Handling
▶ Manufacturing
Assembly
Organisation

FESTO

Pneumatics
Electronics
Mechanics
▶ Sensorics
Software

Hesse

Sensors in Production Engineering

Chinese
▶ English
French
German
Russian
Spanish

Blue Digest on Automation

053 793

Hesse

Sensors in Production Engineering

Manufacturing
Sensorics

Stefan Hesse

Sensors in Production Engineering

Blue Digest
on Automation

Blue Digest on Automation

Ruiter Straße 82
D-73734 Esslingen
Tel. (0711) 347-0
Fax (0711) 347-2144

Preface

Sensor technology, like micro-electronics and gene technology, has developed into a key technology. Scientific and technical innovation is now increasingly closely linked with the term “sensor”. There are few problems today in data acquisition that cannot be solved using sensors. For that reason, sensors occupy a prime position in the broad field of factory automation and in many other applications. They make control systems sensitive, supply status and position values in machine structures and allow equipment to react with a certain degree of intelligence. In short, they relieve the human component in production of a small part of the monotonous thinking and monitoring role. In fact, some processes are not possible without sensors. The number of components, including pneumatic components, with various sensors already integrated will increase in the future. The user must be prepared for this and that is where this digest comes in.

This volume is aimed at practicians and is a concise, illustrated introduction to the main areas in contact and contactless acquisition of up-to-date process data. It is structured according to typical task areas, shows numerous applications and also provides very brief explanations of important physical contexts. Nonetheless, it can only describe a small aspect of operational reality. I am very grateful to Dr. Ute Forstmann and Mr. Armin Seitz (FESTO) for their assistance in the writing and proofing of this manuscript.

Stefan Hesse

Contents

1 Sensors as technical sense organs

A living thing can only survive if it can react to the conditions around it. Even unicellular organisms have developed this capability. Biological structures called receptors exist in order to receive specific stimuli from the surroundings or from inside the body and then forward them to the central nervous system.

Technology has now developed to such an extent that it can also reproduce receptors. These receptors are artificially manufactured and are called sensors. Once integrated in machines, devices, systems, vehicles, coffee machines and other products, receptors help them to react semi-autonomously to specific states and to control the reaction. Sensors allow machines to emulate the human ability to perceive. Each of the human senses can be compared to a sensor type:

- Sight ➔ Optical and visual sensors
- Hearing ➔ Acoustic sensors
- Smell and taste ➔ Chemical sensors
- Touch ➔ Tactile sensors

There are also many chemical, physical and even biological measured variables that cannot be perceived by the human senses but that can be recorded by sensors. Over the past years, the use of sensors has advanced at an above-average pace. Sensor chips are omnipresent, even if they are not immediately obvious.

As the curator of a robot exhibition held a few years ago, R. Malone reckoned that,

"...everything is becoming intelligent these days. At some point, you will have a major argument with your garden furniture. You will say: < What are you doing out here in the rain? Why didn't you go inside like I told you?>"

This remark gives some indication of what we can expect in the future:
The extensive use of sensors in almost everything from machines to basic commodities. Sensors will become commonplace. There is no way around it. Microsystems will become more important. Many sensor tasks, the solutions to which were previously only the stuff of dreams, will become feasible thanks to tiny, but nevertheless powerful, sensors and sensor systems. Motion units, which previously could at best be equipped with a proximity sensor, will offer further sensor functions. Sensors and signal processing will merge. The fact is that automation technology is entering an exciting time. Intensive discussion is needed in order to get to grips with this transition to sensor-supported machinery. This book is intended as an aid to this discussion.

1.1
Why sensors?

A modern industrial society cannot survive without extensive automation. Man first liberated himself from his menial role in production and then introduced drive units. This process lasted centuries and is referred to as mechanisation. It is an indispensable prerequisite for the next step: Gradual automation. A further prerequisite for automation is a high level of control technology. Take for example the English company "Morris Motors" that set up its first indexing line in 1923. It performed 53 operations on cylinder blocks at a rate of 15 pieces per hour. However it proved unreliable as the mechanical control system available at the time could not meet the demands placed upon it. The range of components available today is, by comparison, sublime. Even information processing has been able to scale new heights thanks to microcomputer technology, fuzzy logic, genetic algorithms and the beginnings of artificial intelligence.

Before any information, data or measured values can be processed they must first be acquired. They can either be read from measuring devices by a person and then input or sensors can be used to perform the same function without human assistance. Without sensors, the only type of automation possible is non-reactive in nature. A machine of this type can be compared to a torso that is blind, deaf and removed from reality. For example, if an electric motor did not have a thermostatic switch, a person would have to constantly monitor an indicator and turn off the motor manually if the need arose. The course of development is somewhat different. There is a constant move towards the greater automation of even small-scale production – a move which demands flexibility as the machines must be able adapt to the ever-changing requirements as autonomously as possible. This explains the tremendous boost that sensor technology has experienced in the past 20 years with growth rates in the two digit range.

The following tendencies can be extrapolated for future sensor generations:

- Greater forward integration; i.e. greater intelligence in the sensor and less power requirement
- Miniaturisation through the use of microelectronics and microsystem technology (miniature housings)
- Reduction of costs through mass production methods (thin layer, thick layer, ASICs, etc.)
- Development of communication standards for sensor systems (bus systems, communication between field and management levels, diagnosis, fault finding)
- Considerable reduction of installation and wiring costs; easy integration of sensors and actuators in one bus network
- Improved combination potential for devices from different manufacturers
- More robust measurement methods that are essentially fail-safe and that live up to the motto "Fit and forget"!

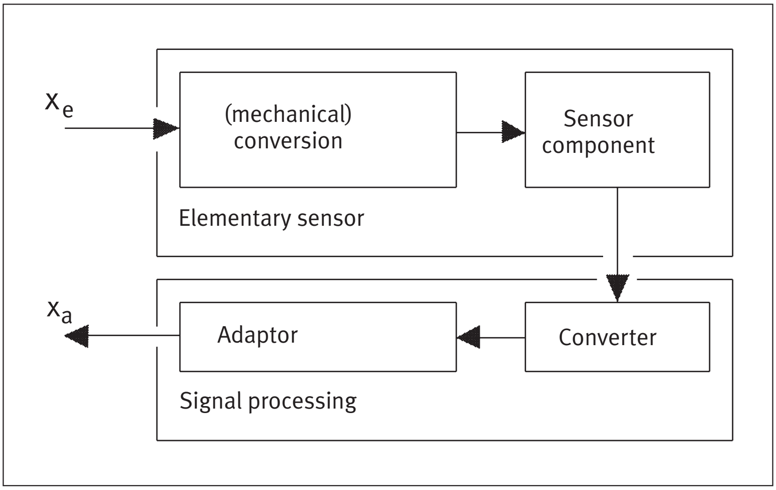
1.2 Classification and terminology

Sensors are detecting elements that detect time-variant physical or even electrochemical variables and convert them into a unique electrical signal. The term "sensor" comes from the Latin sensus for feeling or sense and was first recorded in the reference books in the Seventies. The terms previously used were detector, encoder, indicator, transducer and transmitter.

Fig. 1-1 shows the basic operating principle of a sensor. As can be seen, a certain amount of signal processing (pre-processing) is usually required before the information is forwarded to an executing system with actuators. The sensor function can be realised with the help of different physical operational principles for primary conversion.

Fig. 1-1
Sensor principle

x_e Measured variable
x_a Output signal



If the level of information processing required goes beyond simple pre-processing, the sensor can be linked to a microcomputer and is then often given the catchy title of "intelligent" (*smart*) sensor. As well as the term "sensor", the following terms are also used:

Sensor component or elementary sensor
Designation for the actual converter component that converts a non-electrical variable into an electrical variable on the basis of a physical effect. Every now and then, this happens via an intermediate variable.

Sensor system
Designation for a system made up of numerous measurement and evaluation components. An effective interaction involving the sensor, the item to be measured and the surroundings takes place in this system at the time of measurement. It has a considerable number of signal conditioning functions.

Multisensor system
Designation for a system made up of numerous individual sensors, each of which simultaneously detect measured variables. They are predominantly designed as semiconductor sensors and are therefore very compact. Multisensory solutions can be structured in one of three ways:

- Sensor combination with different measurement principles, e.g. tactile, visual, acoustic (heterogeneous)
- Sensor combination with the same measurement principle at different points in the system (homogenous)
- Individual sensor for detecting several related events, e.g. moving objects

Sensors can also be differentiated on the basis of binary, digital and analogue technology. Binary sensors are bivalent switches that only work with the electrical switch signals ON or OFF, for example proximity sensors, pressure switches or thermostats.

Analogue sensors, on the other hand, supply a continuous physical measured value, usually as a voltage or current. They include sensors for travel, angles, forces and for flow rate, for example. Appropriate calibration allows sensors to be used as transducers. Calibration according to DIN 1319 refers to the determination of the relationship between the measured variable (actual value) and the display (measured value).

For instance: Measured variable = 10.00; display = 10.86;
Calibration: Correction of the display to 10.00

The detection of object characteristics with the help of sensors is based on the principle that energy in any form will be changed or modulated by the object and the information affected by this change or modulation will be analysed by the sensor. A distinction can be made here between active sensors that have transmitters and receivers for said energy and passive sensors that utilise the energy originating from an external source. The sensor types can therefore be classified according to the forms of energy, as Fig. 1-2 shows. The applicable basic laws of physics govern the fundamental characteristics of the sensors and also the scope of their application.

Fig. 1-2
Classification of sensors according to the form of energy

Energy	Sensor type
mechanical	tactile, acoustic, fluidic
electromagnetic	electric, magnetic, inductive, capacitive, dielectric, arc
thermal	thermal, thermal imaging
optical	geometric-optical, imaging
radioactive	radiation absorption, diffusion

Sensors must also be understood and fashioned as structural parts that are integrated in a group of other components and modules. Their failure probability must therefore be low. Further characteristics that sensors must possess are sensitivity to disturbance (cross sensitivity) and the ability to self-align.

2 Sensors in production

The age of industrialisation saw the gradual rationalisation of production processes. With this rationalisation came the desire to transfer the sensitive capabilities of the workers to machines. In the Thirties, for example, photoelectric cells began to be used to sort grains of rice, beans and cigars by colour. They then began to be used to check the labels on jam jars and ultimately their use in an American system for checking cam shafts permitted the rationalisation of 14 positions. Today there is a tried and tested range of sensors and new applications are constantly coming to light. Almost all machines now use sensors.

What was true for James Watt is still true today: You cannot properly control or regulate a variable unless you have first measured it. In his day, James Watt had only mechanical means of control. Today microelectronics and other progressive technologies present completely new possibilities.

Some 150 physical and chemicals effects are used in current practice to acquire all the information from the real world that automation systems need to relieve and protect workers, to be able to make optimum use of machines and to ensure product quality.

2.1 Functions and useable effects

There are some 5000 physical phenomena related to inanimate objects that can be used as basic operational principles for sensors. This book presents and explains the most common of these effects. However do not be surprised if sensors appear that work on a principle not previously used.

How are the variables to be measured recorded?

- Via a direct mechanical contact or via a mechanical interface system (tactile sensor)
- via a system based on the proximity effect (approximative sensor) or
- via an imaging system where the distance to the item to be measured is of no direct significance in terms of the evaluation performed by the sensor (camera with image processing system).

What variables have to be recorded in everyday production and what effects can be used to record them?

Recording mechanical variables
- Law of induction
- piezoelectric effect and reciprocal piezoelectric effect
- electrical resistance as a function of geometric variables
- change in specific resistance as a function of mechanical tension
- coupling of two coils via an iron core
- Inductance of a coil as a function of magnetic resistance
- Capacitance of a capacitor as a function of geometric variables

- change in relative permeability as a function of mechanical tension
- natural frequency of a string or a bar as a function of mechanical tension
- Differential-pressure method
- Preservation of pulse (Coriolis flow meter)
- Vortex formation behind a disturbance body
- Flow measurement via recording of the transfer of heat
- Speed of sound as a function of the speed of the medium

Recording thermal variables
- thermoelectric effect
- pyroelectric effect
- electrical resistance as a function of temperature
- intrinsic conductivity as a function of temperature
- Ferroelectricity
- Quartz resonant frequency as a function of temperature

Recording radiation
- external photoelectric effect
- internal photoelectric effect, insulating layer photoelectric effect
- photoelectric effect, Compton effect and pair generation
- Excitation to luminescence, radioactive radiation

Recording chemical variables
- Formation of electrochemical potentials at boundary layers
- change in the work function at interfaces
- Temperature sensitivity of the paramagnetism as a function of oxygen
- Gas analysis through determination of the thermal conductivity or heat of reaction
- Hydrogen ion conductivity of solid electrolytes
- Flame ionisation detector principle
- hygroscopic characteristics of LiCl
- Capacitance as a function of the dielectric

Sensors are used in the broadest range of fields and industries. Thus sensors used in medical engineering, for example, must satisfy different requirements and boundary conditions to those used in production engineering. What tasks are currently relevant in production engineering?

Establishing the presence of objects
- Checking for the presence of individual objects, e.g. a washer
- Checking that all components are present in the correct number, e.g. in an assembly
- Detecting flowing liquids or quantities
- Counting objects

Recording the identity of objects

- Detecting impermissible (incorrect, defective, ruined) parts in the process
- Classifying permissible objects, e.g. by tolerance classes or types
- Performing optical character checks and recognition, e.g. plain text, bar codes, matrix codes

Recording the position and/or orientation of objects

- Detecting individual objects relative to their surroundings, e.g. parts to be gripped on a conveyor belt
- Detecting the position of objects relative to tools, e.g. the position of a welding groove relative to the welding torch
- Detecting the position of objects against a limited background, e.g. for cut out optimisation (nesting)
- Scanning objects in relation to lengths and angles, e.g. for tolerance checks, offset, deflection, deformation, play, canting, eccentricity, thickness

Recording the shape characteristics of objects

- Checking contours, e.g. to ensure threads are correct
- Checking object regions, e.g. to ensure edges are present
- Checking that the number of shape details is correct, e.g. fully moulded plastic part
- Measuring deformations to permit the determination of force and moment

Recording surface characteristics of objects

- Checking the micro-geometry of objects, e.g. for roughness
- Checking shade, e.g. when sorting coloured broken glass
- Checking for homogeneity of the micro-geometry of objects, e.g. textures, damage or colour flaws

Checking the material characteristics of objects

- Evaluating the transparency of objects or indeed the glossiness
- Distinguishing material types, e.g. when sorting plastic recyclable objects to ensure homogeneity of materials

2.2 Application analysis and selection criteria

There are two questions that must be answered once it becomes clear that sensors are required in an automation task. These are:

- What sensory functions are required?
- What is the requirements profile for each sensor?

The following questions must be considered when analysing the initial situation:

- What are the unknowns in the process?
- What unknowns are not tolerable and are to be controlled using the sensor?
- What are the environmental conditions (dust, moisture, temperature, etc.) to be taken into account?
- What status variables are important and what reference values are available?
- How is the information to be transferred?
- What physical principle promises the greatest success?
- What auxiliary energy is to be provided?

Many aspects must be considered in detail. The table below lists some of these aspects.

Aspects to be considered when assessing the suitability of a sensor for a task	
• Response times, reaction and switching speed • Connection system (2, 3, 4 conductor technology, series connection, parallel connection, etc.) • Operational reliability, failure rate, reliability • Self-monitoring mechanism) • Operating temperature range • Variability of operating points, sensitivity and trigger level • Resolution, accuracy of measurement • Corrosion resistance • Service life • Power limits, operating range • Object characteristics (material, luminance factor, surface pattern, etc.) • Implementation set-up (dimensions, sizes, assembly conditions, adaptation to recording location) • Redundancy of the evaluation unit	• Reproducibility of the switching characteristics • Non-interaction of the physical principle • Switching distance • Switching point drift, switching point hysteresis • Protection class • Voltage supply (operating voltage, voltage fluctuations, voltage peaks • Interference suppression (insensitivity to external disturbances such as oscillations, impacts, external light, etc.) • Technical availability • Temperature resistance • Overload protection (short circuit protection, polarity reversal protection, overload withstand capability) • Economic efficiency (cost/benefit, incl. costs of connection) • Approval for special applications (clean room, explosion and personnel protection, etc.)

These aspects must be weighted when performing a suitability assessment since there is no one sensor that can provide all the characteristics required for the measurement task.

The steps involved in selecting sensors are as follows:

1. Selection of a suitable physical operational principle
2. Determination of the required measuring range
3. Definition of the change to be expected in the measured variables
4. Specification of the measurement signal resolution
5. Specification of the smallest value to be measured
6. Definition of the errors permitted as a side-effect of the static and dynamic characteristics
7. Calculation of the screening costs (electromagnetic compatibility)
8. Calculation of the costs involved in amplifying and evaluating the measurement signal
9. Evaluation of operational reliability, general reliability, service life and maintenance costs
10. Calculation of procurement costs

Here are also many specific recommendations related to the use of sensors. For example, through-beam sensors would be the first choice for optical detection. They guarantee reliable switching with the greatest possible range. Retro-reflective sensors would be the next choice. With a range half that of through-beam sensors, retro-reflective sensors offer a secure switching point for the majority of materials. However light barriers can fail where the objects in question are very shiny. Devices that polarise light are used here in order to increase protection against interference. Since the receiver in light barriers sees the light when there is no workpiece present and the signal drops off when a workpiece is detected, this type of sensor monitors itself. The signal also drops off if the transmitter stops emitting a light beam.

Diffuse sensors are used where objects can only be sensed from one side. They can also be used to detect transparent objects, but are not suitable for detecting matt black parts. Very small objects can be opto-electronically detected using fibre optic cables. Object edges can be better traced using laser retro-reflective sensors where the distances involved are large.

With capacitive sensors, the area around the active zone of metals and materials with high relative permittivity must be kept free. Minimum distances are prescribed when using multiple sensors that interact with each other. Dust deposits can result in malfunctions. With environmental conditions such as these, capacitive sensors with additional compensating electrodes should be used.

Inductive and capacitive sensors are not immune to intensive X-radiation or strong magnetic fields. (The latter occur at resistance welding workstations, for example.) Sensors resistant to welding currents should be selected in cases such as these. The installation environment must also be taken into consideration when installing inductive sensors. If the sensor is to be fitted flush to the surface of a machine component, a recess may need to be made in the surrounding material. Incidentally sensors with LED displays should always be used so that the operating status of the sensor can be monitored.

Reed contact switches, while resistant to shocks many times the acceleration due to gravity when used as signal generators for pneumatic cylinders, should nevertheless be protected against impacts. These sensors can be susceptible to maloperation in strong magnetic fields. There are also minimum distances between pneumatic cylinders that must be observed. Contactless magnetic-inductive proximity switches can be used instead of reed switches. They are slightly more expensive but less sensitive to interference and more accurate.

It is worth mentioning that many sensors are not suitable for direct switching of solenoids in directional control valves. Accordingly an auxiliary relay or a suitable protective circuit should be used with a non-electronic control system.

Pressure switches can exhibit switching point hysteresis caused by internal friction resistance (spring). When the pressure is increasing and once the set point has been reached, the electrical signal will follow. However the sensor does not switch at the same point when the pressure drops. In other words, the switch-on point is not the same as the switch-off point. This behaviour must be taken into consideration when setting the pressure switch regardless of whether or not switching is to take place when the pressure is increasing.

When using ultrasonic reflective sensors in relative proximity, an echo caused by sensor A can also be received by sensor B. This results in an incorrect measurement. This mutual interaction can be ruled out by synchronising all sensors. Once synchronised all sensors transmit at the same time. No problems occur then once the distance the sound has to travel from sensor A to sensor B is greater than the maximum detecting distance. Another solution to the problem of mutual interaction is to use the multiplex operating mode where sensors are activated in succession and cannot interact with each other.

What sensors are used most frequently?

An examination by value of the world sensor market produced the following ranking for the different sensor types (Intechno Consulting, 1998):
- Temperature sensors
- Pressure sensors
- Flow sensors
- Binary position sensors
- Position sensors
- Chemical sensors for liquids
- Filling level sensors
- Speed sensors
- Chemical sensors for gases

The civilian world market for sensors was valued at more than 30 thousand million Euros in the year 2000. This figure will double by the year 2010.

Sensors and their applications – a brief overview

Task	Sensor type
Checking presence	Proximity sensor, radiation sensor, back pressure sensor, vacuum sensor, retro-reflective sensor, reflex sensor, ultrasonic reflective sensor, D field sensor
Measuring distance	Line-scan camera, ultrasonic reflective sensor, microwave sensor, PSD component, tactile sensors, reflex sensor, inductive and capacitive sensors, laser scanner, triangulation sensor, D field sensor
Controlling belt ride and slack	Light curtain, line-scan camera, light barrier, inductive sensors, ultrasonic reflective sensors, air jet sensor
Tracking paths and edges	Force-moment sensor, tactile sensors, line-scan camera, matrix camera, inductive sensors, air jet sensor
Recording speed	Hall sensor, Wiegand sensor, magnetoresistor sensor, reflex light barrier, inductive sensor, high-frequency measuring head, reed switch, light barrier, increment generator
Measuring pressure	Piezo sensor, capacitive sensor, sensor with strain gauge, magneto-elastic sensors
Measuring flow	Turbine wheel flow meter, differential pressure sensors, magnetic-inductive sensor, Coriolis flow meter, ultrasonic reflective sensor, hot-wire anemometer, thin-layer sensors, hot-film anemometer
Measuring filling level	Capacitive sensors, microwave sensor, ultrasonic reflective sensor, optical sensor with fibre optic cable, oscillating fork sensor
Inspection, identification, completeness check	CCD sensor, ultrasonic array, laser scanner, transponder
Collision protection	Ultrasonic reflective sensor, microwave radar, infrared sensor, laser scanner
Measuring force, moment	Strain gauge, dynamometers, inductive sensors, pneumatic sensors, fibre optic sensors, piezo sensor
Checking surfaces	Image sensor, laser scanner, gloss sensor
Detecting positions	Reed switch, light sensor, light barrier, micro sensor, magneto-resistor sensor, reflex sensor, magnetic field sensor, AMR sensor, GMR sensor, ultrasonic reflective sensor, PSD component
Monitoring processes	Thermoelement, flow meter, pressure sensor, proximity sensor, muting sensor
Sorting	Image sensor, ultrasonic array, colour recognition sensor
Detecting parts, positions	Odometer, centrifuge, CCD sensor, laser scanner, detection matrix, split-beam sensor, gyroscope
Scanning objects	Light curtain, line-scan camera, laser scanner
Measuring displacement or angles	Increment generator, resolver, Inductosyn, linear encoder, potentiometer, magnetostrictive sensors, Hall effect sensor, AMR, GMR sensor
Counting objects	Light curtain, fork-type light barrier, ultrasonic reflective sensor, magnetoresistor sensor, air through-beam sensor, fibre optic cable sensor, PVDF film sensor

3 Recording positions

During production, automated tool and workpiece movements must be constantly checked. The position of machine parts and different types of objects must be recorded and provided as signals to this end. Often all that is needed is a check to make sure that an object is in place.

3.1. Electro-mechanical position recording

Tactile sensors are used to determine positions, shapes, temperatures, forces, moments and pressures. Tactile sensors also include mechanical position switches (limit switches, proximity switches, micro switches, precision control units) that are used on many production devices to acknowledge movements. These switches are also referred to as binary sensors as they return only the value ON or OFF. They are very accurate and automatic, however the contacts tend to rebound once they start to wear. They cannot therefore switch as quickly as contactless proximity switches. The operating principle of tactile sensors is shown in Fig. 3-1.

The movement of the stylus is transferred to contacts that open or close a circuit. Spring mechanisms that ensure an abrupt switchover are integrated in many switches of this type in order to ensure an exact switching operation. There are also various actuator elements that can be used to transfer the movement from the machine part to the switch. As well as rollers, there are roller levers, idle return roller levers, spring steel bar adaptors, drawbar eyes, etc. The reproducibility of the switching point is in the region of ± 0.01 even for low-cost sensors and is therefore excellent.

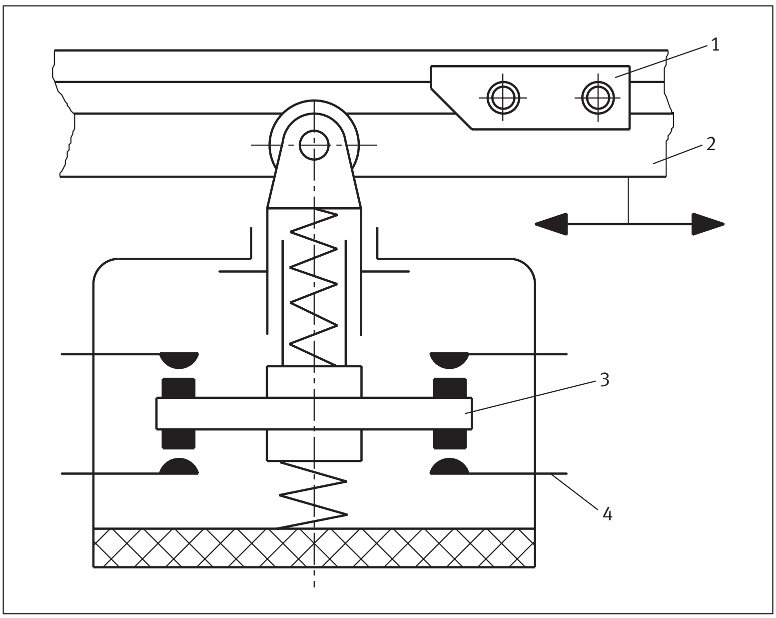


Fig. 3-1
Electro-mechanical sensor

1 Trip cam
2 Machine part
3 Contact blade
4 Contact

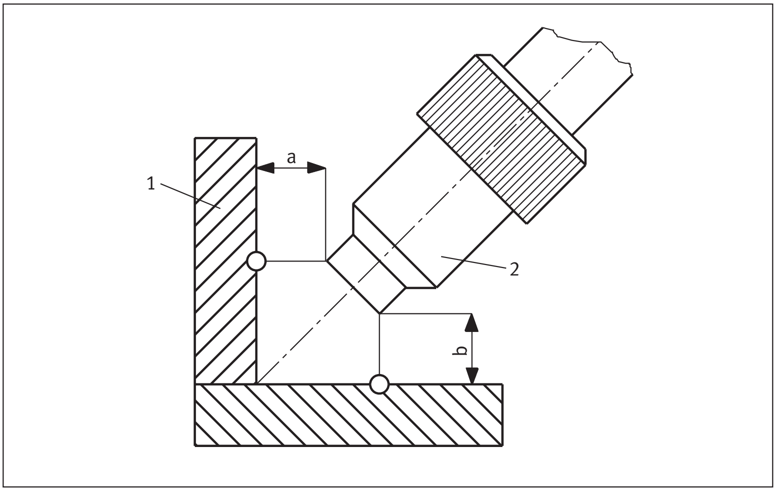
Precision switches can provide a level of accuracy that is greater by the power of ten. Mechanical wear and the erosion of contacts limit the service life of micro switches to 10 million switching cycles. Their function is not impaired by electromagnetic fields and they are also very inexpensive. However it must be pointed out that wearing of limit switches is the main cause of failure in automated systems. Incidentally, the oldest position sensor in the world is the micro switch with push-in switching reed developed by *Honeywell Micro Switch* in 1932.

An electro-mechanical position sensor can also assume a completely different form. Consider a case in welding technology where a joint profile must be determined before the joint can be automatically welded. The characteristics of a corner seam can be measured in a separate pass and the data then used to control the welding torch. The gas nozzle of the welding torch can be used here as a tactile sensor (Fig. 3-2). The welding torch is tentatively moved against both surfaces. When the gas nozzle touches a welding piece, a current flows if a measured voltage is applied to the nozzle. The relevant position value is recorded and saved. Measurement takes place in a separate measurement pass. The distances a and b are used to calculate the exact position of the vertex and the programmed path can then undergo a transformation to the actual alignment of the seam. The measurement pass is followed by the welding pass.

Fig. 3-2
Gas nozzle as tactile sensor

1 Welding piece
2 Gas nozzle

a, b Distances



3.2 Pneumatic position recording

Sensors that work on the basis of air are mainly used as proximity switches. They are also used for direct signal input in pneumatic control systems.
A differentiation is made between back pressure sensors, reflex sensors and air barriers. They have a simple construction and their very operating principle means that they are self-cleaning.

The back pressure sensor works on the nozzle-baffle plate principle (Fig. 3-3a). When the supply pressure p_1 is maintained at a constant level, the pressure p_2 is indirectly proportional to the distance s between the nozzle and the object to be recorded. The measurement distance range for back pressure sensors is between 0.1 and 3 mm when conical nozzles are used. The signal can then be further processed using analogue or digital methods.

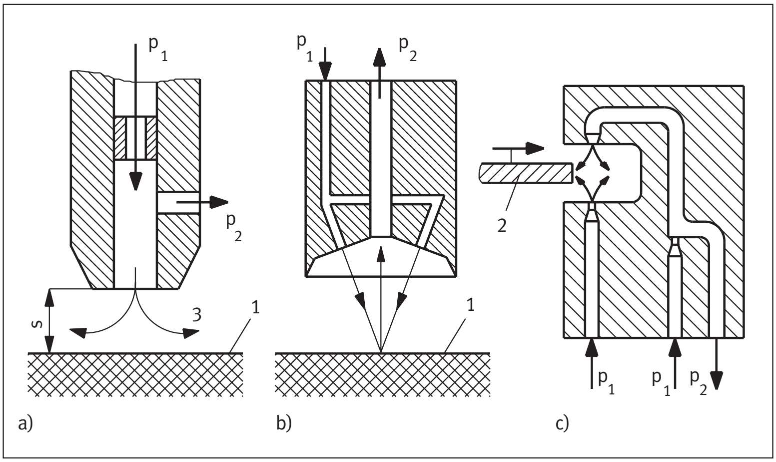


Fig. 3-3
Pneumatic sensors

a) Back pressure sensor
b) Reflex sensor
c) Air barrier

1 Item to be measured
2 Switching lug, object
3 Free jet

p_1 Supply pressure
p_2 Measuring pressure
s Distance from the nozzle to the object

The reflex sensor shown in Fig. 3-3b works on the reflex principle. A ring-shaped free jet is discharged against an object. During this process, some of the jet is diverted inwards and causes an increase in pressure in the central output channel. The differential pressure is evaluated. The signal can then be further processed using digital methods. The measurement distance range is less than 10 mm. Due to its non-linear characteristic curve, the reflex sensor is mainly used to detect the presence of objects.

Air barriers work on the oblique jet principle (Fig. 3-3c). Air flows from both nozzles. The measuring signal is picked up on the receiver side (top). The air barrier's mode of operation is the same as that of the reflex sensor.

Pneumatic proximity switches offer reliable operation, even in the presence of dust and high ambient temperatures. They can be used in explosion protection areas and are not affected even by magnetic interference fields. The measurement distance range extends to approx. 30 mm.

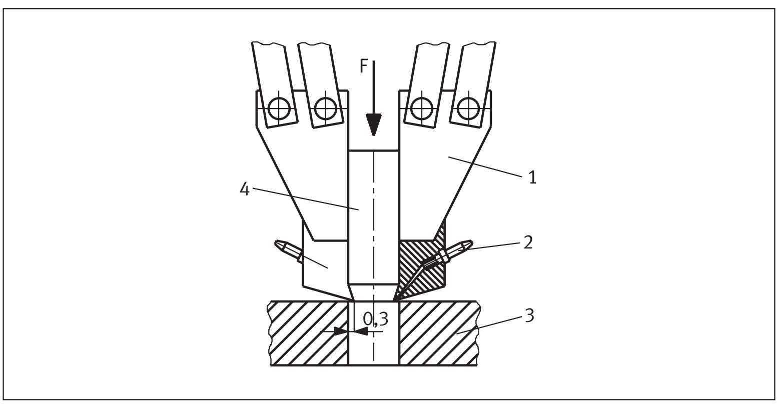


Fig. 3-4
Pneumatic sensors help to find the exact jointing position

1 Gripper jaw
2 Supply port
3 Lower workpiece
4 Assembly part

F Jointing force

Pneumatic sensors can be used for positioning tasks, for example. Fig. 3-4 shows a jointing head for rotationally symmetric workpieces. This technique is suitable for jointed parts with and without chamfers. The sensors are attached to the moving gripper fingers and touch the workpiece surface before the bolt. The differential pressures generated by means of the offset of the bolt relative to the hole are evaluated and used to adjust the supporting device or the robot. A centring accuracy of approx. 10 µm can be achieved within 0.1 s.

Back pressure sensors can be used in the construction of jigs and fixtures, for example, to check that parts inserted for processing are correctly engaged. As can be seen in Fig. 3-5, a check is performed as to whether the part is correctly engaged which will not be the case if dirt or chips have accumulated. To this end, the back pressure at all jet pads is evaluated. If the measured distance is less than 0.05 mm, it is within tolerance and the pressure switch responds. The workpiece is then clamped and can be processed. In the example, all 4 engage units must supply enable signals. The ejector and the pressure switch in the vacuum intake channel compensate any fluctuations in the supply pressure.

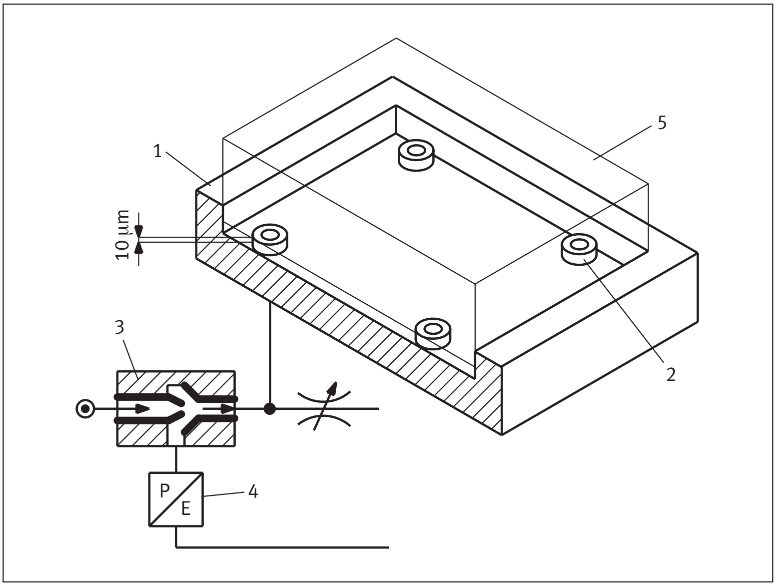


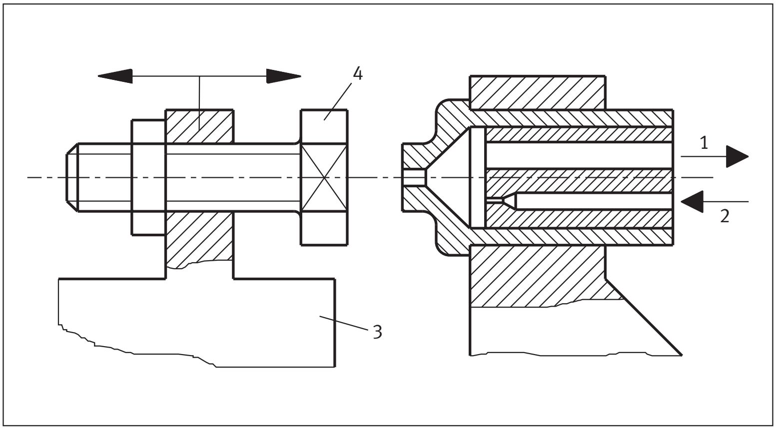
Fig. 3-5
Operating principle of a pneumatic engage control unit (Festo)

1 Jig
2 Pad with integrated nozzle
3 Ejector
4 Pressure sensor
5 Workpiece

Fig. 3-6 shows another interesting application of pneumatic sensors. In this case, the pneumatic sensor serves as a binary sensor in a machine structure and assumes the role of a limit switch. The adjusting screw strikes the stop that acts as a back pressure sensor. This closes the nozzle. The change in pressure is used as a switch signal. The advantage of this approach is that it allows the cost-effective integration of sensor technology in machines.

Fig. 3-6
Pneumatic limit stop sensor

1 **Pneumatic signal**
2 **Supply pressure**
3 **Machine slide**
4 **Adjusting screw**



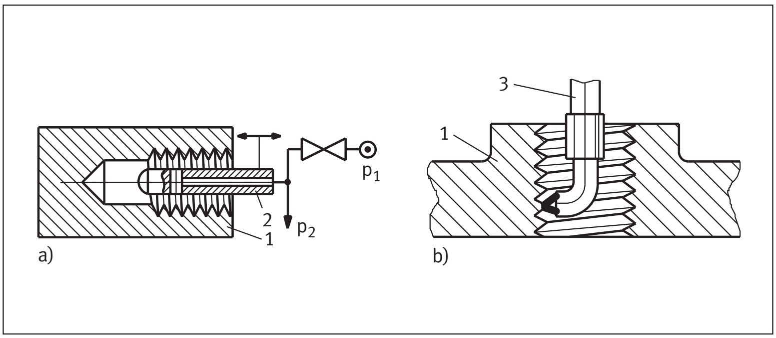
The recording of particular characteristics requires the use of sensors tailored to the task in hand. In Fig. 3-7a, a pneumatic probe is inserted into the threaded hole to determine whether the thread actually exists. As the probe is inserted and removed, the measuring signal fluctuates in tandem with the thread. This solution is very straightforward - all that remains is to convert the pneumatic signal into an electrical signal. In the case of larger threads, this inspection can also be performed using a reflex light sensor using a thin fibre optic cable with a bend in the end (Fig. 3-7b).

Fig. 3-7
Measuring the hole diameter, inspecting the thread and checking for contamination

a) Pneumatic
b) Optical

1 **Workpiece**
2 **Measuring nozzle**
3 **Fibre optic cable**

p_1 Supply pressure
p_2 Measuring pressure



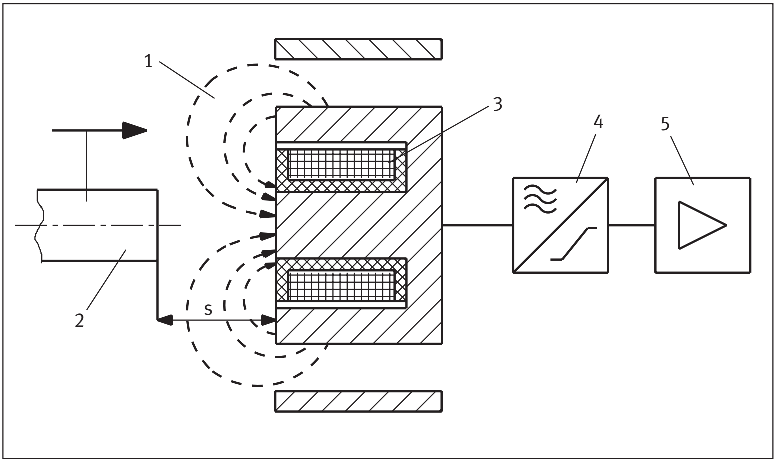
3.3 Inductive pposition recording

Many inductive sensors can be divided up into the function groups oscillator, evaluation unit and output module. They are contactless, wear-resistant, switch quickly and without rebounding and are therefore durable. When a voltage is applied to an oscillator, it begins to oscillate and absorbs a specific current. The high-frequency alternating field extends to the active area. If a metal part (not only ferromagnetic objects) is then introduced into this field at the distance s, an eddy current will be induced in the metal object. This counteracts the high-frequency field, attenuating the oscillator. This results in a change in the current consumption. The downstream evaluation unit detects this change and actuates the output module accordingly, i.e. an electrical signal is output. The basic principle is illustrated in Fig. 3-8.

Fig. 3-8
Operating principle of the inductive sensor

1 Magnetic alternating field
2 Metal object
3 Resonant circuit coil
4 Oscillator
5 Amplifier

s approx. 1...75 mm



If the electrically conductive object is removed once more, the oscillator ceases to be attenuated and starts to oscillate again. The original switching status of the proximity switch is restored. In other words, sensors of this type function as contactless On/Off switches. The metal object then acts as a switching lug. The coils can also be ring-shaped with a rod that moves in and out. There are also slotted versions. Inductive sensors cope very well with extreme environmental conditions, for example pressures of up to 500 bar in hydraulic applications or temperatures of up to 120 °C in hot regions. If the switch output is replaced by an analogue voltage and current output, the result is an inductive contactless displacement sensor that is also insensitive to environmental influences. This permits the recording of absolute actual positions, for example. Fig. 3-9 shows some simplified representations of applications.

Thus it is clear just how versatile this type of sensor is, particularly in production engineering.

As well as measuring, monitoring, controlling and regulating positions, paths and rotation angles, inductive sensors are also suitable for use in defining derived variables such as speed, rotational speed and acceleration. Self-regulating magnetic-electric converters are very suited to use as r.p.m. sensors. They are small and also easily retrofitted in machine structures. Sectional wheels, slotted shafts or toothed wheels made from ferromagnetic material move past the sensor at close range. The sensor records the tooth frequency and outputs it in digital form.

Fig. 3-9
Sample applications of inductive sensors

a) Measuring thicknesses
b) Checking concentricity
c) Monitoring the thickness of oil films in plain bearings
d) Detecting positioning errors
e) Measuring layer thicknesses
f) Monitoring oscillations

1 Sensor
2 Object to be checked, e.g. a coating
3 Lower workpiece
4 Clevis foot

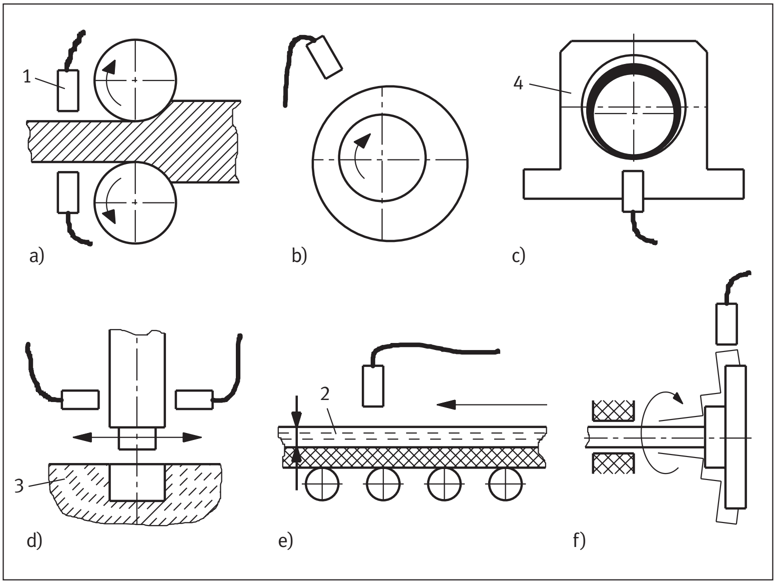
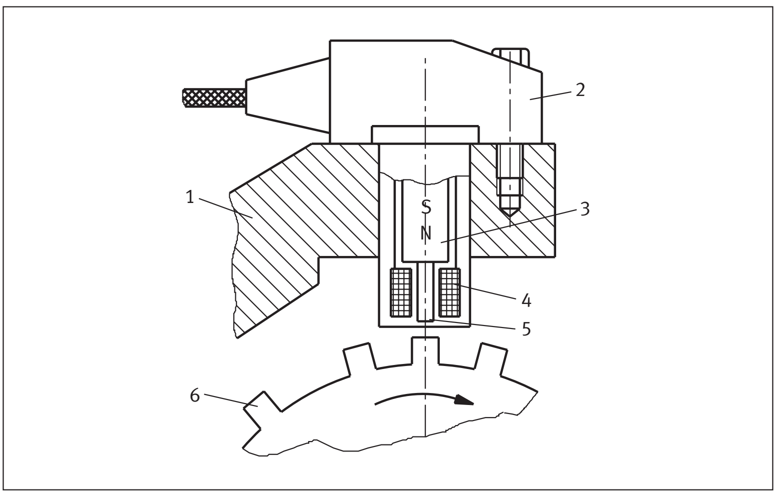


Fig. 3-10 shows the measuring set-up. As the principle is based on the induction of voltage, a minimum speed is needed to produce voltage of a magnitude suitable for evaluation. This means that a rotation starting from the rotational speed “zero” cannot be detected. The advantage of this solution therefore lies in the greater upper critical frequency at 20 kHz and above, for example. The magnetic bias provided by a permanent magnet permits a faster response.

Fig. 3-10
Measuring rotational speed using a magnetic-inductive sensor

1 Housing block
2 Sensor housing
3 Permanent magnet
4 Coil
5 Soft iron core
6 Toothed wheel with reference marks



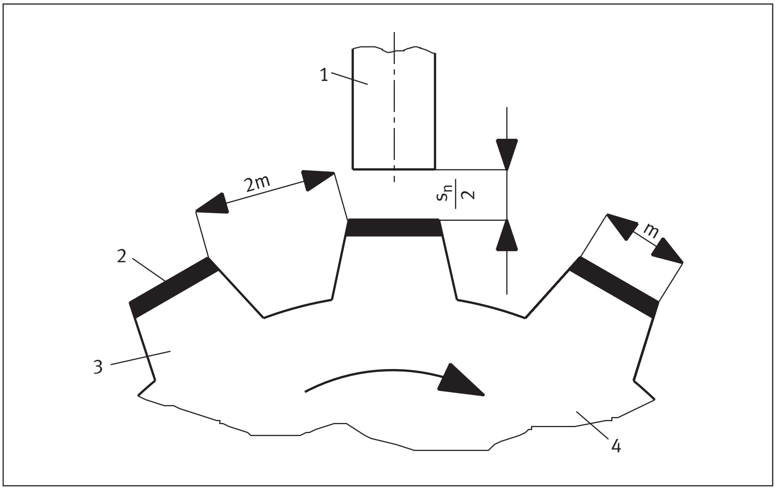
A cost-effective solution can be arrived at through the use of an inductive proximity switch to sense existing toothed wheels or perforated disks with elongated holes in gearings. This results in an inexpensive but reliable “substitute phase sequence indicator”. This measuring method corresponds to the standard EN 60947-5-2. However its resolution and switching frequency are not fully satisfactory. The recommended measuring set-up is illustrated in Fig. 3-11. The tooth-to-gap ratio should be 1:2 and the switching distance s should be set to half the sensor's nominal switching distance sn. This gives almost optimum conditions in relation to resolution and switching frequency (maximum number of cycles from attenuated to unattenuated state per second). The geometry of a standard toothed wheel comes quite close to the ideal shape for sensing. The maximum possible switching frequency is reduced with other pulse/interval ratios.

Specifications relating to switching distances for inductive sensors are always based on actuating elements made from steel (St 37) with defined dimensions. If actuating elements made from other materials and/or with other dimensions are used, then correction factors applied to the switching distance must be taken into consideration, for example 0.35 to 0.5 for aluminium and brass (see Fig. 3-16).

Fig. 3-11
Measuring set-up for the switching frequency of inductive proximity switches (IEC 947.5.2/ENGO 947.5.2)

1 Proximity switch
2 Calibrating plate made from St 37
3 Non-conducting and non-magnetic material
4 Wheel

s_n Nominal switching distance
m Tooth width



Measurement of rotational speed is possible up to 50 000 min^{-1}. The limit for distance measurements is approx. 40 mm.

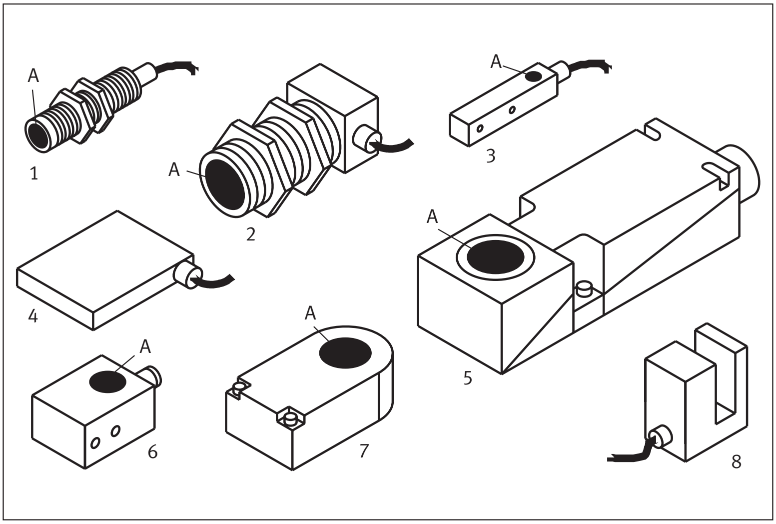
The range of inductive sensors on offer includes many designs and installation types. Fig. 3-12 shows the main designs. These sensors are frequently equipped with a screw-in thread.

When choosing inductive sensors for use in stations with strong magnetic direct and alternating fields, for example resistance welding stations, the sensors selected must be resistant to magnetic fields. This type of sensor uses a special core material, a multiple coil arrangement and a special oscillator rating.
The food and pharmaceutical industries have recently started to use sensors that are enclosed on all sides in stainless steel so that biological material and cleaning solutions have no corroding surfaces and microbial contamination is ruled out.

Fig. 3-12
Various proximity switch designs

1 Cylindrical
2 Cylindrical
3 Bar-type
4 Flat
5 Cuboidal
6 Box-type
7 Semi-circular
8 Forked

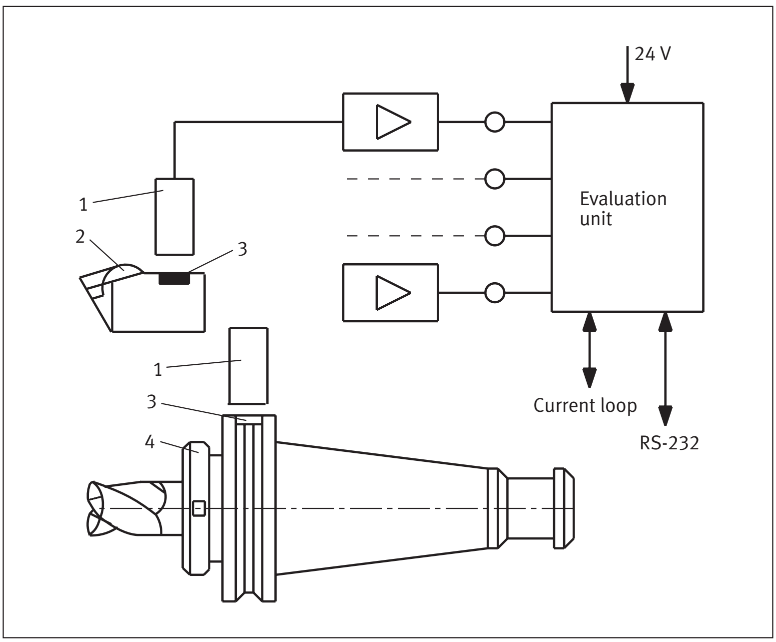
A Active area



The principle of induction can also be used to read and/or write to storage media containing data on objects in workpiece fixture devices or when identifying machine tools in CNC processing centres. This is currently done by integrating memory chips in the tool holder (Fig. 3-13). The chip contains the tool number at the very least, and often also contains tool characteristics. Once it is close enough to the storage medium (up to 5 mm), the read head reads the data by means of induction. This is done via the mutual coupling of two coils. The data (code) medium obtains its energy from the read head.

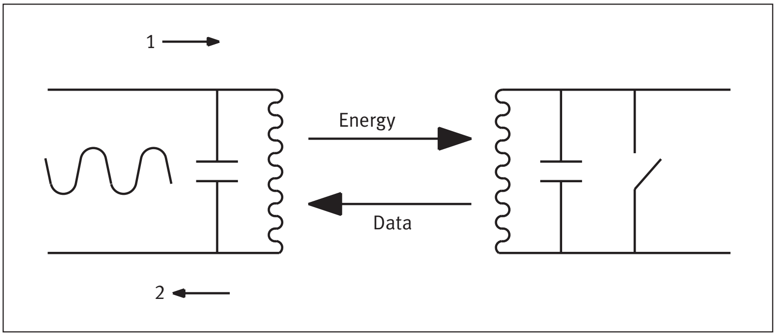
Fig. 3-13
Identifying tools

1 Read-write head
2 Tool head with cutting plate
3 Data storage medium
4 Tool holder with end milling cutter



The sensor (read head) exploits the effect whereby external interference in the electromagnetic alternating field causes a reaction in the resonant circuit that generates the alternating field. This causes a change in the quality of the emitting coil and hence the resonant circuit. The result is a flow of data that acts in the opposite direction to the flow of energy. This is how the information is transferred from the data storage medium back into the read head (Fig. 3-14).

Fig. 3-14
Returning data by influencing the electromagnetic alternating field



Transponders are also increasingly being used for contactless and automatic data acquisition. They are also referred to as RF/ID systems (RF *radio frequency*, high frequency). The term "transponder" is a combination of *transmitter* and *responder*. Passive transponders do not require a battery for contactless data transmission as they are activated by the transmit energy of the reader unit. They can be read and written to from a distance of up to 15 centimetres. They can now be manufactured with a very slim design and can then be used as a dhesive transponder labels, for example with dimensions of 13 x 14 x 0.7 mm. The transponder's conductive track is laminated. This means that the user does not have to execute any additional processing steps to facilitate the supply of information if labels are attached to products anyway.

3.4 Capacitive position recording

Capacitive proximity sensors work without contact according to the mode of operation of a capacitor. They can be used both for objects that conduct electricity and objects that do not conduct electricity. Their basic operating principle is shown in Fig. 3-15. The distance s is measured. The switching distance may not exceed 60 mm. Capacitive sensors are primarily used as the measuring system for precision measuring of paths. Distances of up to 2 mm can be achieved with barrel designs.

The basic operational principle: A high-frequency oscillator responds if the sensitive capacitance C_S of the sensor element is increased by external influences. A noise field forms in front of the base electrode when the oscillator is not switched on. This represents the active zone. Two different facts are exploited here:

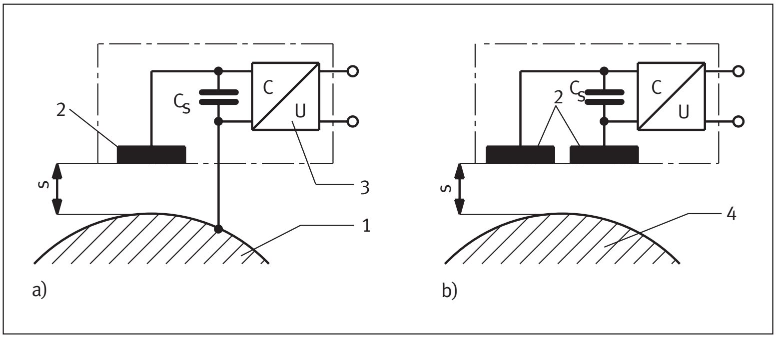
- Conductive materials located in the stray field of the active sensor area act as a counter-electrode.
- Non-conducting materials, i.e. insulators, increase the capacitance of the capacitor to different degrees depending on the type of material (dielectric constant).

Fig. 3-15
Operating principle of the capacitive distance sensor

a) with conductive objects
b) with non-conducting objects

1 Metallic object
2 Free base electrode
3 Capacitance-voltage transducer
4 Non-metallic object

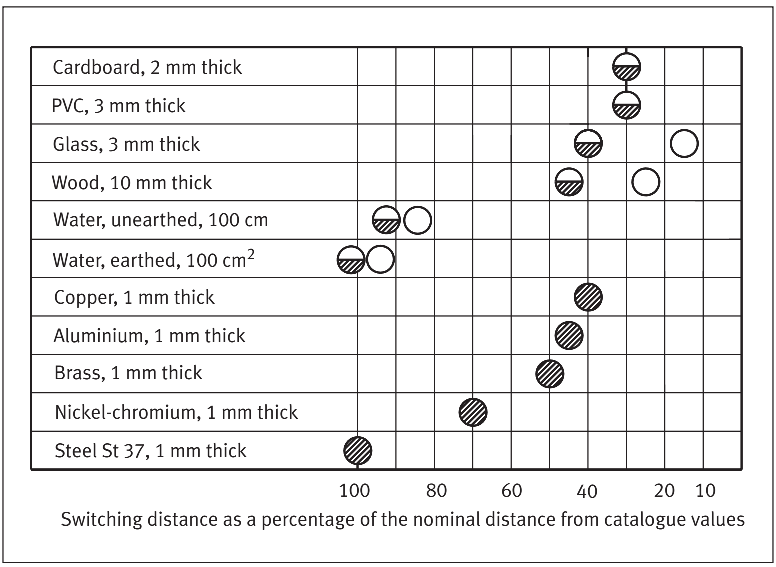
s Switching distance



Greater switching distances can be achieved with conductive objects than with non-conducting objects. The capacitive principle means that dirt deposits and moisture on the sensor surface will be detected. Dust, oil and water represent potential sources of errors as they act as insulators. This can result in malfunctions, where the measured overall distance appears shorter than it actually is. Capacitive sensors with a so-called compensating electrode should be used in cases such as these to prevent undesired switching insofar as possible. The material in question also has a major impact on the function of the sensor. Fig. 3-16 shows how the switching distance with capacitive and inductive proximity switches can change with different materials.

Fig. 3-16
Switching distances with various tool materials

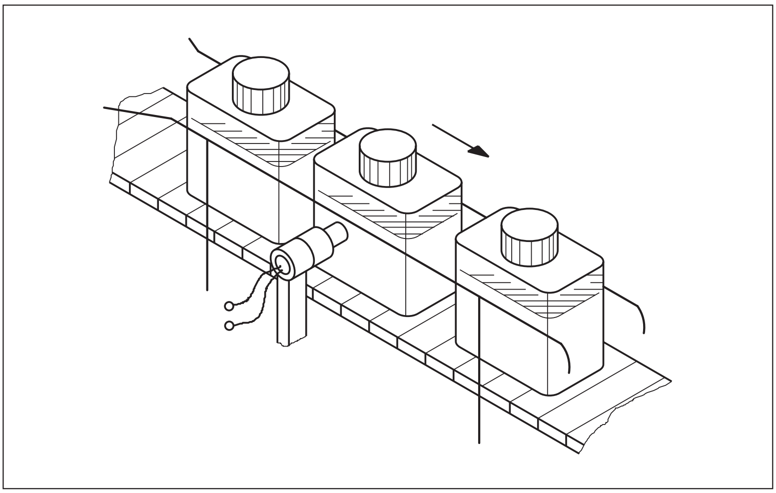
Empty circle: capacitive, metal, moist
Full circle: inductive
Half-full circle: capacitive, non-ferrous metal, dry



There are many cases where one would like to be able to check during a pass whether containers such as bottles, canisters, cartons made from coated cardboard and plastic containers were actually filled. If a jar or bottle is either vacuum-packed or pressurised then the curvature of the lid or the cap, for example, can be optically recorded. Burst or empty plastic bottles can then be detected. Capacitive sensors also offer a simple and sophisticated solution. Fig. 3-17 shows an example of this solution. The level is recorded without contact through the opaque container walls. This solution can also be easily retrofitted into an existing production line. While conventional sensor electronics are best suited to temperatures up to 100 °C, there are also sensor designs that can handle greater temperatures due to their use of highly thermostable materials.

Capacitive sensors can be used for distance measurement, as differential displacement sensors, for differential pressure measurement, as proximity switches, as filling level sensors for fluids and bulk materials as well as for counting operations including rotational speed measurement. However they are not absolutely resistant to interference. High-frequency mains interference can result in incorrect switching. For that reason, new developments favour solutions based on a principle other than the classic oscillator principle that is so frequently used (particularly in proximity switches).

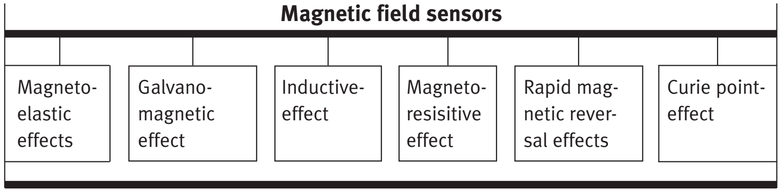
Fig. 3-17
Checking the level in opaque containers using capacitive sensors



3.5 Magneto-inductive position recording

Magnetic field sensors include an entire group of transducers, all of which are characterised by the fact that they exploit the laws and effects of an electromagnetic or magnetic field. Fig. 3-18 shows the effects in question.

Fig. 3-18
Some physical effects used by magnetic sensors

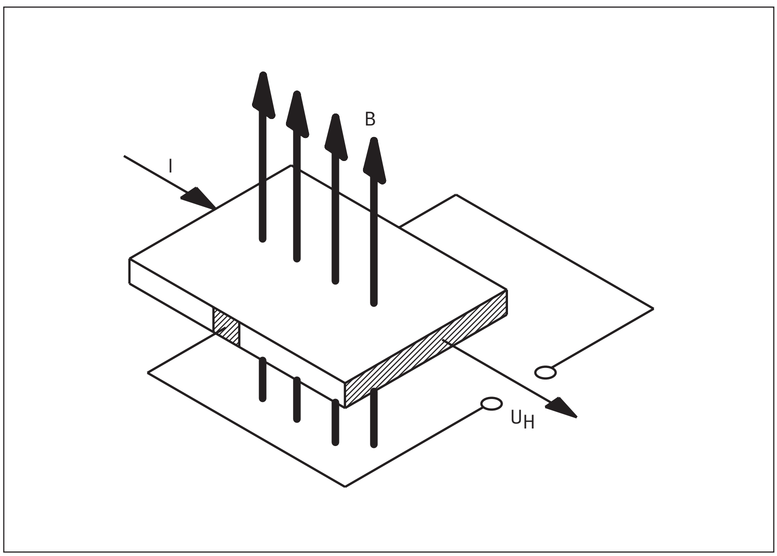


The first solenoid was built in 1825 by the Englishman W. Sturgeon (1783-1850). This was followed in 1838 by the telegraph relay realised by C. Wheatstone (1802-1875). This makes this remote controlled electromagnetic switch more than 160 years old. Some of the oldest magnetic sensors are the inductive sensors already discussed. This section deals with some other frequently used sensors that exploit electromagnetic effects.

3.5.1 Hallsensor

The Hall effect was discovered in 1879. It uses the principle of galvanomagnetism and works as follows: An electric voltage, the Hall voltage U_H, is generated perpendicular to the current flow direction I in an electric conductor if a homogeneous magnetic field B is applied perpendicularly to the conductor (Fig. 3-19). This electric voltage is proportional to the magnetic induction of the external magnetic field B. The Hall effect represents a potential that can be controlled by magnetic means.

Fig. 3-19
Operating principle of the Hall effect sensor



The Hall effect can be used in the design of many sensors, including sensors for recording incremental rotation angles. Fig. 3-20 shows two examples of this application.

In the first example, a ring magnet with n pairs of poles rotates a short distance (air gap) away from the sensor. This causes a fluctuating magnetic field to act on the Hall probe. The Hall voltage generated reflects these fluctuations and can be evaluated. The second example shows how swivel angles are recorded. The output signal can be generated in analogue or digital format.

Hall sensors can be greatly miniaturised when based on semiconductor technology, are completely wear-free and therefore have an almost infinite service life.

Fig. 3-20
Measuring angles using a Hall effect sensor

a) Continuous angle measurement
b) Swivel angle measurement

1 Ring magnet
2 Hall generator with integrated voltage regulator and measuring amplifier
3 Swivel segment
4 Magnetic bar

B Magnetic flux density
S Magnetic south
N Magnetic north
n Number of pole pairs

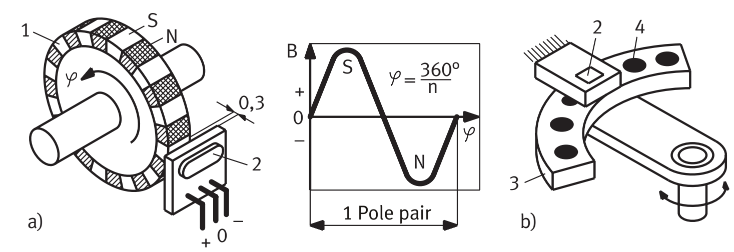
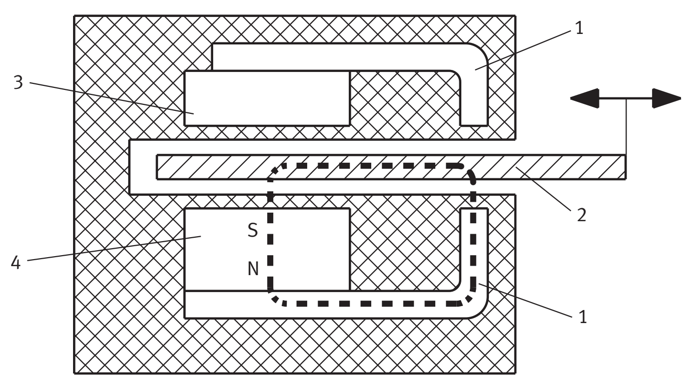


Fig. 3-21 shows a magnetic barrier with a Hall sensor for determining end positions. It is a magnetic proximity switch. It contains a Hall effect sensor in a field generated by a permanent magnet.

Fig. 3-21
Fork-type magnetic barrier with Hall sensor

1 Baffle plate
2 Soft iron stop
3 Hall sensor
4 Permanent magnet

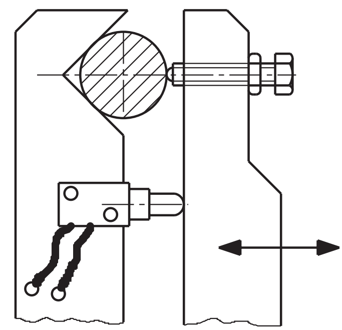


A soft iron stop advances into and withdraws from the air gap. In this way it influences the magnetic field permeating the Hall plate that serves as a measure for the position of the soft iron stop. The Hall voltage is evaluated in an electronic circuit that outputs only two discrete voltage level values (low and high). The soft iron stop can also be a rotating stop, for example as a contactless contact breaker in a vehicle or as an r.p.m. sensor for an anti-lock brake system.

In handling technology, it is often not enough to trust that an intended and expected action has indeed taken place. It must be ensured that the next step in an operation, for example mounting of an assembly, can only go ahead if the previous step was successful. In this case, both the function and the successful outcome can be sensed. Fig. 3-22 explains what is meant by this.

Fig. 3-22
Checking a gripper operation

a) Function trigger
b) Outcome trigger



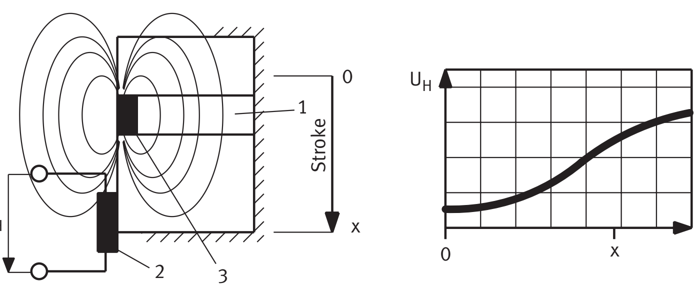
In the case of the function trigger, only the closing of the gripper fingers is monitored, i.e. the functional integrity of the gripper in itself. The acknowledgement signal is sufficient to continue assembly, for example.

In the case of the outcome trigger, a workpiece must actually be detected before the next step in an operation will be started. The gripping function is monitored here. Sensing operations of this type are now executed without contact to reduce wear. The piston stroke in a pneumatically driven gripper can be recorded using a Hall sensor, for example. This is shown in Fig. 3-23.

Fig. 3-23
Monitoring gripping positions using a Hall sensor (Festo)

1 Pneumatic piston (for driving the gripper fingers)
2 Hall sensor
3 Permanent magnet

U_H Hall voltage
x Piston stroke



This solution not only indicates when an end position is reached, but intermediate positions can also be read from the generated Hall voltage. These can be signals for 3 positions: Part 1 gripped, part 2 gripped (if its diameter is different to that of part 1) and gripper open or closed. The sensor is attenuated proportional to the gripping stroke by means of a permanent magnet. The electronic evaluation unit is accommodated in a box, the "trimming box".
The generated analogue signal is pre-processed in this box. The measuring accuracy is ± 0.2 mm.

3.5.2 Magnetic switch

The reed sensor is a classic proximity sensor. It responds to magnetic fields. Fig. 3-24 shows the operating principle of a reed sensor. It consists of 2 sprung ferromagnetic contact blades (Fe-Ni alloy) that are accommodated in a hermetically sealed glass bulb. The tube is filled with an inert gas. When a magnet is moved past the "switching tube", the contact blades touch and make the circuit. The response time is approx. 1 ms. The reed sensor is non-wearing.

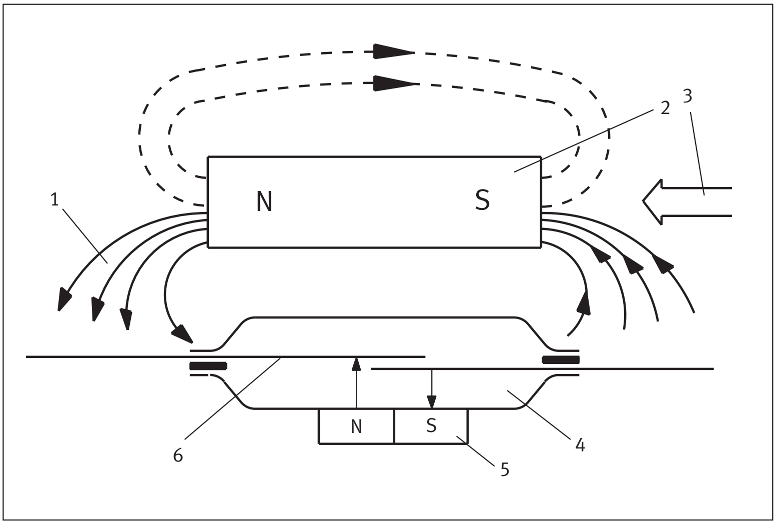


Fig. 3-24
Magnetic proximity switch

1 Magnetic field
2 Switching magnet
3 Direction of movement
4 Glass bulb containing insert gas mixture
5 Bias magnet
6 Switch contacts

N Magnetic north
S Magnetic south

A switching precision of ± 0.1 mm can be reckoned with when this solution is used as a position sensor. Care must naturally be taken to ensure that there are no other disturbing magnetic fields in the vicinity. Screens may need to be constructed if this cannot be ensured. Reed proximity switches are often used as cylinder switches. Fig. 3-25 shows the set-up. A ring magnet in the piston is used for switching. Reed switches can also form a secondary switching range in addition to a main switching range, although this is a slightly awkward approach. The secondary switching range will inevitably have a negative effect unless the actuating forces of the contact blades in the reed switch are accurately adjusted to the force of the magnetic induction.

Fig. 3-25
Operating principle of the magneto-inductive cylinder switch

1 **Cylinder barrel, non-magnetisable**
2 **Ring magnet**
3 **Piston rod**
4 **Sensor, reed switch, enclosed in a plastic block**
5 **Main switching range**
6 **Secondary switching range**
7 **Hysteresis**

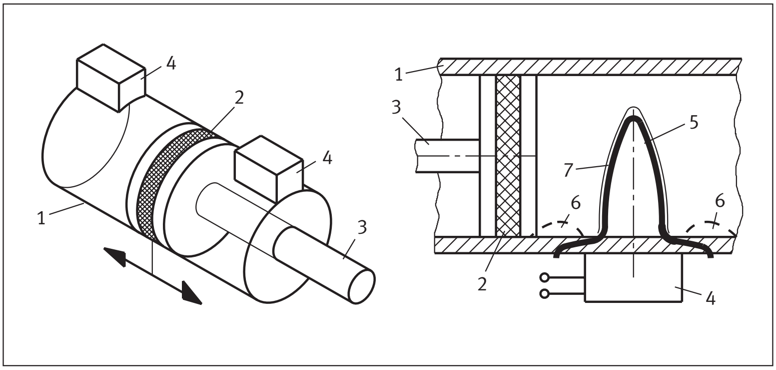


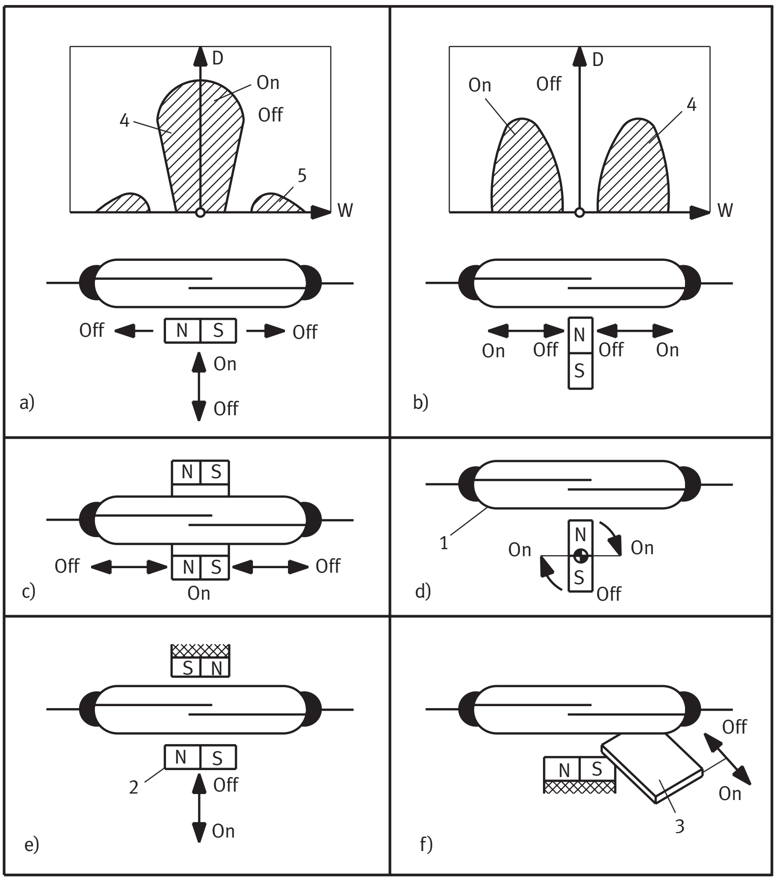
Fig. 3-26a and b show the switching ranges. They depend on the direction of the magnet relative to the poles. This figure also shows some other magnet configurations. Thus, for example, a switching operation can also be triggered using a lug made from sheet steel (Fig. 3-26f). The magnet and reed switch do not move in this configuration.

Fig. 3-26
Possible magnet configurations for actuating a reed switch and switching ranges

a) **Bi-axially movable magnet**
b) **Movable magnetic bar**
c) **Movable ring magnet**
d) **Rotatable magnetic bar**
e) **System with magnets for premagnetisation**
f) **Insertable ferromagnetic sheet metal lug**

1 **Reed switching tube**
2 **Permanent magnet**
3 **Sheet metal lug**
4 **Main switching range**
5 **Secondary switching range**

W **Recording width**
N **Magnetic north**
S **Magnetic south**
D **Recording depth**



In cases where reed sensors are used as “cylinder switches” on pneumatic cylinders, the maximum permissible piston speed must be observed. Malfunctions can occur if the time allowed for the control system's response is too short. The permissible speed v is given by the equation

$$v_{max} = \frac{\text{Switching range of the signal generator}}{\text{Response time of the control system, valve, etc.}}$$

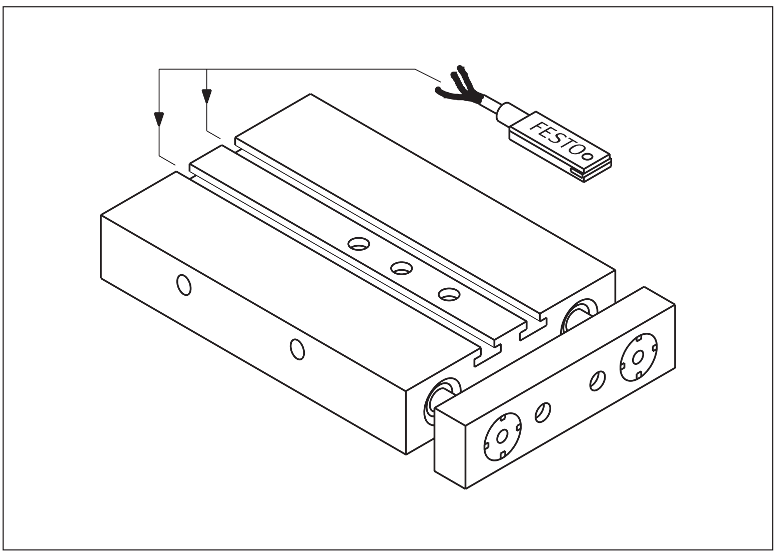
For instance: The response travel for the reed switch in the case of a pneumatic cylinder with a piston diameter of 32 mm is 10 mm. A pulse lasting 30 ms (= 0.03 s) is needed to actuate an electrical valve. The maximum piston speed v is therefore given by the equation

$$v_{max} = \frac{10}{0{,}03} = 333 \text{ mm/s}$$

There is also an unavoidable hysteresis between the switching points ON and OFF when the piston is reversing. This hysteresis is approx. 2 mm for reed switches and approx. 1 mm for contactless switches.

There are also compact, magnetically actuated electrical signal generators that can be used as cylinder sensors. They can be inserted in the profile slots of a pneumatic actuator (Fig. 3-27) and indicate the end positions there. These signal generators exploit either the inductive-magnetic effect, the Hall effect or the Wiegand effect. The electromagnetic field of a cylinder sensor is influenced when a magnet approaches the sensor. This change is converted into an output signal via an amplifier.

Fig. 3-27
Typical installation example for magnetic field sensors in pneumatic linear actuators (Festo)



3.5.3 Magnetically controlled resistors

Magneto-resistive sensors belong to the family of galvanomagnetic measuring sensors. Two different effects are exploited here, the

- transverse magneto-resistive effect (Gauss effect; sensors of this type are magnetoresistor sensors) and the
- longitudinal magneto-resistive effect (sensors of this type are metal thin layer sensors. These sensors exhibit an increase in resistance if a homogeneous magnetic field acts parallel to the conducting path.)

3.5.3.1 Magnetoresistor sensor

A magnetoresistor is a wave-form semi-conductor structure whose resistance increases relative to the force of a magnetic field. The electric current flows straight through the path of resistance provided that there is no magnetic field acting on the resistor. If a magnetic field with the flux density B acts perpendicular to the path of resistance, then the Lorentz force deflects the charge carrier which in turn increases the electrical resistance. A magnetoresistor is therefore a magnetically controlled resistor. Magnetoresistors are used in pairs to facilitate temperature compensation. They are usually linked in a Wheatstone bridge circuit.

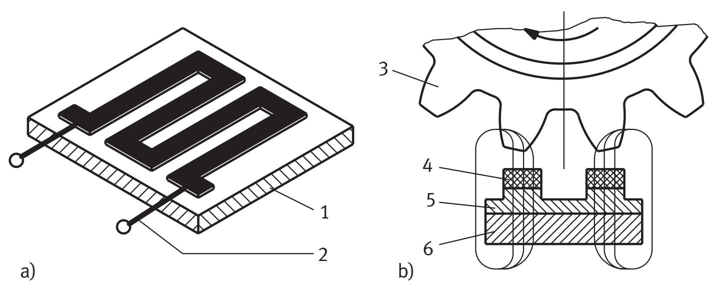


Fig. 3-28
Magnetoresistor sensor

a) Magnetoresistor
b) Use as a sensor system to detect rotational speed and direction

1 Support plate
2 Terminal lug
3 Soft magnetic toothed wheel
4 Magnetoresistor
5 Ferrite
6 Permanent magnet

Sensors have been in production since 1965. They can be used to measure magnetic variables directly and mechanical variables indirectly. In the application example in Fig. 3-28, the sensor is used to measure the rotational speed and/or the rotation angle. The main application of sensors is in contactless switching operations, for example when performing positioning tasks.

3.5.3.2 Magneto-resistive metal thin layer sensors

These sensors, based on NiFe or NiCo, are cost-effective alternatives to magnetoresistor sensors. They can also be used in high temperature conditions (up to 200 °C). The controlling magnetic field acts in the plane of the very thin vacuum-coated metal film. The following effects are exploited:

AMR effect *(anisotropy magnetoresistance effect)*
This effect was proven more than 100 years ago by W. Thomson (1824-1907). It means: The electrical resistance of a magneto-resistive strip changes as a function of the angle between the direction of the current and the direction of magnetisation. Sensors that exploit this effect are manufactured using thin film

technology. This type of sensor can be used to detect the external fields of a rotating magnet, for example, or the change in a fixed magnet when ferromagnetic parts are moved past it.

GMR effect *(giant magnetoresistance effect)*
This effect was discovered in 1989 at the Research Centre Jülich. It is a physical effect that can be observed in ultra-thin stacks of layers (e.g. Co-Cu-Co).
A current flowing through a layer system of this type (magnetic layer S1 – non-magnetic layer NS – magnetic layer S2) experiences fluctuating resistance when there is a change in an external magnetic field as a function of the relative magnetisation directions of the magnetic layers (Fig. 3-29a). These layers are only a few nanometres thick. Sensors of this type are used, for example, to measure rotations in water meters, as angular position transducers (Fig. 3-29b) or as magnetic gear sensors in vehicular ABS systems. Magneto-resistive read heads are found in the fixed-disk storage in computers.

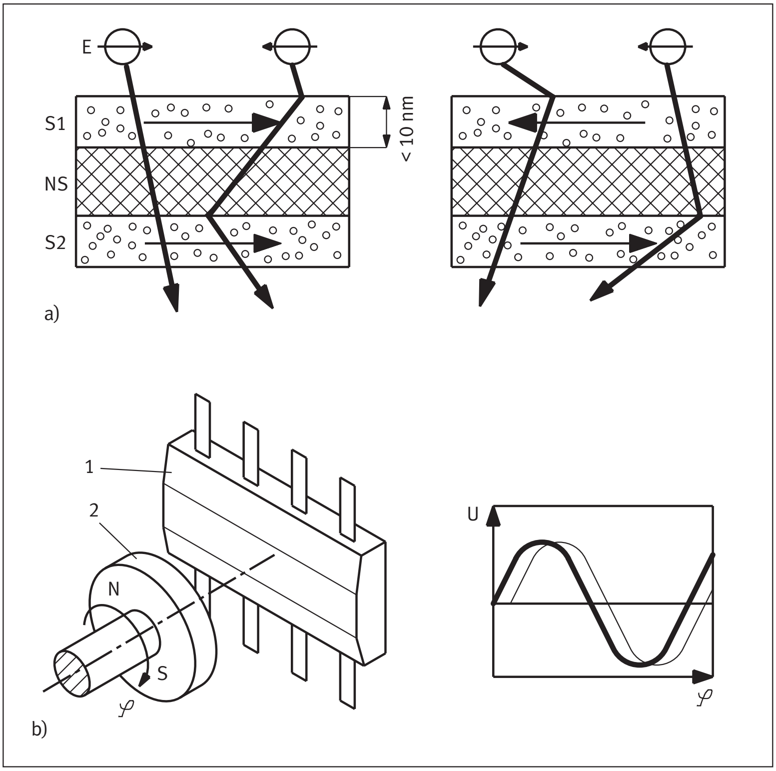


Fig. 3-29
GMR sensor technology

a) With parallel magnetisation, the dispersion of the electrons (characterised by their spinning states) is less than with the anti-parallel magnetisation (Sub-fig. a right) of the layers. This difference causes a change in the electrical resistance
b) Angle sensor

1 Sensor
2 Magnet

E Electrons

3.6 Acoustic position recording

Acoustic sensors work on the basis of ultrasound (16 kHz to 1 GHz). A transducer generates the ultrasound waves that obey, to a large degree, the laws of geometric optics. The reflected waves are recorded once more and evaluated. A digital filter or the process of autocorrelation is used to check whether the acoustic signal picked up is actually the echo of the ultrasound waves sent out. The basic principle is illustrated in Fig. 3-30.

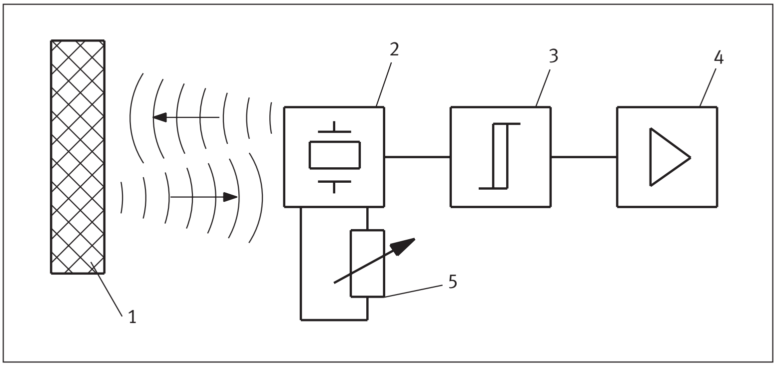


Fig. 3-30
Operating principle of an ultrasound sensor

1 Target object
2 Ultrasonic transducer
3 Evaluation unit
4 Output module
5 Variable resistor

This type is sensor is used to detect the presence of an object. It can also be used to determine the distance to the object without the use of contact. To this end, the echo time of the sonic pulse is measured and the distance is then calculated on the basis that the speed of sound in air is 330 mm/ms. The transmitter and receiver can be piezoelectronic components. The transducer is switched over to receive signals in the pulse transmission pauses. The temperature sensitivity of the sound propagation speed (approx. 0.18 %/K) must be taken into account to ensure accurate readings.

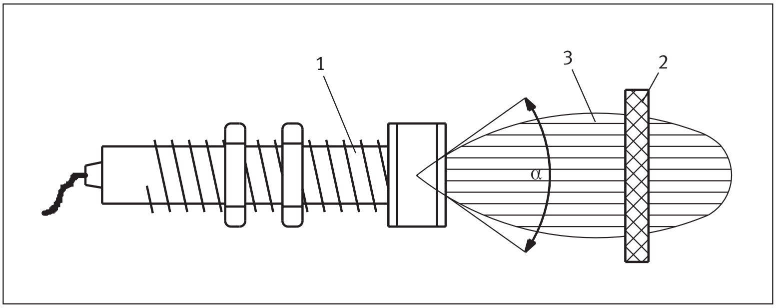
The change in the Doppler frequency (Doppler effect) can be used to detect motion. As well as the reflection method, the penetration method is also used. With this method, the sound intensity or the arrival of a sonic pulse after the sound has travelled through an object is measured (see section 5.2.5).

A considerable advantage of ultrasound is that the object to be sensed can be made of almost any material and have almost any surface finish. The objects can be solid, liquid, transparent, granulated or powder. Their shape and colour are of no matter either. With bevelled surfaces it can happen that the sound is reflected away and the echo does not return to the transmitter. If the object to be sensed is very small, the sonic pulses travel around it and echos are produced in the background. The size that an object must be depends on the opening angle of the sound cone, as shown in Fig. 3-31 using the example of an ultrasonic proximity sensor. Ultrasonic sensors cannot be used where there is excess or low pressure, with very hot objects due to the refraction of sound at the point where layers of air with different temperatures meet or in areas where there is a risk of explosion.

Fig. 3-31
Sound propagation with the ultrasonic reflective sensor

1 Sensor
2 Object
3 Sound cone

α Opening angle of the sound cone



The ultrasonic principle can also be used to generate pictorial representations of objects irradiated with ultrasound waves (special transducers are needed for this application). Imaging ultrasonics can be used in the inspection of sewers and pipes by so-called “drain robots” (teleoperators), for example. They allow damage to the inner and outer walls of the pipes to be made visible. Opto sensors only inspect the surface of the pipe interior.

Several types of ultrasonic sensor are used in the drinks industry to check crates of empties. Light barriers can be used to check that objects cleaned by means of water jets are actually clean. Bottle heights and crate edges are checked to ensure that their dimensions are in line with the preselected dimensions.
A rotary transducer on the conveyor starts the measurement process. An image processing system also checks the crate type and whether the crate contains dirty, incorrect or broken bottles.

Other applications of ultrasonic sensors include the monitoring of storage spaces in warehouses and parking spaces in multi-storey car parks, door opening actions and filling levels for dry bulk materials and for clear boundary layers. There are well-known examples for checking the height of stacks, for controlling take-up units as well as for sorting and alarm systems.

3.7 Opto-electronic position recording

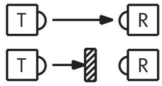
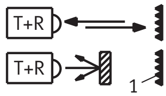
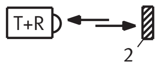
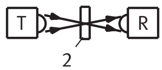
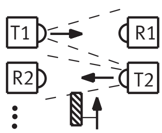
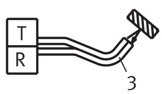
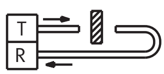
The position of objects can be recorded using opto-electronic sensors that work in the visible or infrared spectrum. Their main area of application is in detecting non-metallic components. They detect glass bodies, record filling levels, check for the presence of parts and are constantly being used for new applications. Optical systems are, however, sensitive to dirt and moisture. For that reason, modern sensors have an operational status indicator that shows when the receiving capacity is sufficient. In very dusty environments the lens can also be cleaned with compressed air.

Light barriers and light sensors are the best known of the opto-electronic sensors. Fig. 3-32 provides an initial overview of these sensors. There are also many variations for each type, for example sensors with diffuse light beam, with focussed light beam or with settings for fixed measurement distances. Light can also be directed around corners through the use of fibre optic cables.

Fig. 3-32
Important optical proximity switches with and without fibre optic cables

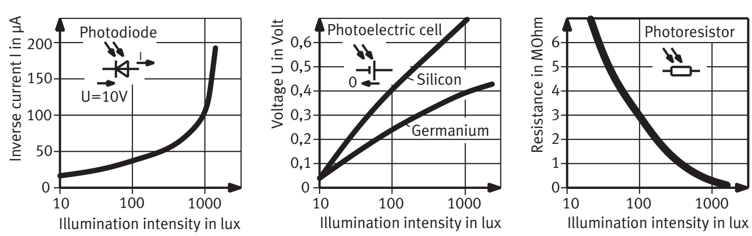
1 Reflector
2 Object
3 Fibre optic cable

T Transmitter
R Receiver

Designation	Configuration	Explanation
Through-beam sensor		Transmitter and receiver are separate and opposing; evaluates the interruption of the light beam; range of up to 30 m.
Retro-reflective sensor		Transmitter and receiver are housed together. A reflector is also needed. Evaluates the interruption of the light beam; range of up to 4 m.
Reflexlight sensor		Transmitter and receiver are housed together. The reflected light is reflected back to the receiver. The object itself acts as the reflector; range from 0.1 to 0.4 m.
Transmission light sensor		Transmitter and receiver are separate. Both are focussed on the sensing plane in between; used for light-coloured, transparent object surfaces
Multi-beam light barrier system		One transmitter can activate several receivers if the light barriers are close together. The transmitters and receivers must therefore be in a reciprocal arrangement.
Reflex light sensor with fibre optic cable		This sensor's function is the same as that of the standard reflex light sensor. The light beam can be directed through the use of flexible fibre optic cables.
Through-beam sensor with fibre optic cable		Transmitter and receiver are accommo-dated together in a compact casing. The light is not radiated freely, instead it runs in fibre optic cables.

Light-sensitive components such as photoelectric cells, phototransistors and photoresistors, for example, are photon receivers. Today they are usually made from the semiconductor material silicon. They are based on the principle that the conductivity of photo semiconductors is greatly improved by the presence of light. This effect is quantified in Fig. 3-33. The sensitivity depends on the wave length.

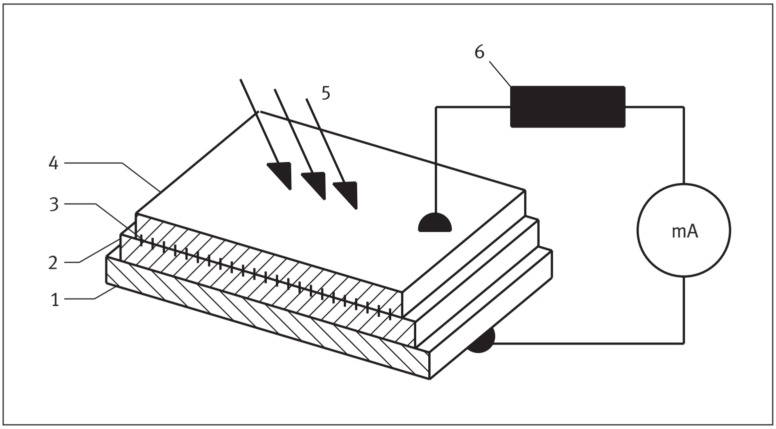
Fig. 3-33
Photo semiconductors and their reaction to various illumination intensities



The basic structure of an original photoelectric cell is shown in Fig. 3-34 (see also Fig. 3-48).

Fig. 3-34
Structure of a photoelectric cell

1 Metal electrode
2 Selenium layer
3 Insulating layer
4 Top electrode, transparent
5 Light
6 Load resistor



The photoelectric cell works as follows: The photons (light quanta) penetrate the selenium layer. This results in the generation of charge carriers that, because of the insulating layer, can only flow in one direction. A photoelectric current then begins to flow through a connected load resistor. A photoelectric cell of this type was first described in 1930, but has now been superseded by modern photodetectors. One special design variation has remained: The solar cell. There is no physical difference between the solar cell and the photodiode; they simply use different operating methods.

The following can be used as a radiation source:

- Filament lamp; radiation intensity in excess of 5 W, average cost
- Spectral lamp; visible, infrared and ultraviolet radiation, expensive
- Light emitting diode (LED); extremely low cost, long service life
- Laser diode; emissions in the far red or infrared spectrum, low cost, extremely high radiance
- He-Ne laser; radiation intensity in excess of 10 mW, high cost

The light beam can either be continuous or pulsed. A continuous beam does not allow long measurement distances for output reasons, but does offer a faster response speed than a pulsed beam. Pulsed beams are primarily used in LEDs and semiconductor lasers. The beam is stronger and less sensitive to external light. Consequently, the measurement distance can be long.

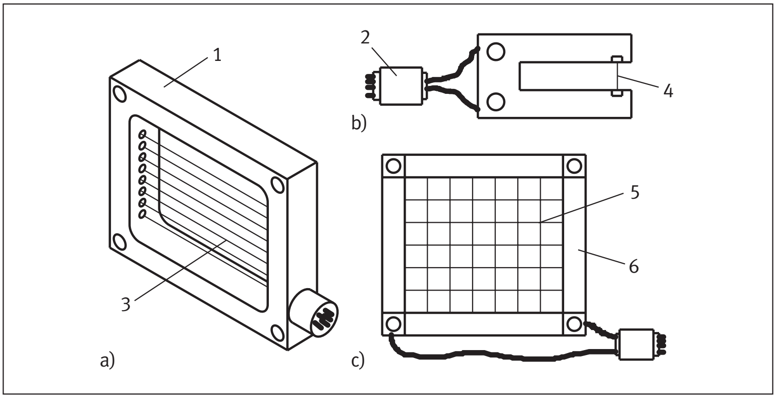
3.7.1 Using optical proximity switches

The classic form of light barrier is the through-beam sensor where the transmitter and receiver are separate and face each other along an imaginary line. The transmitter and receiver can also be installed in a fork-type or frame-type casing. The designs are often connected to the transmitter and receiver using fibre optic cables. Fig. 3-35 shows such design variants, including some multi-beam light barriers. In multi-beam light barriers, the appropriate number of transmitters are switched on one after the other for a short period.

Fig. 3-35
Design variants for light barriers

a) Frame-type light barrier
b) Fork-type light barrier
c) Light barrier with intersecting light beams

1 Housing
2 Attachment plug
3 Parallel rows of luminaires
4 Light beam
5 Intersecting rows of luminaires
6 Frame



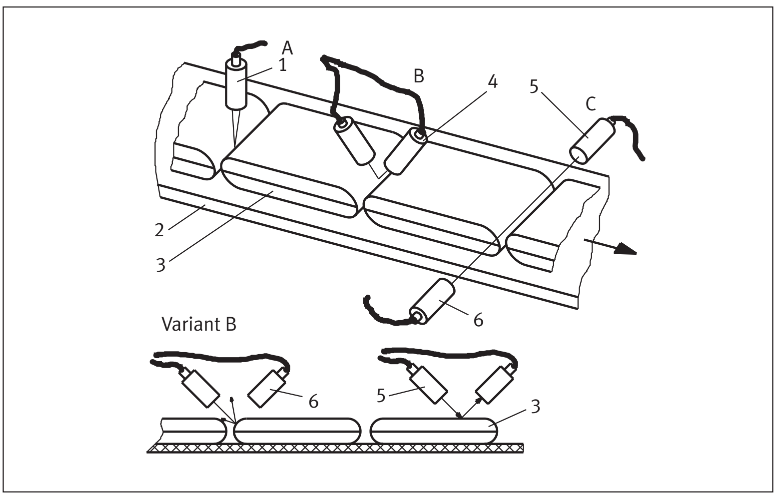
The receivers are queried in the same sequence in a synchronous operation. This means that only one transmitter and receiver are active at any one time. Devices of this type are used for the rough detection of contours, for example of passing objects (see section 3.7.6). The version with intersecting light beams is used for ejection control and for counting very flat parts at machines, for example.

Counting operations must be performed during production so that the flow of objects such as packages, for example, can be quantified and documented. However this is not always easy, particularly if the objects are close together and the sensor can no longer tell where one part stops and the next part begins. Fig. 3-36 shows some variants. Only variant B, where the curve of the parts is optically sensed, is suitable for a closely packed sequence of objects.

Fig. 3-36
Fork-type light barrier sensor for use with closely packed parts

1 Diffuse sensor
2 Conveyor belt
3 Object
4 Light barrier
5 Transmitter
6 Receiver

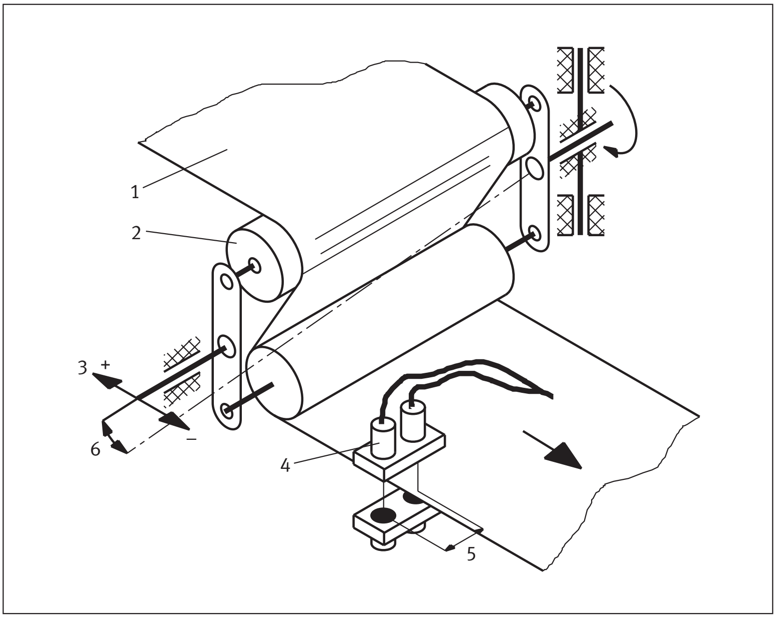
A Reflex light sensor
B Angled light barrier variant
C Light barrier principle



Another application is in checking the belt ride through constant monitoring of the run-in line. To this end, the belt edge is generally sensed. Should the belt drift to the left or right, the belt tightener and control roller combination shown in Fig. 3-37 straightens it by increasing or decreasing the tension on one side (by moving towards plus or minus). Two light barriers can be used here. The tolerance range for belt edge drift is small and is delimited by the two light spots of the light barriers. Other sensors can naturally also be used for sensing the belt edges (air barriers, optical-analogue edge controllers, capacitive proximity switches, tactile magnetic switches in the case of metallic belts). This correction function is always active.

Fig. 3-37
Regulating belt ride

1. **Belt**
2. **Roller combination**
3. **Direction of adjustment**
4. **Through-beam sensor**
5. **Tolerance range**
6. **Angular adjustment implemented**



A compact type of optical proximity switch that needs only one mounting point is the reflex light sensor. The switching function in this type of sensor is triggered by reflected light. Incorrect switching operations can occur if the background behind the object to be sensed is more reflective than the object itself. The light sensor cannot then distinguish the source of the reflected light. The sight is restricted to a defined distance range. Everything short of and past this distance is ignored. The sensing distance can be set and the line between detection and non-detection is very clearly drawn. The corresponding design is the reflex light sensor with V-shaped axial alignment of the optical system shown in Fig. 3-38a. One disadvantage of this type of sensor is the restricted sensing width because the basic distance to the housing cannot be lengthened unless the angle of the beam can be adjusted.

Another solution is to use two receiver components (Fig. 3-38b) or one segmented receiver (PSD component, see Fig. 3-48). With this solution, objects a long way away are no longer mapped to the active area of the receiver. The line between detection and non-detection is very clear here also. When an object comes closer, the reflected light spot moves from the receiver component "Far-off" to the receiver "Nearby". The signal of the nearby object becomes stronger. A comparator compares the signals of both components and activates the signal output when a defined threshold value is reached. This solution permits the detection of a barely reflective object against a gleaming background, for example.

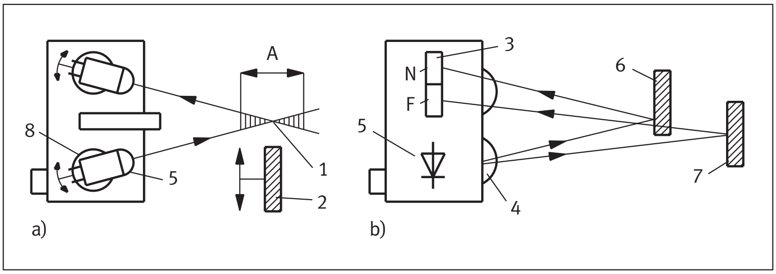


Fig. 3-38
Fading out of foreground and background

a) Fixed focus sensor
b) Background fade-out

1 Fixed focal point
2 Object
3 Differential diode with nearby (N) and faraway (F) receiver range
4 Optical device
5 Transmitter component
6 Nearby object
7 Faraway object
8 Mechanical angular adjustment

A Active area

A different approach must be used when sensing very shiny parts using retro-reflective sensors. This is a very complex sensing task. Therefore the solution uses light that is "sorted" according to the direction of vibration; so-called "polarised" light. Light waves usually vibrate in all possible planes. If, on the other hand, they pass through a polarisation filter, they vibrate in one only plane. If the light hits the retro-reflector (reflective foil, triple reflector), then the polarisation plane is rotated by 90°. This marks the light and "bad" reflected light that has not changed its polarisation is excluded from the evaluation (Fig. 3-39).

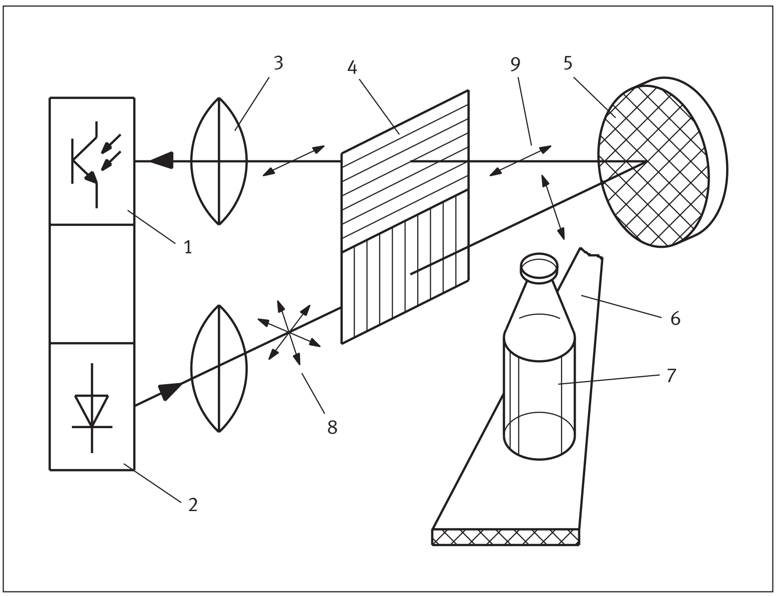


Fig. 3-39
Operating principle of opto sensors that work with polarised light

1 Receiver
2 Transmitter
3 Optical device
4 Polarisation filter
5 Retro-reflector
6 Conveyor
7 Object
8 Directions of vibration
9 Polarisation plane, rotated by 90°

Special linear or circular polarising foils are used as polarisation filters. The filter immediately in front of the receiver practically has the function of an analyser.

A further example of an application of optical reflex light sensors is the detection of objects on roller buffer conveyors (Fig. 3-40). The goods flow system must include buffer sections for reasons related to production technology. Where buffer areas are used, it is desirable to keep the back pressure of the accumulating objects low. This means temporarily turning off subsections of the roller conveyor and turning them back on again to restart conveying. This is frequently done by pneumatically raising or lowering subsections of the roller section. The objects on the buffer section can be released in groups or individually. The latter works particularly well if the objects are on platforms (workpiece supports) and appropriate stoppers (stopper cylinder with thrust roller) are used.

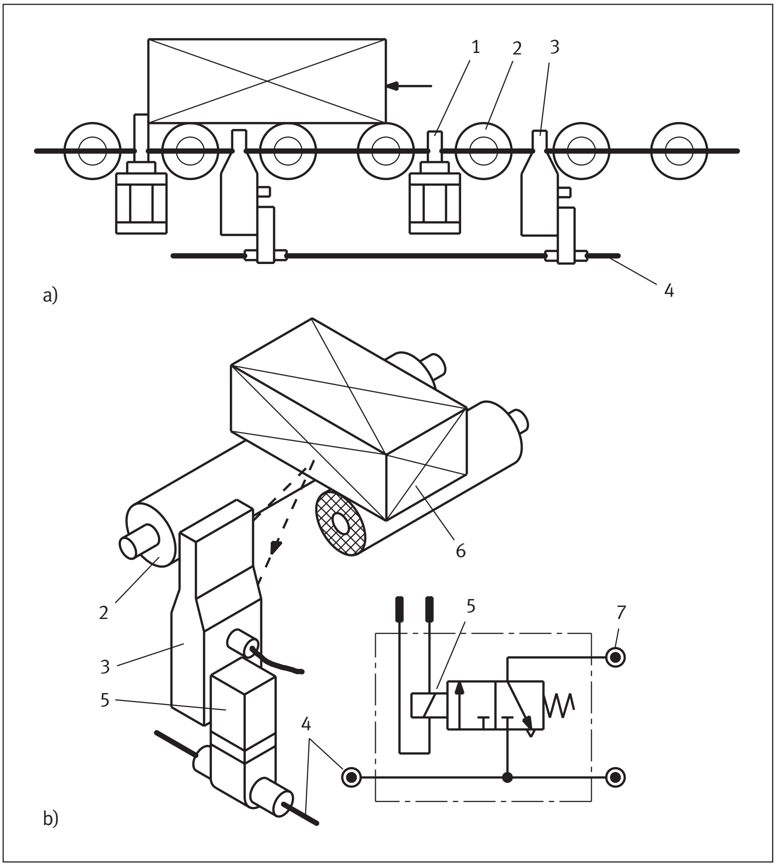


Fig. 3-40
Sensor-controlled buffer conveyor (Festo)

a) Buffer section
b) Installation option

1 Single-acting stopper cylinder
2 Roller section
3 Sensor valve
4 Compressed air supply line
5 Pneumatic directional control valve
6 Transported good
7 Cylinder connection

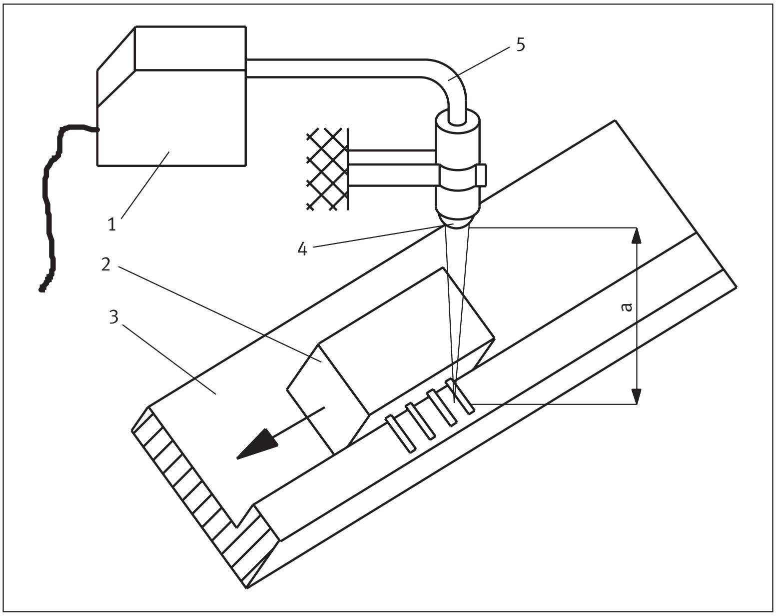
In straightforward cases it is sufficient to simply stop the flow of objects through the use of extending stoppers. For detecting jams there is an opto sensor that, together with a pneumatic directional control valve, forms a compact unit. This sensor is an optical reflex light sensor (PNP, dark switching) with electronic background fade-out. The switching distance can be set from 270 to 550 mm using an integrated potentiometer. The background fade-out mechanism also renders the sensor insensitive to vibration. The slim design of the top half of the sensor (8 mm) means that it can be inserted even in narrow gaps between transport rollers.

As each interruption in the reflected light can also be considered to be a counting pulse, reflex light sensors are very well suited to counting tasks. Apart from counting quantities, components of modules or products must naturally also be counted for the purpose of quality control. Fig. 3-41 shows an application of this type. In this solution, the connector pins in electronic components are to be checked during the pass.

Fig. 3-41
Counting guide pins (Keyence)

1 Reflex light sensor
2 Object to be checked
3 Conveyor trough
4 Focusing lens
5 Fibre optic cable

a Sensing distance

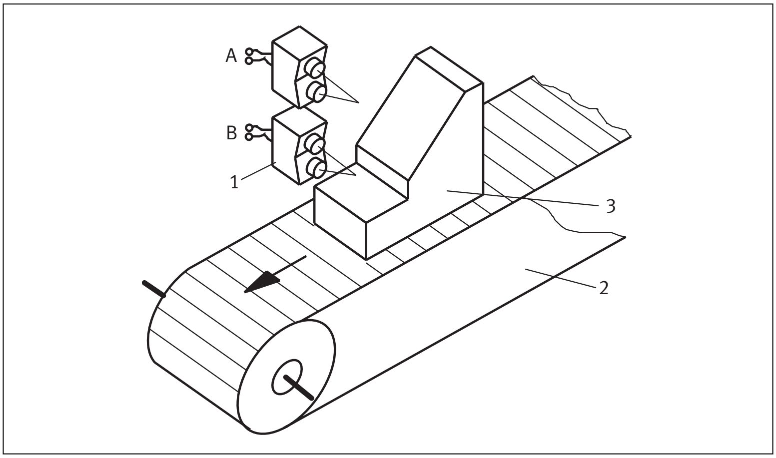


A normal fibre optic cable would emit the light at such a large angle (60º) that thin objects would be missed. This makes reliable counting problematic. For that reason, the light is often tightly bundled at the end by means of a fitted lens. This allows a sample focus diameter of only 0.4 mm at a distance of 7 mm. The direction of light using fibre optic cables has the advantage that the cables do not take up much space at the measuring point.

We will now look at some examples for the detection of object orientation. There are many instances in production where it is necessary to protect tools, machines and other devices against damage caused by the wrong or incorrectly oriented parts. The wrong parts can cause serious damage. The position and orientation of a workpiece can often be determined simply by checking selected points on the workpiece. A so-called point sensor is then sufficient. The sample solution in Fig. 3-42 uses two reflex light sensors. If sensors A and B respond at the same time it means that the incoming part is incorrectly oriented and must be rotated or sorted out.

Fig. 3-42
Optical orientation check

1 Reflex light sensor
2 Conveyor belt
3 Workpiece in correct position



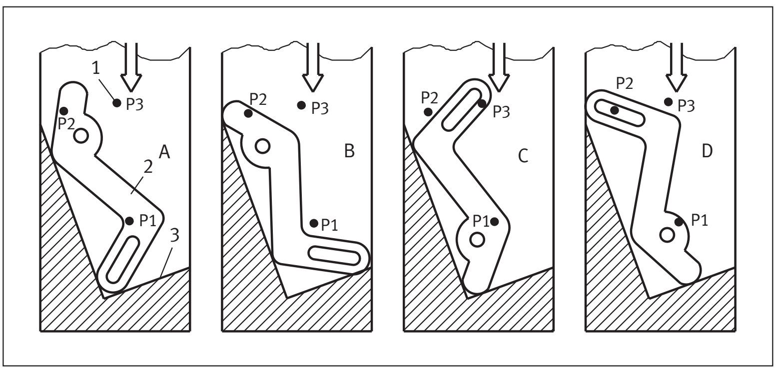
	Correct position	Incorrect position	Incorrect part	No part
Sensor A	0	1	1	0
Sensor B	1	1	0	0

Fig. 3-43 shows a further example of 2D detection. The object of detection here is a sheet blank that can assume 4 different orientations (positions A, B, C or D) once it finds a stable end position on a sliding trough.

Fig. 3-43
Identifying the orientation of stampings

1 Point sensor
2 Workpiece
3 Stop edge

P Point sensor



Orientation	A	B	C	D		Incorrect parts				No part		
P1	1	0	1	1		P1	1	0	0	P1	0	
P2	1	1	0	0		P2	1	1	0	P2	0	
P3	0	0	1	0		P3	1	1	1	P3	0	

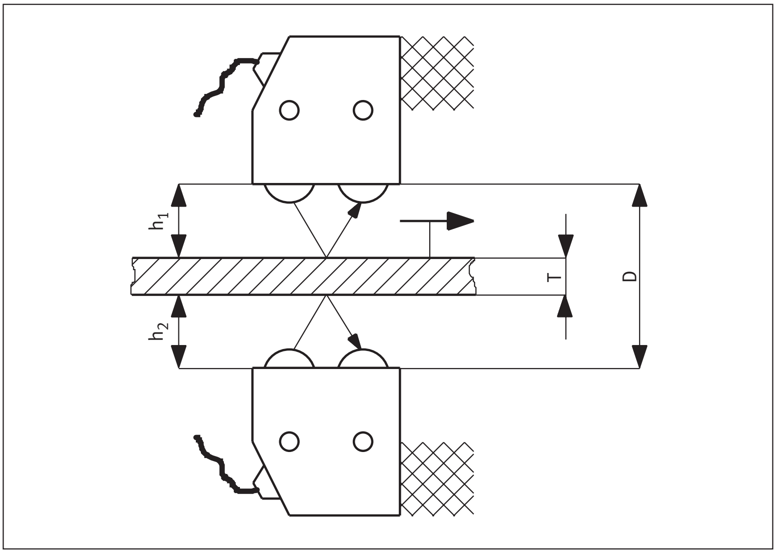
This solution is dependent on finding the points at which the sensors used to distinguish the orientations of A through D are to be attached during the design phase. A reflex light sensor with fibre optic cable is an example of a sensor that can be used in this solution. It should permit movement in 2 axes so that the positions of the sensors can be more accurately set up and to allow for adjustment for other workpieces.

The reflected light principle is also suitable for measuring belt thicknesses, for example. The belt thickness (or layer thickness) can be determined using 2 measuring heads. Fig. 3-44 shows the set-up. The belt does not lie on a support while it is being measured to prevent misreadings or small curvatures in the belt affecting the measurement result. Very accurate thickness measurements can be achieved through the use of measuring heads with a semiconductor laser reflex light sensor. The thickness T of the belt is given by the equation

$$T = D - (h_1 + h_2)$$

Fig. 3-44
Measuring head set-up for measuring the thickness of belts

h **Height**
T **Belt thickness**
D **Distance between sensors**



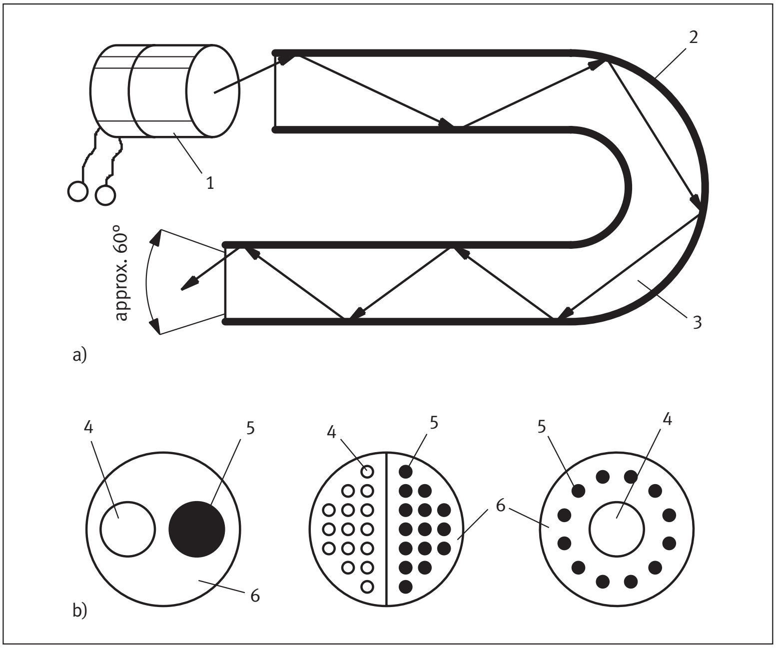
3.7.2 Using fibre optic sensors

The term "fibre optic sensors" refers to photoelectric sensors that use fibre optic cables to direct a beam of light. Fibre optic cables are strings made from plastic or glass fibres that can transmit light, even over curved paths, with a high refractive index as the result of total reflection within a core. Fig. 3-45a shows the principle behind fibre optic cables. Fibre optic cables permit the reliable operation of sensors, even in aggressive and hazardous environments. They can also withstand high temperatures. For coupling with reflex light sensors, the bundle of fibres can be arranged in such a way that the fibres for the transmitter and receiver optics are combined in one cable string (Fig. 3-45b).

Fig. 3-45
Operating principle of the fibre optic cable

a) Mode of operation
b) Profiles

1 LED
2 Cladding (lower refractive index)
3 Core
4 Transmitter fibre optic cable
5 Receiver fibre optic cable
6 Cable string



The laws of geometric optics must be observed when using opto-electronic proximity switches. In particular, these are as follows:

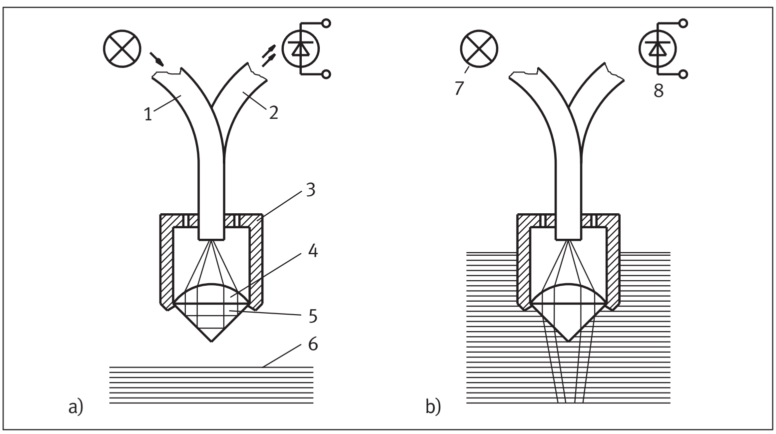
- A beam of light is broken at the boundary of two media with different refractive indices.
- Total reflection occurs at the transition from optically dense to optically less dense media if the critical angle is exceeded.
- The angle of incidence and angle of reflection of a light beam are identical in reflection.

These laws can be exploited in the development of sensors. Fig. 3-46 shows an example of this. The aim of this solution is to indicate the permissible limit of a fluid level.

Fig. 3-46
Opto-electronic filling level switch

a) Prism dry
b) Light beam with a rising level

1 Transmitter fibre optic cable
2 Receiver fibre optic cable
3 Prism casing
4 Parallel aligning lens
5 Prism
6 Fluid level
7 Light source
8 Photodiode



The function: The emitted light hits the prism and is diverted in such a way that 40% of the light reaches the photodiode. This indicates that the fluid level is still below the limit level. When the prism is eventually immersed in the fluid, the moisture adhering to the surface changes how the light is refracted. The light is then absorbed by the fluid and can no longer reach the photodiode. This results in an optical short circuit. In order words, the light beam is interrupted when the fluid reaches a certain level.

Attention: *Fibre optic cables are not as easy to lay as electrical cables. A minimum bending radius must be adhered to in order to prevent losses resulting from attenuation and fracture of the fibre optic cables.*

Scenarios requiring the recording of filling levels and levels in general frequently occur in the food and chemical industries. Good results can be achieved here with cost effective components through the use of photoelectric sensors. Fig. 3-47 shows two solutions.

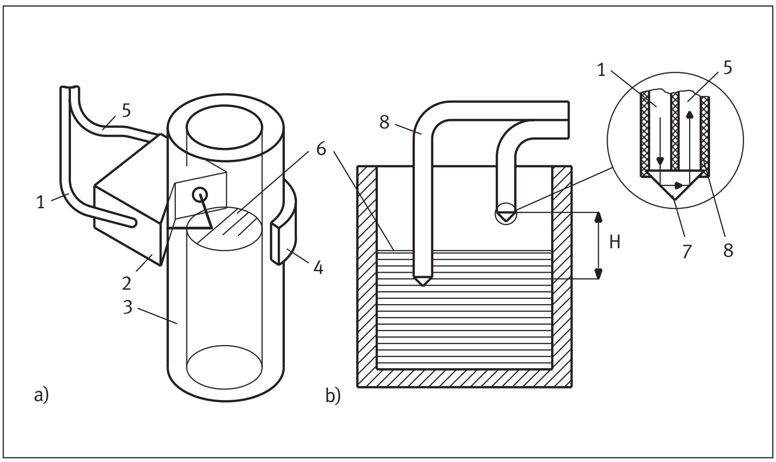
A sensing unit can be attached to a transparent tube using a simple clamping clip (Fig. 3-47a). The fluid level is recorded according to the principle of reflection and the light is forwarded to the reflex light sensor by fibre optic cables. The fluid level changes the refraction of the light at the measuring point and this is converted into a switching signal. The second solution works in a similar way: An appropriate number of sensors with fibre optic cables are arranged to indicate several levels. The light in the glass endpiece (prism or conical microsection) is reflected into the air (see principle in Fig. 3-46). Once the tip is immersed in the fluid, the light is refracted into the fluid. A switching signal is generated from the change in the refractive index.

Fig. 3-47
Opto-electronic recording of filling levels

a) Reflection-type light guide
b) Two-point recording

1 Transmitter fibre optic cable
2 Housing
3 Transparent tube
4 Clamping or retaining clip
5 Receiver fibre optic cable
6 Fluid level
7 Glass endpiece
8 Fibre optic cable pair

H Level difference



3.7.3 Recording positions using position-sensitive photocells

PSD components *(position photosensitive device)*, as they are also called, are position-sensitive photodiodes that have electrodes at both ends of a photovoltaic cell. If a light spot falls on the surface, the high-resistance p layer generates currents that are inversely proportional to the distance from the relevant light spot to the ends. Fig. 3-48a shows the operating principle of a lateral effect photodiode.

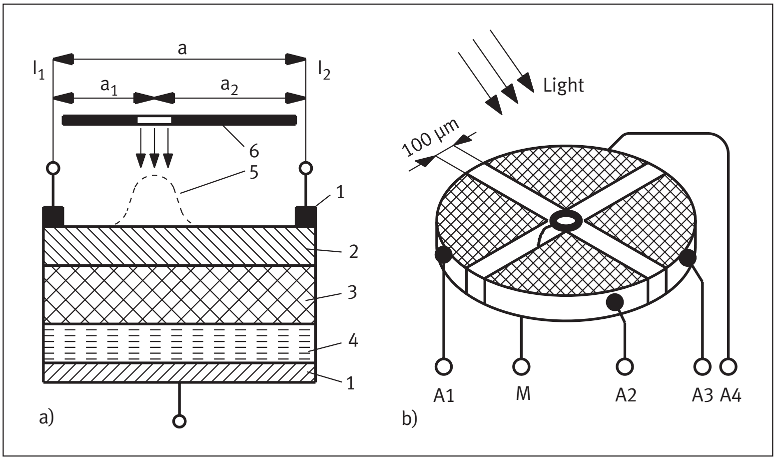


Fig. 3-48
PSD semiconductor components

a) Lateral effect photodiode
b) Four-quadrant photodiode

1 Electrode
2 p-doped layer
3 Intrinsic layer
4 n layer
5 Light intensity
6 Aperture

a_i Distance
Ai Quadrant photoelectric current
I_i Current

The output currents I_1 and I_2 are inversely proportional to the distance a_i from the light spot. This fact can be used to determine the location of the light spot. The following is true:

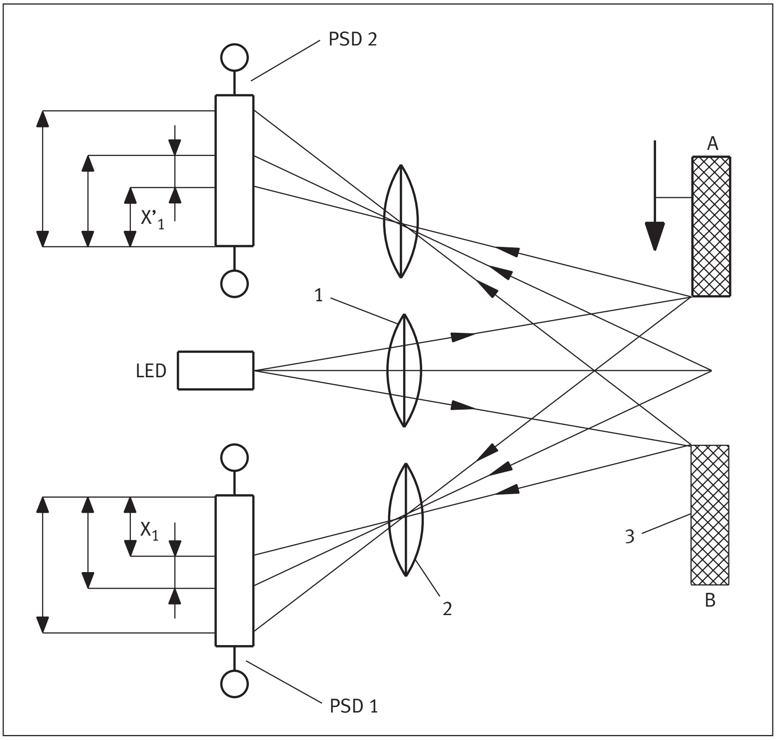
$$I_1 = \frac{a_2}{R} \cdot I \text{ and } I_2 = \frac{a_1}{R} \cdot I \text{ or } \frac{I_1}{I_2} = \frac{a_1}{a_2}$$

I Total current
R Total resistance of the electrode

This component can be used to build a triple beam distance measuring sensor. The double beam method results in range errors during the sensing of moving objects that can be suppressed using the triple beam method. Two PSD components are used in the triple beam sensor (one transmitter beam, two receiver beams). Fig. 3-49 shows the set-up. The object is illuminated using a light emitting diode.

Fig. 3-49
Triple beam distance measuring method (Matsushita)

1 **Optical transmission device**
2 **Optical receiver device**
3 **Object**



It moves past the light sources from A to B. The light is reflected and generates light spots on the PSD components. Two distance signals (x_i and x'_i) are generated from these light spots. These signals are averaged and give the distance to the receiver without the movement of the object causing a range error.
The signals represent two triangulation units.

There are also other PSD component designs, for example the quadrant photodiode shown in Fig. 3-48b. A neutral position is reached if all fields are uniformly illuminated by a light spot. If the light spot is moved, the direction and magnitude of the shift can be calculated from the photocurrents Ai.

3.7.4 Compensating light barrier

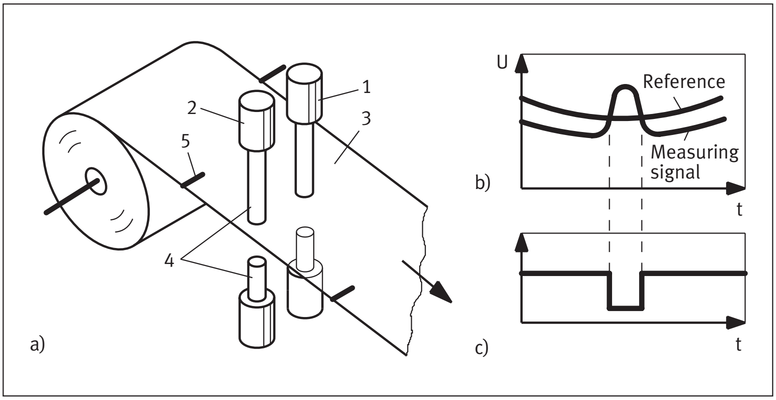
The deflection method is frequently used in measurement tasks as the method of measurement. Unlike the deflection method, the compensation method is a null method. With the compensation method, the measurement signal is immediately compared with a reference signal that is subject to the same environmental conditions. The only difference between compensating light barriers and other light barriers is that compensating light barriers have an additional reference light barrier and the aforementioned adjustable comparator circuit (null indicator). Fig. 3-50 shows a corresponding measuring set-up.

Fig. 3-50
Operating principle of compensating light barriers (eltrotec)

a) Measuring set-up
b) Analogue output
c) Digital output

1 Reference light barrier
2 Measuring light barrier
3 Brown adhesive tape (example)
4 Fibre optic cables
5 Print mark

U Analogue voltage



Sample application:
The aim of this solution is to sense the passing brown adhesive tape in order to detect any black print marks on it. The signal changes are small. For that reason, the measuring signal is constantly compared to a reference signal. The switch output is only activated if the analogue signal of the measuring light barrier exceeds the level of the reference signal ($M_{Sig} = M_{Meas} – M_{Ref}$). This method of measurement will also work with diffuse sensors (without or without a fibre optic cable connection) if the material in question is not sufficiently transparent.

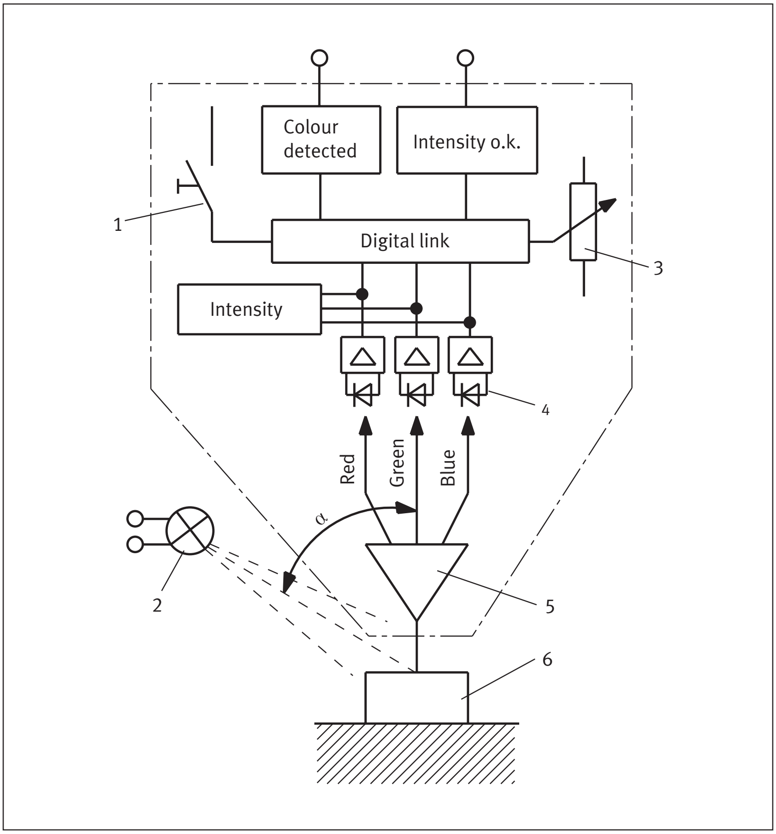
3.7.5 Differentiating coloured objects

Opto-electronic sensors are used here also. Colour measurements can either be performed using the three-colour method based on the Young-Helmholtz three-colour theory or using the spectral method. With the spectral method, the visible spectral range is divided up by means of prisms or optical grids, for example, and recorded or measured by a spectrograph.

With the three-colour method, the object is illuminated using incandescent light (practically daylight in the visible range). Three sublights (red, green, blue) are then formed from the recorded light in an optical filter stage and recorded by photoreceivers. They supply the chromaticity co-ordinates and intensity co-ordinates. The digitised chromaticity co-ordinates are compared with the previously saved reference values and the sensor outputs are switched accordingly. The values for the spectral reference colours are learned from GO samples during the teach-in process. In order to avoid glare, the light must be applied laterally at an angle α (approx. 20° to 40°). This solution must be shielded from sources of strong external light, such as direct sunlight or welding arcs. If the goods to be sorted are not dry, i.e. covered by droplets of moisture, the colour may not be correctly detected and the goods may not be correctly sorted.
Fig. 3-51 shows the operating principle of this colour sensor that is primarily used in industry.

Fig. 3-51
Operating principle of a colour sensor based on the three-colour method (eltrotec)

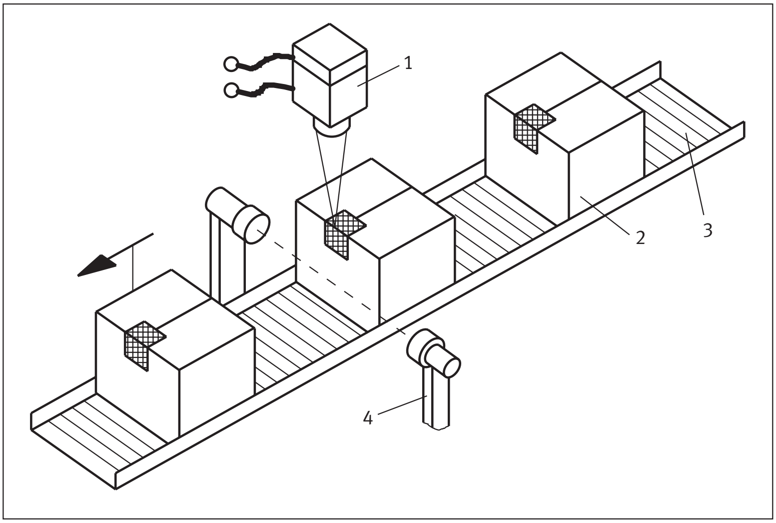
1 Teach-in switch
2 Light source
3 Tolerance setting
4 Receiver
5 Filter stage
6 Object to be checked



Sample applications of colour sensors include sorting coloured glass, detecting seals or end caps, checking the sequence of coloured cable strings, checking the ripeness of fruit or the degree of brownness of biscuits as well as checking colour-coded objects (electronic components, packaging materials, pharma ceutical products, coloured pencils, etc.). Coloured sensors are also used to detect coatings (e.g. liquid seals) or to check their proper application (provided that they are a different colour to the background). The colour information can also be used in checks for presence and completeness - an important task within quality assurance, for example checking that blister packs are completely filled with products or that multi-coloured stickers and labels are present on bottles and packets. The range of sample applications is immense. Fig. 3-52 shows the label check solution. This solution uses a colour-sensitive light sensor.

Fig. 3-52
Checking labels on packages

1 **Reflex light sensor**
2 **Package**
3 **Conveyor**
4 **Light barrier as a synchronising sensor**



The evaluation of the colour proportions of the 3 primary colours gives a reliable test result. This is also necessary if the package is similar in colour to the label. A trigger light barrier supplies the start signal for the inspection operation. The pulses are used at the same time for counting.

3.7.6 Using light curtains

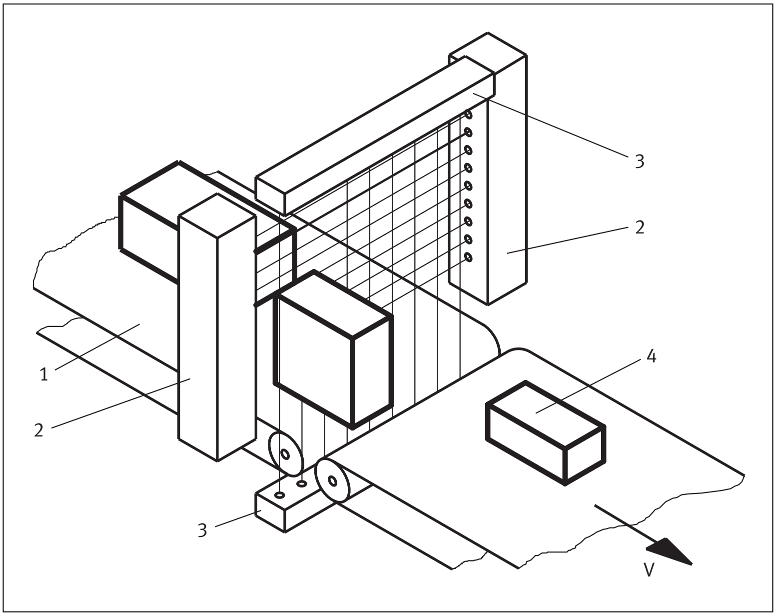
"Measuring" light curtains consist of a series of through-beam sensors whose switching states provide information on the contour of opaque objects. Each light curtain consists of a transmitter, a receiver and a control module controlled by a microprocessor. Example: The distance between beams can be 9.5 mm with 32 beams. The resolution of a light curtain of this type corresponds to the distance between the individual beams. The minimum object size that can be detected is given by twice the resolution. The scanning time is directly dependent on the number of light beams because the light beams are switched on sequentially (one after the other). This approach is necessary due to the proximity of the beams. The scanning time can be approx. 50 msec per beam.

Fig. 3-53 shows a sample application. It scans packages while they are moving along the conveyor belt before being transported to a sorting or stacking system. Two light curtains measure the height and width of the packages. The length is calculated from the conveyor speed v and the duration of interruption of the light beams when the package is passing underneath. The volume can then be calculated from these measurements.

Fig. 3-53
"Measuring" light curtain

1 Conveyor
2 Vertical light curtain (transmitter and receiver)
3 Horizontal light curtain (transmitter and receiver)
4 Package

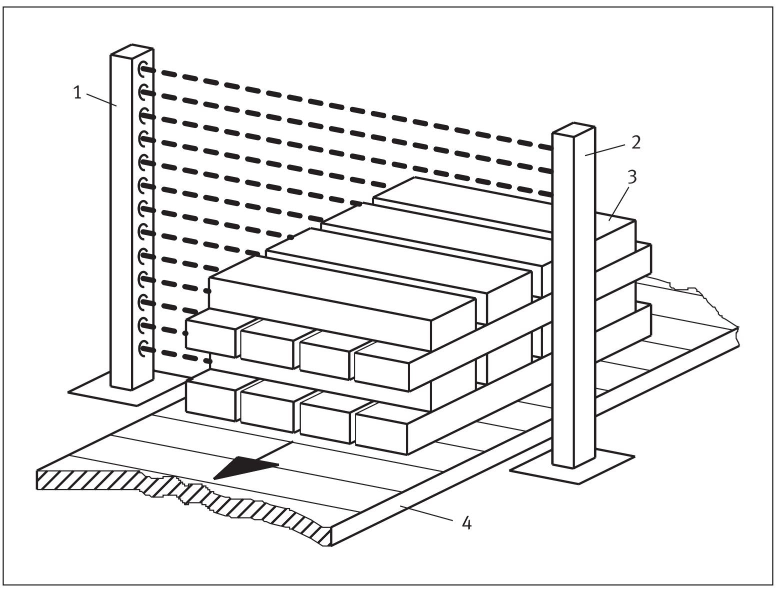
v Conveyor speed



The light curtains, also called area sensors, can be used to scan wooden parts (even when dirty), determine the lateral belt ride or progression, count and scan holes in workpieces, detect the edges or centres of workpieces, find localised cracks in belts and detect jams on conveyor belts. They can naturally also be used to check stacks of wood, as shown in Fig. 3-54. Light curtains with 8 or 16 light beams are often sufficient for simple tasks.

Fig. 3-54
Monitoring stack height

1 Phototransmitter
2 Receiver
3 Stack of wood
4 Conveyor

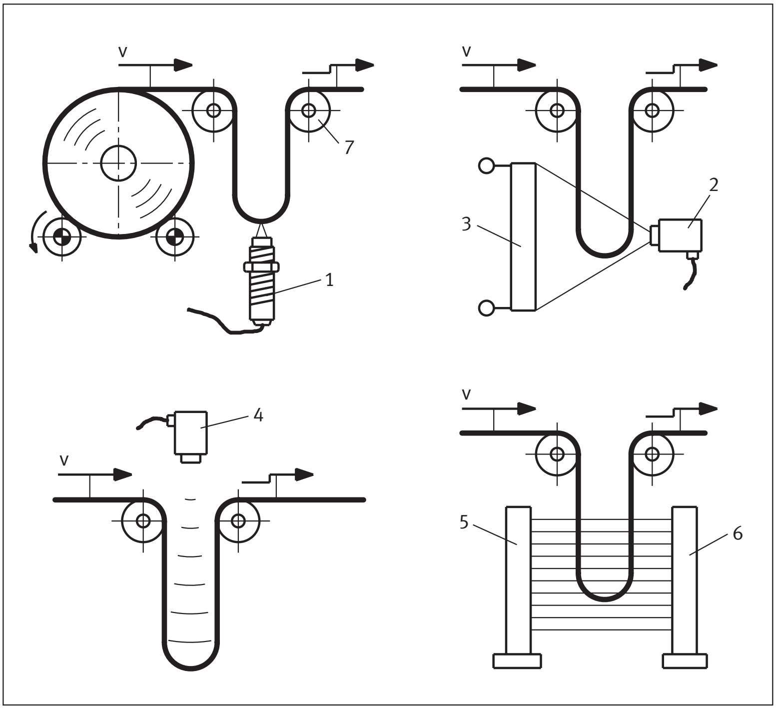


Since each light barrier is individually evaluated, information can be provided on the stack height. An explosion-proof version must be used in environments where there is dry wood dust.

A further application of light barriers is monitoring the slack at belt feeders. Where a belt is drawn in in pulsed mode and paid out in continuous mode, it must be moved in such a way that the pulse is compensated. This is usually achieved by means of belt slack. The slack must be monitored so that the pay-out speed v can be controlled in an appropriate manner and as a function of the roll diameter. Other sensors can naturally also be used for this task, as shown in Fig. 3-55.

Fig. 3-55
Slack sensor

1 Analogue diffuse sensor
2 Phototransmitter with high-frequency fluorescent lamp
3 CCD line-scan camera
4 Analogue inductive sensor or ultrasonic reflective sensor
5 Light curtain transmitter
6 Light curtain receiver
7 Idle roller



Specially developed light grids and light curtains can be used to monitor openings and entrances. Their purpose is to prevent accidents by guarding danger spots. The solutions used are multi-beam, self-monitoring through-beam sensors with a separate transmitter and receiver. Any penetration of the protected zone will be reliably detected by the interruption of even a single light beam. A vital factor in security technology is the ability of these devices to monitor their operatability themselves.

Security light grids generate multiple individual light bundles.
Light curtains generate a close-meshed protected zone with a defined resolution power (in excess of 40 mm).

The area can be protected by means of the vertical attachment of light curtains at a sufficient distance, by means of an inclined arrangement (entry point and rear entry protection) or even by means of a horizontal installation (Fig. 3-56). A person approaching at a speed of v = 2 m/s must not reach the danger spot. Before this could even happen, the equipment must be switched off and a secure state achieved. The protected zone can be up to 2 m high and up to 30 m wide with a vertical arrangement.

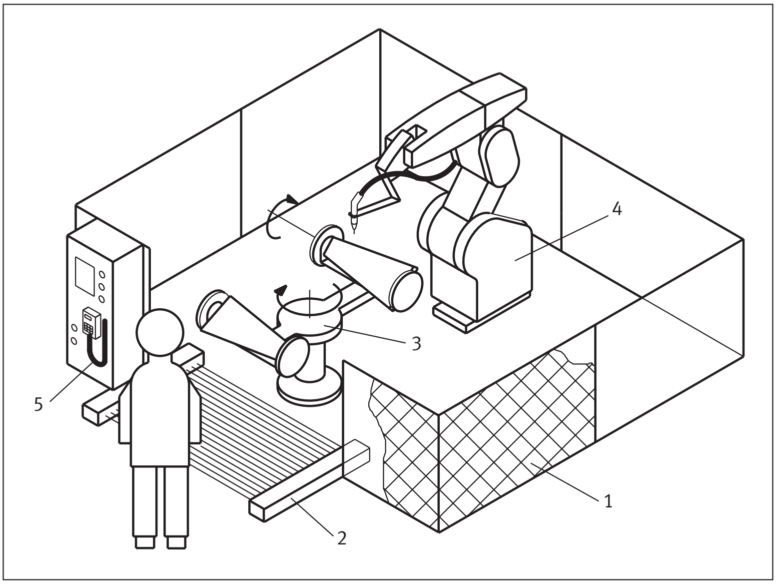


Fig. 3-56
Robotic operating cell with optical protection of the danger zone

1 Protective fence
2 Safety light curtain
3 Dual rotary table
4 Welding robot
5 Controller

The machine must be shut down by means of the power device rather than by a programmable logic controller (PLC) unless the systems used explicitly permit this and are approved for it. Messages relating to the shutdown operation carried out may of course run via the PLC. Security light grids for the protection of personnel must be inspected and approved by the relevant trade association.

Light grid accident prevention systems sometimes offer the following additional functions:

Blanking: This is a programmable function that permits a constant interruption of one or more light beams without resulting in a disconnection. The interruption can be caused by the constant forward and reverse motion of a feed slide, for example. Restricted areas can also be temporarily isolated.

Muting: This refers to the bridging of the light curtains so that material, for example, can be brought into the shielded zone. However, measures must be taken to prevent persons sneaking through at the same time in the object's shadow. To this end, several muting sensors are attached that distinguish material and people and supply their signals for “intelligent” evaluation.

Fig. 3-57 shows a sample arrangement of muting sensors. Here the work space of a production cell is screened by a security light grid. Material can pass without the conveyor stopping. The muting sensor signals are subject to various timeout controls.

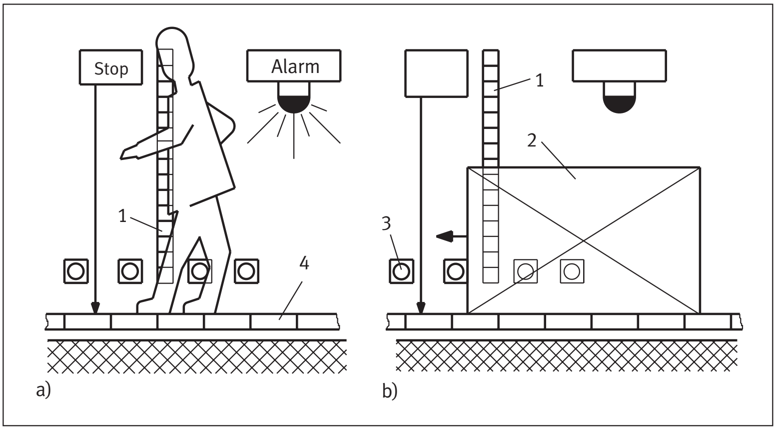


Fig. 3-57
Muting sensor arrangement

a) Illegal passage of personnel
b) Legal passage of material

1 Accident prevention light grid
2 Object to be transported
3 Muting sensor
4 Apron conveyor

3.7.7 Using laser sensors

The term “laser” is an abbreviation for *light amplification by stimulated emission of radiation*. Laser sensors are well suited to producing accurate distance measurements from considerable distances (> 2 m). To achieve these accurate measurements, the light propagation time method is used to calculate the time it takes for a beam of light from a laser diode to go from the sensor to the object and back to the sensor. Accurate measurement results can be achieved since the speed of light is a natural constant. The laser diode emits light pulses in the nanosecond range that are reflected by the object to be measured. The propagation time is calculated in the sensor and this time is then converted into an output voltage that represents the measured time.

Sample application: In a printing works, the paper is taken from a roll of paper weighing anything up to a few tonnes. Accordingly the unwinder must apply a defined, constantly changing driving torque. To this end, the diameter of the roll is determined to the exact millimetre from some distance away and the controller generates the drive parameters from the dimensions calculated from this value.

Optical scanners can also be used to excellent effect in the production of highly accurate object measurements. In this solution, a constantly rotating polygonal mirrored wheel with, for example 7 sides, is used to direct a laser beam over the object to the measured (Fig. 3-58a). A collimating lens ensures that the light beams are parallel (silhouette method). If there is an object in the path of the light, then the photodiode will be cast in shadow for a period of time that depends on that object. This period in shadow can then be used to determine the diameter of a workpiece, for example. Thus the determination of diameter is traced back to a time measurement. The measuring method can be varied greatly in use (Fig. 3-58c to i).

Laser sensors can also be used for the accurate measurement of moving objects since up to 1200 readings can be taken per second. This means that an industrial robot can hold an object in the measuring zone without having to precisely maintain the gripper position while the object is being measured (Fig. 3-58b). Because of their precision, measuring devices of this type are often also referred to as laser micrometers. They can achieve a reproducible accuracy of 0.5 µm over a measuring range of 0.08 to 12 mm, for example.

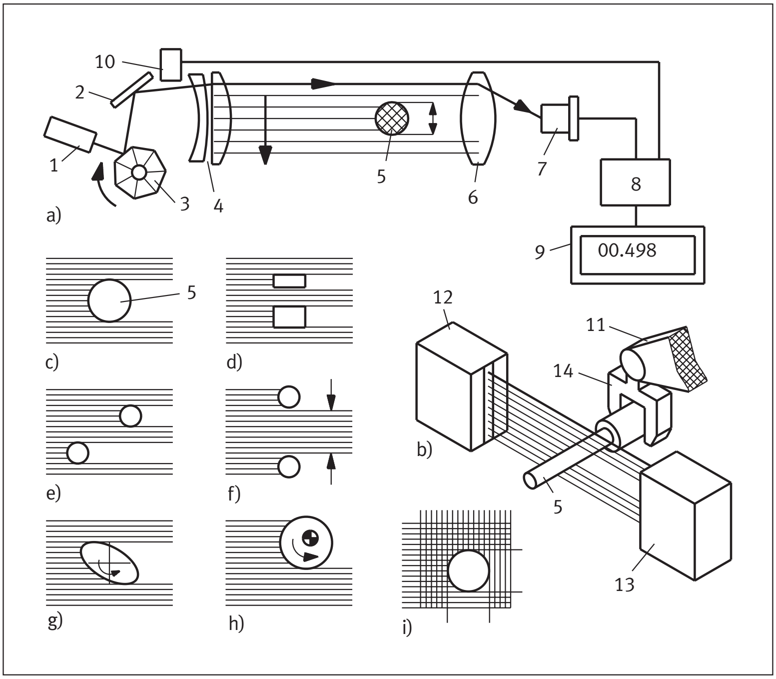


Fig. 3-58
Operating principle of the polygonal wheel laser scanner

a) Measurement principle
b) Sample application
c) Calculating diameter
d) Measuring distance
e) Measuring more than one diameter at the same time
f) Measuring the distance between drums
g) Measuring an ellipse
h) Measuring eccentricity
i) Scanning an object using 2 measuring heads

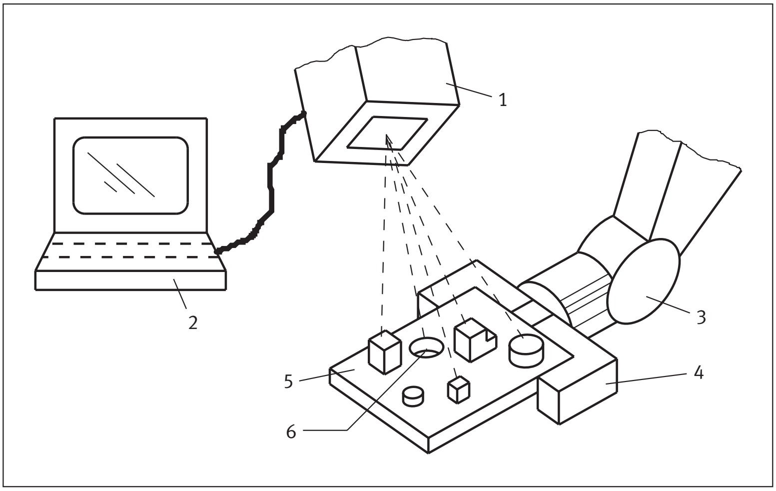
1 Semiconductor laser
2 Flat mirror
3 Polygonal mirrored wheel
4 Collimating lens
5 Item to be measured
6 Receiver lens
7 Photoelectric cell
8 Electronic receiver evaluation unit
9 Display
10 Optical synchronisation component
11 Robot arm
12 Transmitter
13 Receiver
14 Gripper

Another area of application: The success of each assembly operation is to be monitored in production as the inappropriate progression of an assembly will cause a defective component or is not actually possible. Processes such as filling and packing also meet the “assembly” requirements profile. So, for example, an image detection system can be used on strips of tablets during heat sealing to check whether there are any empty spaces or whether fragments of tablets, no matter how small, were included.

Fig. 3-59 shows a solution for checking an assembly, for example an equipped printed circuit board, using a freely programmable laser scanner. In this solution, the sensor is firmly mounted and works on the basis of a helium-neon laser. It directs the laser beam to the successive points where a component should be. The diffuse reflected light beam is then evaluated and compared with the saved reference light values. This comparison allows conclusions to be drawn as to the presence of components. The robot must hold the assembly in a precisely defined position. The distance between the sensor and the object to be measured should not exceed 3 metres.

Fig. 3-59
Checking an assembly using a laser scanner

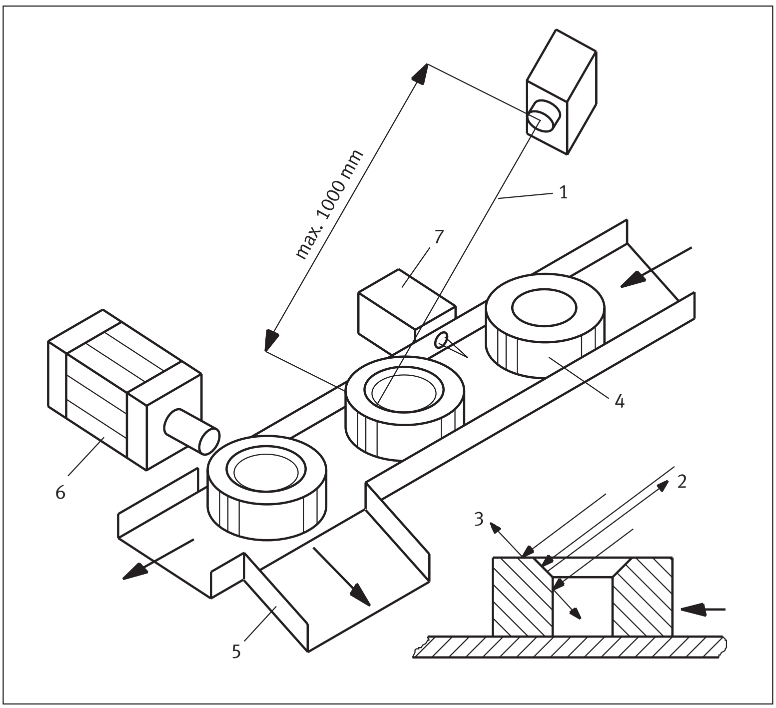
1 **Laser scanner**
2 **Evaluation unit**
3 **Industrial robot**
4 **Gripper**
5 **Assembly**
6 **Empty component space (assembly error)**



The solution in the example below checks that a turned part is facing right side up. It does this by detecting the chamfers on the inner side of the hole (Fig. 3-60).

Fig. 3-60
Detecting a chamfer using a laser scanner

1 **Laser beam**
2 **Beam reflected back to the sensor**
3 **Deflected laser beam**
4 **Workpiece**
5 **Outlet for parts facing wrong side up**
6 **Ejector**
7 **Diffuse sensor for checking for the presence of a part**



If the chamfer is uppermost a beam of light will be briefly reflected, thereby confirming that the part is facing the right way up. If there is no chamfer or it is on the underside of the workpiece, the beam of light will be deflected and go undetected. Defective parts will then be ejected. A diffuse sensor for checking for the presence of parts and for counting the parts is also attached.

Optical sensors, and in particular laser sensors, often work with a very accurately focused light beam. Their function will only be reliably fulfilled if the sensor is correctly mounted. This necessitates:

- Secure mounting joints that prevent self-maladjustment
- Tripods and retainers that are unaffected by vibrations
- Sensitive adjustment controls for horizontal and vertical adjustment as well as adjusting aids (integrated LED)

It may even be necessary to use sprung mounting plates that protect the sensor against impacts and high-frequency vibration when decoupling it.

The optical detection of coding has become a very important area of application of laser sensors. Fig. 3-61 shows a solution for sensing a bar code label using the laser beam. The beam emitted by a laser diode is deflected by a rotating polygonal mirror so that it can be sensed. The diffuse reflected light reaches a photodiode via an optical system.

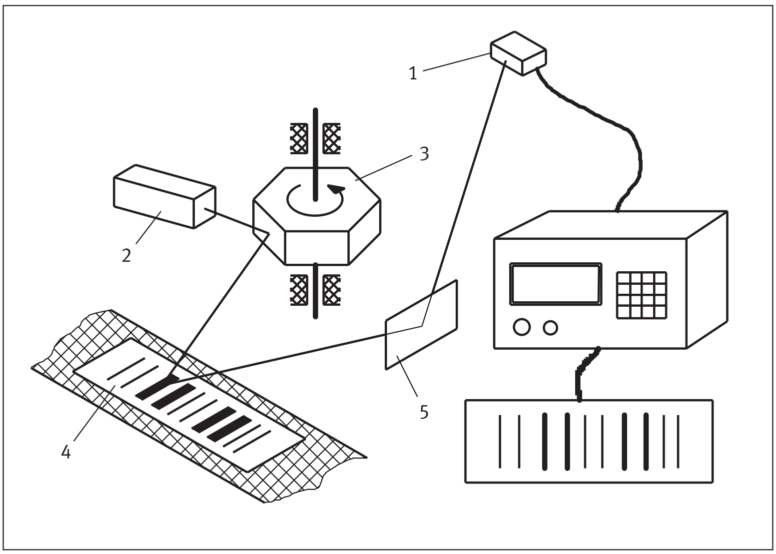


Fig. 3-61
Scanning bar codes using a laser beam

1 Photodiode
2 Laser
3 Polygonal mirror
4 Bar code label
5 Flat mirror

The photodiode generates an analogue signal containing the code information. This signal is converted to a digital signal by an analogue/digital converter so that the bars and gaps can be described more clearly. Finally, the narrow and broad bars as well as the gaps are decoded according to the applicable rules and the data output via an interface.

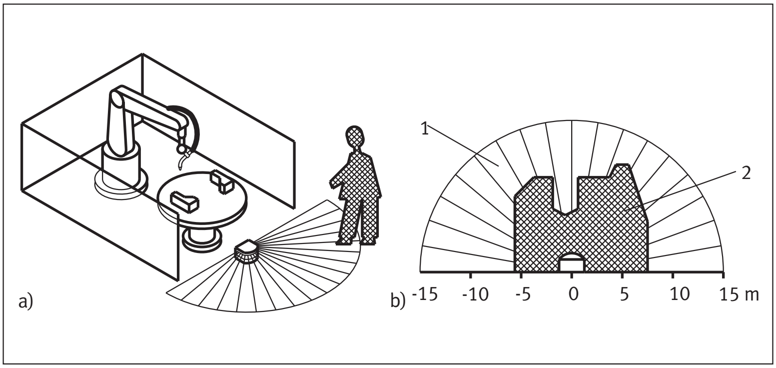
The scanning process can also be divided up into numerous scanning rows or numerous bar code ranges so that good read results can be achieved even if the code print quality is bad. This is referred to as raster scanning.

Laser sensors also offer new solutions for the field of security technology. Semicircular distance sensors, for example, can be used to monitor protected zones. Fig. 3-62 shows a sample solution. The range of the laser beam that constantly scans the protected zone via a rotating mirror has a radius of approx. 15 metres. A distance of 6 metres is approved for the personnel protection function.

Fig. 3-62
Robot workstation with distance sensor

a) Operating cell
b) Example for a protected zone contour

1 Detection range
2 Protected zone



Modern devices of this type even permit programming of the protected zone contour in accordance with local, i.e. structural or equipment-related, conditions relating to the danger spot. Certification of such devices is contingent on them having a redundant processor structure and routines for self-monitoring.

The function: The laser beam is directed over the area to be monitored 10 times per second (for example). The co-ordinates of the detected object are determined from the transmission angle and the propagation delay of a reflected light pulse and compared with the contour of the protected zone. Should a person come too close to the workstation, the dangerous equipment is switched off and an alarm signal is issued.

3.8. Recording positions using microwaves

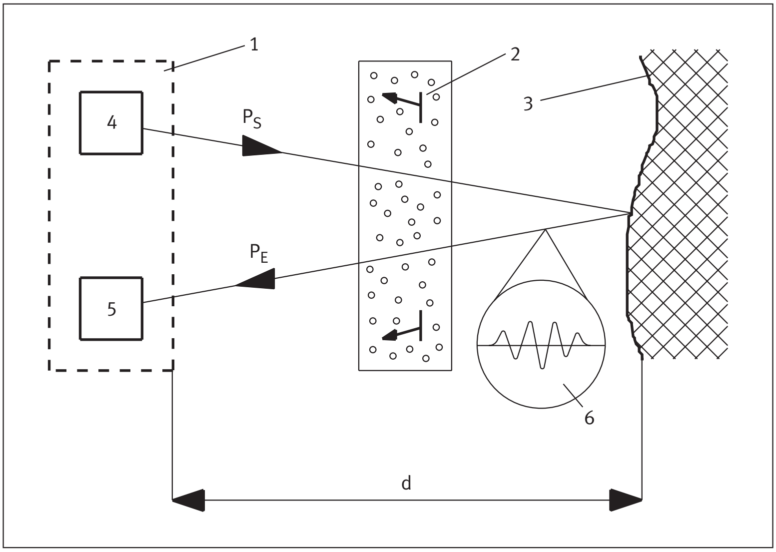
But first: What exactly are microwaves? They are short-wave electromagnetic waves in a frequency range from 300 kHz (television transmission range) to 300 GHz (infrared light). A frequency of 10 GHz corresponds to a wavelength of approx. 30 mm. They undergo linear propagation at the speed of light and are attenuated on passage through matter. Microwaves pass through media that optical sensors cannot. They penetrate plastic coverings and ceramic materials with almost no loss, but are difficult to focus. They are reflected by metal surfaces and diffracted by grid edges. Their directional characteristic depends on the antenna. A transmitter has a range of up to 6 m with a microwave power of only 1 mW.

The principle: The antenna of a radar sensor radiates microsignals in the GHz range as short pulses that are reflected by the sensor environment and the medium to be measured and caught once more by the antenna as radar echos. Fig. 3-63 shows the principle of echo propagation time measurement. The propagation time of the pulses is proportional to the distance d.

Fig. 3-63
Microwave radar

1 Antenna system
2 Attenuation in the propagation medium
3 Object
4 Transmitter
5 Receiver
6 Radar pulse

P_S Radiated transmitter power
P_E Receiver power
d Distance



The FMCW method *(frequency modulation continuous wave*) is used as well as the pulse radar method for distance measurements. With this method, the transmitted signal has a sawtooth form. The reflected signal (echo frequency) is however delayed and therefore differs from the transmit frequency. The frequency difference between the transmit frequency and echo frequency is calculated in a frequency conversion stage and then evaluated. This evaluation returns the distance to the object.

Microwave technology has been particularly useful in providing cost-effective solutions to problems encountered in the measurement of filling levels. Fig. 3-64 shows a sample application where the level in a double-wall container made from fibre glass reinforced material is measured. The actual fill volume is then also known. Measurements of this type can be carried out with accuracy even in very dusty and turbulent environments. Furthermore, the radar sensorics require absolutely no servicing. Temperature changes or high ambient pressure impair the accuracy of measurement only slightly. The more accurate the measurement of the propagation time of the pulse package, the more accurate the determination of the filling level.

In order to achieve an accuracy of just a few centimetres, the time must be measured accurate to a few 100 picoseconds. The radiated microwave power of only 1 mW is not dangerous for humans. Sensors of this type can, therefore, be used in personnel monitoring applications.

Fig. 3-64
Measuring filling levels using a microwave radar

a) Measurement with a closed container
b) Measurement in a silo with strong dust turbulence

1 Pulse radar
2 Combined transmit-receive antenna
3 Double-wall tank made from plastic
4 Filling

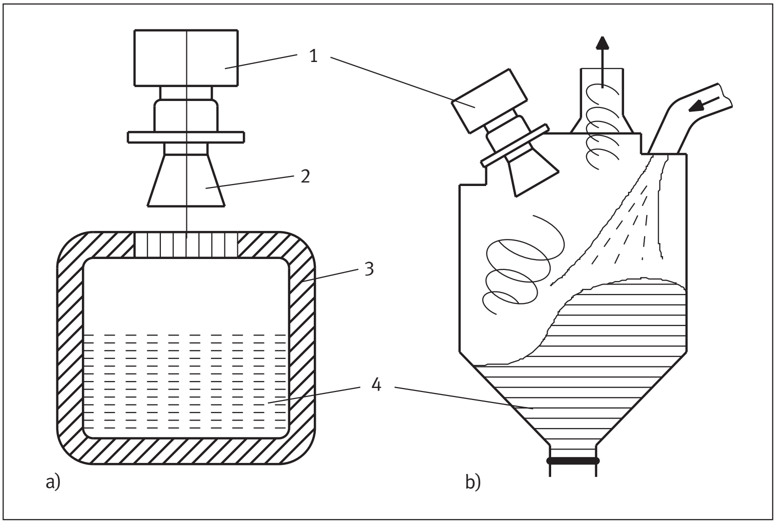
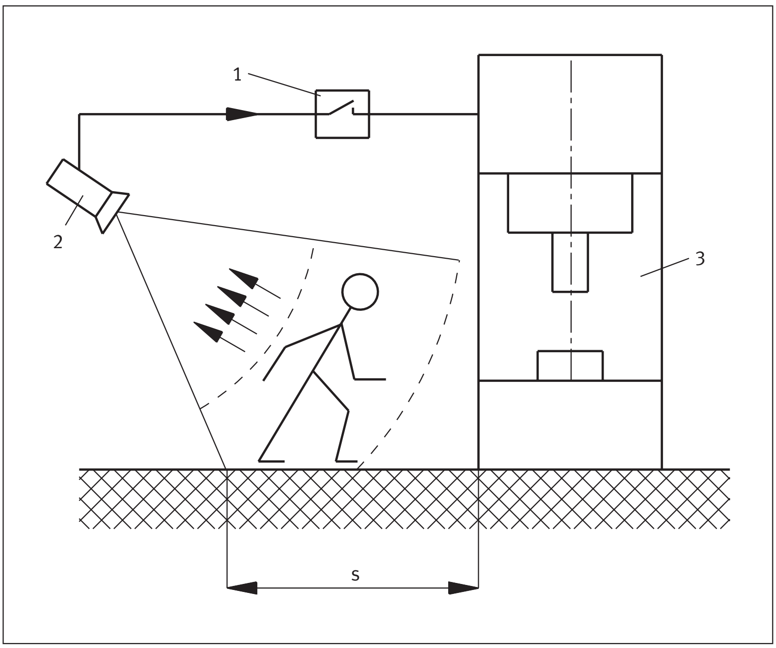


Fig. 3-65 shows a solution that uses a microwave sensor to monitor the access area to a tool room containing a press. If a presence is detected in this protected zone while the press is running, the sensor switches off the press if the safe distance s is breached.

Fig. 3-65
Monitoring a press using a microwave sensor

1 Press controller
2 Microwave sensor
3 Press

s Safe distance



Other evaluation methods can be used to measure flows, surfaces or thin films, for example. Another interesting application of sensors is in the prevention of collisions for autonomous automatic industrial trucks and mobile robots, for example. Highly powerful radar sensors will be integrated in road vehicles in particular in the future, if for no other purpose than to offer greater safety through automatic detection of surroundings. These include stop-and-go radars, parking aids and devices for measuring speed over ground. One of the major advantages of these sensors is their insensitivity to snow, dirt and ice as well as the fact that measurements can be taken in the absence of light (even though sensors of this type work on a similar principle to optical sensors).

3.9 Recording positions using nuclear radiation

Object positions can also be determined using radiation sensors. These sensors exploit the physical effect that radioactive beams passing through matter are either partially absorbed or reflected back. They can therefore be used to perform measurements in accordance with the penetration principle or the reflection principle.

If beta emitters are used for this purpose, then the requirements relating to radiation shielding of operators are straightforward and easy to satisfy. Beta radiation is a “mild” radiation. Fig. 3-66 shows the operating principle of this type of sensor. The radiation emitted by the radiation source is detected by a counter tube. If an object is placed in the path of the radiation, then the radiation is weakened. This weakening is registered and can be evaluated. The range is large. Direct beta radiation will have a range of 4 to 5 m, reflected beta radiation will have a range of 2 to 3 m. This type of sensor is completely insensitive to dirt and moisture. It can be used to check parts made from any kind of material or even parts inside other parts as is typically the case when checking filling levels, for example. It can also be used to establish variations in thickness or height, for example bulk materials on a conveyor belt (radiometric determination of dimension) or the thickness of films in extrusion processes.

The radioisotrope used should have a long half-time (greater than 1 year) to keep the periods between maintenance as long as possible.

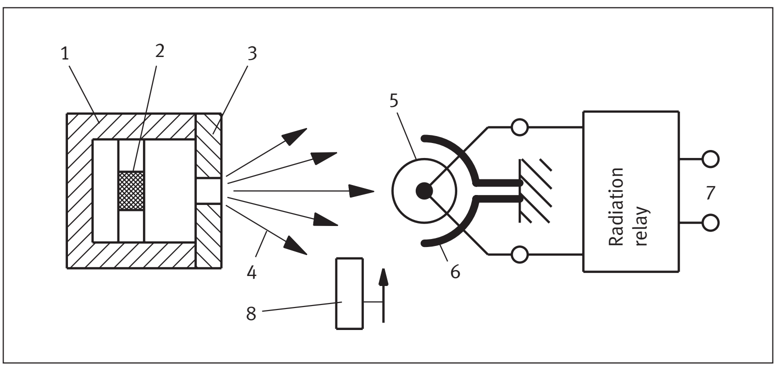


Fig. 3-66
Checking presence using a radiation relay

1 Housing
2 Specimen
3 Collimator
4 Beta radiation
5 Counter tube
6 Protective housing
7 Digital output signal
8 Object

4 Recording mechanical variables

The main mechanical variables are length, angle, force, torque, acceleration and mass (force due to weight). It is imperative for the correct functioning of machines and processes that these variables be known. This section concentrates on force, torque, acceleration and mass.

4.1 Measuring force

The measurement of forces and torques using electricity has become increasingly important in recent times, for example in the automation of assembly operations. The sensors suited to this task can be extremely complicated in terms of their physical method of operation. The reason for this is that forces often cannot be measured directly. They must then be measured indirectly, i.e. by recording the effects caused by the forces. This can generally be done by applying the force to a ductile body, for example a bending bar, and attaching the sensors there. Fig. 4-1 shows the main principles used. It is vital that the force be applied axially as transverse forces can result in damage to the force sensor and incorrect readings.

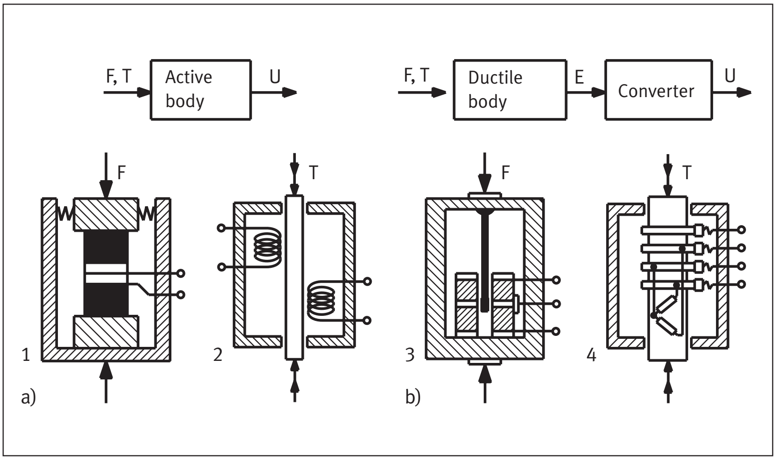


Fig. 4-1
Important sensor designs for force and torque

a) Direct force measurement
b) Indirect force measurement

1 Quartz force sensor
2 Magneto-elastic moment sensor
3 Inductive force sensor
4 Strain gauge moment sensor

F Force
T Torque
U Voltage
E Elongation in various directions

There are many physical effects on which devices for measuring force can be based. Fig. 4-2a, for example, shows a sensor that can be used to measure the bowing of a force measurement stirrup. It works according to the nozzle-baffle plate principle as a “distance meter”. With this type of sensor, the force is depicted as distance. The “softness” of the force measurement stirrup must be adjusted to suit the measuring range.

Fig. 4-2b shows another variant. In this sensor, thin film metal strain gauges are applied to a spring body made of metal (steel, bronze). Photolithographic methods are then used to construct the Wheatstone bridge circuits in which the strain gauges are integrated.

Forces can also be measured using the micro-bending sensor (Fig. 4-2c). With this type of sensor, the force is measured along a distance. In areas where the fibre optic cable is very sharply bent (small bend radius), part of the light travelling through the glass fibre is diverted from the core into the cladding.

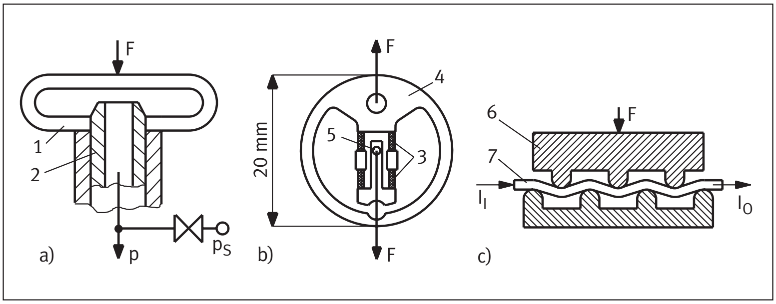
The greater the force, the greater the effect on the wave structure and the lower the intensity of the transmitted light. This fact permits very accurate force and pressure measurements, for example resolution sensitivity 0.05 N, measuring range 2 N.

Fig. 4-2
Measuring forces

a) Pneumatic force sensor
b) Measuring stirrup with strain gauges
c) Fibre optic force measurement

1 Force measurement stirrup
2 Nozzle
3 Strain gauge
4 Clamping zone
5 Point of force application
6 Pressure plate
7 Fibre optic cable

I_I Intensity of incoming light
I_O Intensity of outgoing light
p_s Supply pressure
p Measuring pressure
F Force

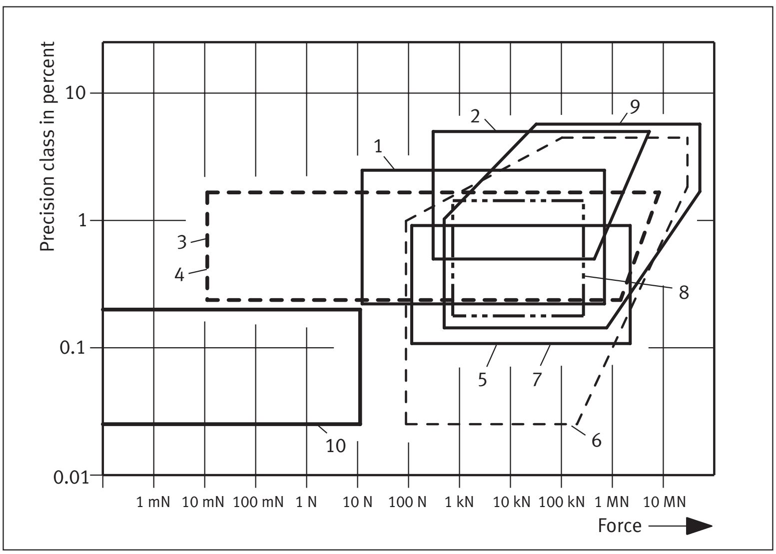


When solving sensor tasks related to the measuring of force, the force range in which the measurement is to take place is particularly important as the physical principle, errors of precision and the nominal force F_N are related by effect. Fig. 4-3 provides an overview of this relationship.

There are many other competing sensor types in the main branch of medium and high nominal forces. The precision class is considered here to be the largest individual error below the value specified as precision.

Fig. 4-3
Applications for principles of force measurement

1 Contact force sensor
2 Potentiometer force sensor
3 Inductive force sensor
4 Capacitive force sensor
5 Oscillating string force sensor
6 Force sensor with strain gauge
7 Semiconductor strain gauge force sensor
8 Quartz force sensor
9 Magneto-elastic force sensor
10 Force compensation sensor

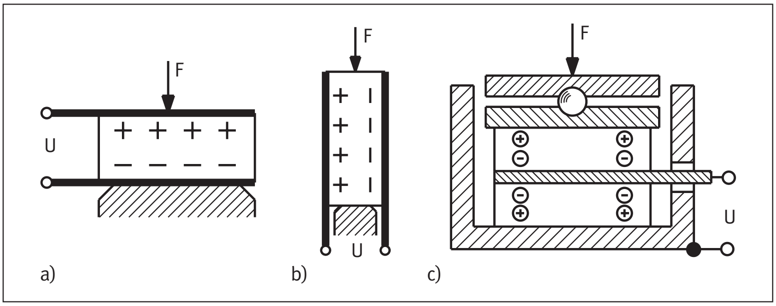


Various physical effects, for example the piezoeffect, can be used to record the deformation of a measurement body under load. The term *piezo* comes from the Greek and means “to press” or “based on pressure”. There are certain crystals (non-regular with a polar axis, e.g. quartz) that generate an electrical charge when a load is applied to their contact surfaces. This charge is approximately proportional to the load factor. This phenomenon was discovered in 1880. Piezo materials, prepared as films or a series of serialised lamina, can now be used as the active body in a force sensor. Fig. 4-4 shows the formation of charges that can be tapped as a measured voltage via lines.

Fig. 4-4
Operating principle of the piezo sensor

a) Longitudinal effect
b) Transverse conversion effect
c) Technical structure

F Load
U Voltage

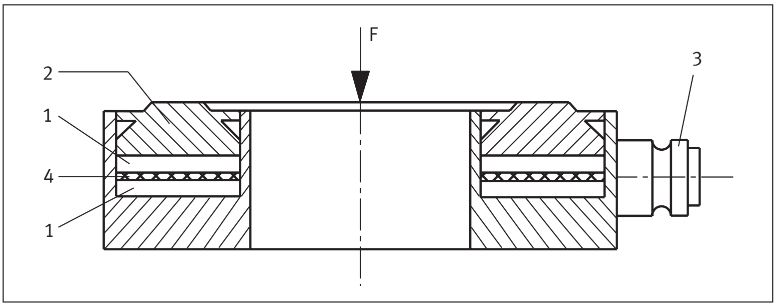


This type of sensor is not well suited to quasi-static measurements. The force must act dynamically because the charge generated is transported away.
The construction of commercially available piezo sensors is very compact. An example is shown in Fig. 4-5. There are naturally many variations such as those shaped like washers that can be placed under a screw head to measure force.

Fig. 4-5
Quartz force sensor (sample design)

1 Quartz slab
2 Pressure plate
3 Terminal
4 Electrode

F Measuring force



Intermittent forces due to weight are also sometimes recorded in order to solve counting tasks. Fig. 4-6 shows an example of a counter based on the mechano-electrical principle. The PVDF film stretches slightly when a workpiece hits the baffle plate, triggering the generation of an electrical voltage U. These signals are then collected in a counting circuit. Polyvinylidene difluoride (PVDF) is a substance with a high molecular weight in film form.

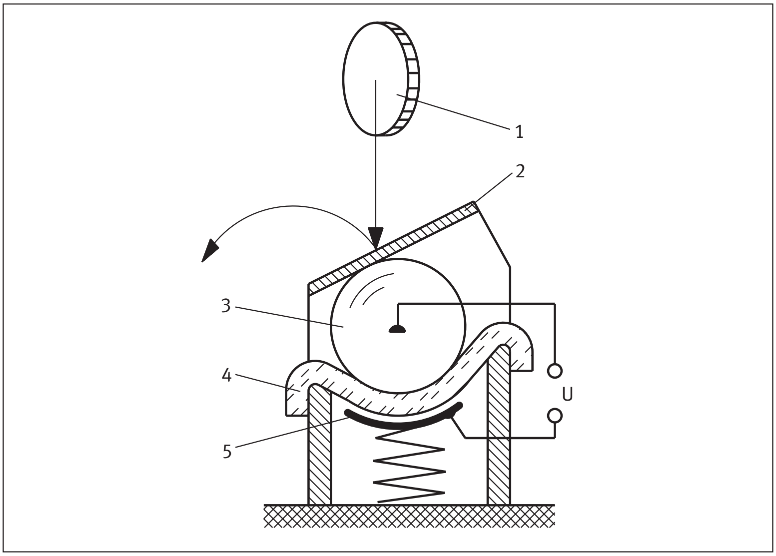
The characteristics of the polymer film make it at least equal to the single crystals with regard to piezoelectric and pyroelectric parameters. These characteristics are not, however, natural. They are the result of an appropriate macroscopic treatment. These films are only suited to the detection of variables that change over time (dynamic variables).

The use of strain gauges in force sensors is very common these days. This type of force sensor works indirectly, i.e. the force is applied to a ductile body and the resulting slight deformations (elongation, compression, deformations resulting

Fig. 4-6
Counter based on a PVDF film

1 Workpiece
2 Anvil, baffle plate
3 Cylinder
4 PVDF film
5 Contact plate

U Voltage

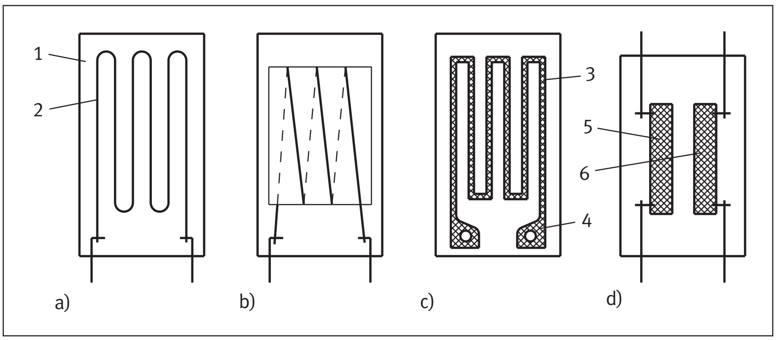


from shear stress) are measured. Strain gauges provide a highly accurate measurement here. They are the actual converter component. Fig. 4-7 shows some classic forms of the many design variants.

Fig. 4-7
Strain gauges

a) Wire strain gauge
b) Coil winding strain gauge (obsolete)
c) Film strain gauge
d) Semiconductor strain gauge

1 Plastic support
2 Wave form winding
3 Rosette
4 Termination point
5 P silicon
6 N silicon



The principle: The basis of the strain gauge is formed by a thin strip made from a metallic high-resistivity material that rests on a pliable support. When the conductive track is stretched, it becomes thinner and longer and the ohmic resistance increases. Since the useful relative elongation of the strain gauge is very small, they are predominantly used in full bridge circuits. This permits the compensation of interferences that affect all strain gauges in the same way. To measure a mechanical deformation, 4 strain gauges are attached in such a way that 2 of the opposing strain gauges in the bridge increase their resistance value (elongation) while the other two reduce their resistance value (compression). The detuning voltage across the bridge diagonal is then the gauge signal (see also Fig. 4-19). Strain gauges can also be used for other applications, for example for correcting linearity or for compensating any response to temperature changes. However 4 strain gauges in a full bridge circuit usually ensure good temperature compensation.

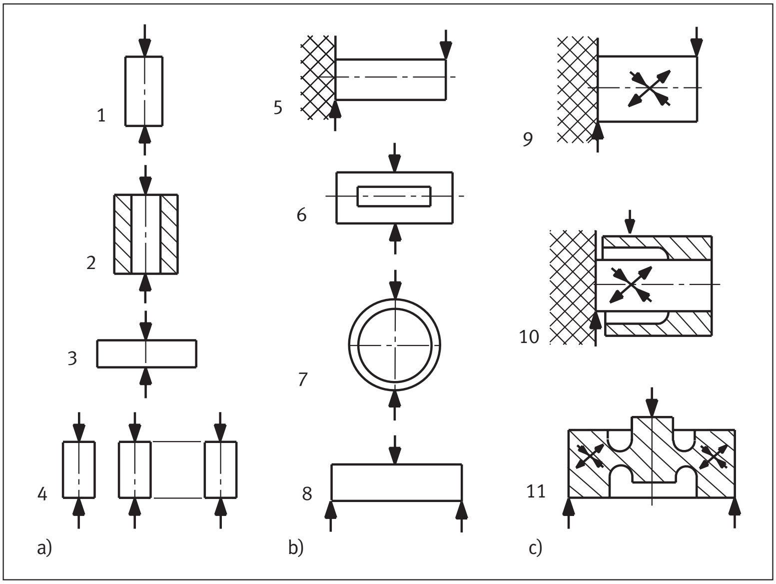
Thanks to modern technology, conductive structures of this type in many different forms can be deposited in a very thin film on a ductile body or a substrate by means of vacuum evaporation. The physical principle of the good old wire strain gauge does not therefore change.

What do ductile bodies bonded to sensor components of this type look like? They can have almost any appearance once they have been customised to meet the requirements of the problem in hand. However there are some basic types, as shown in Fig. 4-8.

Fig. 4-8
Basic types of ductile body

a) Compression body
b) Bending body
c) Shear stress body

1 Column
2 Tube
3 Compression plate
4 Multiple column
5 Single bend body
6 Double bend body
7 Ring
8 Plate
9 Basic shear stress body
10 Shear stress peg
11 Moulded body

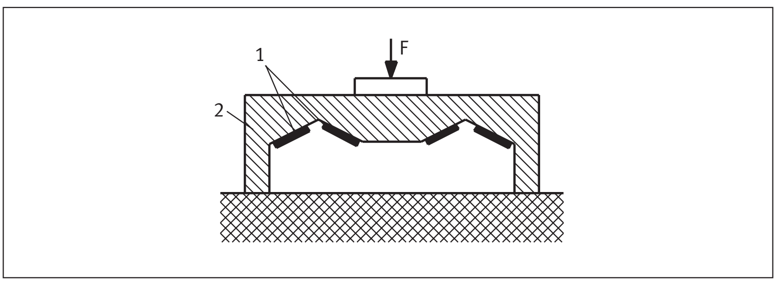


It is also possible to design a plate as a bending plate, for example, and equip it with pairs of strain gauges. Fig. 4-9 shows an application of this type. Strain gauges can naturally also be bonded to shafts to measure the torsion of the shaft under load. The transmitted torque can then be calculated. The result is a torque sensor.

Fig. 4-9
Force sensor based on a bending plate

1 Strain gauges
2 Ductile body

F Load

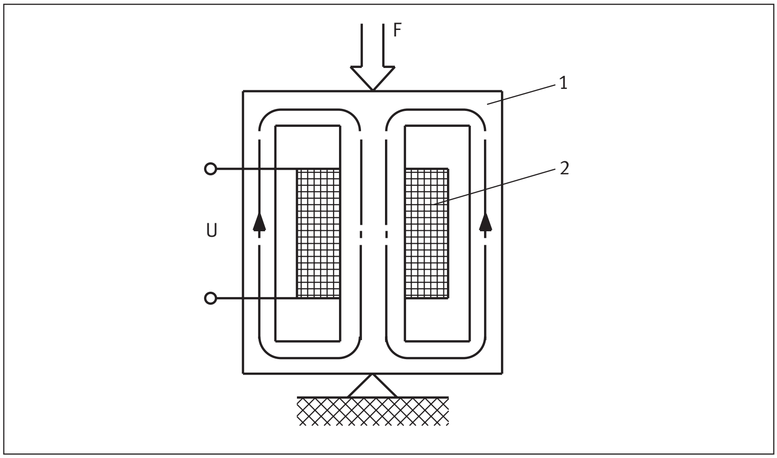


We will now look at the principle behind the magneto-elastic force sensor. With this type of sensor, the internal mechanical field that is proportional to the measured variable causes changes in the magnetic permeability of the active body. These changes can be electrically perceived via coil windings by means of the law of induction. The reciprocal effects that occur are referred to as the magneto-elastic effect. Fig. 4-10 shows a classic sensor of this type.

Fig. 4-10
Ideal form of magneto-elastic force sensor

1 Active body
2 Winding

F Force
U Voltage



Magneto-elastic materials include iron-nickel alloys with a high proportion of nickel and iron-silicon alloys. The winding is embedded in a closed magnetic circuit. If a measuring force is applied to the active body, the inductance changes and can be evaluated electrically. Although this design is very simple, it is not without its problems related to the embedding of the winding, i.e. disconnects are needed on the active body, but they result in undesired air gaps.

Cases frequently arise where it is necessary to measure the load on lifting devices, robots and manipulators in order to prevent overloading of the lifting gear and to permit documentation of the loads. Fig. 4-11 shows some solutions that can be used in these cases. As can be seen, there are different ways of integrating the sensor in the flow of force. The shear force axis shown in Fig. 4-11c connects two levers in one hub. The shear force acting on the axis is measured. It corresponds to the applied tensile force.

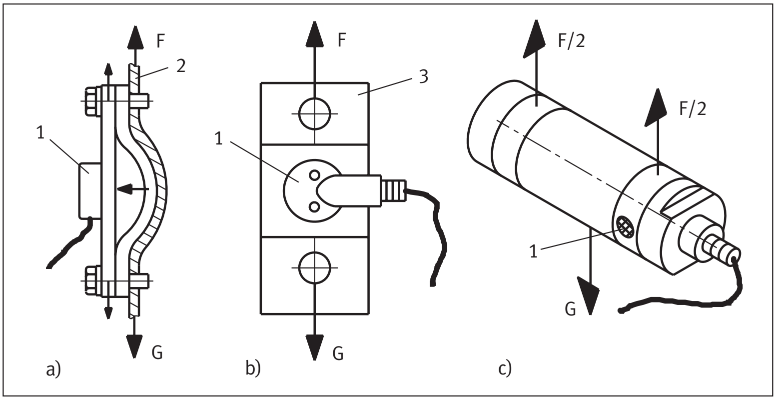
In the cable force measurement solution shown in Fig. 4-11a, there is no need to disconnect the cable in order to measure the force. The tension force in the cable causes the bowed strap to be pressed in, thus causing a tensile force to be generated in the base strap bearing the sensor. In the design with draw shackle (Fig. 4-11b), the sub-base is directly stretched and this elongation can be measured.

Fig. 4-11
Application of force sensors

a) Cable solution
b) Draw shackle solution
c) Shear force axis

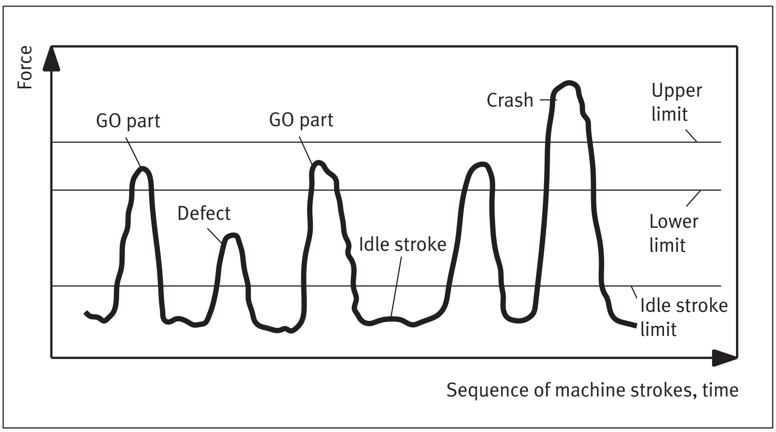
1 Sensor
2 Hoisting cable
3 Draw shackle

G Force due to weight
F Lifting force



The continuous measurement of the forces acting on production machines, for example presses, permits monitoring of the machine and also provides information on the probable quality of the process sequence. This is now an absolute must in high-power systems. Fig. 4-12 shows the force/time graph for a press. If the processing force rises above or falls below the defined limits, a command is issued to the machine (to switch off, for example). Piezoelectric designs with a peg-type construction, for example, can be used as force sensors. A diameter of 8 mm, for instance, allows the integration of the sensors in the machine component under load. Disc-type sensors are also easily integrated in machines.

Fig. 4-12
Force monitoring limits in a press

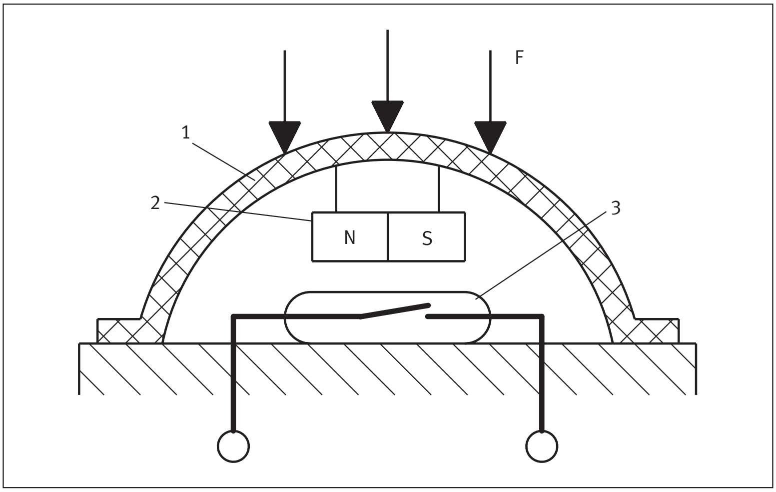


A completely different field where the detection of forces is required is the field of safety and security technology, for example in collision protection for industrial trucks. Collision protection systems work in different ways, for example by evaluating mechanical contacts, obtaining information via reflected light or ultrasound, using a camera system to maintain a constant view of the ground or using a 2D laser scanner. Mobile devices must be able to detect obstacles and execute an automatic stop if they hit an obstacle. This can be done by means of a reed switch integrated behind a rubber profile strip, for example, that is triggered by a magnet in the centre of the rubber profile. Fig. 4-13 shows an installation sketch. The switch responds in the event of a collision and generates the switch-off signal. A fibre optic cable whose conductive properties change when it pressed can also be fitted in the bumper of an autonomous industrial truck. A deflection at any point is echoed in the light beam and can be converted to an electrical switch signal. Profiles of this type are generally sold by the metre and can be prepared to suit the protected zone. In the case of closed profile strips, the internal pressure that increases abruptly when a force dents the profile can also be evaluated.

Fig. 4-13
Shock detector

1 Rubber profile strip
2 Permanent magnet
3 Reed switch

F Force of impact

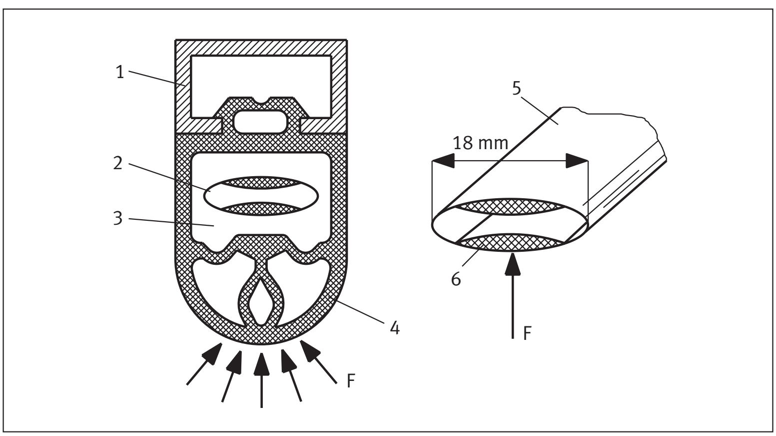


Safety contact strips based on tactile sensor technology are also used in the construction of machines. They can be used to safeguard crushing and shearing equipment in the operating area. A profile strip of this type is shown in Fig. 4-14. The rubber strip contains a switching device that is effective along the length of the strip. A switching signal is triggered if both contacts touch. The material also has a sufficiently high resetting force that it can assume its original position once the load is removed. The system responds to a triggering pressure of 6.5 N/cm^2.

Figure 4-14
Security contact strips

1 Machine component
2 Contact strips
3 Switching chamber
4 Contact mechanism
5 Sheath
6 Reinforced copper wire injection-moulded in conductive plastic

F Force of impact



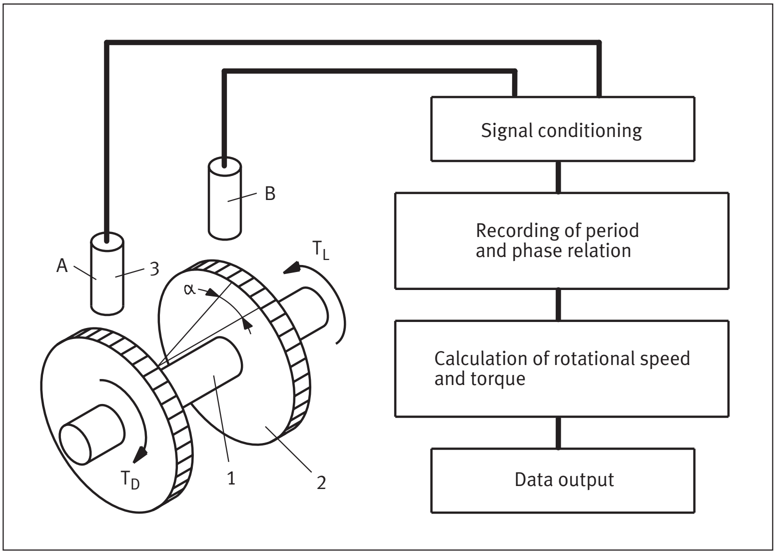
4.2 Measuring moment

Torque is the product of a force and its effective distance given by a lever arm from a reference axis (usually a shaft axis). When measuring torque, the change in geometry resulting from the torsion of a component can be used for the purpose of measurement. The angle of rotation a is then a measure for the applicable torque. In the measuring set-up according to Fig. 4-15, the rotational speed is also determined as a side-effect. Before this can be done however, the reference to pulse trains with a known time profile must first be established (reference counter).

Fig. 4-15
Solution for contactless torque measurement

1 Torsion shaft
2 Incremental disc
3 Opto sensor
α Torsion angle

T_D Driving torque
T_L Load torque



The control pulse from sensor A activates the period and differential counters that register the high-frequency counting pulses. The control pulse B closes the differential counter, while the period counter will only be deactivated by a further control pulse A. The differential counter's reading gives the time delay between the pulses from sensor A and sensor B. The torque is calculated on the basis of a series of these readings. Since torsional stress can be split up into compressive stress and tensile stress, there are also many other physical effects that can be used to measure torque. For example, strain gauges can be applied to, or magneto-elastic effects used on, a shaft. In this case, a magnetically soft, magnetostrictive amorphous metal film must be applied to the shaft surface. The sensor head, consisting of a supply coil and several receiver coils, works on the transformer principle. Amorphous metals, also called metallic glass, are specific alloys of Fe, Ni, Co, Si, B and P that are characterised by their excellent soft magnetic, electrical and mechanical (hardness, apparent yielding point) properties. Torque measurements are required in test bays, at screw driving devices for controlling screwdrivers and, for example, for monitoring driving torques.

4.3 Measuring acceleration

Most people have an acceleration sensor somewhere around them. The airbag in a car is triggered by an acceleration sensor (this sensor responds to negative acceleration, i.e. brake acceleration). Accelerations a can be detected in the following ways:

- Force measurement (force F) where the mass m is known.
  The formula is $a = F/m$.
- Time-dependent displacement measurement.
  The formula is $a = 2s/t^2$

Fig. 4-16 shows some acceleration sensor designs. A common characteristic of these sensors is that they all have a seismic mass. It exerts a force on a measuring element as a result of the acceleration. This element can be a fixed measuring spring, as shown in Fig. 4-16a. This principle is also suited to static measurements. The natural frequency can be up to 10 kHz, the operating frequency range can be extended by means of cushioning with silicone oil. The maximum measuring range is 10^4 m/s^2. The design shown in Fig. 4-16b uses the inductive principle. The acceleration of proportional measured voltages can also be achieved if the seismic mass is allowed to act on a piezo component (Fig. 4-16c). Attachment of sensors of this type requires very precise adjustment in the primary direction in which the sensor works. Otherwise the measurement will be invalidated by high cross sensitivity. In order to compensate effects of this type, several sensors can be arranged in the dimensional axes X, Y and Z or a sensor can be selected that is sensitive in all dimensional axes. Fig. 4-16d shows a sensor of this type. This design permits the detection and compensation of the applied transverse acceleration. The seismic mass can also be modelled as a shared ring-shaped body.

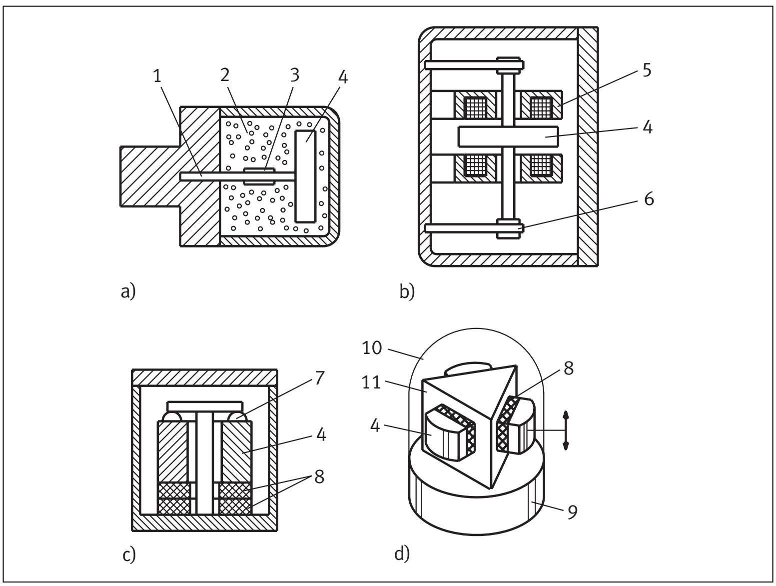


Fig. 4-16
Acceleration sensor designs

a) Measuring spring sensor
b) Transverse armature differential sensor
c) Sensor based on the piezo principle
d) Delta shear detector

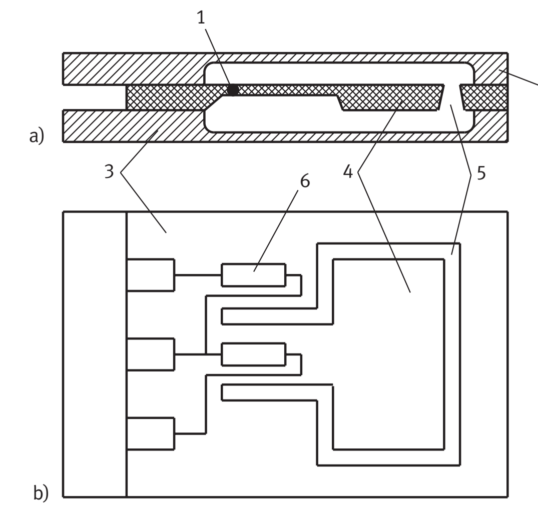
1 Trapezoidal spring
2 Silicone oil
3 Strain gauge
4 Seismic mass
5 Transverse armature differential sensor
6 Spring
7 Compression spring
8 Piezo component
9 Base
10 Protective cover
11 Sensor base

Micromechanics make possible very small acceleration sensors nowadays. Fig. 4-17 shows a design based on the measurement spring principle. This sensor can be sealed in glass and has dimensions of only 2 x 3 x 0.6 mm.

Fig. 4-17
Si acceleration sensor

a) Sectional view
b) Top view

1 Bar with programmed resistance
2 Glass housing
3 Si frame
4 Si mass
5 Air gap
6 Resistor



In this solution, a freely oscillating reed is etched from the silicon substrate. Resistors that change their resistance value in the event of deformation are attached to the bar by means of doping. The measuring range is between 10^{-1} and 10^3 ms^{-2}.

Acceleration measurements are needed in machine diagnosis and, for example, for controlling machines that are equipped with a mechanism for ceasing operation if accelerations exceed a certain limit. A shutdown of microfinishing machines can be necessary if building vibrations exceed an acceptable range. In this case the sensors are then vibration sensors. A typical application of vibration sensors is recording vibrations caused by the unbalanced mass and eccentricity of rotating bodies (shafts, wheels, roller bearings, etc.). The measurement results are used to monitor or to deliberately compensate mass moments of inertia.

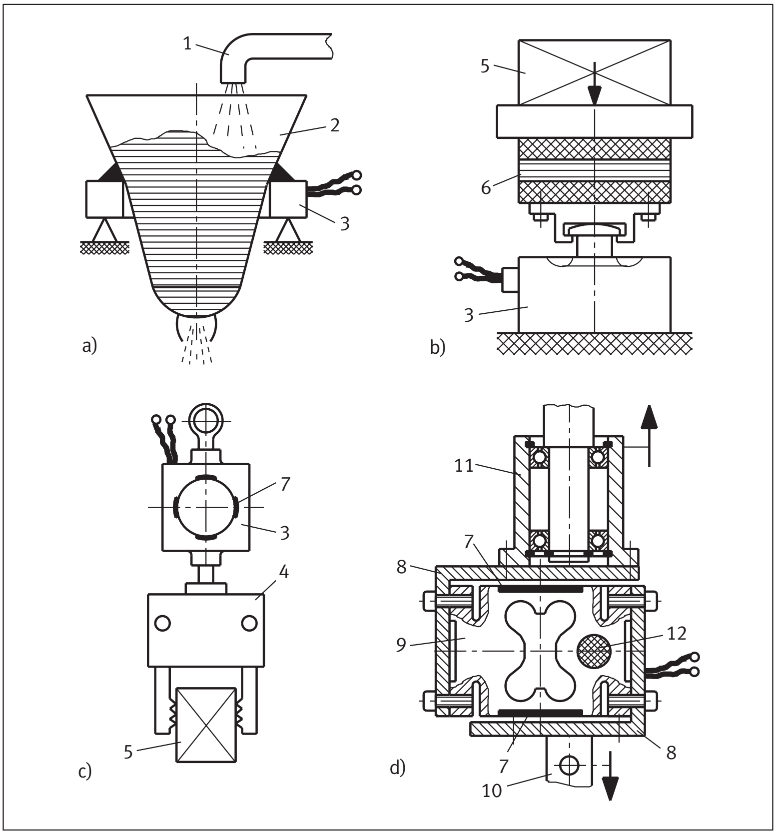
4.4 Determining mass

Scenarios requiring the recording of forces due to weight using load cells occur frequently in the processing of unit loads and liquids. Force measurements can be performed on individual pieces (crane, balancer, heavy goods vehicle scales) or on a continuous flow of goods (conveyor type scales). The deflection and compensation methods are used as methods of measurement. With the deflection method, the measured value is represented as a value proportional to the measured variable. With the compensation method (dynamic weighing), the variable to be measured is compared to a commensurate, but opposite, variable (reference variable). A null indicator shows whether both variables have the same value. The measured value is formed once the difference between the measured variable and the reference variable has become sufficiently small. A pair of scales is an elementary example of this principle. Fig. 4-18 shows some weighing devices.

Fig. 4-18
Various weighing devices

a) Differential proportioning scale
b) Load cell for pressure load
c) Hanging load scale
d) Load cell for tensile load

1 Bulk material inlet
2 Proportioning reservoir
3 Load cell
4 Gripper
5 Object to be weighed
6 Elastomer intermediate layer
7 Strain gauge
8 Elbow connector
9 Ductile body
10 Connection for load suspension device
11 Pivot bearing
12 Measuring amplifier



In the first example, the bulk material is transported from a bin into the proportioning reservoir. This reservoir is supported by a ring-shaped load cell. When proportioning the material, the reduction in weight in a fixed time interval is recorded. This time interval must be matched to the mass flow to be expected. The throughput cannot be determined while the reservoir is being refilled, therefore the bulk material inlet must be equipped with a shut-off device.

In the example in Fig. 4-18b, the weighing platform is connected to the load cell via a mushroom-type connection and an elastic layer. This ensure that only pressure forces are transmitted.

Fig. 4-18c shows a load cell fitted between grippers and a hoisting device. At the heart of the load cell is a cuboid with a perfectly circular recess, with strain gauges bonded to the interior (see also Fig. 4-19).

Fig. 4-18d shows a strain gauge load cell with high resolution and a level of accuracy appropriate for calibration with pronounced mounting surfaces for installation between a manipulator hoisting axis and the load suspension device, for example. This cell is highly resistant to transverse forces. It contains a miniature amplifier for amplifying the bridge output signal of the strain gauge sensor (full bridge) with little drift. It can be connected using 3 or 4-wire technology, for example.

Fig. 4-19
Operating principle of a load cell

a) Ductile body
b) Bridge circuit

1 Ductile body
2 Strain gauge
3 Sensor
4 Fieldbus
µP Microprocessor

A Analogue
D Digital
F Force or force due to weight
V Amplifier

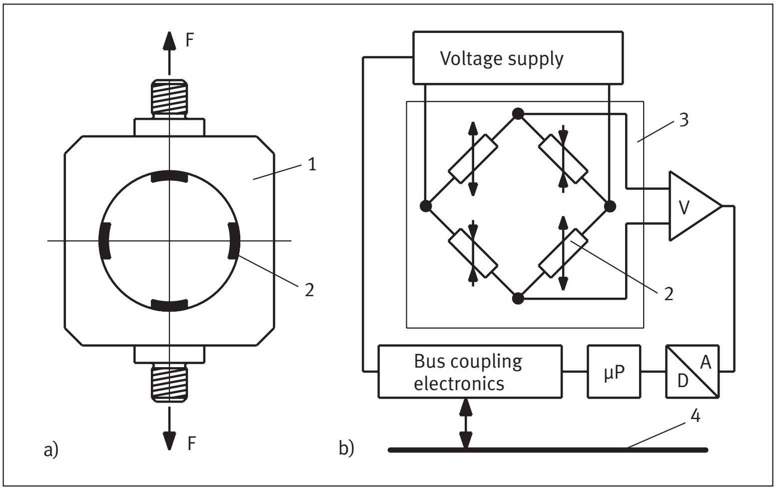
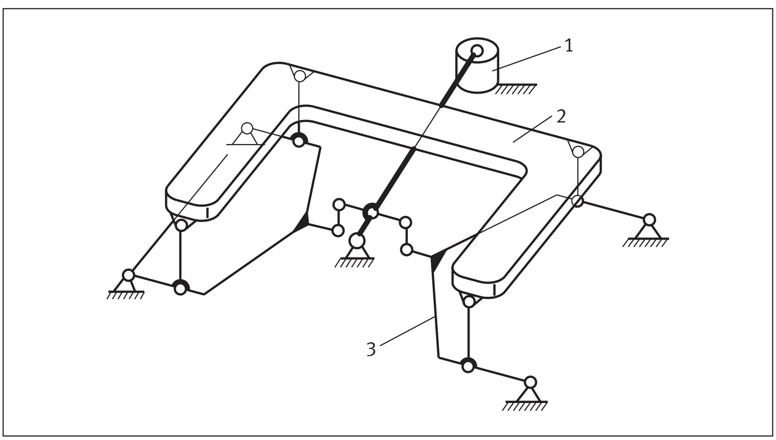


Fig. 4-19 shows the principle of a load cell of this type in a full bridge circuit. This means that two strain gauges are elongated and two are compressed when a load is applied. The mechanisms for managing the bus, startup and weighing can be addressed via a command set. This type of electrical circuit ensures good temperature compensation. However the measured value is invalidated if the electrical resistance of the strain gauges change as the result of a change in temperature rather than the result of elongation. The basic structure of a weighing platform is shown in Fig. 4-20. A mechanical structure suspends the load and directs the force due to weight via a lever arm to a pressure force sensor, as shown in Fig. 4-18b. The articulation structure of the mechanical system is designed in such a way that only pressure forces are directed to the force sensor. Transverse force would invalidate the measurement result.

Fig. 4-20
Mechanical structure of a weighing platform

1 Pressure force sensor
2 Load suspension frame
3 Lever transmission mechanism



5 Recording fluidic variables

Interest in measuring systems that can handle the fluidic variables of pressure as well as volumetric flow or mass flow has increased greatly in recent times. Advances in automation have made it possible to incorporate these variables in monitoring and control systems to a much greater extent than ever before. In process engineering, for example, 30% to 40% of all measurements are pressure measurements. In pneumatics, flow pressure and back pressure are important variables. Service units for compressed air circuits need a pressure gauge and a pressure setting device. In mechanical and plant engineering, bearings that are neither plain bearings nor roller bearings, but are in fact air bearings, are used. The bearing gap contains an air film which guarantees low-friction and wear-resistant operation. This is achieved by boring air inlet nozzles in the bearing shell with a laser or by using a bearing made from porous metals. Compressed air is required to operate these systems. The pressure and flow of the compressed air must be constantly monitored. If the operating parameters are not con sistent, the bearing may be damaged.

5.1 Measuring pressure

Sensors equipped with an internal pressure-sensitive element are used to measure pressure. These sensors output changes in pressure as electrical signals or trigger a switching operation when a specified threshold value is exceeded. It is important to bear in mind which pressure is being measured. A distinction must be made between the following:

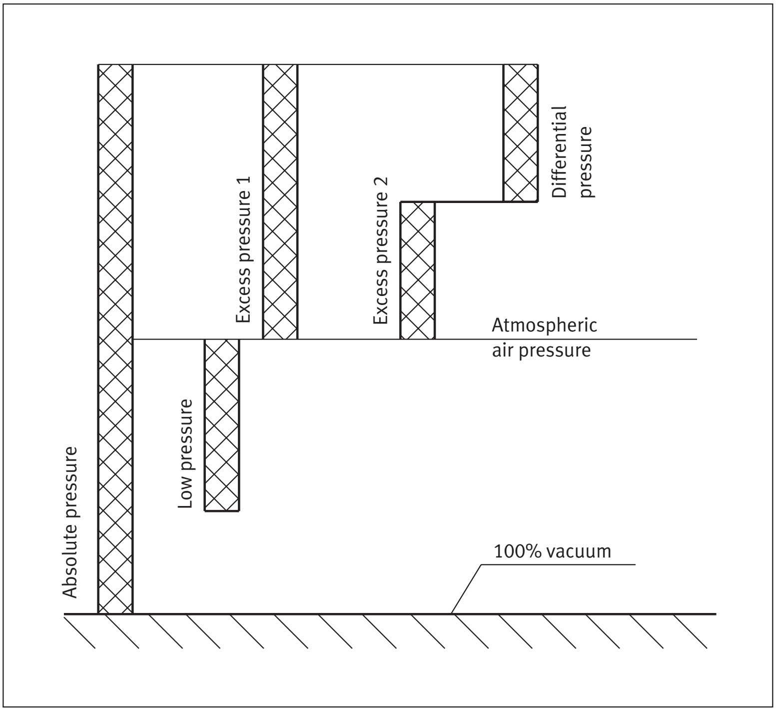
Absolute pressure: Pressure in comparison with absolute vacuum as zero ($p_{abs} = 0$). A direct measurement can be taken using the pressure balance, for instance.

Differential pressure: Pressure that represents the difference between two absolute pressure values ($p_1 – p_2$).

Excess pressure: Pressure that refers to the prevailing atmospheric ambient pressure and uses this as zero. Sensors that do this are known as relative pressure sensors.

The pressure ranges are illustrated in Fig. 5-1. Atmospheric air pressure depends on geographical altitude. Standard pressure refers to sea level (= 0 metres) and has a value of 1013 mbar (DIN 1343). Air pressure falls by approx. 12.5 mbar for every 100 m increase in altitude.

Fig. 5-1
Pressure ranges



Pressure sensors can be classified in two groups:

- Mechanical mode of operation, for example measuring devices with a Bourdon tube. The pressure exerted on the inside of the Bourdon tube causes the entire curved Bourdon tube to arch or contract. Precision mechanical components convert this movement to a deflection of the pointer.
- Electronic mode of operation, for example devices based on silicon and stainless steel membranes or other ductile materials.

In the latter case, the pressure is exerted on a highly elastic membrane, the deflection of which must be measured. Different physical principles can be applied in order to record this deflection. These include inductive, capacitive, piezoresistive, optical, solid state (comprising very small, inseparable electronic components) and ohmic (in the form of strain gauges) principles. Fig. 5-2 shows some designs based on these principles.

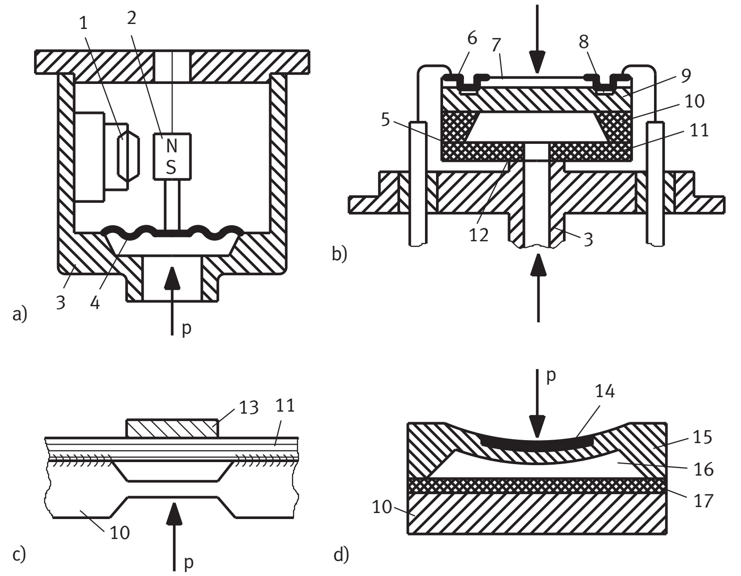
In the case of pressure sensors with a Hall element, a small permanent magnet connected to the membrane causes a change in the Hall voltage. The measuring element of the piezoresistive pressure sensor is a fixed plate which undergoes resistance as a result of diffusion or ion implantation. The electrical resistance of these sensors changes under load. The same applies to the solid state pressure sensor, which is created from silicon using a multi-stage etching procedure. This is represented as an absolute pressure sensor in Fig. 5-2d.

Fig. 5-2
Operating principles of some pressure sensors

a) Pressure sensor with Hall element
b) Piezoresistive pressure sensor
c) Capacitive pressure sensor
d) Solid state pressure sensor

1 Hall generator
2 Permanent magnet
3 Sensor housing
4 Membrane
5 Connecting layer
6 Al contact
7 Passivation
8 Piezo resistor
9 Epitaxial layer
10 Silicon chip
11 Optical fibre
12 Metal connecting layer
13 Disk
14 Resistance caused by diffusion
15 System rail made from silicon
16 Vacuum
17 Welded layer

p Pressure



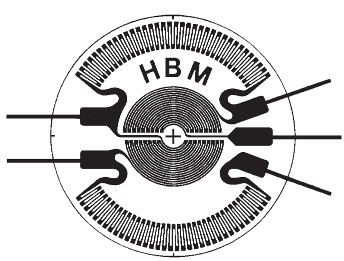
With the capacitive variant, the capacity change of a ceramic membrane caused by deflection against a parallel counter-electrode is evaluated. The membrane is therefore designed as a capacitor plate. The liquid must not be covering the sensor element when the system comes into contact with it.

In capacitive/ceramic-based pressure sensors with signal processing, the following microtechnologies are used:

- Thin film technology for the electrode structures
- Thick film technology for the signal processing hybrid
- Microstructure technology for the ceramics
- ASIC for signal processing

Thanks to developments in modern technology, pressure sensors with strain gauges can now be manufactured efficiently. If you have a fixed circular membrane (measurement membrane, usually made from stainless steel) as the ductile material, you can use rosette film strain gauges (Fig. 5-3).

Fig. 5-3
Strain gauges with membrane rosette design (HBM)



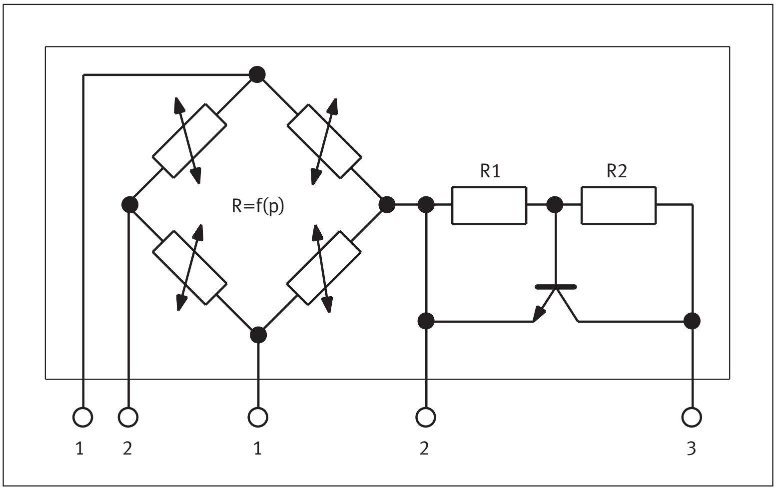
These sensor elements are small (with a diameter of 7 mm, for example) and have a rosette with four segments arranged in a circle. These are connected to form a Wheatstone bridge. Dimensioning of the ductile material is based on the assumption that a tensile stress of 100 µm/m = 1% of the nominal load.

Silicon-based pressure sensors are used for pressure ranges of 0 to 10 bar. Pressure sensors that use thin and thick film technology are suitable for the entire pressure range. They can be made self-learning by combining them with electronic components. Temperature resistors can also be integrated in the structure so that the sensor can also record the temperature of the medium and compensate temperature errors.

Fig. 5-4 also shows how a thick film pressure sensor is wired. The strain gauges are combined to form a pressure measuring bridge. A simple temperature compensating circuit (R1, R2) is connected.

Fig. 5-4
Internal circuitry of a pressure sensor

1 Bridge output voltage
2 Bridge supply voltage
3 Temperature compensation



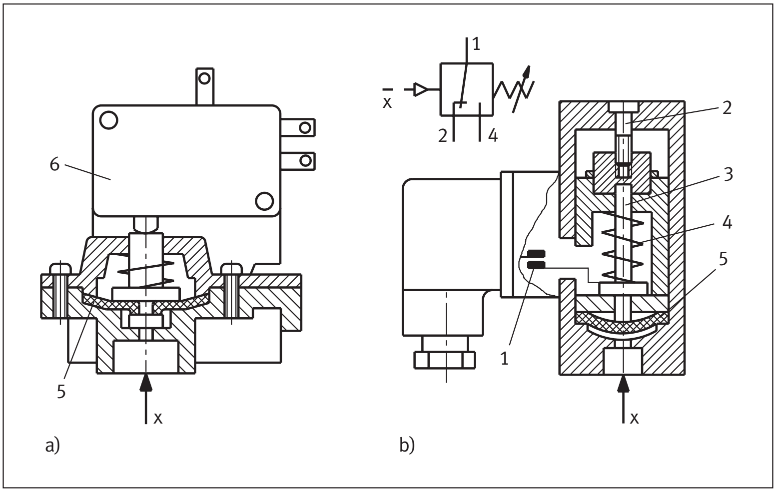
However, in many cases a pressure or vacuum switch or a PE converter will suffice. In the case of the PE converter, a pneumatic pressure signal switches an electrical signal generator, which usually takes the form of a changeover switch. The pressure actuating force can be increased with a suitably large membrane surface. When it is possible to adjust the switching pressure in this way, we talk about a pressure switch (Fig. 5-5).

Fig. 5-5
Pneumatic switching elements

a) PE converter
b) Pressure switch

1 Contact
2 Adjusting screw
3 Stem
4 Compression spring
5 Membrane
6 Stem actuated micro switch

x Pressure line connection



Pressure sensors come with different adjustment options. Low-cost devices have a fixed switching point, which cannot be changed. Statically adjustable devices allow the switching points to be defined individually. With dynamically adjustable devices, the switching points can be adjusted during the process to suit the relevant conditions or can be learned using the static teach-in method.

5.2 Measuring flow

The flow is the volume of a flowing medium per unit of time t, measured in volumetric units ($Q_V = V/t$) or in mass units ($Q_M = m/t$). There are a number of different measured variables that can be used for measurement purposes. Flowmeters are commonly used in industry. Typical applications include:

- Monitoring of coolant and lubricant circuits. Water-cooled spot welding tongs, for example, must be continuously monitored in this way. If the cooling is not activated, this leads to unclean weld joints and, in extreme cases, to the cap coming off the tongs. The water flow is therefore monitored using one pressure sensor and one flow sensor (respectively) in the coolant forward and return flows.
- Monitoring and measurement of flow rates in pipe systems such as water supply systems (dry running protection for pumps), exhaust flow control, leakage recording, press hydraulics and suction units, e.g. in the wood industry.
- Monitoring of air supply systems, ventilators, filter technology and cooling fans using air conditioning and ventilation technology.
- Measurement of filling amounts and the control of flow rates in process engineering as well as in sectors of industry that involve the handling of liquids and gases.

How is the flow rate determined? There are more than 30 different methods available. Some of these methods use ultrasonics, magnetic flux or thermal properties, others use the Coriolis effect, and then there are designs that have turbine or impeller wheels driven by the flow. The following sections examine a few of these methods in more detail.

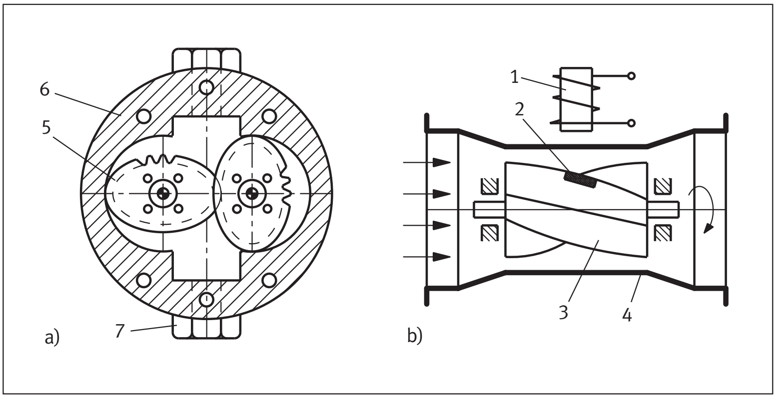
5.2.1 Volumetric measurement

This typically involves measuring "portions" of the medium and adding them up, for example using rotating measurement cells and rotary pistons. These instruments measure directly (Fig. 5-6a). Among the indirect volumetric meters are those where an impeller wheel is set in rotation by the flow. The number of revolutions can therefore be used as a measurement for the volume that has flowed through. Fig. 5-6b shows a sample design. The number of revolutions is measured magnetically. This value, when multiplied by the delivery chamber volume, gives us the volumetric flow rate.

Fig. 5-6
Volumetric flowmeters

a) Oval wheel meter (flux)
b) Axial impeller wheel meter

1 Solenoid
2 Permanent magnet
3 Turbine wheel
4 Measuring tube
5 Oval wheel (stainless steel or plastic)
6 Housing
7 Connection



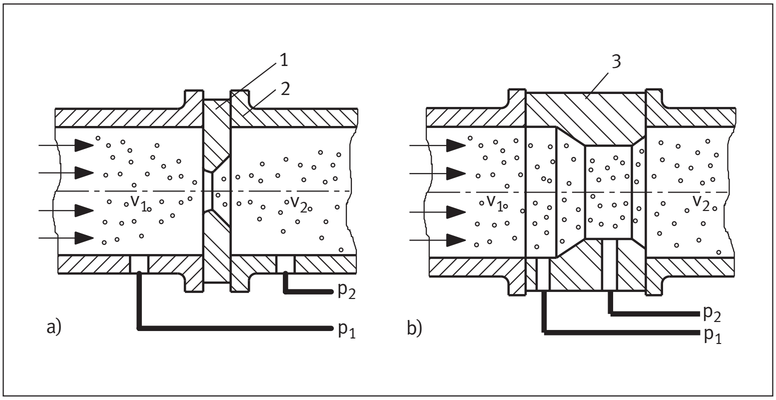
5.2.2 Differential pressure method

The principle of differential pressure measurement utilises the flow-mechanical changes in the medium that occur in the event of a local narrowing of the flow cross-section as a result of the increase in speed here. Various types of orifice are used to narrow the flow cross-section (Fig. 5-7). Information about the flow rate is obtained by evaluating the differential pressure between the pressures p_1 and p_2 measured in front of and behind the orifice. This procedure is ideal for use with large liquid and gas flow rates, as well as for high pressure, high temperature and aggressive media. For smaller flow rates, however, it is better to use calorimetric methods of measurement. Orifice plate systems are today used in almost 60% of all industrial applications.

Fig. 5-7
Differential pressure flowmeter

a) Standard orifice plate
b) Venturi nozzle, $p_1 : p_2 = v_1 : v_2$

1 Standard orifice plate
2 Tubing
3 Venturi nozzle



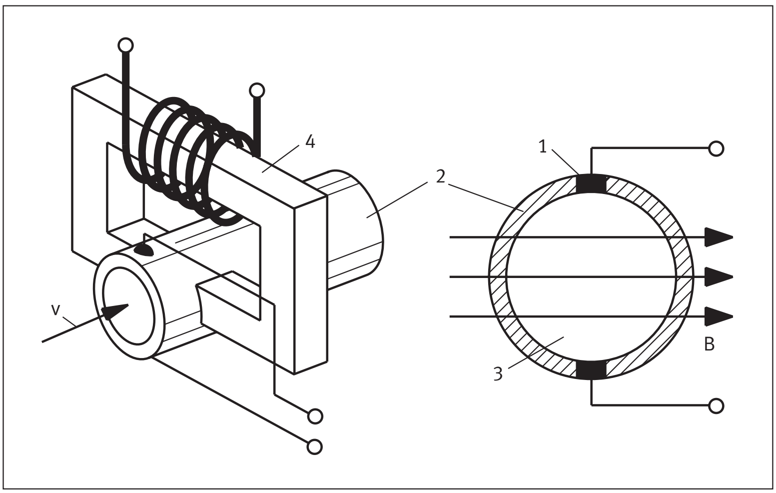
5.2.3 Magnetic flux flow measurement

To measure the flow, the effective force on moving electrical charges Q in a magnetic field is used. The magnetic flux density B is generated by an external magnet. In the case of liquids, the required charges Q are available in the form of ions as a result of widespread dissociation (disintegration of molecules). An electromotive force is created. This is measured by two diametrically opposed electrodes (Fig. 5-8). The measured medium flows through an isolated lined pipe piece. A measured value transducer separates the useful signal from the much larger interference signals.

Fig. 5-8
Magnetic flux flow sensor

1 Electrode
2 Isolated lined pipe
3 Flowing measured medium
4 Solenoid

B Magnetic induction
v Flow rate



The voltage is proportional to the average flow velocity. In order to keep measurement errors as small as possible, a steadying zone of between and 5 times the tubing diameter should be incorporated. The same applies after major cross-sectional changes or elbows. This reference value is valid for most flow sensors, as only measurement in a steadied (laminar) flow produces an acceptable gauge signal.

5.2.4 Flow measurement according to the Coriolis principle

The Coriolis flowmeter has been around for 50 years but has only become popular in recent times. It uses the Coriolis effect, which produces a mass flow when a U-tube is traversed. An electromagnetic converter, for example, causes the tube to vibrate. If there is no mass flow, the mode of motion is retained. When the medium is flowing, the Coriolis effect causes torsional vibration in the elbow. This is measured using sensitive converters (Fig. 5-9). The angle therefore provides a direct measurement for the mass flow. In this case there is no volume to mass conversion and the mass flow rate in kg/h is obtained immediately. This method is particularly suited to the dosing of extremely small to average quantities with measured value accuracy of approximately 0.5%.

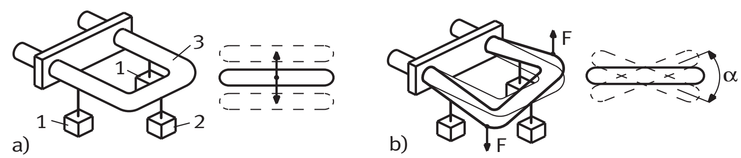


Fig. 5-9
Operating principle of the Coriolis flowmeter

a) Medium not flowing
b) Medium flowing

1 Converter to show torsion
2 Excitation converter
3 Tube

F Force

Meters that operate according to this principle are expensive, but can be used for extremely small quantities, short-time dosing, pulsating flow, high and low temperatures, tubing that is not completely full, and high pressure.

5.2.5 Flow measurement with ultrasonics

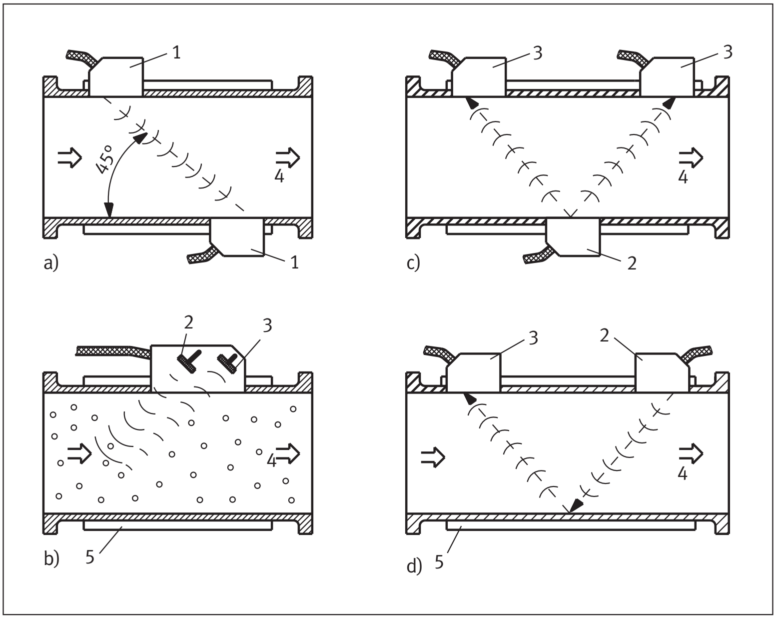
Ultrasonics can also be used to “look into” the liquid and thus give the volumetric flow rate. It utilises the effect, whereby the propagation velocity of sound waves in moving liquids changes with the flow velocity of the transmission medium. The function of the ultrasonic flowmeter is illustrated in Fig. 5-10.

Ultrasonic flowmeters are attached to the tubing. With the Doppler measuring method, acoustic signals are reflected in air bubbles or solid particles (Fig. 5-10b). However, as reflectors, these particles must not be too small. The relative movement of the reflected bodies causes the sound to be compressed to a shorter wavelength, i.e. to a higher frequency. The frequency difference is now directly proportional to the flow velocity. The flow volume can be determined from the tube cross-section and the velocity.

Fig. 5-10
Ultrasonic flowmeter

a) Transmission principle
b) Doppler measuring method
c) Drift method
d) Reflection principle

1 Test probe
2 Transmitter
3 Receiver
4 Flow
5 Tube



With the propagation delay method (transmission principle), the fluid must be "pure". Two test probes lying at a 45° angle to one another send ultrasonic signals at alternate intervals. The signal travelling against the direction of flow is influenced negatively, while the signal travelling with the flow is influenced positively. A propagation delay difference (frequency difference), which is not affected by medium or temperature, is produced in accordance with the flow velocity.

With the drift method (Fig. 5-10c), the directional sound radiation undergoes deflection caused by the flow. This results in a difference between the output amplitudes of both receivers. The mode of action of the various methods can be illustrated by adding the vectors of the velocities crosswise and lengthwise.

The origins of ultrasonic location date as far back as the First World War. Following the sinking of the "Titanic", attempts were made (which were unsuccessful at the time) to locate icebergs (echo depth sounding).

In order to be able to use ultrasonics for smaller and cheaper flowmeters, capacitive ultrasonic membrane arrays that can be manufactured using micro-systems technology are being developed. This development will allow sensor technology and electronics to be integrated on a single chip.

5.2.6 Calorimetric flow measurement

With thermal-based flow measurement, the flow rate of a gas or fluid is inferred from a temperature, a temperature difference or a variable derived from this. The basic measurement principle is thus the quantification of the heat transport. There are different ways of doing this:

Hot-wire method
This method is based on measurement of the heat transport. An electrically heated metal wire with temperature dependent electrical resistance is placed in the flow of gas and cooled down. The electrical data for the heating process and the ohmic resistance of the wire provide information about the flow velocity. When combined with the tube cross-section, this information gives us a value for the volume (assuming that the tube cross-section is filled completely).

Measurement with thermoelectric sensors
Thermistors are placed in the flow and heated electrically. A state of equilibrium is achieved depending on the cooling caused by the flow. In this case, the temperature of the sensor determines its electrical resistance, from which a gauge signal is derived.

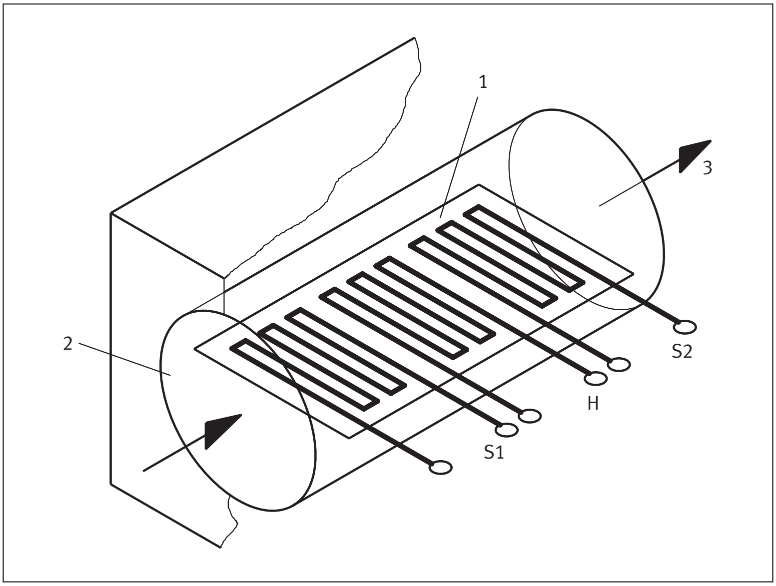
Measurement with a PTC resistor
Although this also involves cooling of a defined heat source by the flow, a PTC resistor is used in this case. This is a temperature dependent resistor which becomes highly resistive with increasing temperature.

Measurement using the heating-up method
A value for the mass flow rate is derived from a heat balance. This is achieved using a heating element and two temperature sensors. The principle is illustrated in Fig. 5-11. The measurement structure is in the form of a grid of thin film resistors on a chip. The temperature sensor S1 measures the input temperature of the liquid. The liquid is then heated up and the sensor S2 measures the temperature rise in the liquid caused by the microheater. The temperature difference between the two sensors provides a measurement for the flow rate when the heating capacity remains constant. When the medium is at rest, the temperature difference is zero.

Fig. 5-11
Schematic design of an electrocaloric flow sensor based on silicon technology

1 Chip
2 Flow channel
3 Flow direction

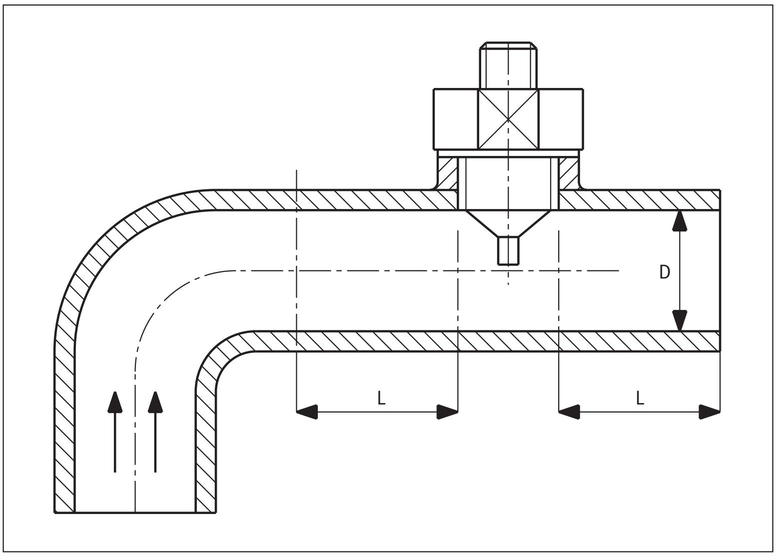
H Microheater
S1 Temperature sensor
S2 Temperature sensor for output temperature



The flow controller can be designed as an immersion device, as illustrated in Fig. 5-12. In order to prevent measuring errors, a distance L from the elbows or cross-sectional changes should be maintained. The minimum steadying zone should also be L ≥ 10 x D before the measuring point and ≥ 6 x D after. This achieves a low-turbulence and largely laminar flow in the measuring device.

Fig. 5-12
Calorimetric flowmeter with an immersion design

L Steadying zone



Measurement with a hot-film anemometer

Fig. 5-13 shows a thermal mass flowmeter for gases such as compressed air, for example. The flow channel contains platinum resistance film positioned in parallel with the flow. The heated resistor 4 is surrounded by the liquid and cooled down. However, a regulator 5 ensures that its temperature remains constant. Therefore, if the flow velocity increases, the current 3 also increases, giving us the value for the mass flow. The resistor 2 acts as a reference for the liquid temperature, so that the temperature difference between resistor 4 and the liquid can be kept constant by the regulator.

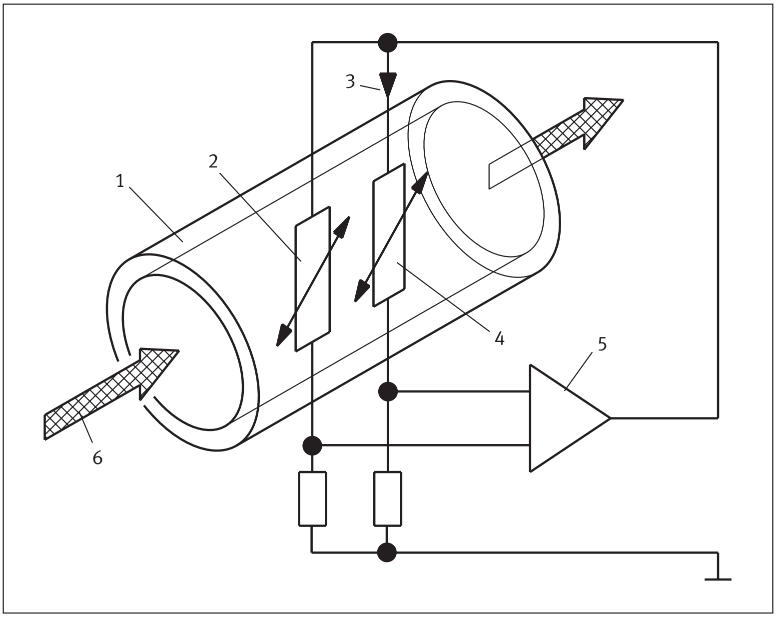


Fig. 5-13
Basic structure of a hot-film anemometer

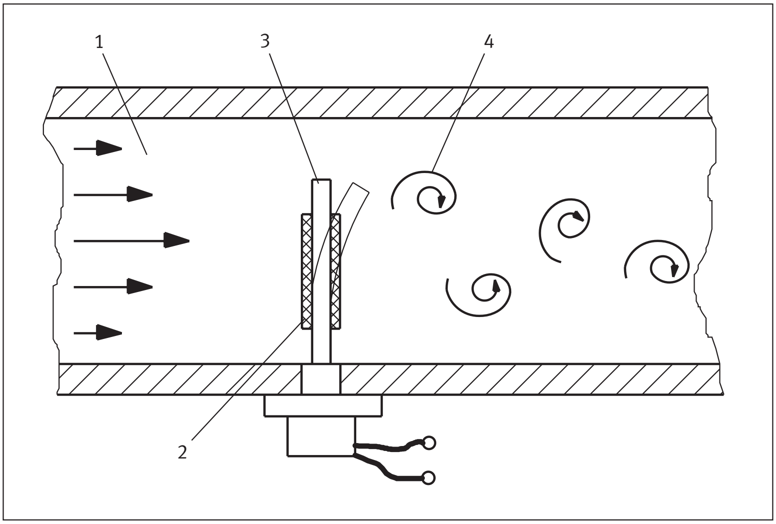
1. **Flow channel**
2. **Thin film resistor for liquid temperature**
3. **Heating current**
4. **Thin film resistor, heated**
5. **Regulator**
6. **Mass flow**

5.2.7 Vortex shedding flow measurement

When a baffle plate is integrated in a flow path, this creates a vortex path in the flow. The number of vortices formed within a wide range is proportional to the flow velocity. The shedding of vortices must thus be measured. This can be done using a number of different methods, for example by measuring the pressure that has been affected by the vortices. Fig. 5-14 shows a sensor design where a bar with strain gauges positioned across the flow enters the laminar flow. Vortices, which are shedded periodically (vortex shedding frequency) are created in the bypass. This process is in turn characterised by local differential pressure that causes the bar – which can also bend – to vibrate. This is recorded using the strain gauges. The number of breakaway pulses is proportional to the flow rate.

Fig. 5-14
Vortex shedding flowmeter (Vortex principle)

1 **Laminar flow**
2 **Strain gauges**
3 **Bending (interference) bar**
4 **Breakaway vortex**



A biologist came up with the idea of measuring the oscillation frequency induced by a vortex path on a Perlon bristle with a 1 mm diameter, which he had attached to an Antarctic penguin. The reversal of the principle produced a floating velocity sensor for research purposes.

6 Recording thermal variables

Temperature is an extremely important variable for technical processes. A great many material properties are dependent on temperature. The thermal status of a substance can basically be defined according to two physical principles.

- Contact thermometry
- Pyrometry

The term “temperature sensor” is used to describe all sensors that measure temperature. The following effects are taken into account for measurement purposes:

- Expansion of solid, liquid or gas substances dependent on temperature (expansion thermometer)
- Changes in resistance or electrical conductivity (resistance thermometer)
- Changes in the potential difference as electromotive force (thermoelement)
- Changes in the natural frequency of vibrating quartz as a function of temperature
- Emission and absorption of infrared radiation

6.1 Thermometry

In thermometry, the temperature sensor is brought into thermal equilibrium with the object or its surface. The temperature of the sensor is then determined with a temperature dependent effect.

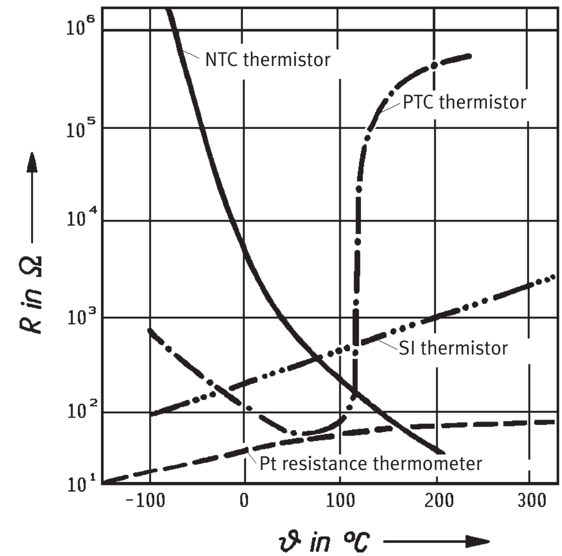
Of the many kinds of temperature sensor available, it is worth mentioning those whose material changes electrical resistance. A distinction needs to be made between NTC *(negative temperature coefficient)* and PTC materials *(positive temperature coefficient)*. An NTC thermistor consists of a polycrystalline sintered compact made from the oxides of metals such as manganese, nickel, iron, cobalt, copper, etc. When heat is supplied, the charge carrier concentration increases according to a logarithmic function. It is extremely sensitive and records even the slightest change in temperature. Fig. 6-1 shows the characteristic curves of various temperature sensors.

The most common electrical contact thermometers are the standardised platinum temperature sensors Pt 100, Pt 500 and Pt 1000. In accordance with IEC 751, the nominal value for the Pt 100 temperature sensor, for example, is 100 ohms resistance at 0 °C.

PTC thermistors are used to monitor the coil temperature of electric motors (thermistor type motor protection). If the coil temperature increases above the permitted values, the motor is disconnected from the mains.

Fig. 6-1
Resistance behaviour of different metal semiconductor resistance thermometers

J Temperature
R Electrical resistance
Si Silicon
Pt Platinum



With resistance thermometers, measurements are always taken over a certain surface area. With thermoelements, on the other hand, temperature measurement can be limited to a small localised point. Thermoelements use the Seebeck effect. Two different metals soldered together (semiconductors can also be used) produce a thermovoltage which is directly proportional to the temperature difference to be measured when the soldered joint is exposed to the temperature of the item to be measured.

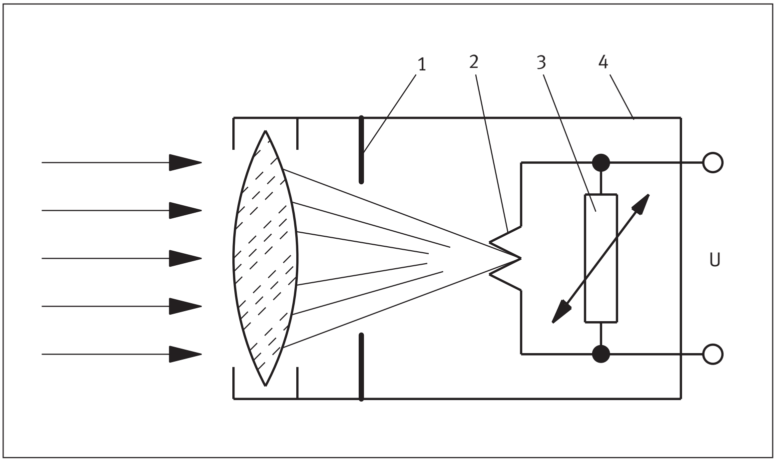
6.2 Pyrometry

According to Planck's radiation formula, every substance (gas, liquid, solid) is a thermal radiator. In pyrometry, this thermal radiation is used to heat a temperature sensor. The temperature of the thermal radiation source is inferred from the temperature that the temperature sensor assumes. Pyrometers are mostly used for temperatures above 800 °C. They operate in a contactless manner using opto-electronics (Fig. 6-2). An imaging lens directs the radiation towards a thermopile or a photodetector. The thermal radiation can also be guided via a fibre optic cable. Measurements taken on polished metal surfaces cause problems, however, because the emissivity is low.

Fig. 6-2
Basic structure of a bandpass pyrometer

1 Cover
2 Thermopile
3 Temperature compensation resistor
4 Housing

U Voltage



The temperature can also be measured in a contactless manner with the aid of infrared radiation emitted by a substance. A wavelength of 0.6 µm to 14 µm is used for this purpose. Infrared detectors normally measure in the range 0° to 300 °C (800 °C) with output currents of between 4 and 20 mA. There are also sensors with a switch output. These respond when the temperature reaches 300 °C, for example. The radiation can also be guided to the amplifier using fibre optic cables.

7 Recording displacement and angles

In the simplest case, this involves identifying a defined position which might, for instance, also be an end position of a moving unit. Only the reaching of a position is signalled in this case. Displacement encoders and angular position measuring systems, on the other hand, are designed to provide information about any given position. Different sensor technologies can be used to record displacement, positions and angles, as the following selection shows.

Sensor-principle	Angle α	Rotational speed in min^{-1}	Displacement in mm	Signal output properties
Electro-mechanical	up to 360°	up to 300	up to 10^6	Low-cost, precise switching point, limited service life, digital
Inductive	up to 360°	up to 504	up to 40	Inexpensive, long service life, sturdy, records only metals, analogue or digital
Electro-magnetic	–	50 up to 104	–	Inexpensive, wear-resistant, high temperature range, not suitable for low rotational speeds, analogue or digital
Hall effect	up to 360°	up to 105	up to 300	Extremely cost-effective, high precision, wear-resistant, switching points partially temperature dependent, analogue or digital
Magneto-resistive	up to 360°	up to 105	up to 30	Large switching distance, low-cost, limited temperature range, unlimited service life, digital or analogue
Opto-electronic	up to 360°	up to 105	up to $7{,}6^5$	Low-cost, non-reacting, sensitive to dust and humidity, analogue or digital
Acoustic, ultrasonic	–	–	up to 2000	Limited resolution, sensitive to humidity, records all materials, analogue or digital, unsuitable for areas with low pressure, excess pressure and explosion protection
Charge coupled, CCD	–	–	up to 2000	High-precision measurements possible, universal compatibility, analogue or digital
Ohmic, potentio-meter	up to 360°	–	up to 750	Low-cost, high precision possible, long service life with contactless design, analogue
Differential-transformer	± 45°	–	± 100	Very large temperature range, long service life, small measuring range, analogue output

When determining distances covered or angles, several positions must be recorded in sequence. This is by far one of the most important functions carried out by motion units, industrial robots and NC machines. Measuring systems have been developed for this purpose. They are often referred to as “internal sensors” because they have become an integral part of the drive axes and are located inside the engineering structures.

Fig. 7-1 shows some commonly used systems based on these principles. There are, of course, a great many other systems. These can be classified as follows:

- Analogue-absolute systems: Potentiometers
- Digital-absolute systems: Code discs and linear encoders
- Incremental systems: Line discs and line rulers (increment generators)
- Cyclic-absolute systems: Resolvers and Inductosyns

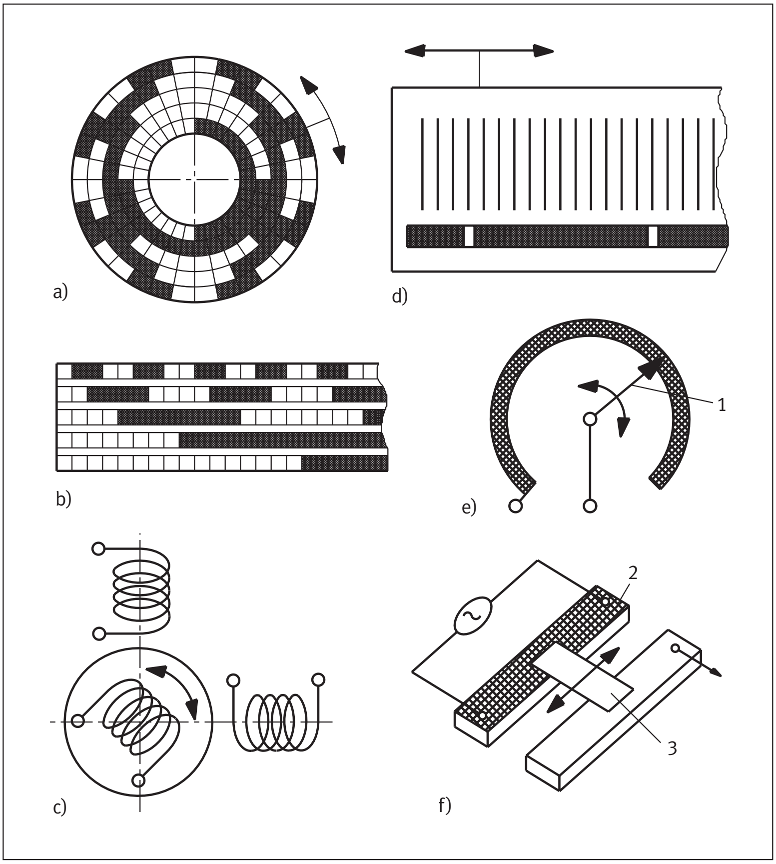


Fig. 7-1
Typical sensors for measuring angles and lengths

a) Code disc
b) Linear encoder
c) Resolver
d) Line ruler
e) Potentiometer
f) Contactless linear potentiometer

1 Wiper
2 Resistor path
3 Test probe

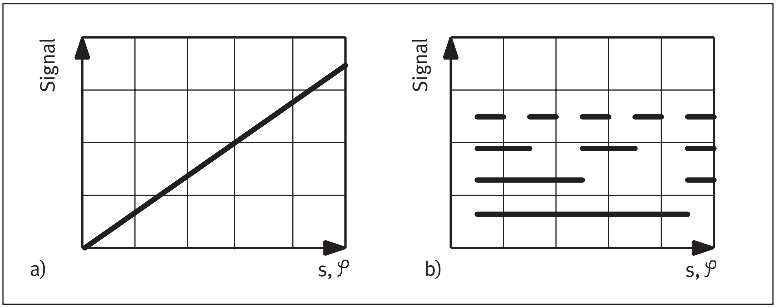
7.1 Absolute displacement encoders

Absolute measurement means measuring from a fixed point of reference (zero point, reference point). With analogue-absolute measurement, a measured value is available at all times. The same applies with absolute-digital measurement, but in this case the signal is non-continuous as a result of the graded rosette (Fig. 7-2).

Fig. 7-2
Signal curve for absolute displacement encoders

a) Analogue-absolute
b) Absolute-digital

s Displacement
φ Angle



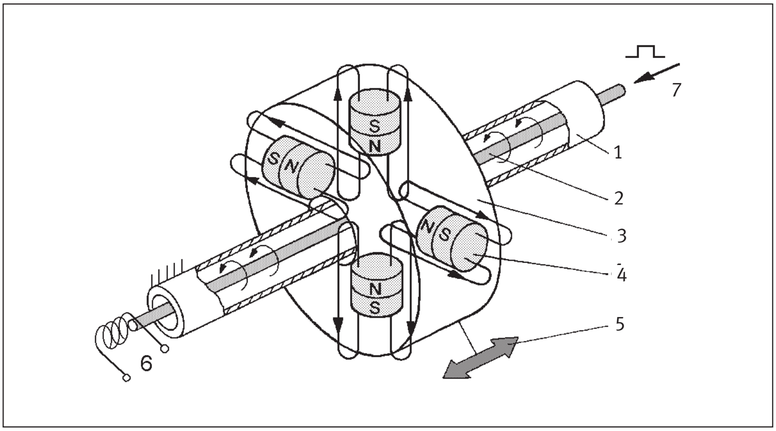
Important measuring systems include the potentiometer, the code disc (see Fig. 7-1), magnetostrictive displacement sensors and differential transformer sensors. Potentiometers consist of a resistor path, which is detected by a wiper or using a contactless method (conductive plastic potentiometer). The position of the contact represents a specific displacement, to which a measured voltage is proportional. With the contactless potentiometer, a test probe is moved over a linearised resistor path and a low impedance collector series. The gauge signal then undergoes capacitive decoupling here. There are also round potentiometers that can handle a 360° measuring range.

With code discs or linear encoders, the rotation angle or displacement is split into small digital steps. The position of each step is uniquely identified by an assigned code. This code is absolute to a fixed zero point. The direction of movement can also be identified from the ascending or descending sequence of the coding. When a machine is switched on, the control system has immediate access to all position values. With incremental measuring systems, a reference point movement must first be performed.

Magnetostrictive displacement sensors are not only very interesting, but also very sturdy contactless sensor elements. They are based on a waveguide principle. The waveguide is a tube made from magnetostrictive material. The inside of the tube contains a copper wire, to which a short current pulse is sent (Fig. 7-3). This creates a magnetic field, which comes into contact with the magnetic field of the position magnet. At this point, the magnetostrictive causes deformation, which is in turn transmitted to the waveguide as a mechanical wave with a speed of 2850 m/s. A solenoid, which can detect the execution time, is attached to the end of the waveguide. The position can now be calculated accurately to within a few micrometers. The output signals are usually converted so that the position value is available in analogue, digital or special formats. There are also magnetostrictive displacement encoders that are designed for installation in working cylinders. The position magnet is located in the piston. The sound waveguide then enters the hollow piston rod. Magnetostriction can only be found in ferromagnetic materials like iron, nickel, cobalt and their alloys.

Fig. 7-3
Magnetostrictive displacement sensor

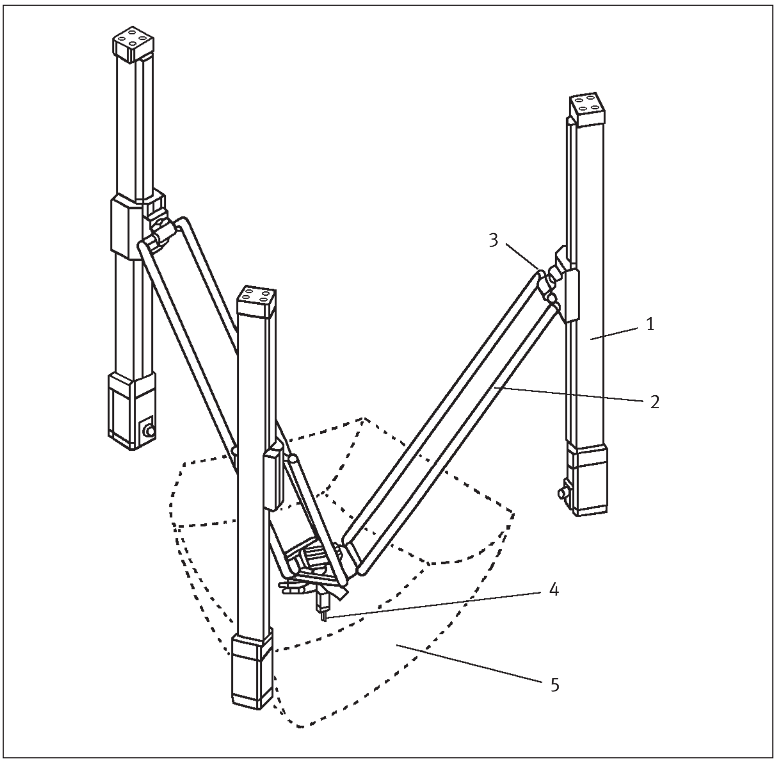
1 Pipe
2 Sound waveguide
3 Position transmitter
4 Permanent magnet
5 Displacement direction during positioning
6 Torsional pulse converter
7 Excitation current pulse



By combining a linear drive such as a rodless cylinder, for example, with a magnetostrictive displacement sensor, it is possible to create a piece of handling equipment with a bar kinematic design. However, such structures are difficult to control because all axes of motion are operating constantly. The example shows that servo-pneumatic master-slave robots are also possible (Fig. 7-4).

Fig. 7-4
Master-slave robot with servo-pneumatic drive and integrated magneto-strictive displacement encoder (Festo, R. Neumann, J. Leiber, P. Post)

1 Rodless pneumatic cylinder
2 Connecting arm
3 Ball joint
4 Gripper
5 Working space



The PLCD (permanentmagnetic linear contactless displacementsensor) displacement sensor also functions in a contactless manner. It consists of a special soft magnetic core, which has a secondary coil wound around its entire length and short primary coils wound around its ends (Fig. 7-5). When a permanent magnet approaches, local magnetic saturation is achieved in the core at this position. The position of this area is calculated differentially by the system of coils. Generation of the operating frequency (e.g. 4 kHz) as well as signal processing through phase-sensitive rectification take place in an external electronics module. A current, which depends on the position of the magnet, is available at the output. The variable position magnet is free. In other words, it is not fixed to the sensor. There are a number of different magnetic control options to choose from, e.g. a ring magnet can be used for filling level measurement.

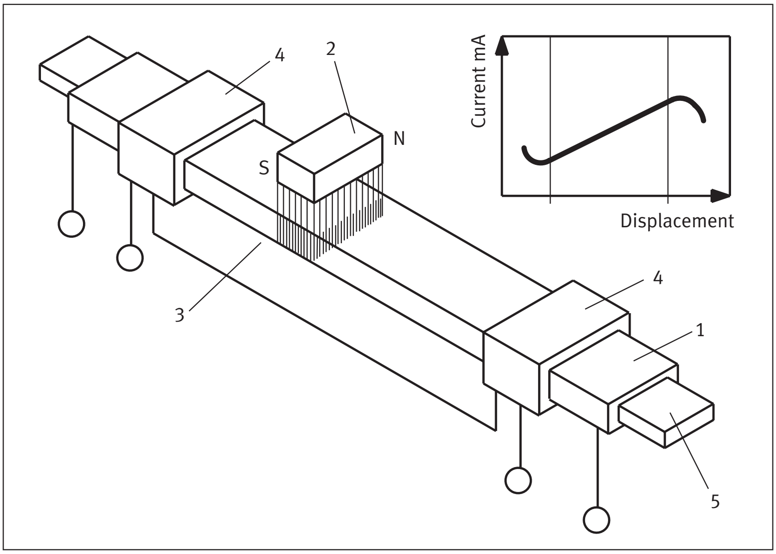


Fig. 7-5
Operating principle of the PLCD displacement sensor

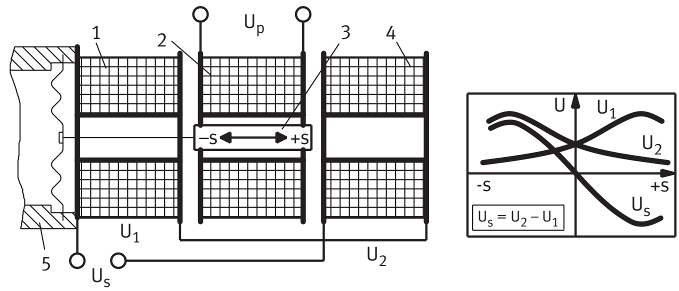
1. **Primary coil**
2. **Magnet**
3. **Magnetically saturated area in the sensor core**
4. **Secondary coil**
5. **Soft magnetic sensor core**

The differential transformer sensor (LVDT, *linear variable differential transformer*) works according to the principle of induction. Fig. 7-6 shows the operating principle of a differential transformer sensor. A soft magnetic core within a magnetic circuit undergoes displacement. If the core is in the centre of the transmitter, the differential voltage is zero. The change in the inductance provides a measurement for the adjustment travel. In order to be able to identify the displacement direction in differential configurations as well, carrier frequency methods with phase-sensitive rectification are needed. The sensor can be used in the ± 3 µm to ± 200 mm range. It is extremely accurate. Conversion to the displacement measured variable allows values for angle, pressure, acceleration and torque to be measured also. It is more expensive than a conductive plastic potentiometer. The temperature drift may be as much as 0.03%/K.

Fig. 7-6
Structure of a differential transformer sensor

1 Secondary coil 1
2 Primary coil
3 Movable iron core
4 Secondary coil 2
5 Single-membrane pressure sensor as an example of a mechanical coupling

U Voltage



7.2
Incremental displacement encoders

Incremental measurement means to measure “relatively”, i.e. not from a fixed zero point. A line scanner on a ruler or disc is used as a material measure.
The line standards contain only single unnamed lines. They are counted from position to position to produce a measurement for the covered distance. In order to be able to identify the direction of movement as well, the scanning grating, which runs above the ruler, has staggered aperture slots. This produces a second out of phase signal. The direction of movement can be identified by the phase displacement of a quarter period. There are also incremental generators for large adjustment travels (up to 250 m), whose standard measure consists of a perforated sheet metal strip which is scanned optically. A resolution of ± 1 mm or ± 0.1 mm is common here.

The structure of the measuring system is shown in Fig. 7-7. One can see that the pulses can be multiplied electronically to increase the resolution. There is no continuous position signal. Incremental sensors are therefore not permitted in cars, for example, for safety reasons. Apart from gratings that are sensed optically, magnetic systems are also coming to the fore.

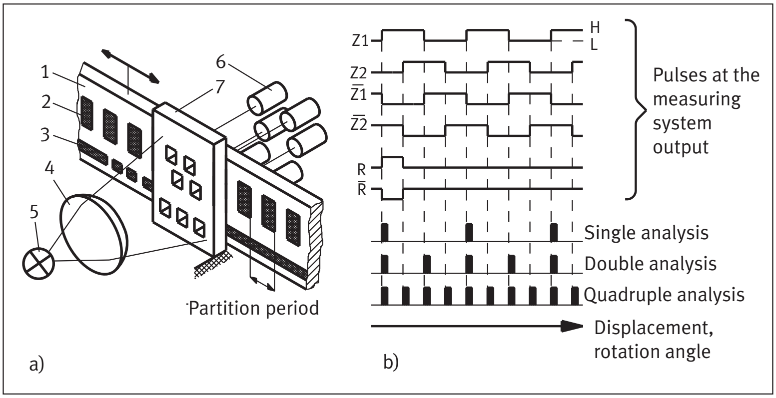
Magnetic length measuring systems are sturdy, economical and accurate.
Fig. 7-8 shows an incremental ruler. Its small dimensions make it ideal for even the most restricted installation conditions.

Fig. 7-7
Principle for the optical scanning of gratings

a) Component layout
b) Pulse train and its analysis with a multichannel incremental generator

1 Glass scale
2 Grating
3 Track with reference marks
4 Lens
5 Light source
6 Photoelectric cell
7 Scanning plate

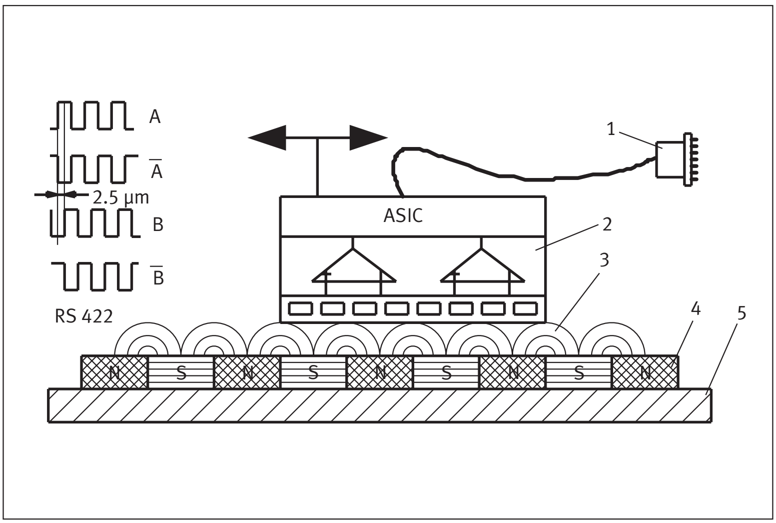
H High
L Low
R Reset pulse
R̄ Negated reset pulse
Z Pulse
Z̄ Negated counting pulse



The function: A read head with magneto-resistive properties runs a short distance (approx. 0.1 mm) above the fields of the magnetic scale. This read head is made up of a row of small magnets (magnetic north and south poles), which are positioned 250 µm apart from one another, for example. An electronic module in the read head interpolates the analogue sensor signals, for example 50 times, and supplies TTL counting pulses as the output signal. The path resolution can be up to 2.5 µm or better.

Fig. 7-8
Digital-magnetic length measuring system with TTL output signal (Märzhäuser)

1 Connector
2 Read head with ASIC interpolator
3 Magnetic field line
4 Magnetic scale
5 Scale support



The magnetic sensing of gears, as illustrated in Figs. 3-20 and 3-28, also comes under the category of incremental angular position measuring systems.

7.3 Cyclic-absolute measuring systems

Cyclic-absolute measuring systems are absolute-analogue in a small range. The typical signal curve in comparison with incremental systems is shown in Fig. 7-9b.

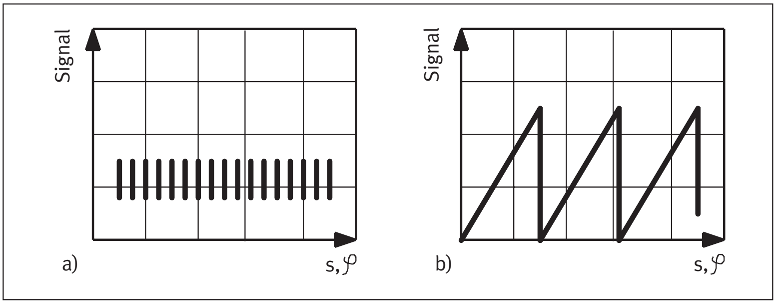


Fig. 7-9
Signal curve for non-absolute displacement encoders

a) Incremental
b) Cyclic-absolute

s Displacement
φ Angle

The round design is the resolver (Fig. 7-1/3), while the “bent upright” variant is the Inductosyn, a linear design. In the case of the resolver, a rotor coil moves against two stator coils turned at 90°. Two harmonic currents in phase quadrature with the same amplitude are supplied to these coils. A voltage is induced in the rotor coil and then output and analysed. This gives us the current rotation angle as an analogue variable. This situation is repeated continuously, which means that the number of runs must be added to obtain the distance covered. This is why the measuring systems are also known as cyclic-absolute systems.

Accuracy and resolution are important factors to consider when assessing displacement encoders. To demonstrate this, consider a clock. A clock can lose several hours (inaccurate). However, if it has a second hand, it can still break down time well.

8 Imaging

Compared with proximity sensors or tactile sensors, image sensor technology is based on a fundamentally different philosophy with regard to the gathering of information. The former gather information by taking a sample from selected points of the surroundings. Although this type of sensor technology is less complex, great care must be taken to adapt it to the specific requirements of each individual case. It tends to be less flexible in its application.

Image sensor technology, on the other hand, senses the entire surroundings and then extracts representative characteristics for evaluation purposes. While this may be more complex in terms of the hardware and programs involved, adaptation to specific tasks is a lot less problematic. The hardware is universally compatible, while the software is programmed to meet the requirements of the problem in hand. The following sensors are used to record a (manufacturing) environment:

- Image sensor, which records an environment like a snapshot
- Radar sensors, which sense the surroundings in the linear grating at high speed

8.1 Opto-visual image recording

When talking about image sensors, it is important to make a distinction between line sensors and area sensors. Line sensors also provide a two-dimensional image of an object if apparent motion can be configured between the sensor and the object. Fig. 8-1 shows object recognition using a CCD line *(charge coupled device)*. The workpiece is on a moving conveyor. The line sensing produces signals which enable the workpiece profile to be identified by comparing it with previously saved reference patterns. There must be sufficient contrast between the conveyor and the object.

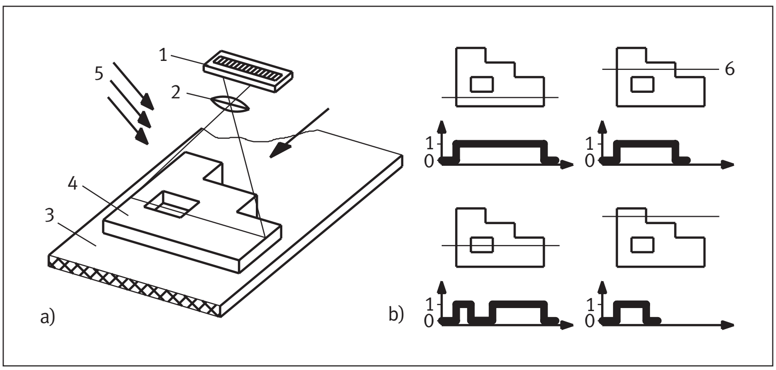


Fig. 8-1
Object recognition with a CCD line

a) Measuring set-up
b) Signal curve

1 CCD line
2 Optical system
3 Conveyor
4 Workpiece
5 Lighting
6 Sensing line

There is, however, another method, which is known as the light section procedure. With this procedure, a “light plane” is projected onto the object. This light plane intersects the object along a profile line (hence the name of the method).

The points of this profile line are marked visually by the light. If one views this line from the side using a camera, the profile appears in the image as a curved line. The raised parts and recesses stand out clearly. Because the positions of the camera and light source as well as the viewing direction of the camera are known, the position of any point on the profile line can be worked out using a quick and simple arithmetic operation based on the triangulation method.
The principle is shown in Fig. 8-2. The type of part or any damage that may have been caused is identified by comparing it with previously saved reference patterns. The sensor learns this information from some good parts using the teach-in method.

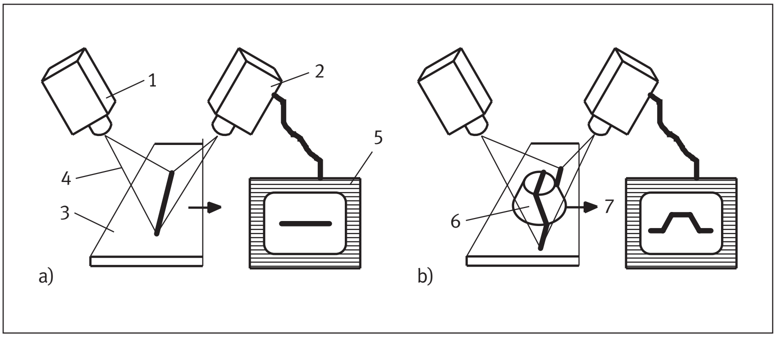


Fig. 8-2
Principle of the light section procedure

a) Light section on a plane
b) Light section on an object

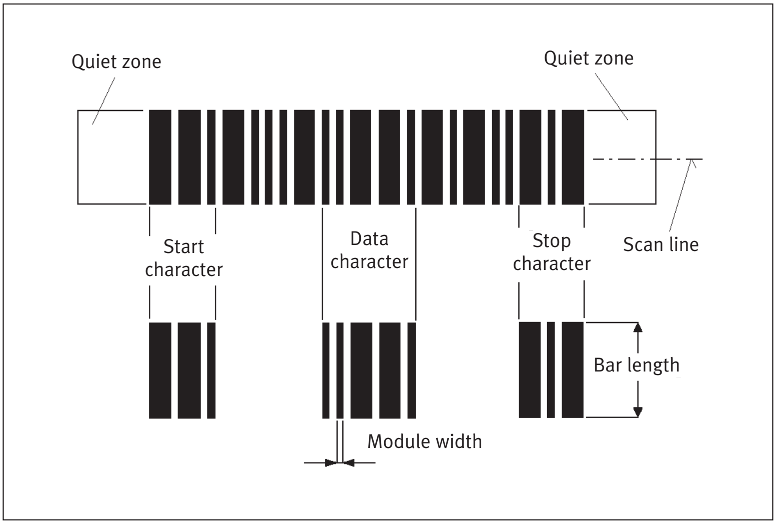
1 Projector
2 Camera
3 Plane of projection
4 Light plane
5 Monitor
6 Object
7 Direction of travel

A more sophisticated variant of the light section procedure is the coded light method. With this method, the projector is used for the transmission of a succession of structure patterns in Gray code. The three-dimensional profile of the viewed objects can then be determined from the various light planes, once again using the triangulation method. Compared with the basic line section procedure, the coded light method involves fewer measurements, which basically means an increase in the speed for identification or measurement of the profile of a three-dimensional object.

Another important application of line detection is the reading of bar codes, which are used not just in the consumer goods sector, but also in production. One of the effects that production automation has had is the merging of the information and material (product) flow. This has put the issue of access to up-to-date data from the material flow firmly at the top of the agenda. Only by having this data can the flow of parts in production, which has become much faster in recent times, be properly controlled. These changing requirements have stimulated rapid development in identification technology over the past few years. Today, it is an integral part of automated production processes.

Without going into the many automatic (mostly optical) readable codes in great detail, Fig. 8-3 shows the structure of a bar code.

Fig. 8-3
Structure of a bar code



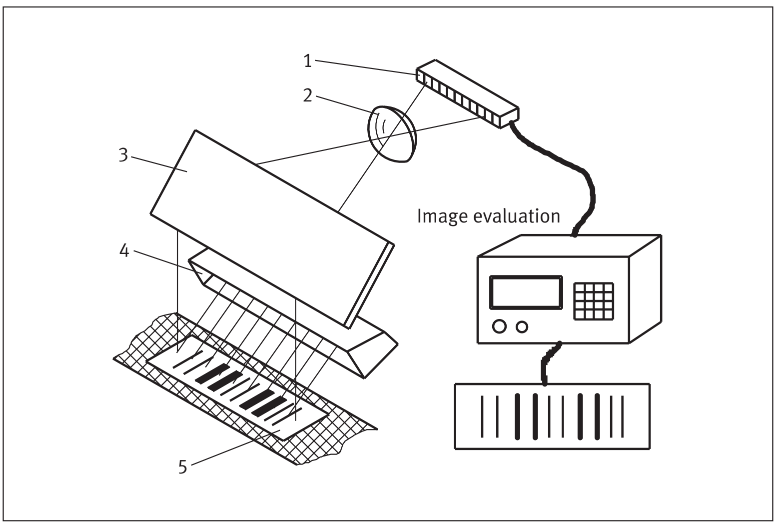
The sensor that reads the bar code must record the entire width including the rest (skip) zones. Bar codes can be recorded in two ways:

- Recorded as a complete image, e.g. with a CCD image sensor
- Line scanning with a laser beam (see Fig. 3-61)

In the first case, as shown in Fig. 8-4, the entire bar code area is recorded as an image. The bar code is lit with an LED and the CCD image sensor receives the diffuse reflected light.

Fig. 8-4
Bar code reader based on the CCD principle (Keyence)

1 CCD image sensor
2 Optical system
3 Reflection mirror
4 Red LED
5 Bar code label

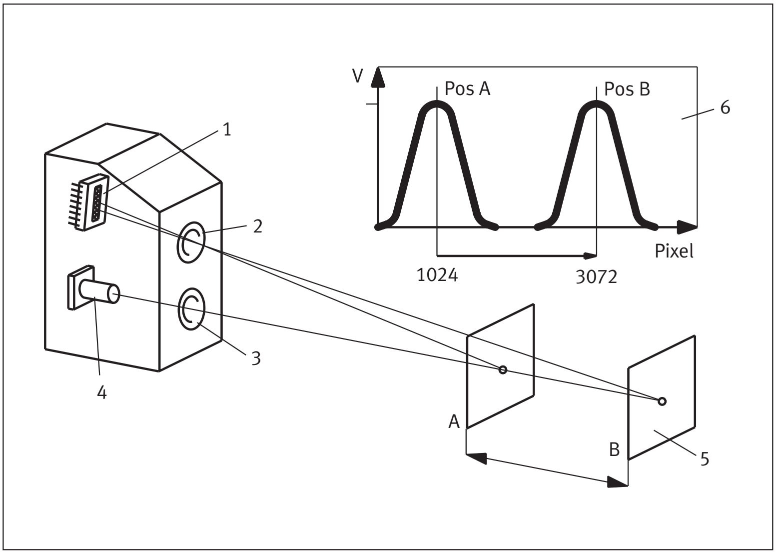


This is followed by evaluation of the image data and then decoding of the symbols. The bar code is thus read using the image data.

Another application: Triangulation sensors are also fitted with a CCD line. This allows optical distance measurement using the triangulation method. This goes to show that in measuring technology, there are sometimes three sides to every story. Fig. 8-5 shows the operating principle of a triangulation sensor. With the triangulation sensor, a light spot is generally projected onto the object using a laser diode. An imaging lens then transmits the reflected light to the detector, for example a CCD line. The distance can then be determined from the position of the projection of the light spot on the CCD line. If the object moves from A to B, the pixels of the CCD line correspond to what is depicted in the detector diagram. The measurement principle uses the fact that when the length of one side and two angles of a triangle are known, the length of the remaining sides can be determined. The transmitter, receiver and object are therefore arranged in a triangle. This same principle was also used in ancient times for navigation and land surveying purposes.

Fig. 8-5
Triangulation sensor

1 Detector
2 Imaging lens
3 Projection lens
4 Laser diode
5 Workpiece
6 Detection diagram



Some triangulation sensors cover a measuring range of ± 250 mm with a reference distance of 500 mm. This makes it possible to accurately measure, for example, the height (and consequently the quantity) of a stack of thin, flat parts. In printed circuit board production, the height at the soldering points can be measured. This in turn can be used as an indicator of quality in the soldering process. Measuring ranges of a few millimetres to several metres are common here.

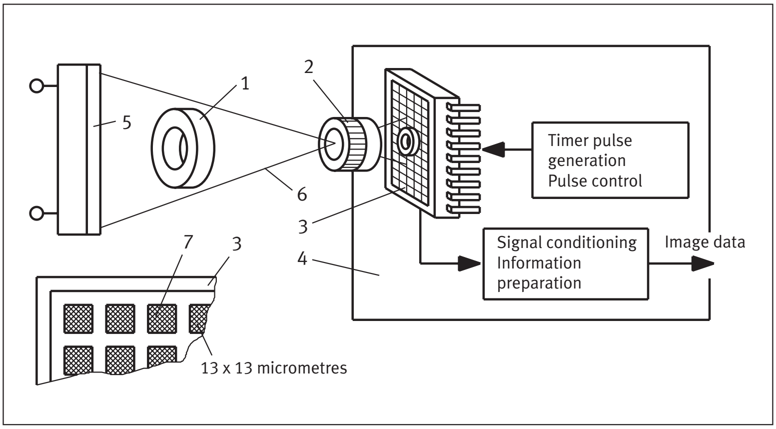
The acquisition of measurement data through images, i.e. multi-dimensionally, has a number of significant advantages over other methods. These are:

- The measurements are taken without contact or the use of mechanical devices such as sensors, for example. They are therefore non-reacting.
- An area sensor (CCD chip) can capture a large amount of measurement data in a single action. This data can then be analysed in different ways using suitable algorithms.

Most optical area sensors nowadays are in the form of a CCD chip. The sensitive area of the chip comprises a field array with a large number of small photoelectric cells, for example 752 x 562 picture elements (pixels). The image is projected onto the picture elements using a lens (Fig. 8-6).

Fig. 8-6
Principle of CCD recording technology

1 Object to be projected
2 Lens
3 CCD chip
4 Camera
5 Light source
6 Visual range
7 Picture element



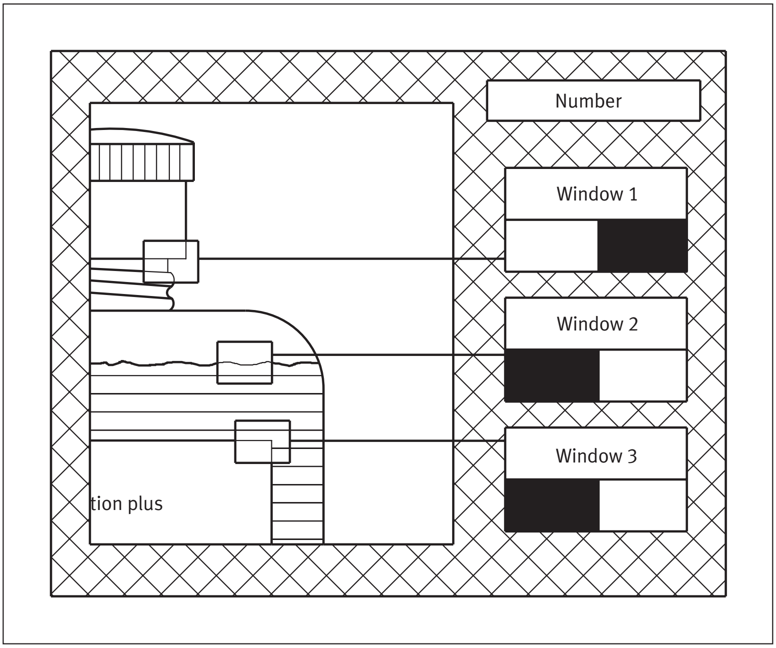
The light generates charge carrier pairs, which are added up during the average time, in proportion with the light intensity. The electrical status of the photodiodes is then read at very short intervals and the image information is transmitted as a series of signals. There are a number of read methods (frame transfer principle, line transfer principle) that can be used here.

Imaging makes it possible to create a wide variety of test set-ups. A sample task involves checking whether labels have actually been attached to a predefined field. This can be checked using measuring light barriers with an analogue output, for instance. The analogue signal is compared with limit values. From this one can determine whether the label was, for example, attached within a tolerance of ± 2 mm. If, on the other hand, CCD cameras were used, several things could be checked at once. In most cases, it is not necessary to analyse the entire image, but just selected windows. An example is shown in Fig. 8-7. The following areas from the recorded image are analysed:

- Window 1: Is the screw cap available? Is the cap screwed on or loose?
- Window 2: Has the liquid been added and was the filling level reached?
- Window 3: Has a label been attached?
  Was the intended sticking position reached?

This solution is also suitable for high-performance production plants, as it can achieve test frequencies of up to 60 cycles per minute.

Fig. 8-7
Checking bottles in the pharmaceutical industry

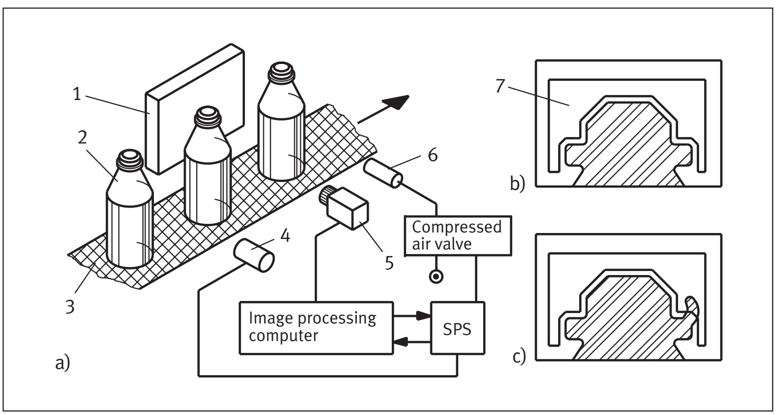


Another example is the checking of the contours of plastic bottles. During the manufacture of these bottles, a ridge is sometimes formed around the neck of the bottle, which results in the bottle being rejected. Only random manual sampling can be done because at a flow velocity of 0.3 m/s, for example, two bottles would have to be checked every second, which is not humanly possible. Image processing systems are ideal for such tasks, as they can perform a full contour check. With this kind of system, the object to be checked is positioned between the camera and luminous surface. In other words, the object is lit by transmitted light. The contour is therefore projected as a sharp, high-contrast silhouette. Fig. 8-8 shows the layout.

Fig. 8-8
Checking contours with an image processing system

a) Component layout
b) Good part contour
c) Faulty part

1 Luminous field
2 Object to be checked
3 Conveyor
4 Trigger light barrier
5 Camera
6 Ejection air nozzle
7 Test contour used by the computer



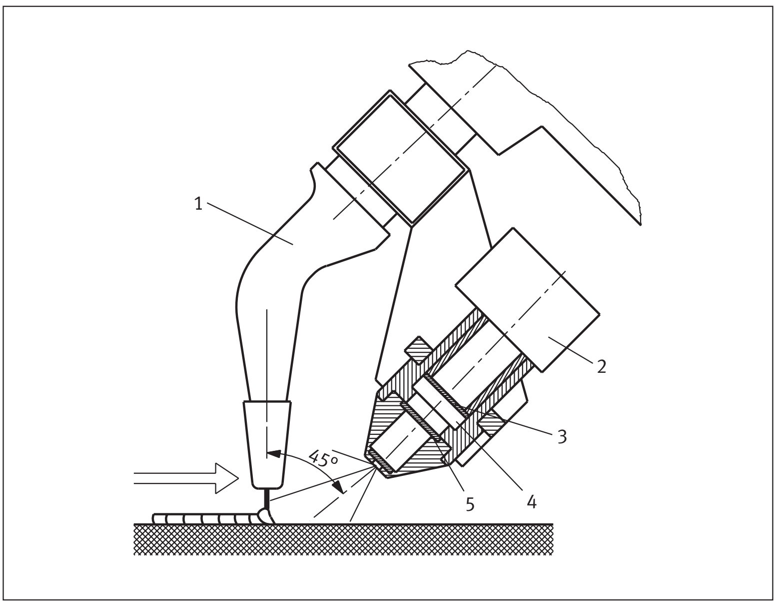
Only the part of the bottle that represents the *Area of Interest* (AOI) needs to be examined. Faulty parts are ejected immediately after the camera position as reject or rework parts. A trigger light barrier produces a signal which activates image recording a few milliseconds later. The programmable logic controller also gathers process data, such as the number of parts checked and error rates, and then compiles statistics to be displayed on the process monitor. If an object type is changed, the system can "learn" how to handle the new testing task with the aid of good objects.

There are also difficult identification tasks to be performed with arc welding. The primary tasks are: finding welding joints, identifying the start of the weld seam, tracking the welding joint and identifying the end of the joint. These tasks can be performed with the aid of different sensors, which allow sensing not only of the process, but also the geometry.

Fig. 8-9 shows an optical welding seam identification system, just one of the many options available. A camera continuously observes the welding process and joint profile. This includes the distance between the torch and the joint, the offset between the wire electrode and the centre of the joint, as well as geometric characteristics of the weld pool formation. This data is used to produce control information to help guide the torch along the centre of the joint at the correct speed. Workpiece tolerances and thermal distortion are taken into account. Weld defects can be identified by evaluating the weld pool formation. The enormous volume of light generated during the process is reduced using an orifice plate, while an interference filter in the light beam reduces the light to a narrow spectral band.

Fig. 8-9
Welding seam sensor

1 Torch
2 CCD matrix camera
3 Filter
4 Lens
5 Protecting glass



The weld sensors must also be fairly hard-wearing. Firstly, they must be positioned as close as possible to the effective zone, and secondly, they must be able to withstand extremely tough environmental conditions. If the sensor is too far in front of the effective area (due to mounting conditions), it is difficult to record the welding seam profile correctly because the active sensor detection field may be forced into another path section by a curving seam profile, for example.

In arc welding, the quality of the welding seam depends in particular on the welding current intensity, the wire feed speed, the electric arc voltage, the welding speed and, most importantly of all, on the accurate positioning of the welding gun and the arc to the welding joint. Errors that a welder can correct using his senses in the case of manual welding must be corrected automatically in the case of automatic welding. Sensors make this possible.

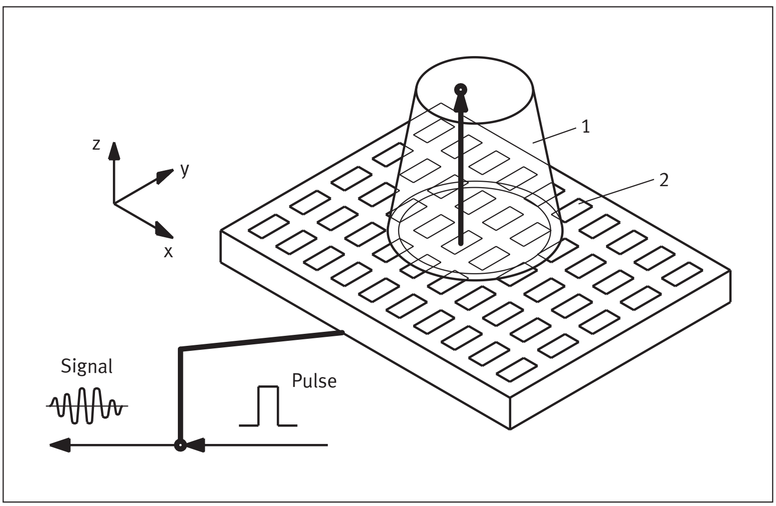
8.2 Non-optical sensing systems

Non-optical sensing is performed using devices that, at the very least, provide two-dimensional information and do not employ any opto-electronic means in the process. These are:

- Sensing matrices, which “feel” contours or a surface structure electromechanically (pin sensors), using pressure-sensitive film, using Hall sensors in a field array, etc.
- Sensing surroundings using moving ultrasonics or ultrasonic converters, which are combined to form an array. This allows pixel representation. A basic example is shown in Fig. 8-10. The trend in this area is towards high-resolution sensing systems.
- Sensing scenes using a microwave sensor. This can also be done by recording the complete surroundings around a mobile robot or an autonomous industrial truck, for example. The identification of objects is also necessary for collision protection.

Fig. 8-10
Ultrasonic array

1 Object
2 Ultrasonic transmitter/receiver



9 Sensor networks

Sensors are being used in ever-increasing numbers in machines, systems and processes. With conventional circuitry, connecting sensors to the control systems would involve a massive tangle of wires. There is therefore a need for signal transmission technology which allows sensors, actuators and control systems to be linked with the minimum of wiring. A system of this kind must be interference free, universally compatible and open. Sensors thus reach their maximum level of effectiveness when they are “intelligent” to a certain extent and are connected to bus systems. To achieve this, they must also be bus compatible and suitable for communication purposes.

9.1 Sensor connection technology

A distinction is generally made between two types of sensor depending on the task to be performed: measured value forming and binary sensors. Both types convert physical measured variables into electrical signals, but are optimised according to different criteria. Depending on the design, sensors can be connected as follows:

Two-wire technology
With this type of connection technology, the sensor is connected in series with the consuming device like a mechanical switch. The sensor has only two connecting lines as a result. This line is connected in series with the load to be switched (Fig. 9-1a). The switches are normally closed contacts or, as shown here, normally open contacts. A separate power supply is not required because the auxiliary energy for the measuring transducer amplifier is decoupled from the current signal. Two-wire technology is only used for inductive and capacitive sensors. Sensors with large current consumption are not suitable for two-wire technology.

Three-wire technology
In a three-wire system, two wires are used for the power supply, while the third wire guarantees the signal output (Fig. 9-1b). The load L can have an earth reference (PNP output) or plus reference (NPN output).

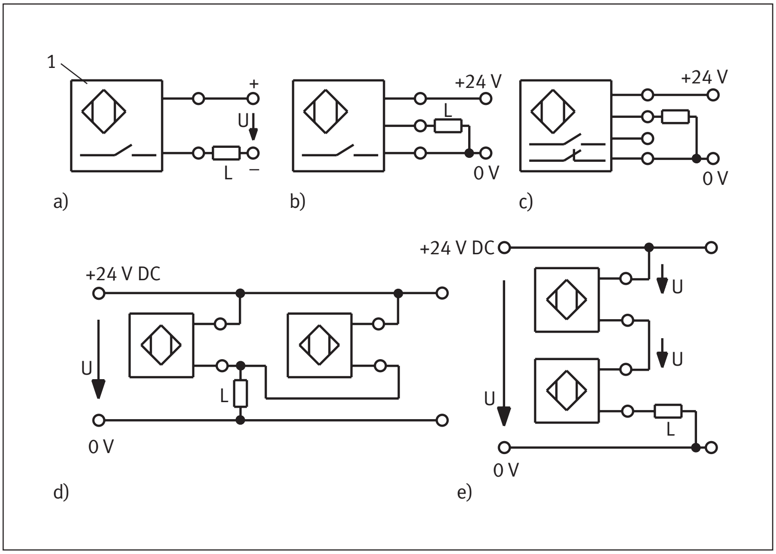
Four-wire technology
Most four-wire proximity sensors (four-pin plug, four-pin cable) are fitted with an antivalent switching function, i.e. they have one normally closed contact output and one normally open contact output (changeover switch). This is illustrated in Fig. 9-1c. In this case, two wires are used to supply current and two as a voltage tap on the generator. This means more wiring. In some cases, the fourth wire is available for programming the normally open or normally closed contact function.

Fig. 9-1
Connecting proximity sensors

a) Normally open contact, positive switching
b) PNP normally open contact
c) PNP normally open/ normally closed contact
d) Parallel connection using two-wire technology
e) Series connection using two-wire technology

1 Proximity-sensitive device

L Load
DC Direct current (symbol to DIN 40900)



Five-wire technology
This technology usually involves electrical isolation between the control voltage circuit and the supply voltage (relay output).

If we consider connection in the context of resistance temperature measurement using a Pt 100 sensor, two-wire technology interchanges too high a temperature, because the measuring resistance and the resistance of the supply lines are added together. This error must therefore be corrected by means of compensati-on. With four-wire technology, on the other hand, the circuit logic can completely eliminate the influence of the supply lines while still using the same sensor.

By combining proximity sensors, it is possible to implement logic functions without the need for a PLC (programmable logic controller), for example.
The following conditions apply:

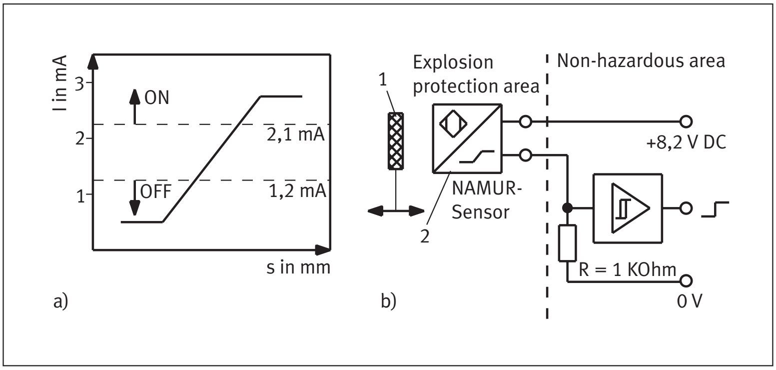
	Series connection as per Fig. 9-1e	**Parallel connection** as per Fig. 9-1d
Normally open contact	AND	OR
Normally closed contact	NOR	NAND

The NAMUR sensor (DIN 19234) was developed for use in hazardous areas. This is a polarised 2-wire sensor. When actuated, it changes the current flow in the circuit. The analogue signal is converted to a digital input/output signal in the evaluation unit with the aid of a comparator. The operating range, within which the switching status is changed, is defined as a current flow of between 1.2 and 2.1 mA. Fig. 9-2 illustrates a possible evaluation unit for NAMUR sensors and a displacement-current characteristic curve for an inductive sensor.

Fig. 9-2
Example of a NAMUR circuit (NAMUR = standards association for measuring and control technology in the chemical industry)

a) Signal curve for a NAMUR sensor
b) Comparator circuit

1 Object
2 Two-wire direct voltage switch

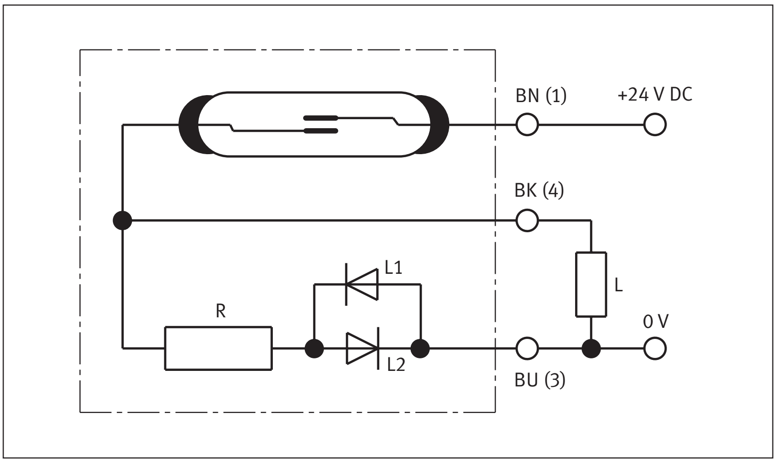


In explosion-proof areas, NAMUR sensors must be operated using suitable disconnector amplifiers with intrinsically safe control circuits.

Fig. 9-3 shows the connection of a reed switch. LEDs are frequently used for the switching status display. The LEDs, together with the series resistor R, also provide the protective circuit function for inductive load.

Fig. 9-3
Basic circuit diagram for a reed switch with LEDs

L Load resistor
R Protective resistor
L1 LED
L2 LED
BK Black wire
BN Brown
BU Blue



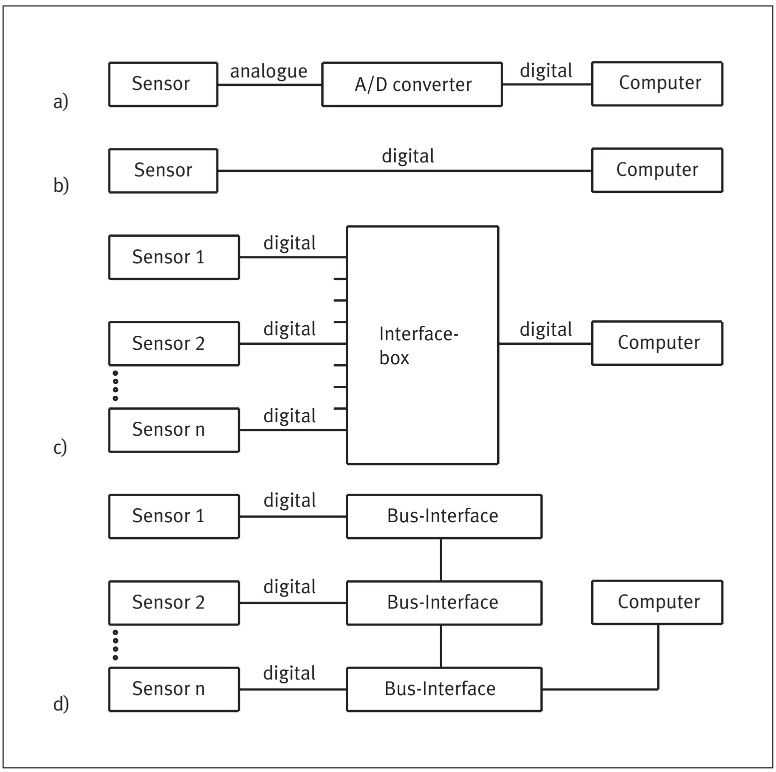
9.2 Bus systems

Since the beginning of the 1990's, fieldbus systems have become an increasingly popular method of networking sensors. They tend to be more cost-effective than conventional technologies. A bus generally takes the form of a data transmission line on which more than two stations can communicate with one another. Technical and organisational measures ensure that there are no mix-ups in the sending and receiving of data or commands. When using the AS-i interface (a joint development by several companies), for example, a standard two-wire line guided through the system to the sensors and actuators in a tree structure, is sufficient. The tasks of data transmission and power supply are performed via the two lines. With this system, sensors such as proximity sensors, for example, are connected first and foremost to perform basic switching functions. Connection to higher-order bus systems is possible. The concept of networking of sensors and actuators with the aid of a fieldbus has its origins in the petrochemical industry.

Here, the complex individual wiring of measuring sensors over systems covering a large area became untenable. In the meantime, the idea of bus technology had begun to take root in production engineering. If we disregard basic manual measuring equipment, the sensors contained in measuring equipment must somehow be connected to computer or a control system. Fig. 9-4 shows different connection technologies.

Fig. 9-4
Connection technologies between sensors and computers

a) Analogue/digital interface
b) Digital-signal interface
c) Interface box
d) Fieldbus

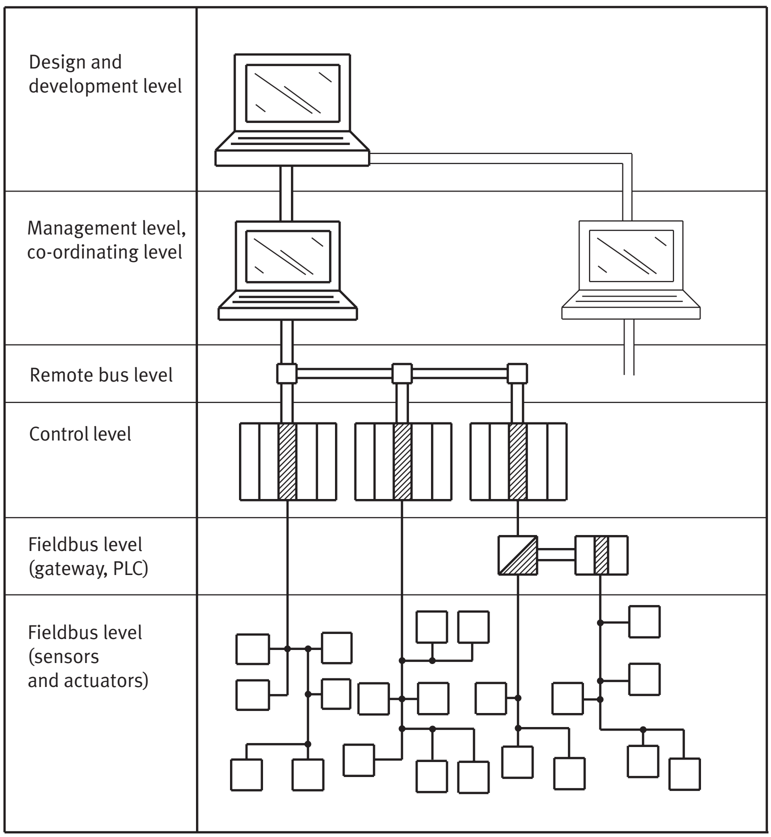


In the simplest case, the analogue signal is electronically filtered, amplified and forwarded in digitised format. Digital signals are less sensitive to interference along the transmission path. Interface boxes can, for example, manage 128 channels simultaneously. This is handy when using a larger number of sensors. Serial fieldbus systems are used particularly where there are large distances between measuring points and sensors with low transmission rates.

Fieldbus systems perform important communication tasks for automation in all industrial environments. Fieldbuses transport all digital information such as pressure, mass flow, temperature, position, switch signals, etc., which is needed for correct intervention in a process or to make it transparent for the user.

Modern sensors have built-in signal processing functions, which make them “intelligent”. They are also bus compatible. Subsequent expansion is also possible. An example of one of these structures is shown in Fig. 9-5. This type of structure offers a number of advantages that would not be possible with conventional circuitry such as, for example, remote adjustment or parameterisation of sensors or detection of faulty functions and rapid localisation of the fault.

Fig. 9-5
Distributed networking via an AS-i interface



However, attempts to manage as many requirements as possible using large bus systems result in “average solutions” which do not fulfil all requirements satisfactorily. This particularly affects areas such as low connection costs, preservation of settings when replacing faulty sensors, high data transfer rates, communication in areas with explosion protection, easy commissioning, use of unshielded two-wire lines and easy network connection. The area of fieldbus systems is undergoing enormous change at the moment, so we can expect to see some interesting new solutions in the future.

Glossary

Absorption
Reduction (loss) of radiation on passage through a medium.

Adapter
Coupling device in electrical measuring technology; a name used for the measuring amplifiers, transducers, measuring converters and arithmetic units that are placed between measuring sensors and measuring output devices.

Area sensor
Sensor that does not function on the basis of specific points, but instead has elementary sensors, for example a CCD array distributed over a given area.

ASIC
Application specific (customer-specific) integrated circuit.

Autocorrelation
Mathematical interpretation of the degree of conformity between two signal sensings, used to distinguish the periodic and stochastic parts of a gauge signal from one another.

Background fade-out
With opto-electronic proximity sensors, this is the suppression of all events that occur outside of the active sensing area.

Calibration
Determining the relationship between the display (output variable) of a sensor or of an entire measuring device and the defined value for the measured variable (input variable). Unlike gauging, there is no legal background to this procedure.

Calibration capability
Ability of measuring equipment to restore a primary standard.

Comparator
Module in measuring devices and control systems for comparing electromotive forces and signalling where there is uniformity.

Compensation method
Fundamental procedure in measuring technology, in which the value of the measured variable is defined in such a way that it specifies its effect on a null instrument and that the opposite effect will achieve a null balance.

Constant light
Light with a radiation intensity that is invariable with time, mostly produced by an LED or a bulb connected to a direct voltage source.

Coriolis force
Inertial force that tangentially accelerates a body moving radially towards or away from an axis of rotation.

Cross sensitivity
Attribute of a sensor, which causes it to react also to accompanying phenomena that cannot be measured. This results in measurement errors. The term "interference sensibility" is the preferred term nowadays.

Dark switching
With opto-electronic sensors, this is an attribute of the switch output, which is then activated when no light falls on the photoreceiver. The downstream amplifier is switched through and the output relay is energised. When light falls on the receiver, the relay is de-energised. Antonym: Light switching

Dead zero
Feature of signals whereby the signal range contains the value zero, the opposite of live zero.

Diffuse
Name used to describe radiation, for example light, that is reflected in a non-directional way.

Diffuse reflection
The reflection of radiation on non-transparent, non-reflective surfaces.

Doppler effect
Change in frequency of a wave operation which occurs when the observer (sensor) and wave generator (moving object) move in relation to each other.

Drift
Change in a gauge signal at the sensor signal output which depends only on the advancing time where the input variable is constant.

Emission
Umbrella term for the giving off of electromagnetic particles or waves, for example as light, heat or radiation.

Emissivity
Ratio of the radiant intensity of a thermal radiator to the maximum possible radiant intensity of a (black) body of the same temperature.

Extinction
The weakening of radiation which, in the case of light barriers, for example, can be caused by the atmosphere.

Fail-safe behaviour
Principle of limited failure without causing consequential damage.
Example: Output of the signal "zero" when a sensor fails due to a wire break, for instance.

Galvano-magnetic effect
The physical effects that occur in an energised electric conductor when it is located in a homogeneous magnetic field.

Gauging
The testing of measuring sensors, sensors or measuring devices with the aid of standard values and the application of calibration marks to ensure that they accurately reproduce or display legally defined measured variables.

Gauss effect
If a homogeneous magnetic field is operating perpendicular to a conducting path in a plate-like conductor or semiconductor, the conducting path is extended, which can be seen through an increase in resistance.

Graded index fibre
Optical fibre whose refractive index decreases steadily from the centre to the edge (according to a quadratic function).

Hysteresis
The largest difference between the output values, for example switch-on and switch-off points, when the measured value range is passed through first in ascending and then in descending order.

Identity check
A check to ascertain the uniformity of objects, combined with a reading of other relevant information such as serial numbers or quality data.

Impedance
Electrical impedance (surge impedance) of alternating current, specified as a quotient of voltage and current.

Intrinsic current consumption
The current consumption of an unactuated sensor.

Intrinsic safety
Protection class for electrical devices, which exists when the temperatures or sparks that can ignite an explosive mixture cannot occur, even in the event of a short circuit.

Light switching
With opto-electronic sensors, this is an attribute of the switch output, which is then activated when light falls on the photoreceiver. The downstream amplifier is tripped and the output relay is energised. When the optical path is interrupted, the relay is de-energised.

Line section procedure
Optical object recognition procedure, in which an object is lit using a light gap. The intersection points of the streak of light with the object characterise the object shape and are used for analysis purposes.

Line sensor
Sensor that does not function on the basis of specific points, but instead has elementary sensors, for example a CCD line, arranged in a linear structure.

Live zero current signal
Attribute of signals, whereby the signal range does not contain the value zero. Example: The measured variable 0 °C is assigned a standardised signal of 4 mA. This makes it easy to distinguish malfunctions such as auxiliary power failure, for example, from the signal value zero.

Lorentz force
Galvano-magnetic effect in conductors and semiconductors; effective force on energised conductors caused by the effect of a magnetic field.

Machine intelligence
Ability of a machine to adapt its actions to the changing conditions of its effective area.

Modulation
Effect of a (high-frequency) carrier frequency on the pulse of a (low-frequency) frequency. Pulsed voltages can be modulated in their amplitude, phase and pulse length.

Multiplex operation
Multiple use of electrical lines through signal transmission that has been staggered over time with the aid of a signal converter.

NPN design
Transistorised component, whose output module contains an NPN transistor which switches the load against the negative supply.

Odometry
Procedure (dead reckoning navigation) and means of determining the position, e.g. of a mobile robot, through the continuous offsetting of the position data. The rotation of the driving wheels and the steering direction are measured. Disadvantage: Position errors are inherited and increase on a continuous basis.

Offset
Name for the quantity of an output signal that exists without the application of a measured value.

Operating reserve
With opto-electronic sensors, this is a measurement for the excess radiation intensity that falls on the light entry surface and is analysed by the photo-receiver.

Opto-electronics
Name for a technology, in which optical and electronic components interact in such a way that advantages can be gained from the interaction between optical radiation and electronic methods, for example obtaining information.

PNP design
The output module of a transistorised contains a PNP transistor (bipolar transistor with the sequence of zones pnp) which switches the load against the positive supply.

Proximity sensor
Contactless signal generator, which is mounted on a cylinder and displays and reports the piston position. It is actuated magnetically by a ring magnet in the piston.

Pulsed light
Light with a periodically changing radiation intensity
(light frequency, pulse shape).

Redundancy
Availability of more technical resources than are needed for the intended function. The configuration of multiple elements guarantees greater reliability in the event of a total failure.

Reflection
Deflection and reflection of radiation on the contact surfaces of different media. A specular reflection is known as a mirror image.

Refractive index
In optics, this is the measurement for the change in direction that a light beam undergoes when it travels from a vacuum to a specific medium.

Relative permittivity
Another name for the dielectric constant.

Residual ripple
Name for an alternating component superimposed on a DC operating voltage.

Resolution
With indicating measuring devices, this is the smallest change in the measured variable that can be detected by the device.

Retro-reflection
Specular reflection of radiation back to the radiation source, i.e. “onto itself”, provided the light falls more or less vertically.

Reverse polarity protection
Protection of the sensor against the interchange of the supply voltage connection.

Sensor
Information-gathering element of controlled technical systems, which records a measured variable and usually performs a measured variable conversion.

Standardised signal
Gauge signal whose minimum and maximum values are defined through standardisation.

Sub-pixeling
In image processing, this is a procedure that involves the further breaking down of the pixels being analysed, for example 1 pixel into 10x10 fields, each 0.1 pixel in size. This allows more precise measurements to be taken.

Switching distance
Distance between an object and a sensor which activates switching once reached.

Thermistor
Highly temperature dependent resistor with a non-linear characteristic curve. Its impedance lowers as temperature rises. It is therefore used as a temperature sensor.

Total reflection
Optical refraction phenomenon. When light travels from a medium with a higher refractive index to one with a lower refractive index, the path of the beam is intersected by the axis of incidence. If the angle of incidence increases beyond a critical angle, total reflection occurs, i.e. no light enters the second medium. The light is completely reflected.

Transmission
Passage of radiation through a medium. This allows the radiation to be controlled. It is also referred to as diffuse transmission.

Transponder
Device for the transfer of information; technical term derived from transmitter and responder. The transponder consists of a chip and an antenna. The chip can store data as well as modify, add to and delete it. Data exchange with the reader unit is contactless through the use of electromagnetic fields.

Triple reflector
Optical device for retro-reflection through multiple reflection on the inner surfaces of a pyramidal, light transmitting body.

TTL
Abbreviation for transistor transistor logic; a specific type of circuit technology for a series of integrated standard circuits.

V. 24 sensor
Sensor whose output signal is made available to a V.24/RS232C serial interface.

Wiegand effect
Sudden magnetic reversal of a crystalline wire made of FeCoV alloys, which has undergone special mechanical pre-treatment.

Bibliography

Adam, W. (ed.): Sensoren für die Produktionstechnik,
Springer Verlag, Berlin/Heidelberg 1997

Baumann, E.: Sensortechnik für Kraft und Drehmoment,
Verlag Technik, Berlin 1983

Fetzer, H.; Hippenmeyer, H.: Optoelektrische Sensoren,
verlag moderne Industrie, Landsberg 1988

Hesse, S.: Lexikon Sensoren in Fertigung und Betrieb,
expert Verlag, Renningen 1996

Juckenack, D.: Handbuch der Sensortechnik,
verlag moderne Industrie, Landsberg 1989

Kleger, R.: Sensorik für Praktiker,
AZ Verlag und VDE-Verlag, Aarau und Berlin 1998

Profos, P.; Domeisen, H.: Lexikon und Wörterbuch der industriellen Messtechnik,
Oldenbourg Verlag, München, Wien 1993

Rascher, M.; Klemmt, H.: Lichtschranken -
Anwendungen in der industriellen Automation,
Hüthig Verlag, Heidelberg 1987

Schiesle, E.: Sensortechnik und Messwertaufnahme,
Vogel Buchverlag, Würzburg 1992

Schnell, G. (ed.): Sensoren in der Automatisierungstechnik,
Vieweg Verlag, Braunschweig, Wiesbaden 1993

Schoppnies, E. (ed.): Lexikon der Sensortechnik, VDE Verlag, Berlin 1992

Schrüfer, E. (ed.): Lexikon der Mess- und Automatisierungstechnik,
VDI Verlag, Düsseldorf 1992

Tränkler, H.-R.; Obermeier, E.: Sensortechnik,
Springer Verlag, Berlin, Heidelberg 1998

Weisshaupt, B.; Gubler, G.: Identifikations- und Kommunikationssysteme,
verlag moderne Industrie, Landsberg 1992

Index