9 Sensors

Sensors and the associated measuring systems provide the required measurable information about the process in mechatronic systems. They represent an essential link between the process and the information-processing part, *i.e.,* microcomputers, see Figure 9.1. Sensors that measure mechanical or thermal quantities and transform them into an electrical signal are of special importance for mechatronic systems. This chapter gives a brief overview of some of the characteristic features, signal types and measurement principles. A more detailed description of the broad field of metrology is given in, *e.g.*, Jones (1977), Schrüfer (1983), Jüttemann (1988), Czichos (1989), Juckenack (1990), Thiel (1990), Profos, Pfeifer (1992), Schaumburg (1992), Tränkler (1992), Beckwith *et al.* (1995), Bauer (1996), Christiansen (1996), Jurgen (1997).

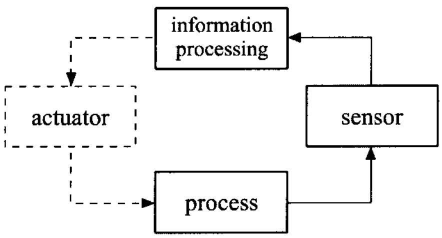


Figure 9.1. Sensors as links between a process and the information-processing unit

9.1 MEASURING SYSTEM

The purpose of a measuring system is to observe and quantify a variable physical quantity (called a measurand) and to process the obtained information. The first element of this system is the sensor or sensing element (increasingly used instead of "pickup"). Its primary function is to detect the measurand and transform it into a suitable signal, see Figure 9.2. Mechatronic systems generally rely on sensors with an electrical output signal. The characteristics of the output signal depends on the measurement principle of the sensor. Transducers and amplifiers transform the electric sensor output signal into a standardized electrical signal, *e.g.*, 0...20 mA or 4...20 mA or 0...10 V, which is more suitable for further processing. If high-frequency disturbances contaminate the usable signal, a low-pass filter is applied in order to decrease the influence. A sample and hold device and an analog-to-digital converter are necessary if the sensor signal is to be processed by a microcomputer.

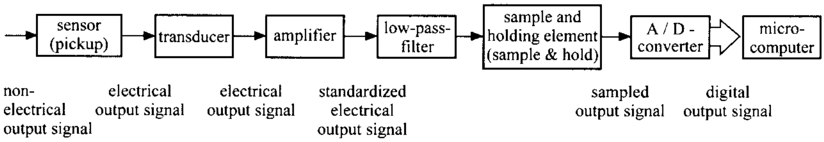


Figure 9.2. Measuring system

Consumer goods and low-cost appliances do not require high-precision measurement and a modular arrangement of the measuring system. Therefore, simplifications may be made in order to reduce costs, *e.g.*, by omitting the generation of standardized electrical signals.

9.2 CLASSIFICATION OF SENSORS

Because of the broad spectrum of metrology, it is difficult to classify sensors and the corresponding signal processing devices. A survey entitled "Technical Sensors" (1983) proposed a hierarchical division consisting of five levels and 75 subdivisions. Important features for the classification of sensors are:

- measured quantity;
- sensor-principle;
- manufacturing technology;
- signal types and interfaces;
- fields of application;
- properties, features;
- quality class;
- cost.

Table 9.1 gives an overview of the classification of some important measurands. A rough classification might be:

- mechanical quantities;
- thermal/caloric quantities;
- electrical quantities;
- chemical and physical quantities.

Table 9.1. Survey of the classification of important measuring quantities

class		measuring quantity
mechanical quantities	geometrical quantities	displacement, angle, level, gradient
	kinematic quantities	speed acceleration oscillation flow
	stress quantities	force, pressure torque
	material characteristics	mass, density viscosity
	acoustic quantities	sound velocity sound pressure sound frequency
thermal quantities	temperature	temperature of contact temperature of radiation
electrical quantities	electrical state variable	voltage current electrical power
	electrical parameter	resistance impedance capacity inductance
	field variable	magnetic field electrical field
chemical and physical quantities	concentration	pH value humidity heat conduction
	size of particle	content of suspended matter content of dust
	kind of molecule	gas molecules fluid molecules rigid body molecules
	optical quantities	intensity wavelength, color

The following sections will deal with properties and features of sensors, as well as different kinds of signal types. In addition, the principles of some sensors with an electrical output signal will be described.

9.3 SENSOR PROPERTIES

The transformation of non-electrical quantities into electrical ones depends on physical or chemical effects. These may be divided into *main* and *side* effects. The main effect is responsible for generating the desired measuring signal, *e.g.*, the electrical voltage of a piezoelectric pressure sensor. However, disturbing side effects are frequently superimposed, *e.g.*, the influence of temperature changes. The design process for sensors needs to take these side effects (sometimes called "cross sensitivity") into account. Their influence should have only little effect or should be compensated by appropriate measures.

The most important criteria for evaluating sensors are:

- static behavior;
- dynamic behavior;
- quality class, measuring range;
- overload capacity;
- compatibility with associated components;
- environmental influences;
- reliability.

A sensor's static behavior is described by the characteristics of the sensor. It defines the sensitivity of a sensor, *i.e.,* the ratio of the change of the electrical output signal to the change of the measured variable. Other important properties of a sensor are linearity, hysteresis and repeatability (reproducibility).

The dynamic behavior is described by a sensor's frequency response or simple characteristic values, *e.g.*, cut-off frequencies or time constants. The sensor dynamics have to be adjusted to the process and the measuring task.

The quality class gives a basic measure about a sensor's accuracy. It is the percentage maximum error of a measurement with reference to the full scale. Applications for consumer goods don't need a high accuracy (2% to 5% is sufficient). Industrial applications, on the other hand, require a much higher precision (0.05% to 1%). Equipment for high-precision measurements, *e.g.*, calibration and test equipment, have to meet very strict requirements. The measuring range describes the range in which the sensor's specifications are met.

The overload capacity specifies the range in which a sensor may be operated without changes in the sensor's characteristics or damage to itself. Typical overload capacities are between 200% and 500%.

A sensor's compatibility depends on the output signal type (see next section). Environmental influences, *e.g.*, temperature, acceleration, corrosion, contamination, wear and tear, are especially important.

The reliability of a sensor is described by characteristic parameters, *e.g.*, the "mean time between failures" (MTBF in [h] or its reciprocal value the mean failure rate ([h^{-1}])).

9.4 SIGNAL TYPES, TRANSDUCERS, MEASURING AMPLIFIERS

The type of signal supplied by the sensor depends on both the measuring principle and on the associated signal transmission and signal processing devices. Signal types may be subdivided into the following categories:

- amplitude-modulated signals;
- frequency-modulated signals;
- digital signals.

Amplitude-modulated signals are characterized by a proportional relationship between the signal amplitude and the measured quantity. If the signal frequency is proportional to the measured quantity, the signal is called a frequency-modulated signal. Digital signals encode a measured quantity using serial or parallel binary signals.

Table 9.2 describes some of the properties of these signal types, *cf.*, Schrüfer (1983) and Tränkler (1992).

Table 9.2. Some properties of signal types for measuring signals

signal type / properties	amplitude-modulated	frequency-modulated	digital
static accuracy	large	large	limited by word length
dynamic behavior	very fast	limited through transducer	limited through sampling
noise sensitivity	medium/large	small	small
galvanic separation	costly	simple (transducer)	simple (optical coupling)
interfacing to a digital computer	analog-digital converter	simple (frequency counter)	simple
computational operation	very limited	limited	simple, if microcomputer

Transducers convert the amplitude-modulated signal into another appropriate electrical signal. Examples of transducer circuits without amplification are:

- voltage-current transducer with precision resistor;
- voltage divider, current divider;

- resistance-current transducer;
- compensation network for measuring voltage, current or resistance (resistance bridge).

Measuring amplifiers raise low-power sensor output signals to a higher power level or generate more powerful standardized signals (0 ... 10 V, 0 ... 20 mA). High-power sensor output signals are needed for associated components of the measuring chain, *e.g.*, transmission links, filters and displays. Measuring amplifiers often consist of operational amplifiers made out of resistors and transistors in the form of analog integrated circuits. Operational amplifiers possess high gains, which may vary considerably due to aging and dependence on temperature. Without additional circuitry, operational amplifiers may only be used as zero gains for comparator or compensator circuits. By adding a negative feedback, one observes that the gain of the entire circuit depends mainly on the resistors of the negative feedback for the case of high feedforward gains of the operational amplifier. Measuring amplifiers with negative feedback are divided into four basic types of circuits:

- voltage amplifiers;
- voltage amplifiers with current output;
- current amplifiers;
- current amplifiers with voltage output.

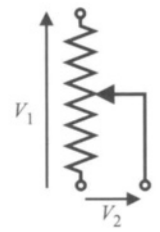
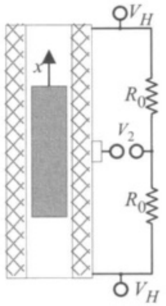
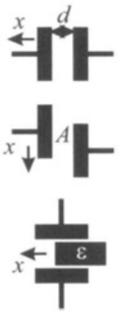
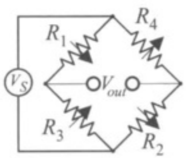
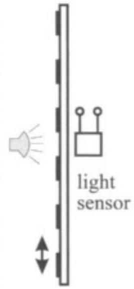
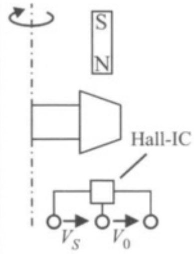
The following sections give a short description of some important sensor principles. For a more detailed description, refer to the references given in the bibliography.

9.5 DISPLACEMENT MEASUREMENT

a) Resistive sensing elements

Resistive pick-ups exploit the proportional relationship between the length of a wire or film resistor and its electrical resistance, see Table 9.3. They are potentiometers made of electrically conductive plastics or metal wire. Potentiometers are wired as voltage dividers and are offered as linear or rotational sensing elements, in the latter form as multiplex potentiometers (*e.g.*, 10 revolutions). The measuring range of linear sensing elements starts at a few millimeters and goes up to about two meters. Encapsulation of the sensor housing enables the deployment of the sensor in rough environments. Safety rails ensure a movement of the brush free of lateral forces. Sensing elements made out of electrically conductive plastics have a very high resolution, *e.g.*, measurement of 100 mm with a resolution of 0.01 mm. However, a high accuracy requires a very precise voltage source.

Table 9.3. Displacement sensors (linear)

	resistive sensors	inductive sensors	capacitive sensors	strain gauge	code sensors	incremental sensors	Hall sensor
sensor principle (example)							
material	metal, semiconductors, conductive plastics	ferromagnetic metal	capacitor	metal, semiconductor	optical encoders	glass, metals	Hall semiconductor
output signal	analog voltage	analog voltage	analog voltage	analog voltage	binary signal	binary signal	binary signal
measurement range	1 cm...2 m 300° (angular displacement)	±100 μm...±50 cm	0.1 cm...10 cm			10 mm...3 m	360°
maximum sensitivity	0.2 V/° or 2 V/cm	0.1 V/cm...40 mV/μm		$k = \frac{\Delta R/R}{\Delta l/l} = 2$(metal) k = 100 (semiconductor)	4096 pulses/rev		4000 pulses per revolution
accuracy, resolution	max. 40 μm or 0.1°	0.1 μm	<0.1 nm		1 LSB	0.1 μm 0.00005°	10^{-5} revs
temperature range	-50°C...+250°C	-40°C...+100°C	up to 800°C	-270°C...+1000°C	-50°C...+100°C	0°C...+50°C	-200°C...150°C

b) Inductive sensing elements

Inductive sensing elements rely on the dependence of the change in the self and mutual inductance on the element's position. The inductance of coil arrays is changed by variation of the air gap. A lattice network consisting of differential coils ensures an almost linear characteristic.

Differential transformers exploit the relationship of the mutual inductance between the primary and secondary coil and a displacement of the iron core. The primary coil is subjected to a carrier frequency. The difference in the voltage of the secondary coil acts as a displacement-dependent output signal. Inductive sensors are non-contact sensing elements. Their measuring range starts at a few millimeters and goes up to about one meter. Other designs are displacement angle sensing elements.

c) Capacitive sensing elements

A change in plate distance, plate area or of the dielectric material between plates influences the capacitance of a capacitor. The signal processing circuits consist of AC lattice networks (capacitive bridge). They have to be operated with a high carrier frequency (0.5 ... 1 MHz) because of small capacitances.

d) Strain gauge

Strain gauges (SG) transform small linear deformations into electrical signals. They are based on the effect that a change in the length of an electrical conductor results in a change in the electrical resistance. If one expands a wire of length L by ΔL, the electrical resistance of the wire changes due to changes in the specific electrical resistance (because of structural deformations), the length and the cross-sectional area.

Metal wire and film SG consist of thin constantan wires or films. Changes in the length and cross-sectional area lead to a change in the electrical resistance, while the specific electrical resistance is not affected. For *semiconductor* SG, the main effect is the change in the specific resistance due to the structural deformation by elongation. Semiconductor SG are much more sensitive to elongation (about 40 to 80 times more sensitive than constantan) but have non-linear characteristics at large elongations and are much more expensive than metal SG. Embedded between thin films, SG are pasted directly onto the measuring object. This could directly be the constructive component whose elongation is to be measured. SG in conjunction with special spring elements and diaphragms serve as force, torque and pressure sensors. The change in the electrical resistance is evaluated with lattice networks (bridge circuits). A temperature compensation is often provided.

e) Encoders

Encoders use code rulers or code discs on which the discrete displacement data is encoded. The allocation is absolute because they do not need an external reference. Unit-distance codes, *e.g.*, Gray code, are often used for coding. The sampling is performed optically. In order to distinguish between 2^n different discrete positions, one needs n sampling tracks. This makes this kind of sensing element relatively complicated. Coded sensing elements are mainly used in industrial metrology, *e.g.*, for numerically controlled machine tools and robots.

f) Incremental sensing elements

Incremental position and angle sensors count the number of so-called notches or slots, *i.e.*, *increments*, relative to an initial point. Sampling is performed either by optical (*e.g.*, diodes) or inductive methods, resulting in pulse trains that are counted. The initial point can be chosen arbitrarily. If a failure (*e.g.*, power failure) occurs, the initial point gets lost and must therefore be reset by moving to a reference position. A fault while counting the increments influences all the following readings. Additional circuitry with two samplers per scale enables detection of movement direction and a pulse multiplication.

The sensor housing often contains a pulse-shaping circuitry. Incremental sensors are mainly used in industrial metrology, *e.g.*, manufacturing. Linear scales with a range of up to 3 m and a graduation of 1 μm are available. Shaft encoders with up to 36.000 slots are used for precision applications. Using pulse multiplication (interpolation), a resolution of about 0.00005° is achievable.

g) Hall effect sensors

If a voltage is applied to a conductor or semiconductor located in a magnetic field perpendicular (right angled with the current flow) to the applied voltage, the Hall voltage is generated, which is perpendicular to both the current flow and the magnetic field. The dependence of the Hall voltage on the magnetization is now used for proximity or position measurement. If the semiconductor is a silicon Hall plate, the voltage has to be amplified. Integrated Hall ICs exist, which incorporate amplification, stabilization and temperature compensation. A rotational position sensor now consists of a permanent magnet and a soft magnetic tooth wheel moving through a gap between the magnet and the Hall IC (*e.g.*, bipolar technology). Hence, by interruption of the magnetic field, a pulse train is generated whose frequency is proportional to the rotational velocity. The Hall IC requires a supply voltage (*e.g.*, 12 V). This type of sensor is used, for example, for rotor position sensing of brushless DC motors and for ignition triggering of SI engines (Bauer 1996).

h) Further measuring methods

Ultrasonic distance sensors are used for level measurement (bulk material, fluids) or as distance meters (park assistance for an automobile). They rely on the time interval between transmission and echo-return of the ultrasonic signal. *Laser interferometers* are based on the phase comparison of coherent light and are used for contactless precision displacement measurement.

All of the above-mentioned measuring methods may also be used for the measurement of force or pressure. They detect displacement of springs or membranes and transform it into an electrical signal.

9.6 VELOCITY MEASUREMENT

One possibility of measuring velocities is to differentiate the signal of displacement or angular sensors. However, this has the disadvantage of amplifying the noise relative to the usable signal. Therefore, direct measuring methods for velocity measuring are more suitable. Angular velocity sensors especially are of practical significance. Translational velocities are often converted into rotational velocities for measurement purposes (speedometer).

a) Active electrodynamic sensing elements

Active electrodynamic sensing elements operate like generators, see Table 9.4. If N electrical conductors move through a magnetic field with magnetic flux Φ, this induces a voltage

$$V = -N d\Phi / dt$$

in the conductors according to the law of induction, see Section 5.2.4. As Table 9.4 shows, one can distinguish:

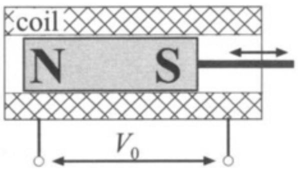
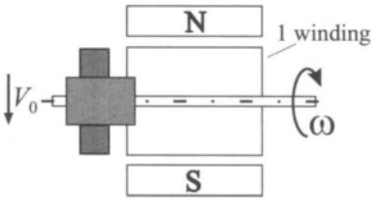
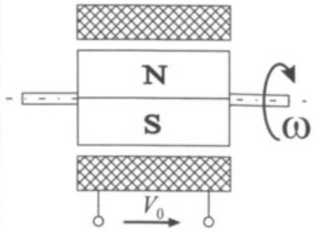
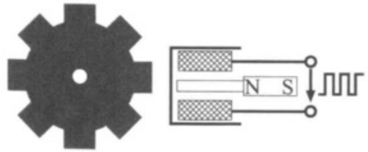
Sensors for translation: a permanent magnet moves inside a coil and induces a voltage that is proportional to the velocity.

Sensors for rotation: AC generators use a permanent magnetic rotor and a stator winding. In order to measure the rotational speed, both the output signal's frequency and voltage may be used. A linear voltage characteristic results. DC tacho generators consist of a commutator and a coil rotating in a constant magnetic field derived from a permanent magnet. The generated voltages are then proportional to the rotational speed. The polarity of the voltage depends on the sense of rotation. This sort of sensing element has a linear characteristic but a rippled voltage signal because of the commutation.

b) Incremental inductive sensors

These sensing elements correspond to incremental displacement sensors. A ferromagnetic ring gear with rectangular teeth passes an inductive sensor, Table 9.4. This sensor consists of a bar magnet with a soft magnetic pole pin and an induction coil. The voltage in the coil is proportional to the periodic variation in the magnetic flux. The output signal therefore is a pulse sequence and its frequency is related to the rotational speed. A frequency-voltage converter transforms the pulse frequency into a voltage. Discrete evaluation is performed by counting the number of pulses during a certain time-span or by measuring the time interval between two pulses.

Table 9.4. Velocity sensors

	translational velocity sensor	DC generator (tacho-generator)	AC generator	incremental velocity sensors
sensor principle (example)				
output signal	analog voltage	analog voltage	analog voltage	voltage pulses
measurement range		$\pm$6000 rev/min		
sensitivity	10 mV(mm/s)	5 V per 1000 rev/min		
accuracy, resolution				

The number of pulses per rotation depends on the specific application and ranges from one to several thousand pulses. This sensor is, for example, used for engine crankshafts and wheels for ABS (antilock braking system) functions. It does not need an electrical power supply.

c) Other methods

Another method of measuring translational velocity exploits the *Doppler effect.* A velocity-dependent frequency shift between a transmitted and a reflected signal by a moving object occurs. Well-known examples for these kinds of sensors are the Doppler radar (traffic radar) and the laser Doppler for high precision, contactless measurement, but these are at a high cost.

Yet another method utilizes *cross-correlation* between two stochastic or periodic signals. Two identical sensing elements are placed at distance l and the measurement of the time delay τ between the transmitted and received signal enables the determination of the velocity $v = l/\tau$. This is, for example, used with optical sensors for rough surfaces or for fluids.

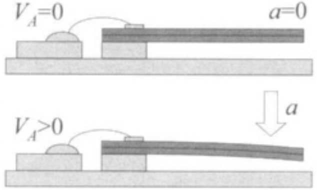
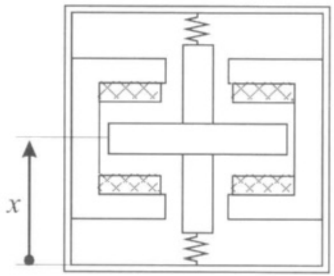
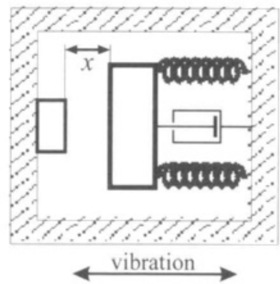
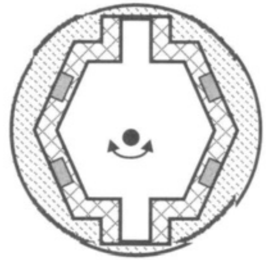
9.7 ACCELERATION MEASUREMENT

Measurement of acceleration is frequently based on force measurement using the relationship between the acceleration a of a mass m and the inertial force F: $a = F/m$. For direct measurement of the force F *piezoelectric force sensors* may be used, see Table 9.5. Due to the large spring stiffness and small masses of these transducers, it is possible to achieve high natural frequencies (100 kHz).

Spring-mass systems consist of a seismic mass connected to the sensor casing with springs and dampers. The acceleration is determined by measuring the displacement of the spring (*e.g.*, inductively). There are many different kinds of acceleration sensors that are capable of measuring accelerations of, *e.g.*, 10^{-6} g for inertial navigation purposes or up to 10^5 g for measuring explosions. Masses, springs and dampers are chosen such that high natural frequencies (15 Hz to over 100 kHz) are achieved. The utilizable measurement frequency reaches about half of the natural frequency. Sensors for angular acceleration use equivalent arrangements. Table 9.5 shows some examples.

An acceleration may also be determined by differentiating the signal of a velocity sensor once or by differentiating the signal of a displacement sensor twice. However, this leads to an increase in high-frequency noise and makes low-pass filtering inevitable.

Table 9.5. Acceleration and vibration sensors

	piezoelectric acceleration sensor	acceleration sensor with seismic mass	vibration sensor with seismic mass	angular vibration sensor
sensor principle (example)				
material	piezoelectric lever mass	seismic mass with large natural frequencies	seismic mass with small natural frequencies	seismic mass with small natural frequencies
output signal	analog voltage	amplitude-modulated analog voltage	amplitude-modulated analog voltage	amplitude-modulated analog voltage
measurement range	±500 g	5 Hz – 50 kHz	±2000 g	
sensitivity	0.1 mV(m/s²)			
accuracy, resolution	0.01 g		0.1 g	

9.8 VIBRATION AND OSCILLATION MEASUREMENT

The measurement of relative vibrations is based on the displacement between two reference points, which is measured by displacement sensors. For measuring absolute vibrations, the missing second reference point has to be replaced by a seismic mass, see Table 9.5. Measurement of the oscillation amplitude requires a large seismic mass and a small spring constant of the suspension (small natural frequency). This leads to a motionless seismic mass and an oscillating sensor housing. A displacement sensor (*e.g.*, inductive sensor) measures the displacement between the seismic mass and the sensor housing. The same applies to electrodynamic velocity sensors, which measure the vibration velocity. Vibration acceleration is measured with acceleration sensors calibrated for high natural frequencies.

9.9 FORCE AND PRESSURE MEASUREMENT

Measurement of pressure and force is performed indirectly by measuring the spring or diaphragm deflection with displacement sensors like those described in Section 9.5 (especially strain gauges, used for so-called load cells, and inductive sensing elements).

Piezo-sensing elements are of special importance for pressure and force gauging. Piezoelectric sensing elements exploit the piezoelectric effect: a displacement results in an electrical charge at the surface of a crystal lattice. The arising displacement is very small (a few μm). The electrical charge charges the artificial capacitance (consisting of the sensing element, wire and amplifier input). The resulting voltage V decays with the time constant $T = RL$. This is the reason why piezoelectric sensing elements are suitable for dynamic measurement only.

The subsequent measuring amplifier has to have a very high input resistance ($R > 10^{13}\,\Omega$) in order to obtain a large time constant. Charge amplifiers are used with time constants of up to several hours. The maximum measuring frequency is about 100 kHz.

Piezoresistive sensing elements exploit the piezoresistive effect. In this case, a crystal subjected to mechanical forces changes its electrical resistance due to a dislocation in the crystal lattice structure. This also allows static measurements.

9.10 TORQUE MEASUREMENT

Torque is measured by gauging the torsion of a shaft section using angular, displacement or elongation sensors. For this purpose, special *torquemeters* may be attached to the shaft using flanges with or without bearings. Another possibility is to base the measurement of torque on the torsion of the shaft due to a load. The signal transmission depends on whether the shaft is rotating or not. If the shaft is rotating, the revolving sensors transmit their signals to the stationary electronic signal-processing unit via a slip-ring or without direct electrical contact, *e.g.*, through inductive coupling.

Measurements of a shaft's torsion can be obtained by employing either of the two following methods. The first method uses wire strain gauges, which are placed on the shaft with an inclination of 45° to its longitudinal axis, interconnected to a Wheatstone network, see Table 9.6. The second method measures the change of permeability by measuring the voltage induced in coils. Both measurement principles may be applied directly to the shaft or in conjunction with special torquemeters. In many cases, *torque-gauge heads* are necessary, which are easily incorporable, do not require much space and do not introduce too much elasticity. Additional requirements include the possibility of connecting a sensor via, *e.g.*, a flange to the shaft or integration of the sensor into pulleys.

The rotational angle between two twisted discs or axial dislocation of discs due to kinematic transmission may be measured inductively. Another measurement principle uses disc- or sleeve-like parts that consist of electrically conductive and non-conductive zones. Twisting of the shaft leads to a shift of the zones against each other and results in a change of the eddy current. This yields a change in the impedance of a stationary measuring coil. Additional possibilities for measuring torque include the use of surface-resonators and piezoelectric sensors, which are placed into the force flux. Pahl (1992) gives an overview of different torque sensors.

9.11 TEMPERATURE MEASUREMENT

a) Resistance thermometers

Passive resistance thermometers exploit the sensitivity of electrical resistors to temperature variation, compare Table 9.7. Metal resistance thermometers consist of nickel or platinum wire wound in the form of a free spiral around thin mica or laminated paper strips or embedded in glass. The resistance-temperature sensitivity is 0.358 Ω/K for platinum (Pt100) and 0.612 Ω/K for nickel (Ni100). The nominal resistance in each case is 100 Ω and the maximum measuring temperature is 150°C for Ni and 500°C for Pt.

Table 9.6. Force, torque and pressure sensors

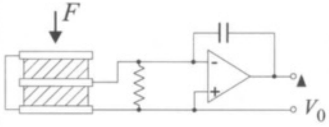
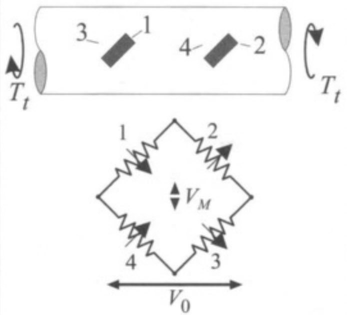
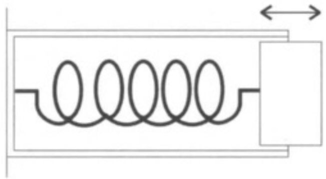
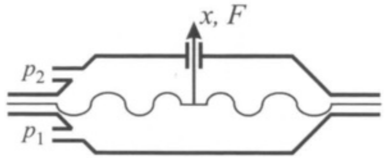
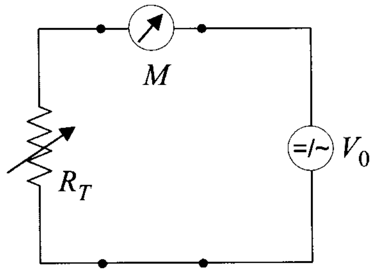
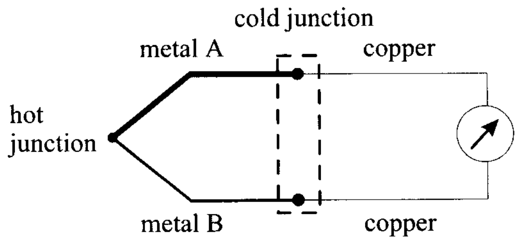
	piezoelectric force sensor	torque measurement using strain gauges	force spring deflection sensor	pressure diaphragm sensor
sensor principle (example)				
material	piezoelectric material	strain gauges on surface	spring in a casing	flexible diaphragm
output signal	analog voltage	analog voltage	analog displacement	analog displacement
measurement range	1 N...1 MN	0.05 Nm...50 kNm		0.1 bar...10000 bar
sensitivity	125 V/kN			
temperature	−80°C...+150°C	+10°C...+60°C	−40°C...+60°C	−25°C...+100°C

Table 9.7. Temperature sensors

	resistance thermometers				thermocouples	
sensor principle (example)						
material	metal resistor		semiconductor resistor		Fe-Co	Pt-Rh
	Pt	Ni	NTC	PTC		
output signal	analog voltage				analog voltage	
measurement range	-250°C...+1000°C		-40°C... +850°C	-200°C... +850°C	-180°C...+760°C	0°C...+1750°C
sensitivity	<5 mV/°C				53 μV/°C	8 μV/°C
accuracy, resolution	0.3% ... 0.25% of measured temperature				0.25% ... 0.75% of measured temperature	

A thermistor is a resistance thermometer consisting of a metal oxide semiconductor material. It is about 10 times as sensitive as metal resistance thermometers, has a strong non-linear characteristic and is less accurate. Commercial forms are very small (< 0.5 mm) and thus possess a low heat capacity. This makes thermistors suitable for measuring surface temperatures and for the measurement of dynamic processes. If the semiconductor possesses a negative temperature coefficient (electrical conductivity increases if temperature rises), it is called an NTC thermistor, while a semiconductor with a positive temperature coefficient (electrical conductivity decreases if temperature rises) is called a PTC thermistor. These metallic resistors can be produced as thin-film or thick-film sensors and are then integrated upon a single substrate wafer with neutral trimming resistors for precision manufacturing, Bauer (1996). Maximum temperatures range from 100°C to 1000°C for NTC thermistors and from −10°C to 500°C for PTC thermistors.

b) Thermocouples

The arrangement of two lengths of dissimilar wire, insulated from each other but joined at one end, is known as a thermocouple, Jones (1977). Thermocouples are active temperature sensors. Exposing the junction of the two metals to heat generates an EMF that depends on the temperature at the junction. This is called the *Seebeck effect.* When the junction between two dissimilar metals is heated or cooled relative to a second reference junction, the resulting overall voltage is a function of the difference temperature of the two junctions. The performance of a thermocouple is usually specified in relation to a reference temperature of 0°C (ice water). In many practical arrangements, the reference junction is located in a controlled environment with a non-zero reference temperature.

The temperature-voltage characteristic is non-linear but a linearization is possible for a wide range of operation. The advantages of thermocouples are their small dimension, which leads to small measuring points, and that they do not need a power supply. However, they have low sensitivities and the output signal level is small. Thermocouples enclosed in protective tubes with a diameter of 0.25 mm to 3 mm have a wide measuring range of 220°C to 2400°C. Due to the small heat capacities of such sensors, it is possible to measure even rapid temperature changes.

9.12 ANALOG-TO-DIGITAL CONVERSION

The discussed sensing elements transform a physical quantity into a change of electrical resistance, capacitance or inductance. DC or AC lattice networks transform these changes of electrical properties into a voltage signal and amplify it. Other sensing elements produce low-power voltage or current signals that need to be amplified by special circuits, *e.g.*, voltage or current amplifiers, electrometer or charge amplifiers.

If a microcomputer is used for data acquisition purposes, analog-to-digital conversion is necessary. A low-pass filter limits the measurement signal bandwidth if necessary in order to achieve compliance with the sampling theorem. The filter is followed by a sample and hold device and finally the analog-to-digital converter (ADC), see Section 11.3. The precision of the ADC is chosen depending on the application. Standard ADCs have an 8-, 10- or 12-bit precision, while high-precision applications need 16-bit. Converters that use time interval or frequency as intermediate quantity (charge-balancing or dual-slope converters) integrate the input voltage over a fixed input sample time (the measuring interval). An example is the digital voltmeter. This kind of conversion method is very precise but the measured quantity may not change rapidly. Often, low-pass filters and sample and hold devices are not used in this conversion process. ADCs that use the principle of compensation, *e.g.*, successive-approximation converters, operate by comparing the input voltage with the output of a digital-to-analog converter (DAC). The ADC employs the DAC in a feedback loop, Jones (1977). In conjunction with sample and hold devices, this type of converter makes conversion rates of up to 1 MHz possible. Parallel ADC (flash converters) reach even higher conversion rates (up to 100 MHz with a 10-bit precision).

9.13 ELECTROMAGNETIC COMPATIBILITY (EMC)

The surroundings in which a sensor system is applied influences the selection of a sensor type. The environmental conditions are of a mechanical (vibration, shock), thermal and chemical (water, salt, oil, solvents) nature. Electromagnetic radiation from the surrounding environment poses another important influence on sensor systems. A sensor system's property of remaining neutral to this influence is called *electromagnetic compatibility* (EMC). The sources of this sort of interference are manifold and cover a wide range of frequencies, *e.g.*, from 16 2/3 Hz (power supply of trains) to several GHz (radar installations). The power supply of trains, electrical substations, transmission lines, radio, television and communication transmissions, radar installations, welding tools, lightning, *etc.*, all emit electro-magnetic energy that influences a system from a distance. Other interferences are due to wire-bound influences from the power supply. Examples of this are peak loads of other electrical consumers, commutator sparking of electric motors, variations of the power supply level, *e.g.*, in a 12 V vehicle electrical system, or spikes and collapses in the power supply due to a breakdown of other systems. In addition to this electrical and electronic devices influence each other. This so-called near-field influence has to be taken into account, too. This is especially the case if the devices are mounted in a confined space. Examples for near-field influence include crosstalk between wires in a cable tree, emission of interference by electrical drives, the clock rate of microprocessors and other digital devices, thyristor circuits and ignition systems. In addition to these effects, one has to take into account static charges, accidental earths and handling errors, *e.g.*, faulty connections or short circuits. There are a lot of problems of this sort, especially in automotive applications.

Suppression or reduction of the interference emission at its source is an important countermeasure. There are several methods for achieving this, *e.g.*, appropriate housing or use of interference suppressor coils in supply lines. Limits for noise field intensities are given in the appropriate regulations like VDE 0874 and VDE 0871.

Sufficient space between devices, especially between wires, helps to reduce the noise level. Instrumentation and power cables should always be installed separately. The use of radio shielding (metal casing) is one possibility to shield devices and components. Transmission lines configured as twisted pairs are less susceptible to inductive influences and may be shielded from capacitive (and high-frequency magnetic) influences. A proper connection of the shielding to earth is essential, Lauber (1989). An effective method for avoiding problems with EMC is reducing the length of wires needed for interconnecting devices. This is achievable by integrating the sensor, measuring amplifier and signal conditioning device into a single unit. Using signal transmission that is safe from interference (use of high signal levels, current transmission 4–20 mA, encoded transmission with error detection) further improves the EMC. Optical transmission using fibre cables in conjunction with measuring principles that are insensitive to electromagnetic influences (optical, digital) leads to even less susceptibility to interference.

Examining the EMC properties of parts of a system or of an entire system (EMC/EMP tests) is very expensive and difficult. A complete examination of all interactions in a complex system is usually impossible. Therefore, it is necessary to consider EMC aspects during the design of a system or component. Both emission of interference and susceptibility to interference of all components has to be minimized.

9.14 INTEGRATED AND INTELLIGENT SENSORS

Sensors are designed with two goals in mind. The desired signal should be the dominating signal a sensor measures and the measured signal must correspond to the actual physical quantity unambiguously. In reality, these goals cannot be fulfilled entirely. Sensors are subjected to side effects, *e.g.*, cross-sensitivity, perturbations, non-linear transmission (non-linear characteristics, hysteresis, responsiveness, null drift), drift, aging, slow dynamic behavior and individual manufacturing tolerances. Disregarding these non-ideal properties during signal processing leads to faulty measurements. This is why steps have to be taken to compensate for some of these side effects, even when using analog evaluation circuits. These steps include the use of filters, signal differences of two identical sensors or special circuits to suppress the null drift, Tränkler, Böttcher (1992). However, many additional and new possibilities arise with the use of *digital signal processing.*

Figure 9.3a shows a conventional measuring chain with associated analog-to-digital converter and a microcomputer or microcontroller. If, for example, the non-linear characteristics of the sensor do not change over time, it is possible to linearize or adjust them by using the microcomputer. This enables calibration of each individual sensor during its manufacturing and decreases the necessary measures on the analog part of the sensor. The use of microcontrollers makes frequency-modulated and incremental sensors economic because of the built-in counters that are able to measure frequencies easily.

Further improvement is possible by *integration* of sensor, signal processing, ADC and microcomputer with a bus interface into one single unit, Figure 9.3b. This integration (possibly onto one single chip) has several important advantages: reduction of costs for large-scale manufacturing, reduction of space requirements, higher precision, decrease of susceptibility to noise. Because of this integration, however, the requirements for robustness and reliability increase because a sensor is often subject to a rough environment.

Integrated sensor components allow the realization of additional functions. This leads to so-called "smart sensors" or "intelligent sensors", Figure 9.4. One example is the use of a second sensor to measure a parasitic quantity, *e.g.*, temperature, and using this measurement to compensate for an unwanted side effect. Other examples result from the use of special algorithms built into the microcomputer. These algorithms serve as noise filters, for compensation and linearization purposes, for compensating for hysteresis effects (due to magnetic properties, friction, responsiveness), dynamic delays and drift and aging effects. It is possible to introduce self-calibration for all algorithms during manufacturing and maintenance, and even fault detection and fault diagnosis schemes are possible. The fact that all of these algorithms may be programmed individually for each sensor is also very important. Manufacturing tolerances for the sensors need not be as small as in the conventional case. One way of realizing the digital processing chip is through an application-specific integrated circuit or ASIC. Kleinschmidt (1990), Tränkler (1992) and Kiencke (1992) describe the development of intelligent sensors.

It is interesting to see that sensor technology development follows a path similar to that of mechatronic system development, *i.e.*, by reducing the requirements on the sensor elements and to shift certain functions into microelectronics by including even more intelligent functions as described in Chapter 1.

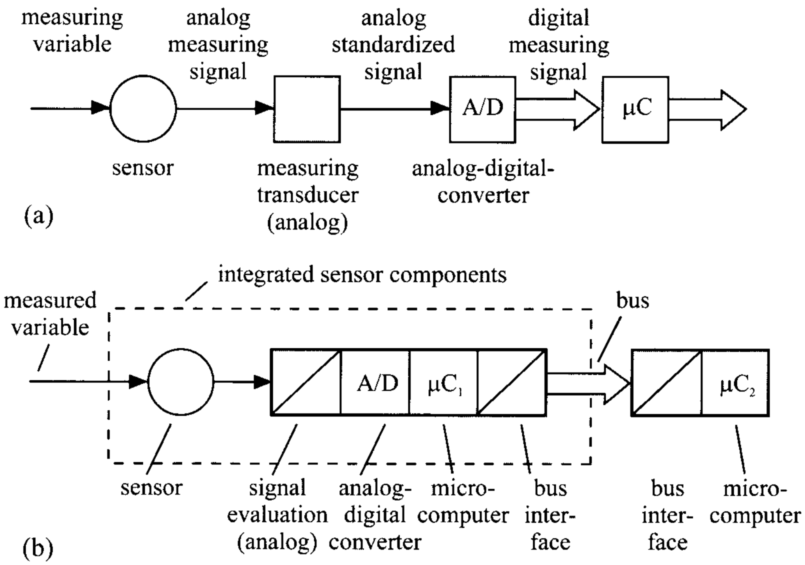


Figure 9.3. Integration of sensor technology: (a) conventional measuring chain with digital-processing unit; (b) integrated sensor components with digital-processing unit

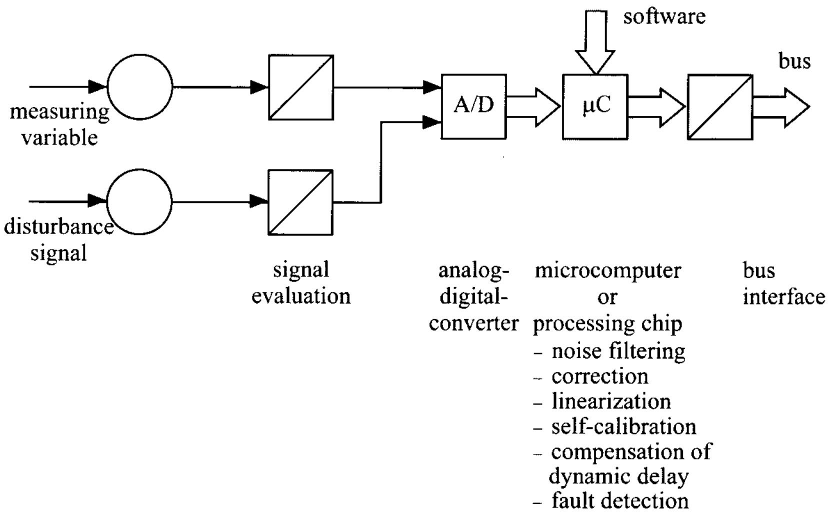


Figure 9.4. Integrated sensor components with "intelligent" functions

Further possibilities arise with the use of multi-sensor technology, *i.e.*, a combination of similar or different types of sensors, and the many developments that are emerging through micromechanics.

9. 15 PROBLEMS

9.15.1 Compare the merits of a platinum resistance thermometer, a thermistor and a thermocouple for temperature measurement.

9.15.2 Consider a capacitive displacement transducer to be governed by the relationship $C = 0.225A\ d$, where A is the cross-sectional area of the transducer tip (in cm^2) and d is the air gap distance (in mm). Determine the change in voltage when the air gap changes from 2 mm to 3 mm.

9.15.3 A choice of an incremental shaft encoder or an absolute shaft encoder is offered for the measurement of an angular displacement. What is the main difference between the results that can be obtained?

9.15.4 A pressure sensor consisting of a diaphragm with strain gauges bonded to its surface has the following information in its specification:
Ranges: 0 to 1400 kPa.
Non-linearity error: ± 0.15% of full range
Hysteresis error: ± 0.05% of full range.
What is the total error due to non-linearity and hysteresis for a reading of 1000 kPa?

9.15.5 A vibration measuring system indicates an overshoot of 37% when subjected to a step input. Calculate the damping ratio of the system. If the damping ratio of the system in question was changed to 0.9, determine the percentage overshoot to be expected when a step input signal is applied.

9.15.6 A sensor gives a maximum analog output of 5 V. What word length is required for an analog-to-digital converter for a resolution of 10 mV?

9.15.7 Digital signals from a sensor are often polluted by noise typically of the order of 100 V or more. Explain how protection can be afforded for a following microprocessor.

9.15.8 A rotary variable differential transformer (RVDT) has a specification that includes the following information:
Ranges: ± 30°, linearity error ± 0.5% full range
± 60°, linearity error ± 2.0% full range
Sensitivity: 1.1 (mV/V input)/degree
Impedance: Primary 750 Ω, Secondary 2000 Ω.

What will be the error in a reading of 40° due to non-linearity when the RVDT is used on the $\pm$ 60° range and the output voltage change that occurs per degree if there is an input voltage of 3 V?

9.15.9 It is desired to construct a dynamic compression force cell capable of measuring forces in the range of $\pm$ 1000 N. If a quartz disc 1.0 mm thick and 10 mm in diameter is used as the sensing element, determine the force cell sensitivity (mV/N).

9.15.10 Describe the methods for decreasing the influences of electromagnetic radiation on a measurement system.