitoring in such cases where remedial measures are easy to apply when the limits are reached. If remedial measures are more difficult, then multi-step curves (Fig. 11c) can be used for an earlier warning.

Type of output signal

Sensors may also be distinguished by the type of output signals (Fig. 13):

Analog signals

- Current/voltage, or a corresponding amplitude
- Frequency/period duration
- Pulse duration/pulse duty factor

Discrete output signal

- Two-step (binary coded).
- Multi-step, with irregular steps (analog coded).
- Multi-step equidistant (analog or digital coded).
- A further distinction must be made, as is represented in Figure 12 in a systematic overview of the determined, i.e. nonrandom (stochastic) signal – as to whether the signal is permanently available at the sensor output (continuously) or only at discrete intervals (discontinuously).

For instance, the signal is bound to be discontinuous if it is digital and issued in bit-serial form.

13 Signal shapes

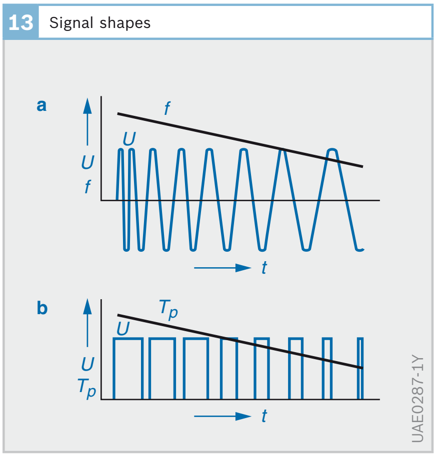
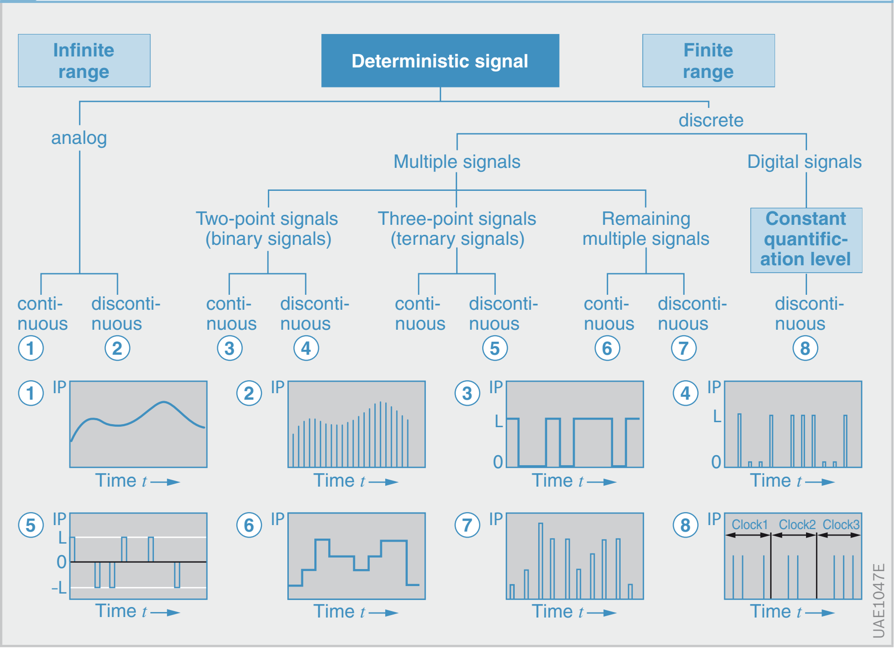


Fig. 13

a Output signal U, information parameter: frequency f

b Output signal U, information parameter: pulse duration T_P

12 Classification of the determined signals according to the information parameter (IP) with examples



Error types and tolerance requirements

The deviation of the actual characteristic curve of a sensor from its reference characteristic curve is designated its error e. It is best stated in relation to the input range y (measured variable) and not to the output range x (output signal):

(3) $e = y_{\text{indicated}} - y_{\text{true}}$

$y_{\text{indicated}}$ = indicated value for the measured variable

y_{true} = ideal value, setpoint value for the measured variable (is determined with a measuring sensor that is more accurate than the sensor being examined by at least 1 class)

The amount of the deviation represents, as shown in Figure 14, the absolute error e_{abs} (unit as measured variable). Related to the true measured value y_{true}, this becomes the relative error (% of reading), related to the measuring-range final value it becomes the percentage error of the range.

14 Characteristic curves and error graph for a sensor

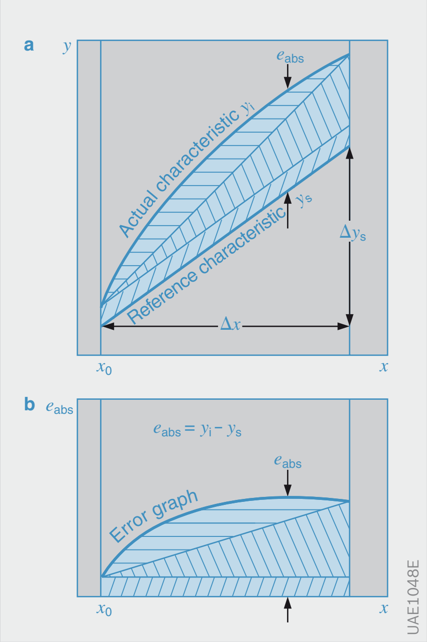


Fig. 14

a	Actual and reference characteristic
b	Error graph
y	Measured variable
x	Output signal
Δx	Measuring range
e	Error (deviation)

Assuming a generally desirable linear characteristic, the absolute deviation e_{abs} can be classified into three categories (Fig. 15):

- Zero offset (offset error) e_{zero}
- Gradient deviation (gain error) e_{gain}
- Linearity deviation e_{lin}

The causes of these errors are predominantly found in

- The production scatter of the characteristic curve

15 Subdivision of the total error

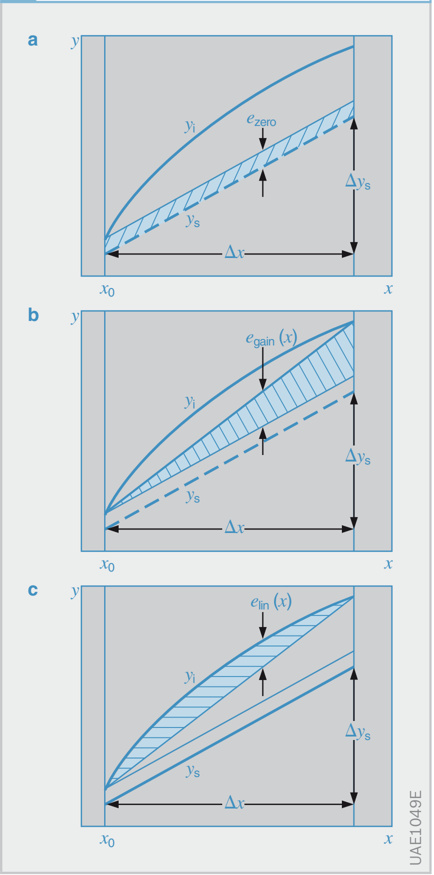


Fig. 15

a	Zero error
b	Gradient error
c	Linearity error
y	Measured variable
x	Output signal
Δx	Measuring range
e	Error

- The temperature sensitivity of the characteristic curve and
- The production scatter of the temperature sensitivity

The deviations referred to are exclusively systematic or terministic errors which, by contrast with random (stochastic) errors, are well defined, foreseeable and, as a matter of principle, correctable, and are also for the most part more or less precisely corrected.

The non-correctable, stochastic errors include, for example,

- Drift (low and higher frequency background noise) and
- The effects of aging

In the specification of a sensor, the total error in the new state and after aging is prescribed in the product specifications by means of a tolerance graph (Fig. 16). Sometimes, however the permissible individual error shares such as the offset, lead and linear deviations are additionally specified.

Strict metrology teaching states that, in the case of systematic errors, the sum of the amounts of the individual errors must be assumed as the total error (these may add up in the worst case). In the case of stochastic errors, statistical addition, which calculates the total error as the root of the sum of squares of the individual errors, is permitted. As statistical addition leads to a smaller total error, it is, however, often also applied to the systematic errors in a less strict configuration:

(4) $e_{\text{total}} = \sum_{1}^{n} |e_i|$ Sum of n systematic errors

(5) $e_{\text{total}} = \sqrt{\sum_{1}^{n} e_i^2}$ Sum of n stochastic errors (statistical addition)

Reliability

Failure rate

The operational reliability of a sensor is a purely statistical quantity and, as with any component, is characterized by its failure rate λ, which is stated in 1/h, %/h or ppm/h. Here λ is determined with a large number of parts. If it is wished to determine approximately the failure rate with a number N (< 40) of sensors that is not too great, it is possible to observe the failure behavior of this random sample under operating conditions until, after a finite time, all the parts have failed. If this observation is begun at time t_0 and if the inventory of parts remaining at a later point t_i is identified as $B(t_i)$, then a good approximation for the failure rate λ is the failure quota q:

(6) $q(\Delta t_i, t_i) = \dfrac{B(t_i) - B(t_{i+1})}{\Delta t_i \cdot B(t_i)}$ Failure quota

where $\Delta t_i = t_{i+1} - t_i$

t_i are the times at which individual parts or several parts fail (Fig. 17). The ratio of the current inventory of parts to the initial inventory of parts is known as the relative inventory B_R:

16 Tolerance graph for a sensor

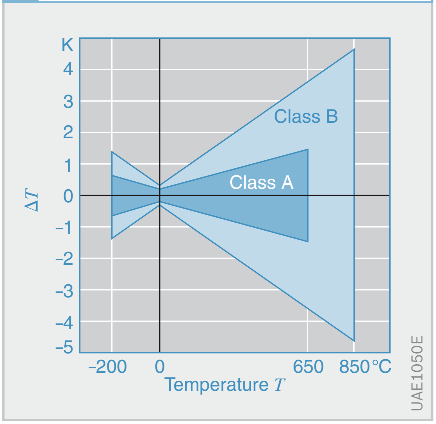


Fig. 16
Tolerance graph illustrated on the example of a resistance temperature sensor

$$(7)\quad B_R(t_i, t_0) = \frac{B(t_i)}{B(t_0)}$$

With a very large number of parts (N → ∞), the survival probability $R(t)$ at the, here now continuously variable, time t corresponds to this. The failure rate is calculated here for a large number (in practice N ≈ 2,000) of sensors as a percentage variation on the survival probability R per unit of time dt as:

$$(8)\quad \lambda(t) = -\frac{1}{R(t)} \cdot \frac{dR}{dt} \qquad \text{Failure rate}$$

Reliability is the inverse value of the failure rate:

$$(9)\quad z = \frac{1}{\lambda} \qquad \text{Reliability}$$

The definition of the failure rate λ demands a failure criterion:

- Complete failure
- Partial failure
- Sudden failure (sudden change in a feature)
- Drift failure (gradual change in a feature)

Furthermore, it is absolutely necessary to specify under what operating conditions the failure rate defined in this way is to be understood. Particularly in the case of electrical components such as sensors, for example, it is necessary to distinguish between true, active operating time (switched on state) and service life in the sense of pure storage time. Any statement of a failure rate without this additional information is worthless.

Failure rates are normally determined using time-acceleration methods. The acceleration factors are achieved here by exposing the sensors to enhanced operating conditions. A high degree of experience is required in order to apply time acceleration methods that truly reflect reality.

The concept of the mean service life T_M is also used to characterize the reliability of a sensor. A good approximation of this can be calculated from a random sample from the sum of the individual service lives T_i:

$$(10)\quad T_M \approx \frac{1}{N} \cdot \sum_{1}^{N} T_i \qquad \text{or}$$

$$(11)\quad T_M = \int_0^\infty R(t)\,dt \qquad \text{for a very large number of parts}$$

17 Inventory and relative inventory of a random sample

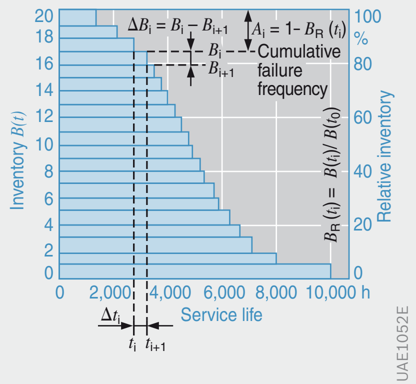
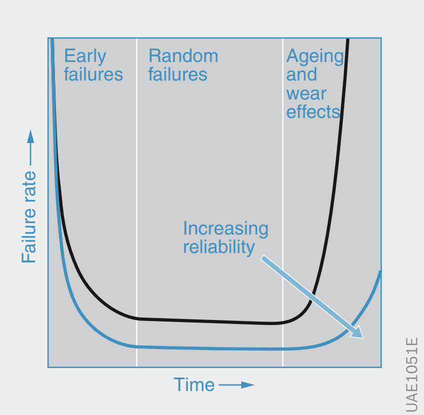


Fig. 17
Observation for a random sample of N = 20 sensors; mean service life T_M = 4,965 h.

18 Distribution of the failure rate λ(t) over time



The failure rate of a product against time shows a typical bathtub pattern (Fig. 18). At the start, the failure rate is somewhat high because of early failures, it then passes through a longer, relatively low, horizontal range, then to rise again drastically towards the end of the service life (aging and wear effects). In the case of sensors for which high operational reliability is demanded, an attempt is made to avoid the elevated failure rate at the start by sorting out the early failures by pre-aging, e.g. by conditioning at higher temperatures ("burn in"). Early failures are basically nothing other than manufacturing defects that have not been recognized.

Table 3 gives some examples of permissible failure rates λ applicable for the vehicle. The ppm values given relate to a period of 10 years, or alternatively to 150,000 km covered, if this is completed in a shorter time. Where the sensors are given a flat rate of <10 ppm, it means that in 10 years, only fewer than 10 of 1 million sensors may fail. This value is, however, substantially lower for sensors in passenger protection systems.

Measures for increasing reliability

The best method for ensuring high quality is to engineer and design in reliability. This means that as soon as the sensor is designed, correspondingly durable materials must be selected and solid protective measures against anticipated mechanical, chemical and electrical ambient influences must be provided (packaging, passivation). On the other hand, it is costly to create operational reliability by testing alone, i.e. to exclude early failures through premature aging.

It is sensible to provide monitoring and diagnostic capabilities for sensors in complex systems (e.g. signal range check, etc.), so that any failures occurring may be detected in good time. In an emergency, a sensor's function can here be temporarily replaced by other measured variables or sensible fixed values (limp-home mode, back up). A sensor-less, often purely mechanical, limp-home mode can be provided. For instance, should the accelerator-pedal sensor failure in a diesel vehicle, the vehicle could also be driven slowly back for repair under regulated idle speed alone (limp home).

Where reliability must be guaranteed with a probability bordering on certainty (e.g. for sensors in electronic braking and steering systems), redundancy, i.e. provision of multiple parts, is generally the means used. Dual redundancy of a sensor of the same type here only permits failure detection for the case of widely different indications, whereas triple redundancy with 2 from 3 analysis additionally still supplies a correct measured value. Here, however, care must be taken to provide not only redundancy of the sensors, but other essential parts such as the power supply, signal evaluation and transmission means must also be correspondingly redundant, as otherwise the probability of simultaneous failure increases. It is often also advisable to provide sensor redundancy in different technologies.

Table 3

3 Reliability requirements on vehicle systems

	Warranty target: 150,000 km/10 years	
→	ECU failure rate (field)	< 50 ppm
→	ECU failure rate (0 km)	< 15 ppm
→	**Failure rate of modules and sensors**	**< 10 ppm**
→	ASIC failure rate	< 3 ppm
→	IC failure rate	<< 1 ppm
→	Failure rate of discrete components	< 0.5 ppm
→	*For comparison* Mobile phone	~ 5,000 ppm

Main requirements, trends

The vehicle sensors customized for the requirements of special electronic systems in the vehicle, unlike the universal sensors conventionally found in the market, are subject to five strict requirements (Fig. 19) which must be fulfilled by development and to which the most important development trends also correspond.

Low manufacturing costs

Electronic systems in modern vehicles easily contain up to 150 sensors. Compared to other sectors of sensor application, this abundance forces a radical reduction in costs. The target costs – typically in the range of € 1 to 30 – are here often less than one-hundredth of those for conventional sensors of the same capacity. Naturally, particularly with the introduction of a new technique or technology, the costs are generally on a falling learning curve, starting from a higher level.

Development trends

Automated manufacturing processes (Fig. 20) are largely used, working to a high yield. This means that each process step is always executed for a large number of sensors simultaneously. For example, semiconductor sensors are manufactured using “batch processing” in which 100 to 1,000 sensors are manufactured simultaneously on a single silicon wafer. On the other hand, such manufacturing equipment is only an economic proposition when correspondingly large numbers of sensors are produced. These quantities sometimes exceed an automotive-industry supplier’s own in-house requirements, and can typically often be between 1 and 10 million per year. Here, the high numbers of sensors needed by the automotive industry has played an unprecedented and revolutionary role, and set completely new standards.

High reliability

In accordance with their assignments, vehicle sensors are subdivided into the following reliability classes, given in descending order of severity:

- Steering, brake, passenger protection
- Engine/drivetrain, chassis/tires
- Comfort and convenience, diagnosis, information, and theft deterrence

19 Principal requirements on vehicle sensors

Vehicle sensor		Requirement
Rational mass production	⇦	Low costs
Robust, proven technology	⇦	High reliability
Appropriate packaging technology	⇦	Extremely severe operating conditions
Appropriate miniaturization technologies	⇦	Low space requirement
On-site error compensation	⇦	High-level accuracy

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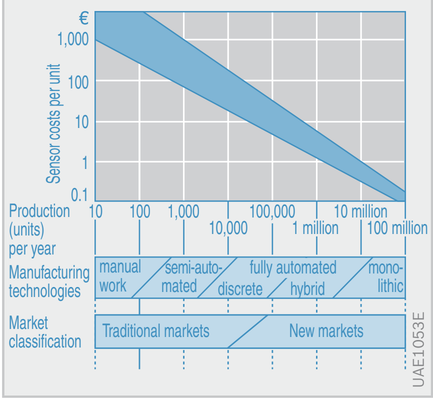
20 Relationship of costs, markets, technologies



The requirements on the highest class here easily match the high reliability values familiar from aerospace applications. To some extent, they demand similar measures, such as the use of the best materials, redundant componentry, self-monitoring, (short-term) backup power supply, multiple programming of critical decision-making algorithms.

Development trends

Appropriate design measures guarantee built-in reliability. For instance, this necessitates the use of reliable, top-quality components and materials, coupled with rugged and well-proven techniques and engineering. And furthermore, an effort is made to achieve a consistent integration of the systems to avoid connection points which may be broken and are at risk of failure. This is possible, for instance, with radio-scanned sensors based on the antenna-coupled SAW (Surface Acoustic Wave) elements which do without wiring completely. If necessary, redundant sensor systems are fitted.

21 Technologies accompanying sensors

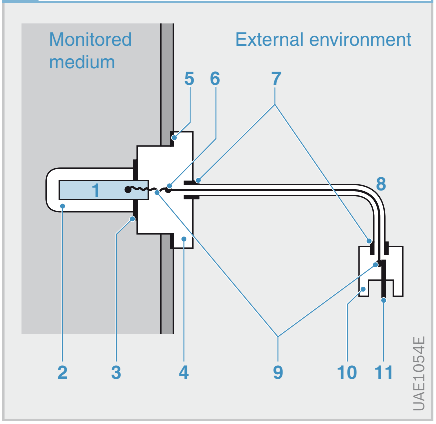


Fig. 21
1 Sensor
2 Protective sleeve (coating)
3 Seal
4 Mount
5 Seal, mounting
6 Data point
7 Seal, strain relief
8 Insulation (flexible)
9 Contacts
10 Plug housing
11 Plug contact

Severe operating conditions

Like practically no other breed, vehicle sensors are exposed to extreme stresses because of where they are fitted, and must withstand all kinds of aggression:

- Mechanical (vibration, shock)
- Climatic (temperature, moisture)
- Chemical (e.g. spray, salt mist, fuel, engine oil, electrolyte)
- Electromagnetic (incident radiation, line-conducted interference, excess voltages, polarity reversal)

It is this trend of using sensors immediately at the site where the measurement is taken in order to exploit the benefits associated with this which itself leads to the requirements being considerably cranked up.

Figure 21 illustrates this problem on a sensor which might be a temperature sensor, speed sensor, flow-rate sensor or concentration sensor, for instance. The sensor cannot in the slightest always be surrounded by a hermetic protective sleeve. Although this sleeve could offer rough protection for the measurement of temperature, flow rates and concentration, it must permit more or less direct contact between the sensor and the generally very aggressive monitored medium (an exception to this is the inertia sensor). Sometimes, thin, but very resistant, passivation layers are permissible on the sensor.

The form of the plug-in sensor demands a permanently tight seat of the mount in the associated wall (inner packaging, outer packaging). The sensor may be connected to the electronic control units via a fixed housing plug or also, as illustrated, via a plug flexibly fastened with a length of cable (e.g. ABS wheel-speed sensor). Here, too, there are three critical electrical connection points that absolutely must be protected against conductive fluids and corrosion: the inner connection on the sensor element, the connection of the cable tail and finally the connection of the partially shielded cable to the external plug connection. If the seal is inadequate, it is only a question of time until corrosive liquids penetrate from the external connector into the internal sensor terminal.

The plug-in connection itself must be sufficiently tight overall, that no shunts form at the sensor output. The cable itself must retain its flexibility and tightness after many years of operation under the most adverse conditions.

Separable plug-in connections in the vehicle unfortunately still represent one of the most frequent causes of failure. Wireless signal connections (e.g. infrared light or radio) could break down this problem in the longer view, especially if the sensors were even to have a wireless energy supply (autonomous sensors).

The costs of these indispensable technologies complementary to the sensors often exceed those of the actual sensor element many times over. They constitute the actual value of an vehicle sensor, not only in terms of cost, but also in terms of function.

Development trends

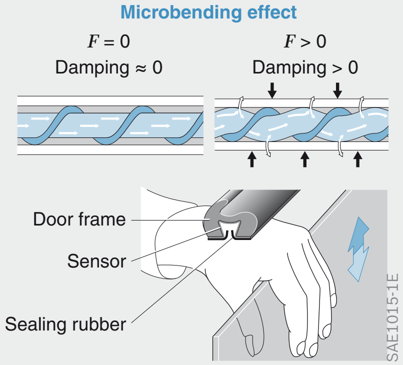
Protective measures against the stresses referred to demand a very high degree of specific know-how in the field of sensor packaging.

- Passivation and connecting techniques
- Sealing and joining techniques
- EMC protective measures
- Low-vibration installation
- Service life test and simulation methods
- The use of resistant materials, etc.

Furthermore, detailed knowledge of the loading to which the sensor will be subjected at the particular installation point is required. It is often forgotten that the quality of a sensor stands and falls with total competence with these protective measures.

Fiber-optic sensors in which the light guided in the optical fibers (glass, plastic) can be modified as a function of the measured variable are particularly immune to electromagnetic interference. This is true up to the point at which the optical signals are converted back into electrical signals. If these are to be used in the future, there will have to be some development work the provision of low-priced measuring elements and the accompanying technologies. There are, for example, some very interesting applications for this in the field of force measurement, e.g. in providing finger protection for electric power windows and sliding sunroofs (Fig. 22). Sensors of this type have also been tested very successfully as very early responding, distributed sensors in the door and frontal area of the vehicle for triggering passenger and pedestrian protective systems.

22 Microbending effect



Example of development: fiber-optic finger protection in power windows based on the microbending effect:
The light in an optical fiber is attenuated proportionally to the corrugated distortion on the application of a force F transverse to the fiber (large measuring effect), independently of where the force is applied or whether it is acting at a point or is distributed (distributed sensors).

Low-volume design

On the one side, the number of electronic systems in the vehicle continues to climb steadily. On the other, today's vehicles are becoming more and more compact. These facts, together with the need to retain the high level of passenger-compartment comfort forces development to concentrate on an extreme space-saving designs. Furthermore, the increasing demand for further improvements in fuel economy mean that minimization of the vehicle's weight is of prime importance.

Development trends

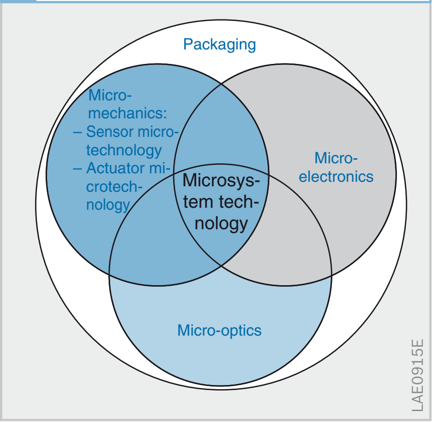
Widespread use is made of the familiar technologies applied in circuit engineering for the miniaturization of electronic components:

- Film and hybrid technologies (deformation-dependent resistors, thermistors, and magnetoresistors); nanotechology
- Semiconductor technology (Hall-effect and temperature sensors)
- Surface and bulk micromechanical techniques (silicon pressure, acceleration and yaw-rate sensors)
- Microsystem technology (combination of two and more microtechnologies such as microelectronics and micromechanics, Fig. 23)

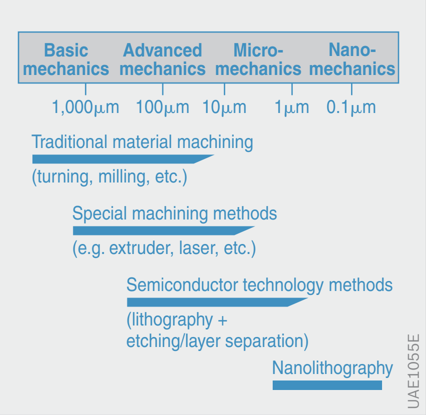
Micromechanical manufacturing refers on the one hand to dimensions in the µm-range and tolerances in the sub-µ-range which cannot be achieved with conventional machining methods. On the other hand, sensors which may have dimensions in the mm-range, but which are manufactured with micromechanical methods, are also considered micromechanical (Fig. 24). We will discuss only the most well-known and important method here, anisotropic etching of silicon. This is the most important method, because silicon is manufactured to high precision and in large numbers at low cost, and is the most thoroughly researched and best known material. In addition, it offers the capability of the monolithic integration of sensor and evaluation electronics. The etching speeds, which can be very different depending on the crystal axis (1:100), with which suitable etching fluids such as KOH attack are exploited in this method (Fig. 25); some crystal faces, for instance, remain practically untouched, while other faces are rapidly etched to some depth.

In conjunction with appropriate etching stop methods (doping, depletion layer) practically three-dimensional structures of the smallest dimensions may be produced to the highest precision in this way

23 Microsystem technology



24 Micromechanics and mechanical structures

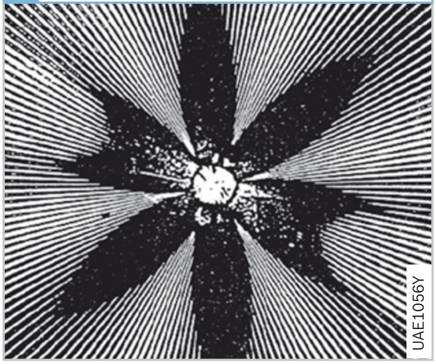


(Figs. 26, 27). The problem of simultaneously integrating the circuit can be considered largely resolved, even if currently the associated circuit for most sensors is still made separately for reasons of a better yield and higher flexibility.

By contrast with bulk micromechanics, anisotropic, often wafer-depth etching has no role to play in surface micromechanics (SMM). SMM sensor structures are mostly built up additively on the surface of a silicon substrate (Figs. 28 and 29). Even if the dimensions of bulk silicon sensors are still mostly in the mm-range, those of SMM structures are an order of magnitude smaller (typically 100 µm), as a rule.

Frequently, mechanically indispensable parts are used simultaneously for enclosing and even cooling (associated) sensors and electronics (e.g. microhybrid control unit as an add-on control unit to the VP44 diesel distributor-type injection pump). This fusion of mechanical and electronic components known as mechatronics is coming more and more to the forefront in the search for cost and space savings. In the foreseeable future, practically all systems will operate on this basis.

25 Test structure for the determination of the etching rate in Si monocrystal wafers



26 Anisotropic etching of (100) silicon

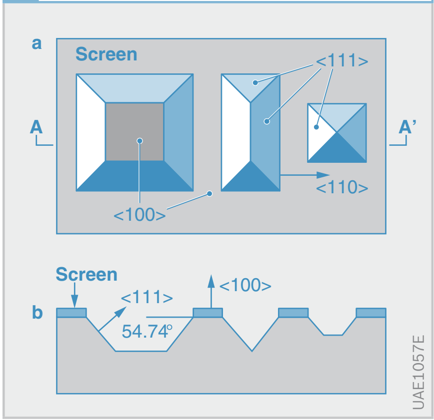


Fig. 26
a Top view
b Cross-section at AA'

27 First attempts at three-dimensional forming of silicon

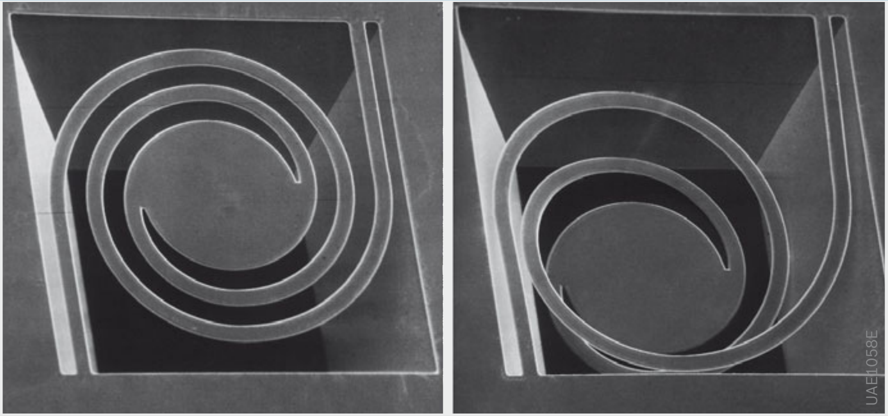


Fig. 27
Source:
Prof. Heuberger,
Fhg Berlin

Another example of a mechatronic sensor system is the Hall-effect speed sensor built into the wheel bearing. The addition of magnetic particles to the indispensable shaft seal in the bearing can even give it the function of the rotor or a pole wheel. The sensor benefits from excellent protection and encapsulation along with the high precision of the roller bearing and no longer needs any bias magnets. Finally, the Hall-effect technology allows installation in the very tight space within the bearing.

28 Surface micromechanical pressure sensor with piezoresistive pick-off

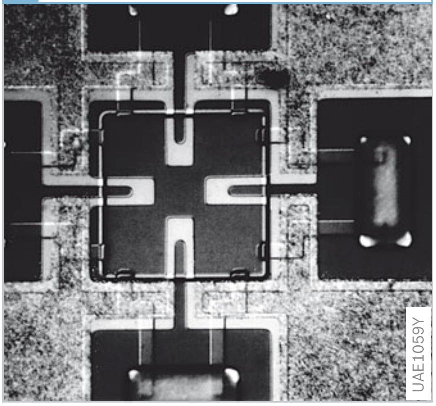
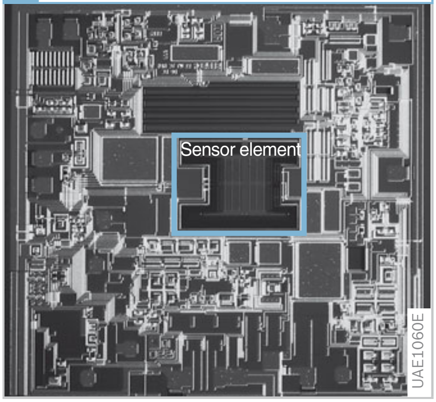


Fig. 28
Source:
Prof. Guckel,
University of Michigan
in Madison, USA

29 Surface micromechanical acceleration sensor with capacitive pick-off



High accuracy

By comparison with the probes and sensors used for instance in the processing industry, with only a few exceptions (e.g. the air-mass meter), the accuracy demands made on vehicle sensors are relatively modest. Generally, the permissible deviations are > 1 % of the measuring-range final value. This applies in particular when considering the unavoidable effects of aging. The permissible deviations are normally achieved by the application of complex techniques to compensate for manufacturing tolerances, and to balance the effective compensation measures used against interference. Particularly since the above-mentioned requirements have for the most part become achievable, continually more demanding and sophisticated systems are imposing higher and higher demands in this sector.

Development trends

Initially, a tightening up of the tolerances in manufacture, and refinement of the calibration and compensation techniques help in this regard. An important step forward here is the hybrid or monolithic integration of the sensor and signal electronics directly at the measuring point, even embracing complex digital circuits such as analog/digital converters and microcomputers (Fig. 30).

Such microsystems are also known as “intelligent sensors”. They take full advantage of the sensor’s inherent accuracy, and offer the following features:

- Reduction of the load on the control unit
- Uniform, flexible, bus-compatible interface
- Multiple application of sensors
- Use of smaller measuring effects and of radio frequency measuring effects (local amplification and demodulation)
- Correction of sensor deviations at the measuring point, and mutual calibration and compensation of sensor and electronics, is simplified and improved by

storing the individual correction information in the PROM

While simultaneously detecting and digitizing interfering factors, intelligent sensors can calculate the required measured variable practically without error by applying the mathematical sensor model (Fig. 31). Here, the item-specific model parameters are defined in a preceding process which is equivalent to the calibration as previously performed, and stored in a PROM integrated within the sensor. In this manner, it is possible to considerably improve the sensor's static and dynamic characteristics (evaluation of the differential equation which defines the dynamic performance).

Local electronic circuitry necessitates the use of multi-sensor structures which use a number of identical sensors, or a number of different sensors, to register a variety of highly complex facts and locally reduce these to their basic information content, as necessary. This applies in particular to imaging sensors which in future will play an ever increasing role in detecting the situation inside and outside the vehicle.

30 Sensor integration levels

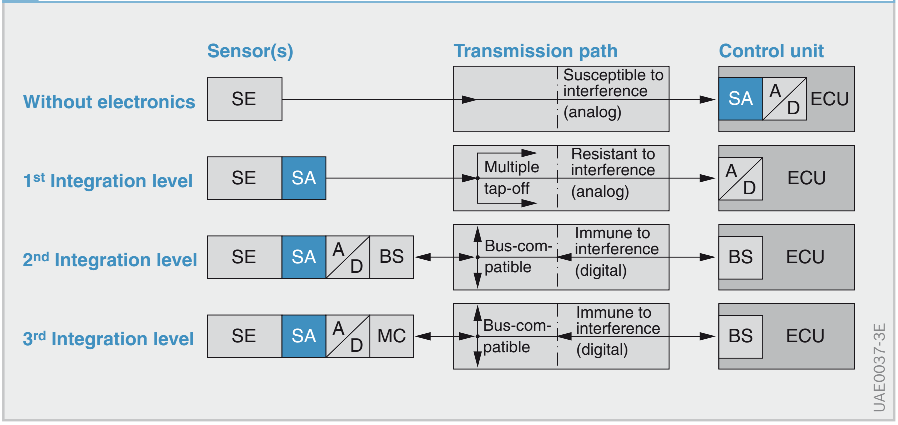
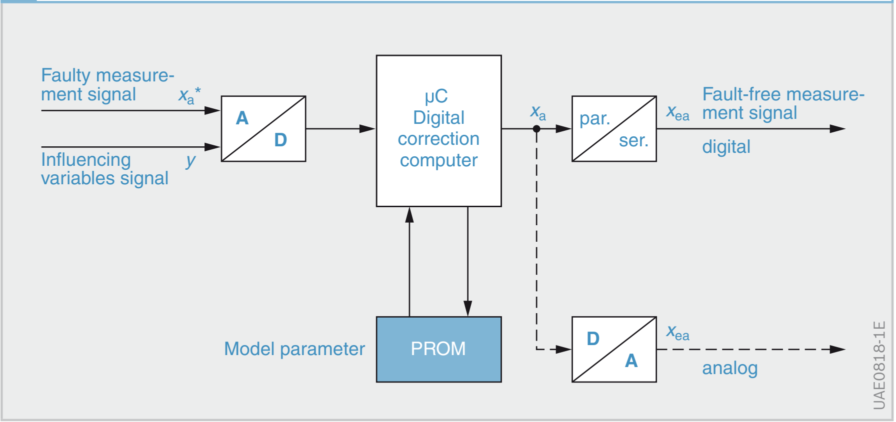


Fig. 30

SE Sensors
SA Signal conditioning
A/D Analog-Digital converter
ECU Control unit
MC Microcontroller
BS Bus interface

31 Correction model for a smart sensor



With a number of pressure sensors integrated into the smallest of spaces, it is possible to not only increase the reliability of measurement, but also to reduce the, generally irregular, aging drift by applying mean-value generation. Individual failures (outliers) can also be detected and eliminated. Sensors of this type are also known as soft sensors. If the individual sensor elements are designed for differing measuring ranges – and at the same time feature high overload capabilities (e.g. capacitive) – such a sensor can be used to considerably extend the high-acccuracy measuring range. Sensor structures of this type were developed and tested years ago, but have not been converted into marketable products.

Overview of the physical effects for sensors

The sensors are not classified here into a systematic structure by measuring effect, but rather by measured variable. For this reason, the most important physical effects or measuring concepts exploitable for measuring purposes will here only be reproduced in the form of a rough overview, which cannot be complete. Overlaps between the various categories are unavoidable. The table specifies principally the actual electrical effects; mechanical or fluid prior stages, such as strain springs (force), membranes (pressure), spring-mass systems (acceleration), vibration systems (tuning forks) or even fixed and rotating turbine blades (flow) are not included.

4 Physical effects for sensors

Physical effect	Example	As at: Series production1)/ Development2)
Resistive effects (dependency of electrical resistance):		
Influence of temperature on metallic and semiconductor materials	NTC and thin-film resistors for the measurement of air and engine temperature	S
Length or angular proportionality of resistors (potentiometer sensors)	Accelerator-pedal and throttle-valve sensor, fuel tank level	S
(In plane) tension or pressure dependency (piezoresistive): strain-gage resistors	High-pressure sensors (e.g. common rail, ABS):	
	metal diaphragm,	S
	low pressure sensors (silicon diaphragm),	S
Vertical pressure dependency (out of plane)	force sensor	D
Magnetic field dependency (magnetoresistive): semiconductor (magnetoresistors), AMR3) thin metal layers (e.g. NiFe, also in barber's pole form), GMR4) sensors (nanolayers)	Speed or delivery angle measurement in diesel distributor injection pumps	S/D
Light dependency: semiconductor photoresistors	Rain sensor, dirt sensor for headlight cleaning, automatic headlights, automatic low-beams	S
Inductive effects (effects of Faraday's law)		
Induction voltage sensors (alternator): movement in the magnetic field	Wheel, camshaft, engine speed, needle lift (injection nozzle)	S
Wiegand effect	Speed of rotation	D
Variation in inductance as a result of the positional change of a ferromagnetic coil core	Solenoid armature sensor	D
Variation in inductance as a result of field limiting conductive elements (eddy current)	Semi-differential short-circuiting ring sensor (diesel pump load sensor)	S

Table 4

1) Series production, at RB or competitors, possible also already phased out

2) Development possibly also concluded and in reserve

3) AMR = Anisotrop Magneto Resistive

4) GMR = Giant Magneto Resistive

Physical effect	Example	As at: Series production[1]/ Development[2]
Variation of the degree of transformer coupling (by electrical or magnetic conductive elements)	Full-differential short-circuiting ring sensor	D
Variation in inductance or of the degree of transformer coupling (by magneto-elastic conductive elements)	Load bolt (Hitchtronik), braking force	S D
Saturation core sensors (e.g. Foerster probe)	Compass sensor	S
Capacitive effects (influence)		
Capacitance change as a result in change in plate distance and degree of cover	Micromechanical acceleration sensors, e.g. for airbag, ESP, MM2 yaw-rate sensor, pressure sensor	S S D
Capacitance change as a result in a change of the relative dielectric constant	Oil grade, humidity sensors	S S
Capacitance change as a result of change in the electrolyte level with a dielectric medium	Fuel tank level	D
Charge generating effects		
Piezoelectric effect (quartz, piezoceramics)	Knock sensor, airbag sensor, DRS1 yaw-rate sensor	S S
Pyroelectric effect	IR sensor (dynamic)	D
Photoelectric charge generation	CCD and CMOS imaging sensor (also IR range)	D
Voltage generating, galvanic effects		
Hall effect (out-of-plane sensitivity, semiconductor material)	Hall switch (ignition), wheel and engine speed, acceleration sensor (ABS, 2*g*), front passenger weight detection (iBolt™), ARS1,2 (accelerator pedal etc.)	S
Pseudo-Hall effect (in-plane sensitivity, metal thin film)	LWS2 and LSW4 steering-angle sensors	S
Electrolytic diffusion probes (doped Zr oxide ceramic)	Lambda oxygen sensors	S
Thermocouple, thermopile	IR sensor (Bolometer)	D
Photoelectric and fiber-optic effects		
Photoelectric cells, photodiodes, phototransistors (also in IR range)	Rain sensor, dirt sensor for headlight cleaning, automatic headlights, automatic low beams	S
Medium-dependent absorption	Soot particles, humidity	D
Extrinsic and intrinsic fiber-optic effects: influence on intensity, interference (influencing phases), influencing polarization; e.g. microbending effect	Finger protection (windows, sliding sunroof), pedal force, collision	D
Thermal effects		
Resistor cooling as a function of the flow velocity, of the medium, of the density or fill level of a medium	HFM air-mass sensors, analysis, concentration, fill level (fuel tank)	S – – D
Wave propagation effects		
Sound waves: propagation time effects (echo sounding), superposition with medium speed, Doppler effect (moving source/receiver)	Parking-aid assistant, volume flow rate, speed over the ground	S D S
Light waves: total reflection on boundary surfaces, optical resonators (color analysis) Sagnac effect Propagation time	Rain sensor, fiber-optic finger protection, fill level (analog, limit value), yaw rate: fiber and laser gyroscopes, lidar (light wave radar)	S D D D D
Electromagnetic radiation: Doppler, FMCW, propagation time radar	ACC distance sensor	S

1) Series production, at RB or competitors, possibly also already phased out

2) Development possibly also concluded and in reserve

3) AMR = Anisotrop Magneto Resistive

4) GMR = Giant Magneto Resistive

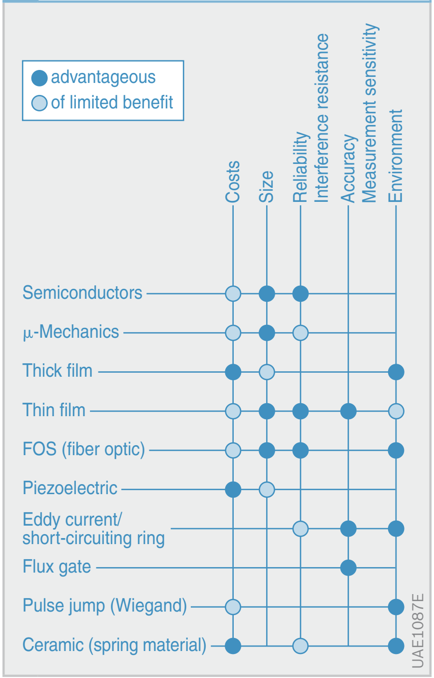
Overview and selection of sensor technologies

The various sensor technologies for exploiting the measuring effects described are naturally closely bound up with the measuring principle. They will first be listed here in a rough overview:

- Wound or photolithographically produced induction coils (with electrical or magnetic conductors), eddy current and short-circuiting ring sensors
- Flux gate probes (Metglas etc.) for magnetic field measurement
- Pulse jump sensors (Wiegand)
- Wire-wound (inductance-free) resistors
- Foil resistors (laminated onto plastic substrates)
- Sintered ceramic resistors
- Thin- and thick-film techniques (especially resistors and capacitances)
- Semiconductor technology (monocrystalline or polycrystalline resistors, depletion layers, charge-storage cells, etc.), electronics for signal conditioning: Si (bipolar, CMOS, BICMOS, EEPROM), GaAs
- Micromechanics (silicon and other materials, e.g. quartz, metal (LIGA technology) etc.)
- Piezoceramics
- Piezofoil
- Isolating ceramics as a spring material (e.g. as a pressure-sensor diaphragm)
- Ceramic solid electrolytes (e.g. as Lambda oxygen sensor)
- Quartz and other piezoelectric crystals
- Glass or plastic optical fibers or plates

The matrix shown in Figure 32 indicates which sensor technologies should be taken for various requirements. Thus, for instance, should the requirements be for small size, high reliability and high accuracy, it is appropriate to take a thin-film technology, as long as this is available for the measured variable desired.

32 Selection of suitable sensor technologies



● advantageous
○ of limited benefit

	Costs	Size	Reliability Interference resistance	Accuracy Measurement sensitivity	Environment
Semiconductors	○	●	●		
µ-Mechanics	○	●	○		
Thick film	●	○			●
Thin film	○	●	●	●	○
FOS (fiber optic)	○	●	●		●
Piezoelectric	●	○			
Eddy current/ short-circuiting ring			○	●	●
Flux gate				●	
Pulse jump (Wiegand)	○				●
Ceramic (spring material)	●		○		●