



2. Instrumentation and Control

Instrumentation - Sensors and actors

2.1

Instrumentation - Capteurs et actionneurs

Instrumentierung - Sensoren und Aktoren

Prof. Dr. H. Kirrmann

ABB Research Center, Baden, Switzerland

2.1.1 Market

2.1 Instrumentation

2.1.1 Market

2.1.2 Binary instruments

2.1.3 Analog Instruments

2.1.4 Actors

2.1.5 Transducers

2.1.6 Instrumentation diagrams

2.1.7 Protection classes

2.2 Control

2.3 Programmable Logic Controllers

The instrumentation market

Emerson (Fisher-Rosemount): 27 %

Invensys: 4-5%

ABB: 4-5%

Honeywell: 3-4%

one dominant player a lot of small players...

Example Nuclear power plant

Nombre de capteurs et d'actionneurs pour une tranche et selon les paliers
(number of sensors and actors for each slice and according to the level)

Capteur ou actionneur (sensor or actor) (Sensor oder Aktor)	Tranches 900 MW	Tranches 1300 MW	Tranches 1450 MW
Capteurs tout ou rien (binary sensors) (Initiatoren)	1 930	1 560	1 660
Fins de course de vannes manuelles et de registres (position sensor for manual valves and dampers)	330	140	700
Capteurs analogiques (mesures) (analog sensors) (Analoge Messgaräte)	1 360	2 050	2 280
Appareils de coupure 6,6 / 7,2 kV (circuit breakers) (Leistungsschalter)	40	95	74
Contacteurs 380 V (switches 380V) (Schalter)	340	600	540
Vannes motorisées (motor valves) (Steuerschieber)	190	300	250
Robinets pneumatiques TOR (on-off pneumatic switches) (pneumatische Schalter)	480	470	670
Vannes réglantes (proportional valves) (Regelschieber)	180	500	110

Jean CHABERT, Bernard APPELL, Guy GUESNIER, 1998

Concepts

instruments = sensors (*capteurs, Messgeber*) and actors (*actionneurs, Stellglieder*)

binary (on/off) and analog (continuous) instruments are distinguished.

industrial conditions:

- temperature range commercial: (0°C to +70°C)
 industry (-40°C..+85°C)
 extended industrial(-40°C..+125°C)
- mechanical resilience (shocks and vibrations) EN 60068
- protection: Electro-Magnetic (EM)-disturbances EN 55022, EN55024)
- protection: water and moisture (IP67=completely sealed, IP20 = normal)
- protection: NEMP (Nuclear EM Pulse) - water distribution, civil protection
- mounting and replacement
- robust connectors
- power: DC mostly 24V= because of battery back-up, sometimes 48V=)

2.1.2 Binary Instruments

2.1 Instrumentation

2.1.1 Market

2.1.2 Binary instruments

2.1.3 Analog Instruments

2.1.4 Actors

2.1.5 Transducers

2.1.6 Instrumentation diagrams

2.1.7 Protection classes

2.2 Control

2.3 Programmable Logic Controllers

Binary position measurement

binary sensors (*Geber*, "*Initiator*", *indicateur "tout ou rien"*):

- micro-switch (*Endschalter*, *contact fin de course*) +cheap, -wear, bouncing
- optical sensor (*Lichtschranke*, *barrière optique*) +reliable, -dust or liquid sensitive
- magnetic sensor (*Näherungsschalter*, *détecteur de proximité*) +dust-insensitive, - magnetic



Binary Signal processing

Physical attachment

- Level adaptation,
- Galvanical separation
- EMC barrier (against sparks, radio, disturbances)

Acquisition

- Convert to standard levels
- Relay contacts 24V (most frequent), 48V, 110V (electrical substations)
- Electronic signals 24V —>10V-60V,
- Output: 0..24V@100mA
- Counter inputs: Gray, BCD or binary

Processing

- Filtering (e.g. 0..8 ms filter),
- Plausibility (*Antivalenz*, *Antivalence*),
- Bounce-free (*Entprellen*, *Anti-rebond*)

2.1.3 Analog Instruments

2.1 Instrumentation

2.1.1 Market

2.1.2 Binary instruments

2.1.3 Analog Instruments

2.1.3.1 Position and speed

2.1.3.2 Temperature

2.1.3.3 Hydraulic

2.1.4 Actors

2.1.5 Transducers

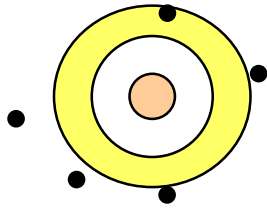
2.1.6 Instrumentation diagrams

2.1.7 Protection classes

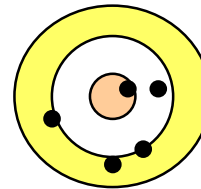
2.2 Control

2.3 Programmable Logic Controllers

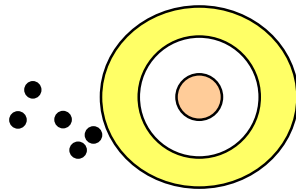
Repeatability and accuracy



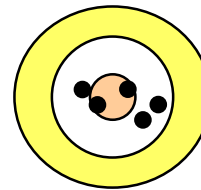
Not repeatable
Not accurate



Not repeatable
Accurate



Repeatable
Not accurate



Repeatable
Accurate

2.1.3.1 Analog mechanical position

potentiometer

capacitive

balanced transformer (LVDT)

(linear or sin/cos encoder)

strain gauges

piezo-electric

+cheap, -wear, bad resolution

+cheap, -bad resolution

+reliable, robust - small displacements

+reliable, very small displacements

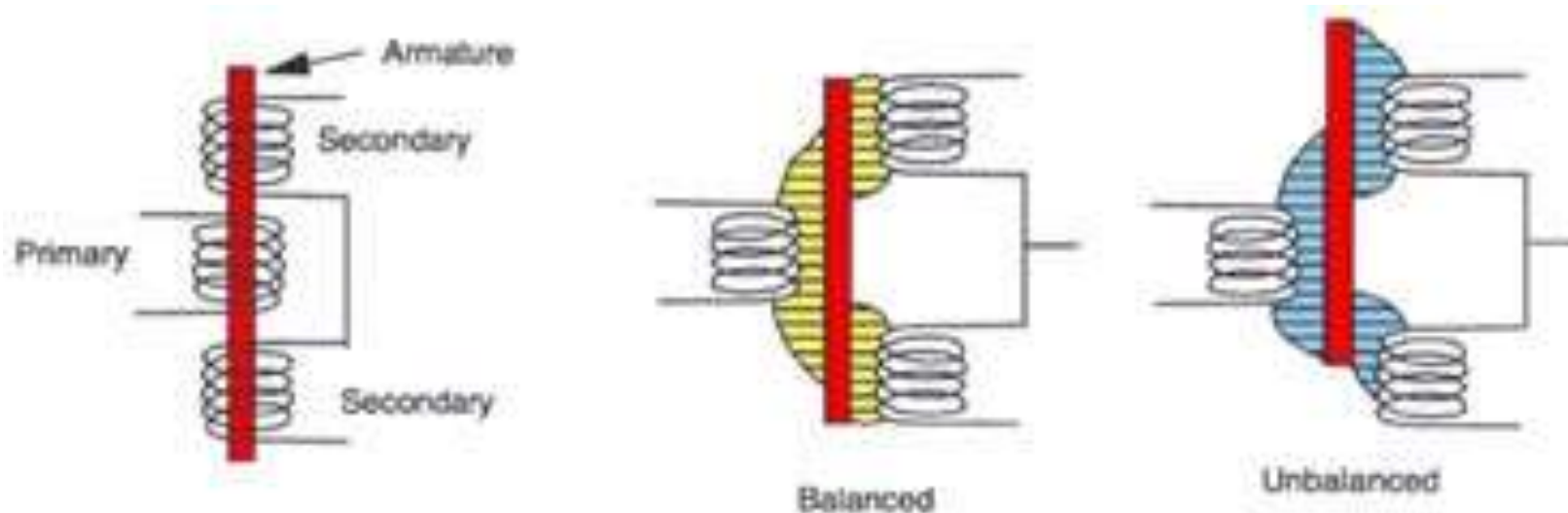
+extremely small displacements

Variable differential transformer (LVDT)



The LVDT is a variable-reluctance device, where a primary center coil establishes a magnetic flux that is coupled through a mobile armature to a symmetrically-wound secondary coil on either side of the primary.

Two components comprise the LVDT: the mobile armature and the outer transformer windings. The secondary coils are series-opposed; wound in series but in opposite directions.



When the moving armature is centered between the two series-opposed secondaries, equal magnetic flux couples into both secondaries; the voltage induced in one half of the secondary winding is 180 degrees out-of-phase with the voltage induced in the other half of the secondary winding.

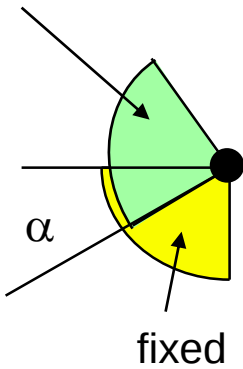
When the armature is moved out of that position, a voltage proportional to the displacement appears

source: www.sensorland.com

Capacitive angle or position measurement

$$C = \varepsilon \frac{A}{d} \approx \alpha$$

movable

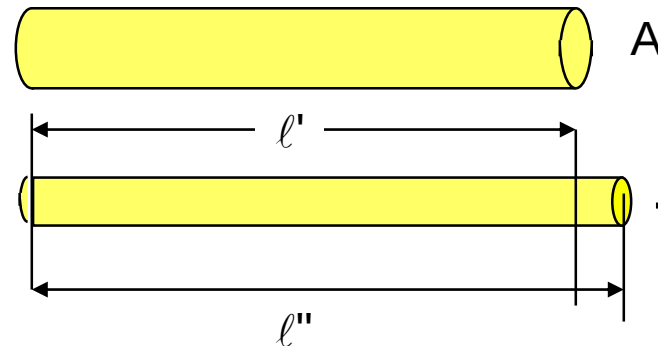
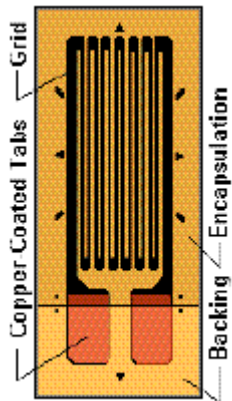


capacitance is evaluated by
modifying the frequency of
an oscillator

Small position measurement: strain gauges

Dehnungsmessstreifen (DMS), *jauges de contrainte*

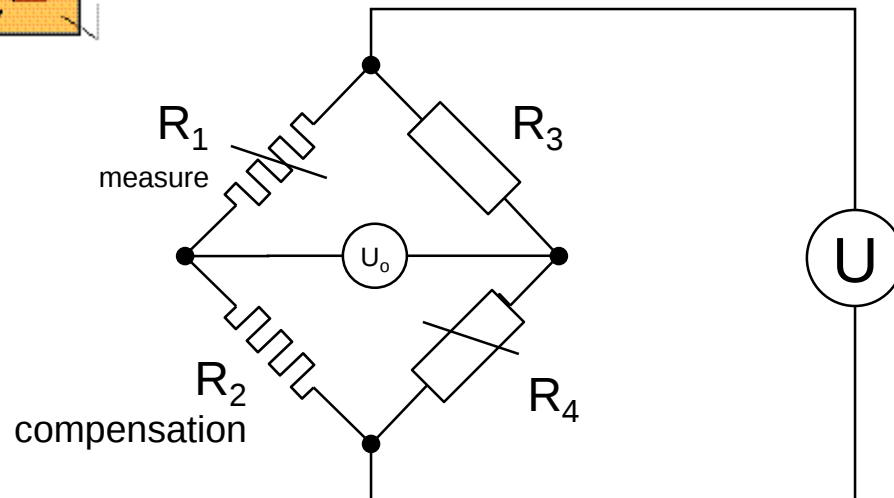
Principle: the resistance of a wire with resistivity ρ increases when this wire is stretched:



ρ = resistivity

$$R = \rho \frac{\ell}{A} = \rho \frac{\ell^2}{V} \approx \ell^2$$

volume = constant, ρ = constant



measurement in bridge
(if $U_0 = 0$: $R_1 R_4 = R_2 R_3$)

temperature compensation
by "dummy" gauges

frequently used in buildings, bridges,
dams for detecting movements.

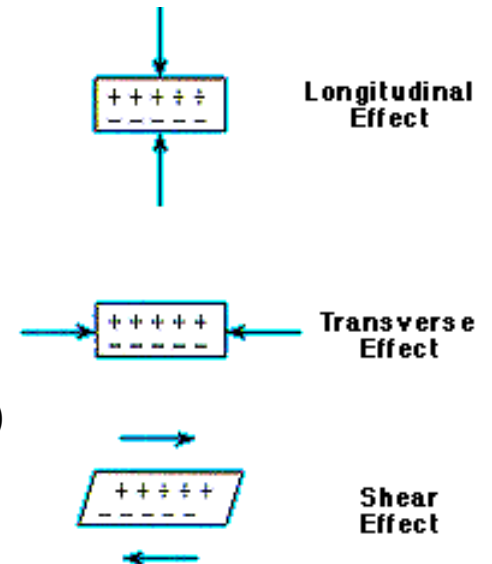
Piezo-electrical effect

Piezoelectric materials (crystals) change form when an electrical field is applied to them. Conversely, piezoelectric materials produce an electrical field when deformed.

Quartz transducers exhibit remarkable properties that justify their large scale use in research, development, production and testing. They are extremely stable, rugged and compact.

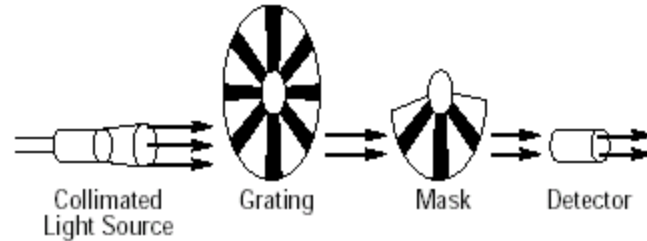
Of the large number of piezoelectric materials available today, quartz is employed preferentially in transducer designs because of the following excellent properties:

- high material stress limit, around 100 MPa (~ 14 km water depth)
- temperature resistance (up to 500C)
- very high rigidity, high linearity and negligible hysteresis
- almost constant sensitivity over a wide temperature range
- ultra high insulation resistance (10^{+14} ohms) allowing low frequency measurements (<1 Hz)



source: Kistler

Principle of optical angle encoder



Optical encoders operate by means of a grating that moves between a light source and a detector. The detector registers when light passes through the transparent areas of the grating.

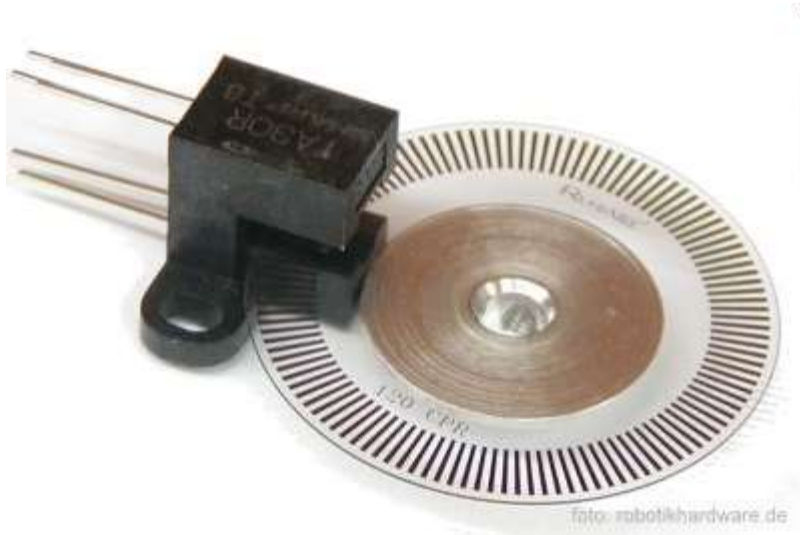
For increased resolution, the light source is collimated and a mask is placed between the grating and the detector. The grating and the mask produce a shuttering effect, so that only when their transparent sections are in alignment is light allowed to pass to the detector.

An incremental encoder generates a pulse for a given increment of shaft rotation (rotary encoder), or a pulse for a given linear distance travelled (linear encoder). Total distance travelled or shaft angular rotation is determined by counting the encoder output pulses.

An absolute encoder has a number of output channels, such that every shaft position may be described by its own unique code. The higher the resolution the more output channels are required.

courtesy Parker Motion & Control

Incremental angle encoder



open mounted



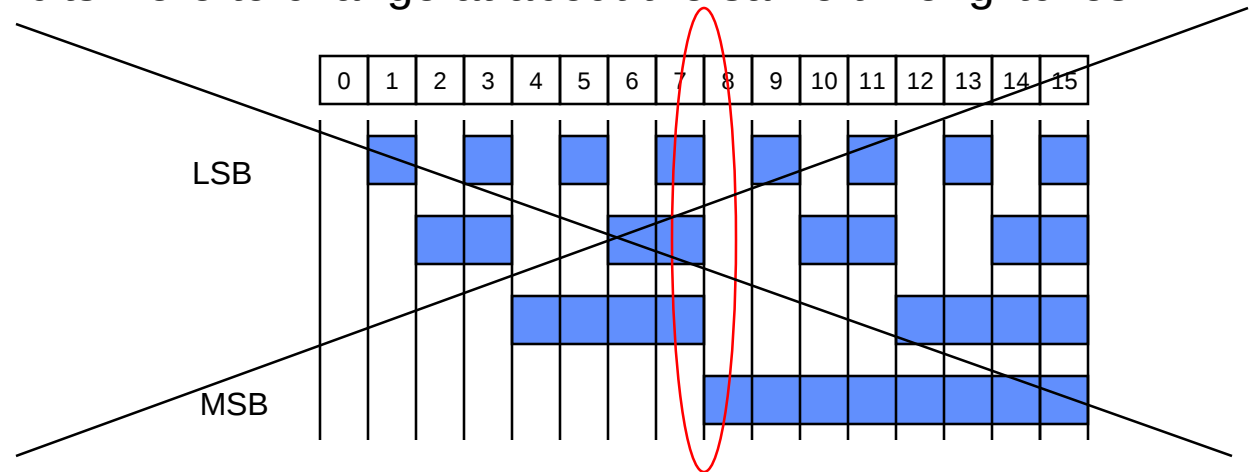
Photo: Lenord & Bauer



Photo: Baumer

Absolute digital position: Gray encoder

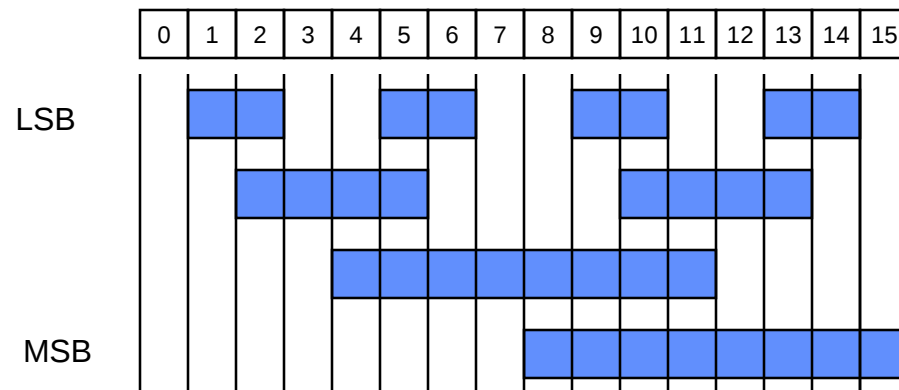
binary code: if all bits were to change at about the same time: glitches



Gray code: only one bit changes at a time: no glitch



Gray disk (8 bit)



Linear encoder

Also with magnetic instead of optical grating



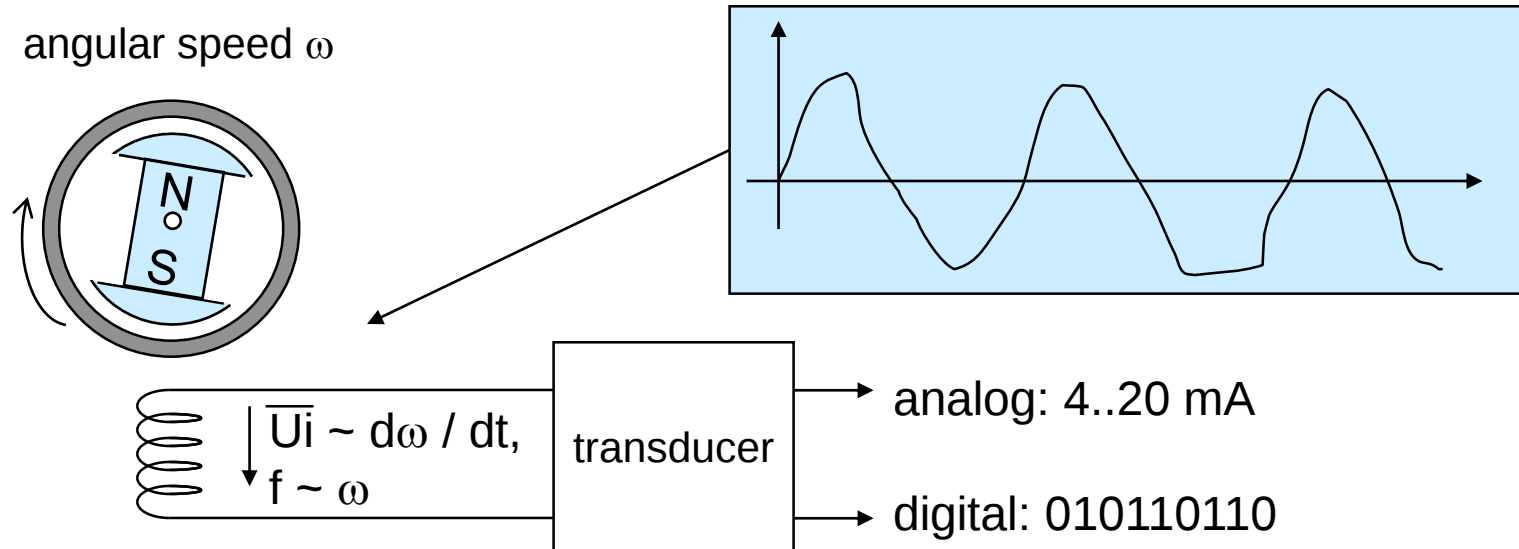
Force measurement

Force / Torque / Weight / Pressure is measured by small displacements ($F = k \cdot x$):

- piezo-electrical transducers
- strain gauges

Acceleration is measured by way of force / displacement measurement ($F = M \cdot \gamma$)

Analog speed measurement: tachometer



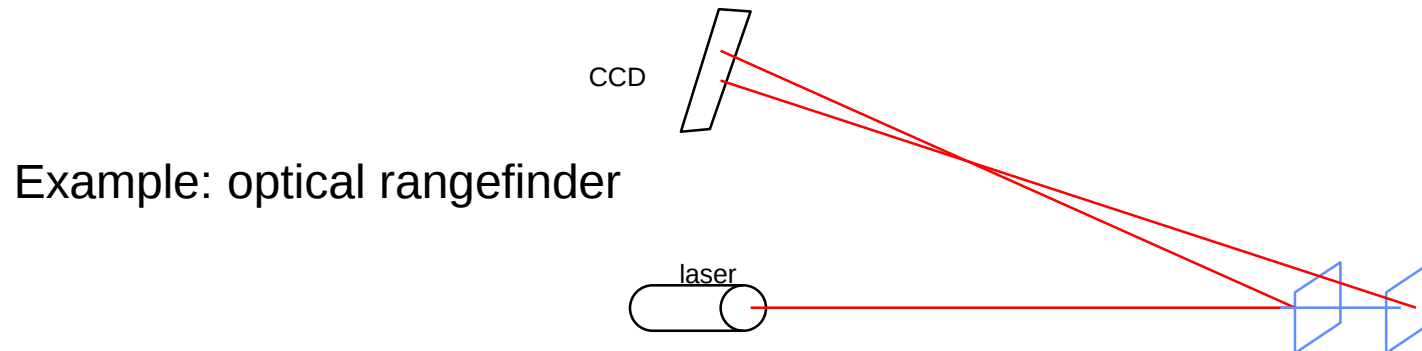
a simple tachometer is a rotating permanent magnet that induces a voltage into a stator winding.

this voltage is converted into an analog voltage or current, later converted to a digital value,

alternatively, the frequency of the signal can be measured to yield directly a digital value

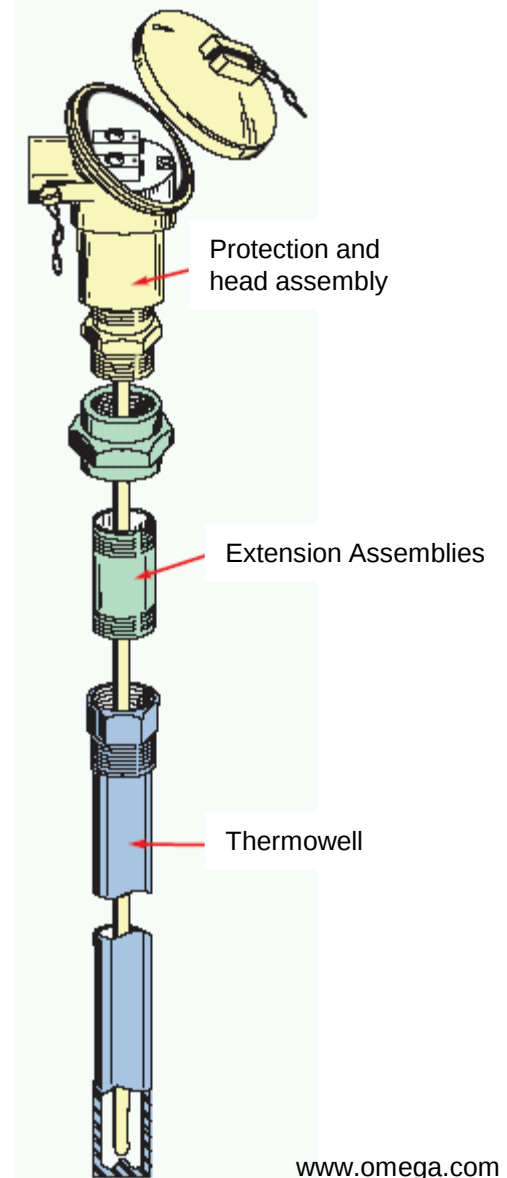
Measuring distance without mechanical contact

principle	inductive	optical	ultra-sound
range	0..10mm	15..1000 mm	20..2599mm
resolution	0,1 μ m	2 μ m	300 μ m
repeatability	1 μ m	2 μ m	500 μ m
linearity	0,4..5%	0,06..1,2%	0,5%
reactivity	0,35ms	0,9ms	30ms
remark	for electrically conducting materials, small cheap	for small and mobile parts	highly linear long range dust resilient



2.1.3.2 Temperature measurement

the most frequently measured value in industry



www.omega.com

Temperature measurement

Thermistance (RTD - resistance temperature detector):

metal whose resistance depends on temperature:

- + cheap, robust, high temperature range (-180°C .. 600°C),
- require current source, non-linear.

Thermistor (NTC - negative temperature coefficient):

semiconductor whose resistance depends on temperature:

- + very cheap, sensible,
- low temperature, imprecise, needs current source, strongly non-linear, fragile, self-heating

Thermo-element (*Thermoelement*, *thermocouple*):

pair of dissimilar metals that generate a voltage proportional to the temperature difference between warm and cold junction (Seebeck effect)

- + high precision, high temperature, punctual measurement
- low voltage, requires cold junction compensation, high amplification, linearization

Spectrometer:

measures infrared radiation by photo-sensitive semiconductors

- + highest temperature, measures surfaces, no contact
- highest price

Bimetal (*Bimetall*, *bilame*):

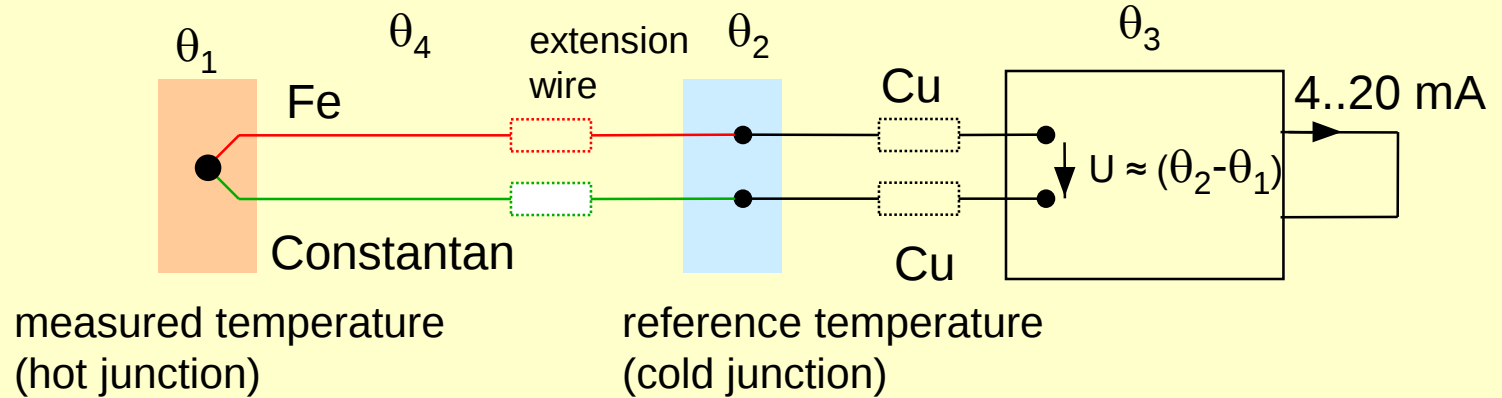
mechanical (yes/no) temperature indicator using the difference in the dilatation coefficients of two metals, very cheap, widely used (toasters...)

Thermo-element and Thermo-resistance

Thermo-element (*Thermocouple*)

two dissimilar
electrical
conductors

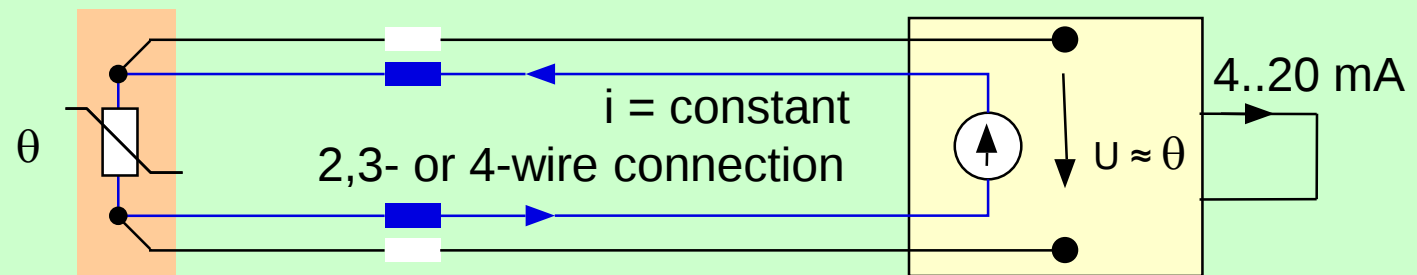
Fe-Const
also: Pt/Rh - Pt



Thermoresistance (semiconductor or metal)

one material whose
resistance is
temperature-
dependent

Platinum (Pt 100)



2 or 4 wire connection (to compensate voltage drop)

Cold junction box



2.1.3.3 Hydraulic measurements

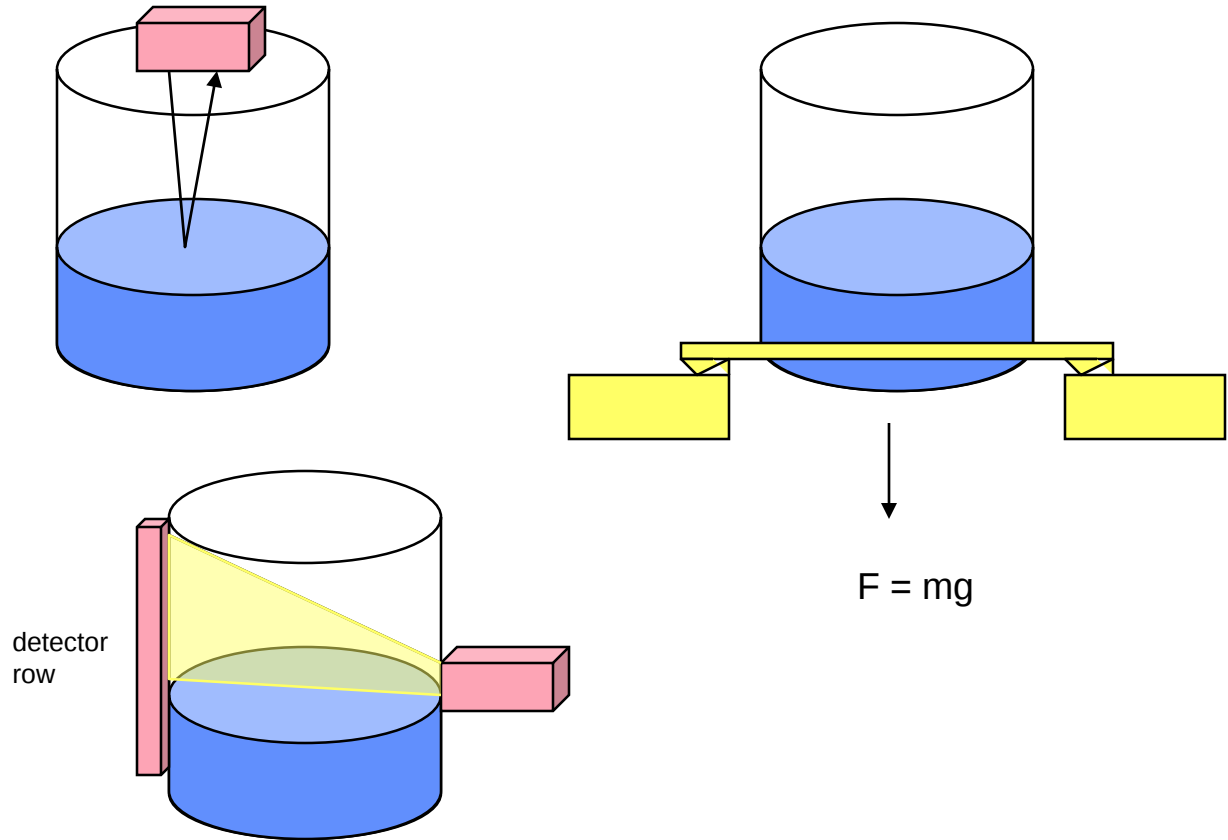
- Flow,
- Mass Flow,
- Level,
- Pressure,
- Conductivity,
- pH-Sensor,
- Viscosity,
- Humidity,



special requirements: intrinsic safety = explosive environment, sea floor = high pressure

Level measurement

- pulsed laser
- load cell
- pulsed microwave
- nuclear
- ultrasonic (40-60 kHz)
- low power ultrasonic



see Control Engineering, Aug 2003

Flow measurement

Distinguish:

volumetric flow (m^3/s)

mass flow: (kg / s)

identical when the density of the liquid is constant

main methods:

- floater

- turbine

- pressure difference

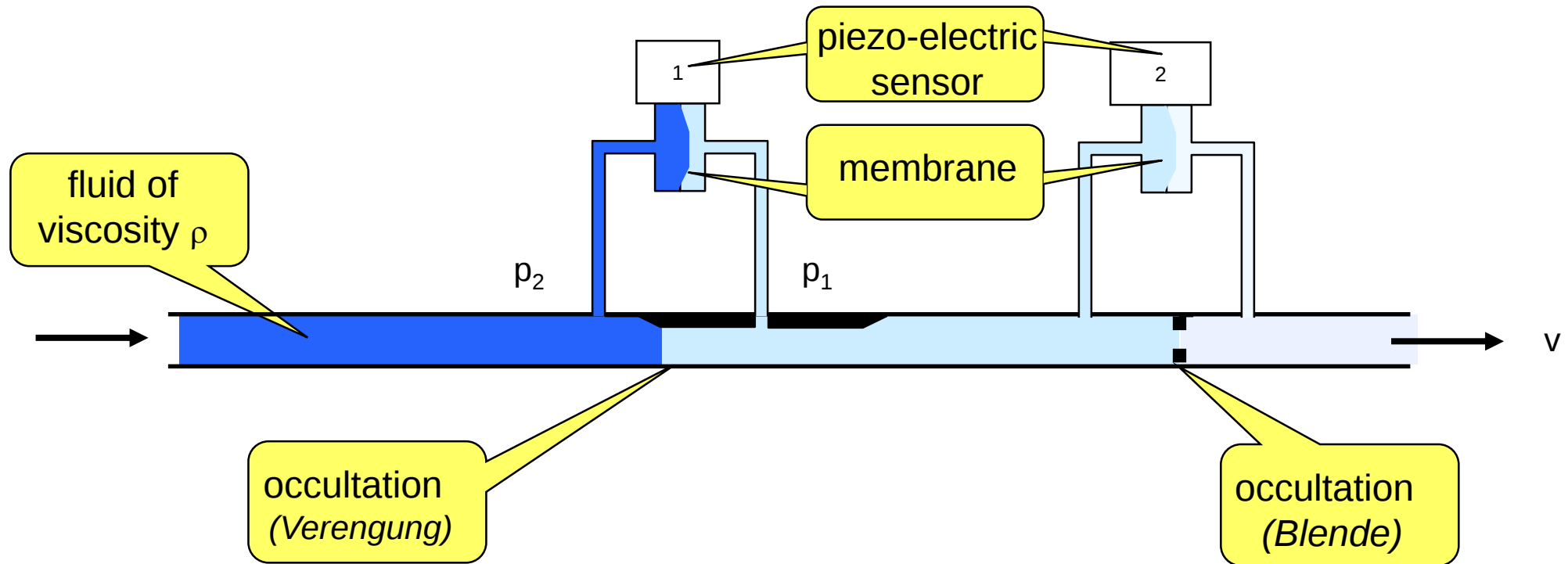
- vortex

- temperature gradient

- ultrasonic

- electrodynamics

Flow velocity measurement: differential pressure (2 methods)

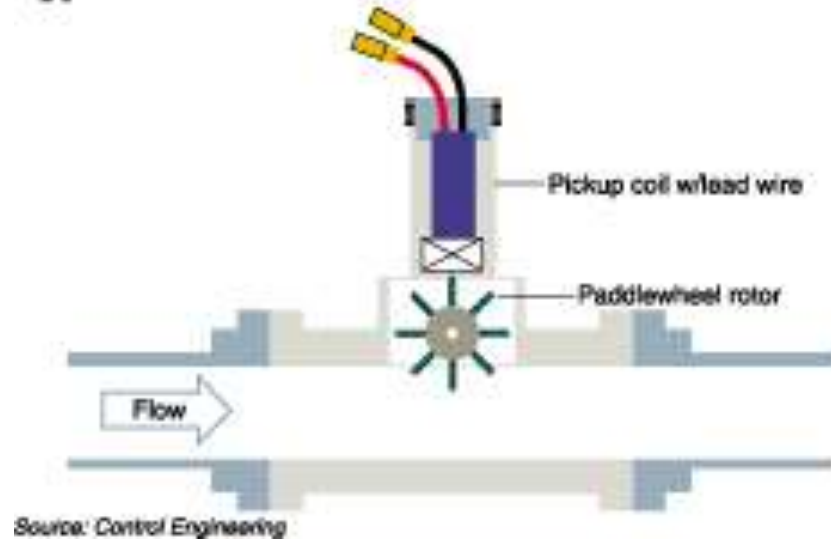


$$p_2 - p_1 = \frac{1}{2} \rho v^2 \quad (\text{Bernoulli effect})$$

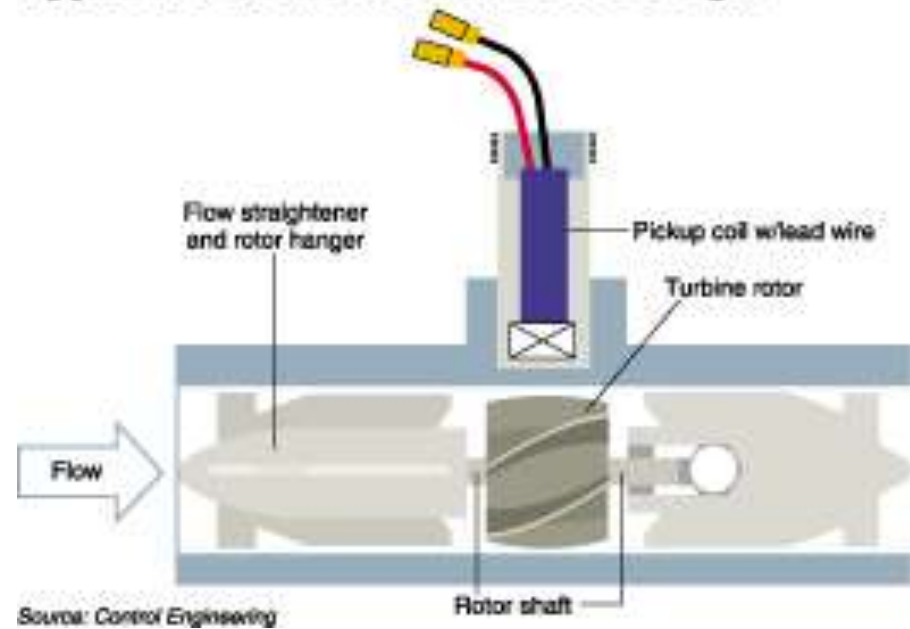
the flow velocity is proportional to the square root of the pressure difference

Flow measurement

Typical Paddlewheel Flowmeter Installation



Typical Turbine Flowmeter Design



Other means:

Magnetic-dynamic

Coriolis

Ultra-sound

Flow measurement in a plant



2.1.4 Actors

2.1 Instrumentation

2.1.1 Market

2.1.2 Binary instruments

2.1.3 Analog Instruments

2.1.4 Actors

2.1.5 Transducers

2.1.6 Instrumentation diagrams

2.1.7 Protection classes

2.2 Control

2.3 Programmable Logic Controllers

Actors (Actuators)

Stellantriebe, *Servomoteurs*

About 10% of the field elements are actors (that influence the process).
Actors can be binary (on/off) or analog (e.g. variable speed drive)

The most common are:

- electric contactors (relays)
- heating elements
- pneumatic and hydraulic movers (valve, pump)
- electric motors (rotating and linear)

Solenoids,

DC motor

Asynchronous Motors (Induction)

Synchronous motors

Step motors, reluctance motors



Actors are controlled by the same electrical signal levels as sensors use (4..20mA, 0..10V, 0..24V, etc.) but at higher power levels (e.g. to directly move a contactor (*disjoncteur*)).

Drives (variateurs de vitesse, Stellantriebe)

Variable speed drives control speed and acceleration and protect the motor (over-current, torque, temperature).

High-power drives can feed back energy to the grid when braking (inverters).

Drives is an own market (“Automation & Drives”)



simple motor control

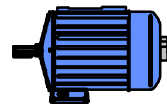


cabinet for power of > 10 kW

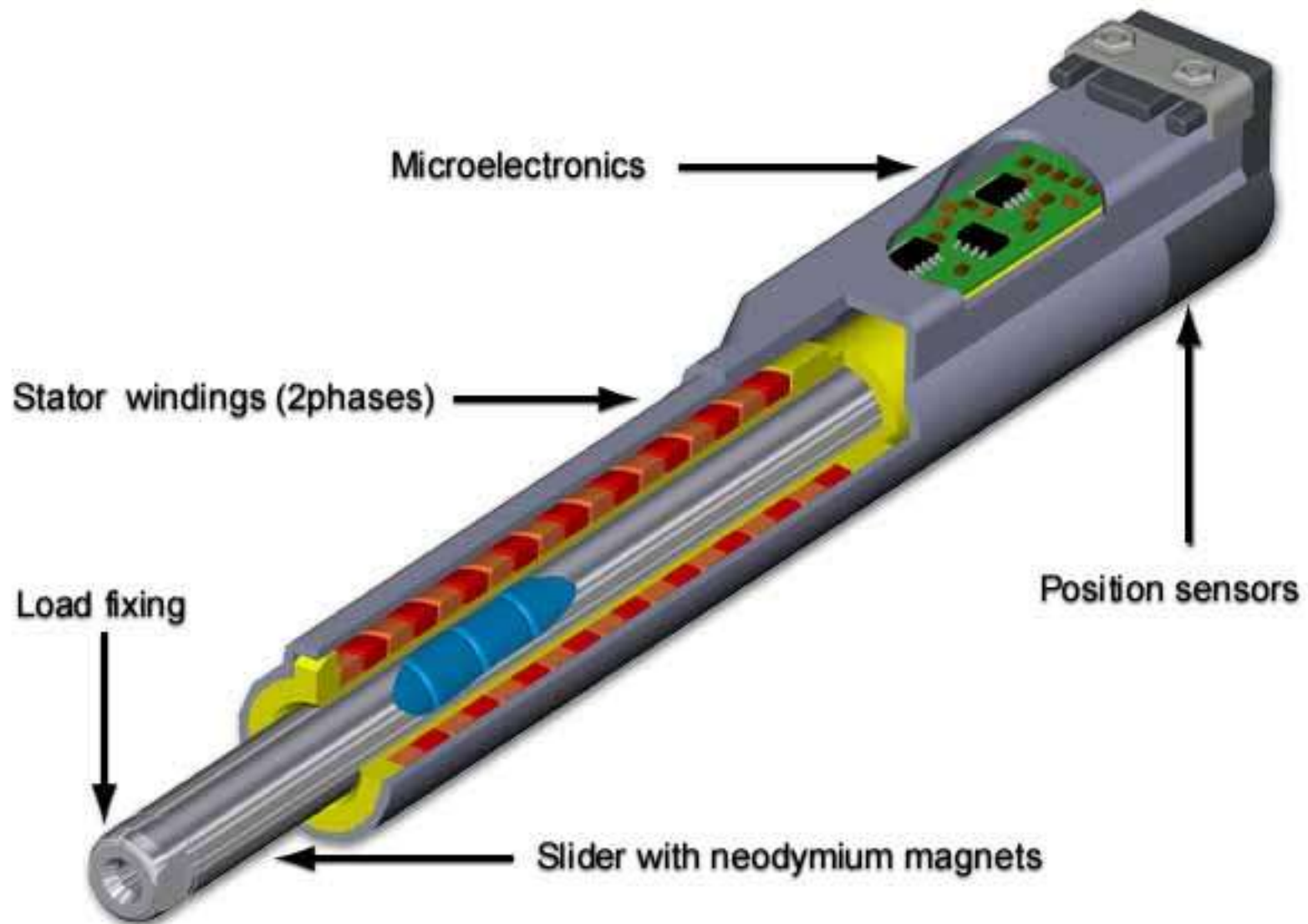


small drive control < 10 kW
(Rockwell)

Motors and drives are separate businesses



Linear Motors



source: LinMot ([/www.linmot.com](http://www.linmot.com))

Hydraulics and fluidics...

Pumps, valves, rods,...

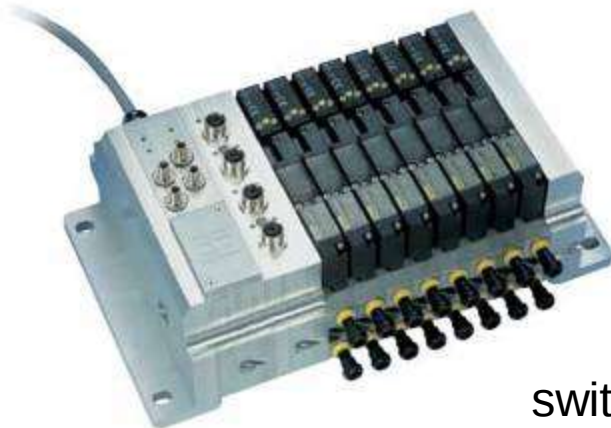
the most widespread actor in industry
(lightweight, reliable, cheap)



fluidic switches



I/P or E/P = electro-pneumatic transducers



switchboard ("Ventilinsel")

source: www.bachofen.ch

2.1.5 Transducers

2.1 Instrumentation

2.1.1 Market

2.1.2 Binary instruments

2.1.3 Analog Instruments

2.1.4 Actors

2.1.5 Transducers

2.1.6 Instrumentation diagrams

2.1.7 Protection classes

2.2 Control

2.3 Programmable Logic Controllers

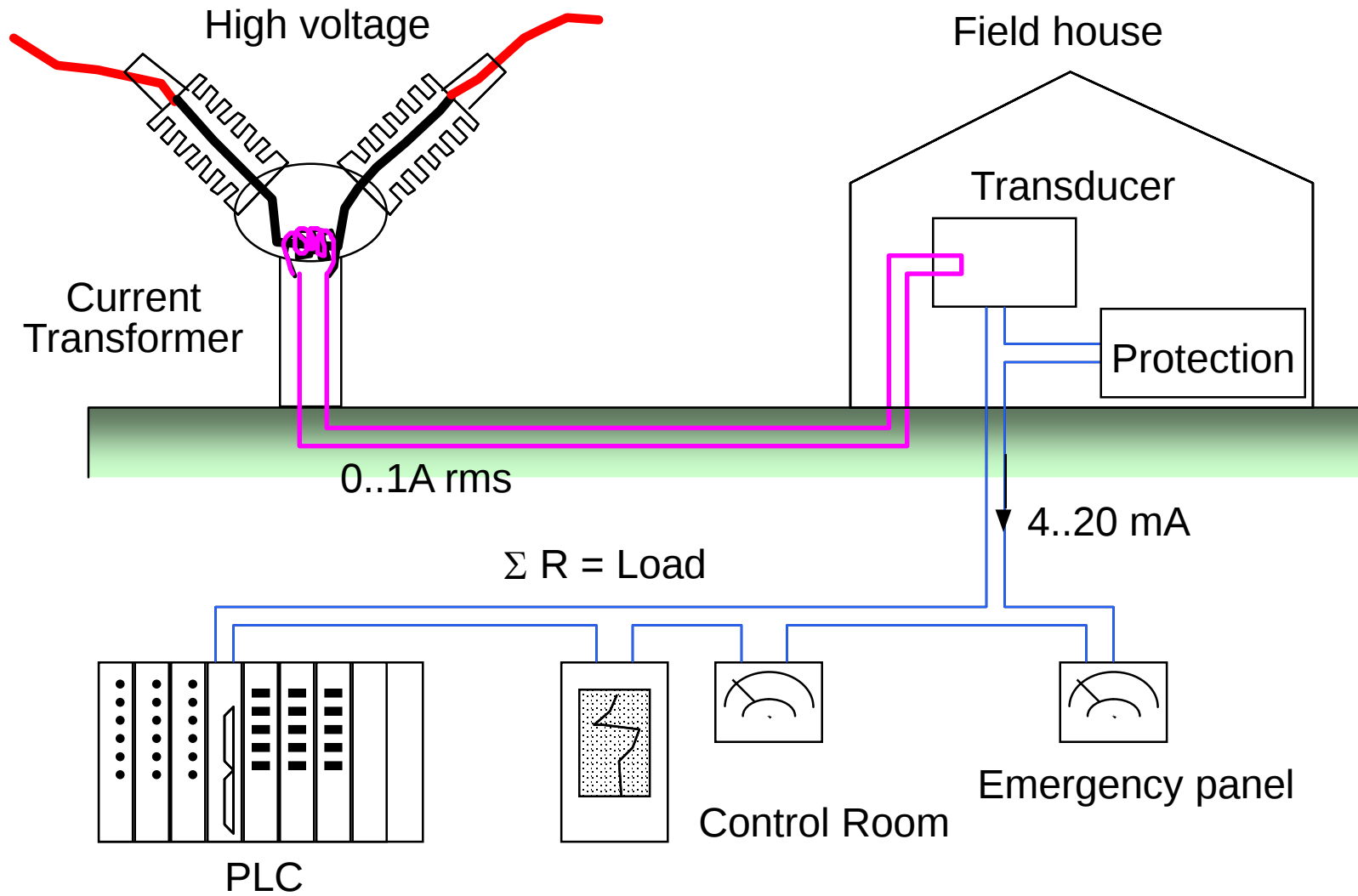
Transducer

A transducer converts the information supplied by a sensor (piezo, resistance,...) into a standardized signal which can be processed digitally.

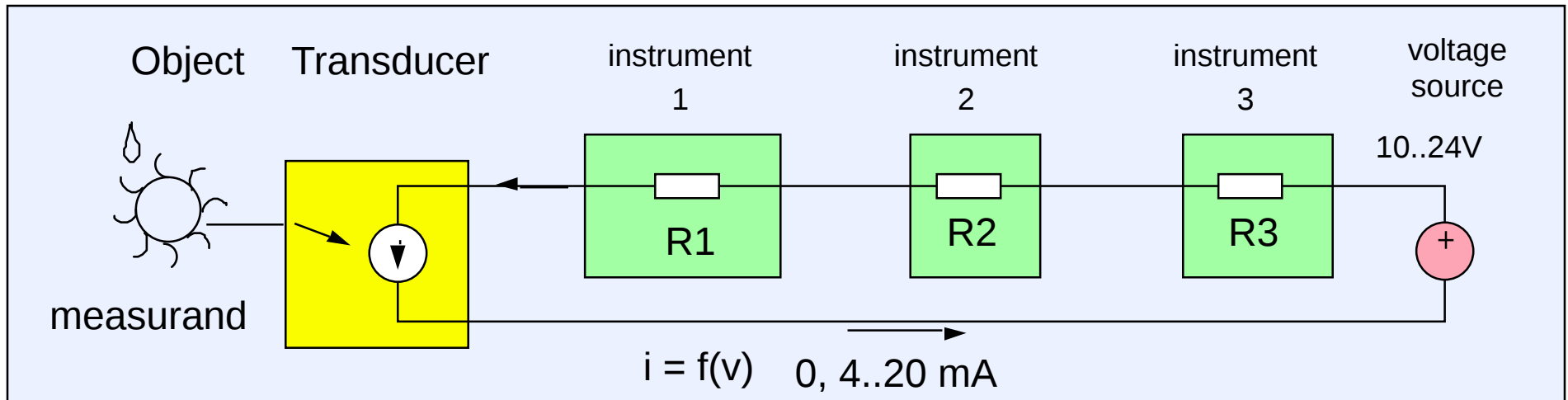
Some transducers have directly a digital (field bus) output and are integrated in the sensor.

Other are located at distances of several meters from the sensor.

Example of analog transducer



4-20 mA loop standard



The transducer acts as a current source which delivers a current between 4 and 20 mA, proportional to the measurand (*Messgrösse, valeur mesurée*).

Information is conveyed by a current, the voltage drop along the cable induces no error.

0 mA signals an error (wire disconnection)

The number of loads connected in series is limited by the operating voltage (10..24 V).
e.g. if $(R1 + R2 + R3) = 1.5 \text{ k}\Omega$, $i = 24 / 1.5 = 16 \text{ mA}$, which is $< 20 \text{ mA}$: NOT o.k.)

Simple devices are powered directly by the residual current (4mA) allowing to transmit signal and power through a single pair of wires.

Analog measurements processing in the transducer

Acquisition (*Erfassung/Saisie*)

Normalized Signals: 0-10V, 2-10V, (0/4-20mA), ± 20 mA,
Resistance thermometer (Pt100),
Thermo-element

Shaping (*Aufbereitung/conditionnement*)

Filtering against 50Hz/60Hz noise and its harmonics

Scaling,

Linearization of sensors (Pt100, Fe-Const), correction (square root for flow).

Averaging and Computation of Root Mean Square (Effektivwert, valeur efficace),

Analog-Digital Conversion

Plausibility

Range, Limit supervision, Wire integrity

Error report, diagnostic, disabling.

Combined measurement

Correction of pressure and temperature measurement for moist gases,
correction of level in function of pressure,
power and energy computation, cumulative measurements

2.1.6 Instrumentation diagrams: P&ID

2.1 Instrumentation

2.1.1 Market

2.1.2 Binary instruments

2.1.3 Analog Instruments

2.1.4 Actors

2.1.5 Transducers

2.1.6 Instrumentation diagrams

2.1.7 Protection classes

2.2 Control

2.3 Programmable Logic Controllers

Instrumentation Diagrams

Similarly to electrical schemas, the control industry (especially the chemical and process industry) describes its plants and their instrumentation by a

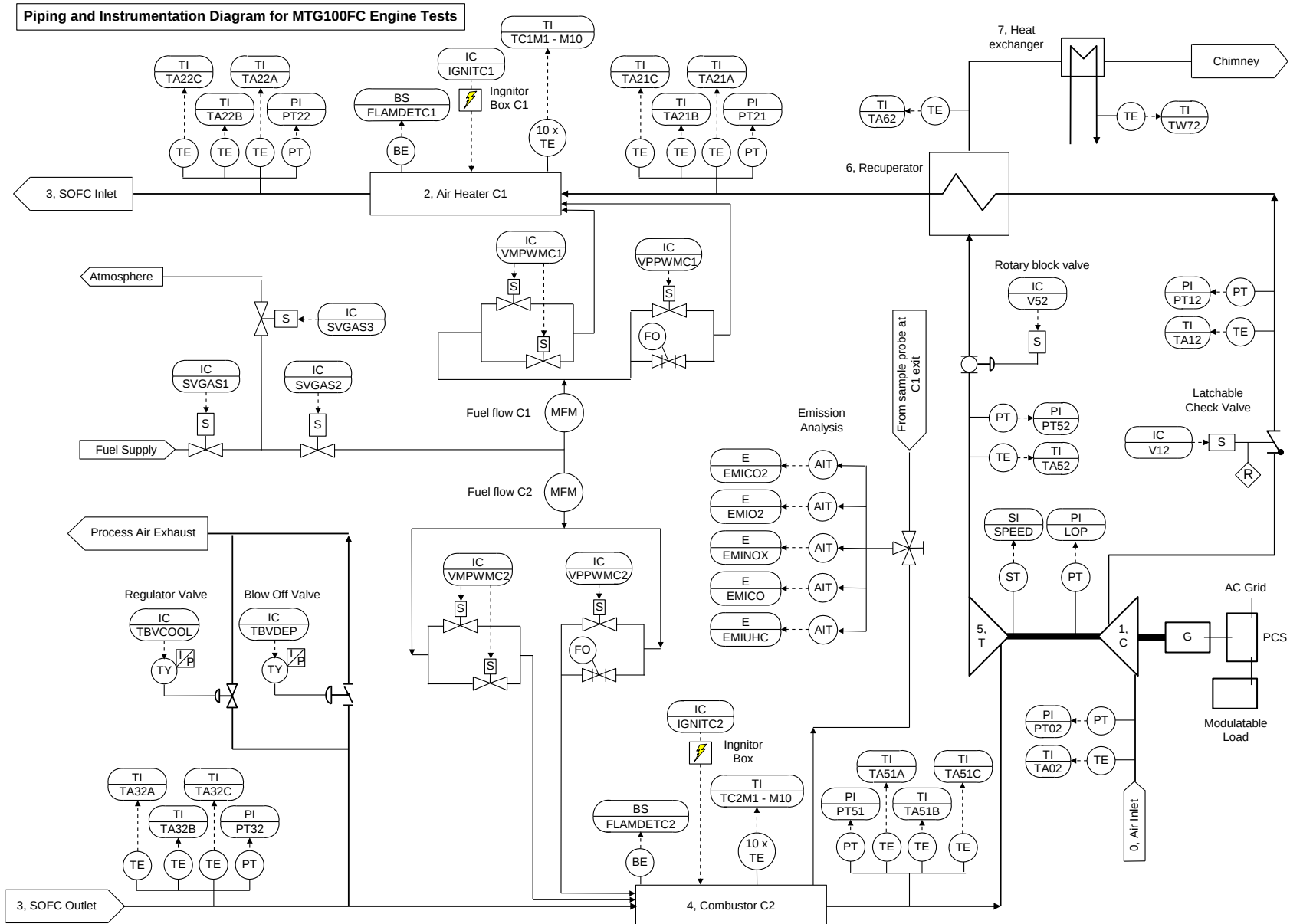
P&ID (pronounce P.N.I.D.) (Piping aNd Instrumentation Diagram), sometimes called P&WD (Piping and wiring diagrams)

The P&ID shows the flows in a plant (in the chemical or process industry) and the corresponding sensors or actors.

At the same time, the P&ID gives a name ("tag") to each sensor and actor, along with additional parameters.

This tag identifies a "point" not only on the screens and controllers, but also on the objects in the field.

P&ID example

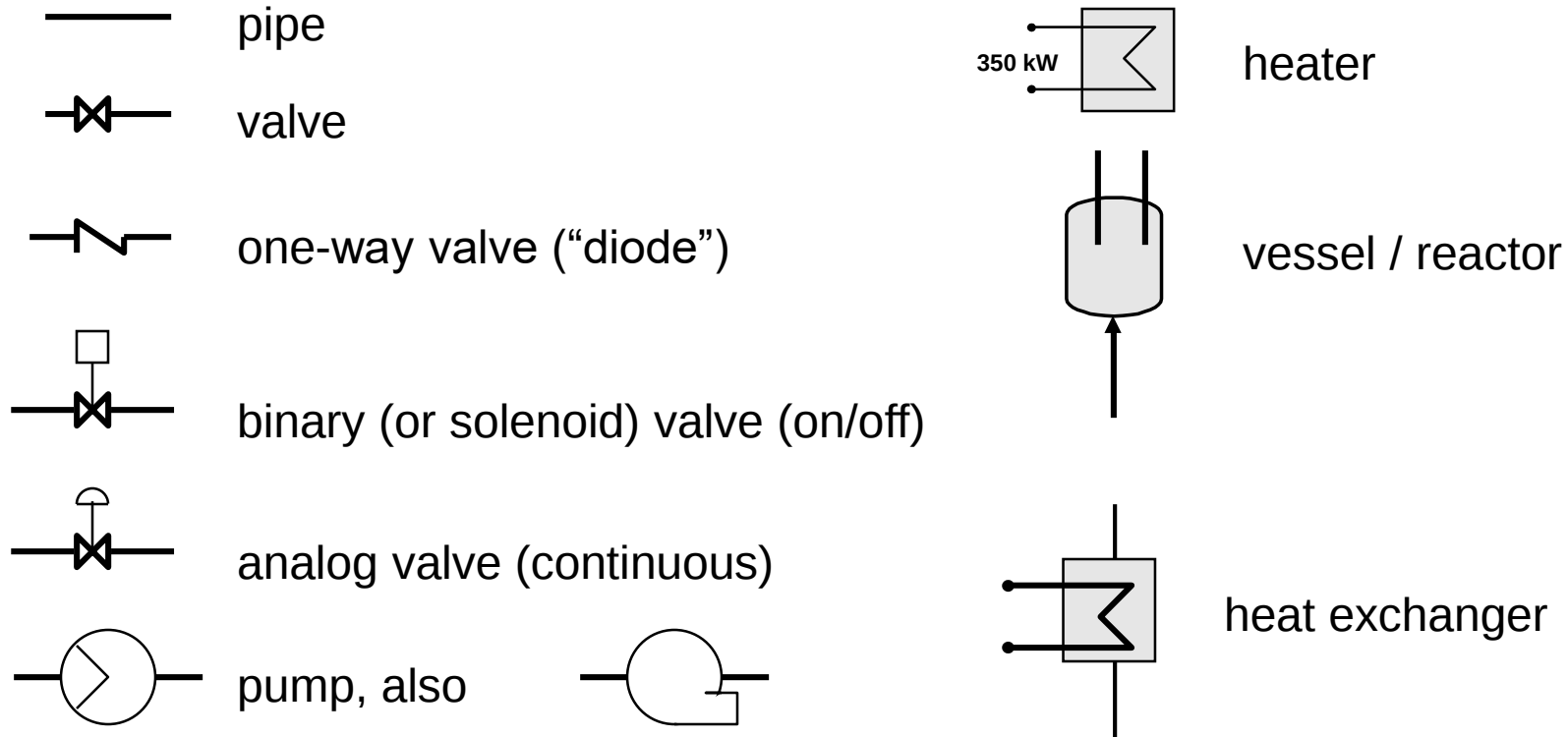


P&ID

The P&ID mixes pneumatic / hydraulic elements, electrical elements and instruments on the same diagram

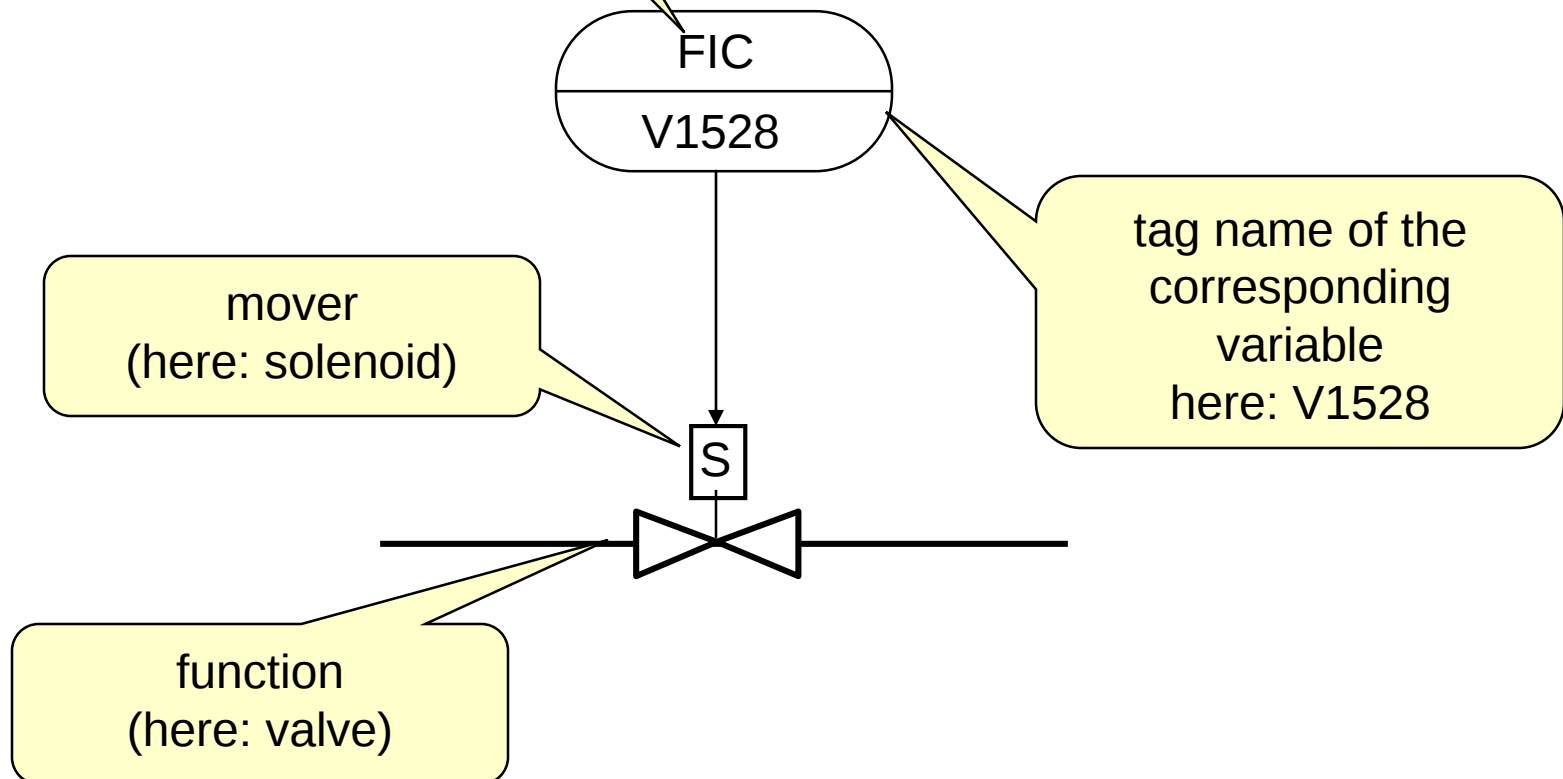
It uses a set of symbols defined in the ISA S5.1 standard.

Examples of pneumatic / hydraulic symbols:



Instrumentation identification

The first letter defines the measured or initiating variables such as Analysis (A), Flow (F), Temperature (T), etc. with succeeding letters defining readout, passive, or output functions such as Indicator (I), Record (R), Transmit (T), see next slides, here: flow indicator digital



ISA S5.1 General instrument or function symbols

	Primary location accessible to operator	Field mounted	Auxiliary location accessible to operator
Discrete instruments	1 	2 	3 
Shared display, shared control	4 	5 	6 
Computer function	7 	8 	9 
Programmable logic control	10 	11 	12 
1. Symbol size may vary according to the user's needs and the type of document. 2. Abbreviations of the user's choice may be used when necessary to specify location. 3. Inaccessible (behind the panel) devices may be depicted using the same symbol but with a dashed horizontal bar. Source: Control Engineering with data from ISA S5.1 standard			

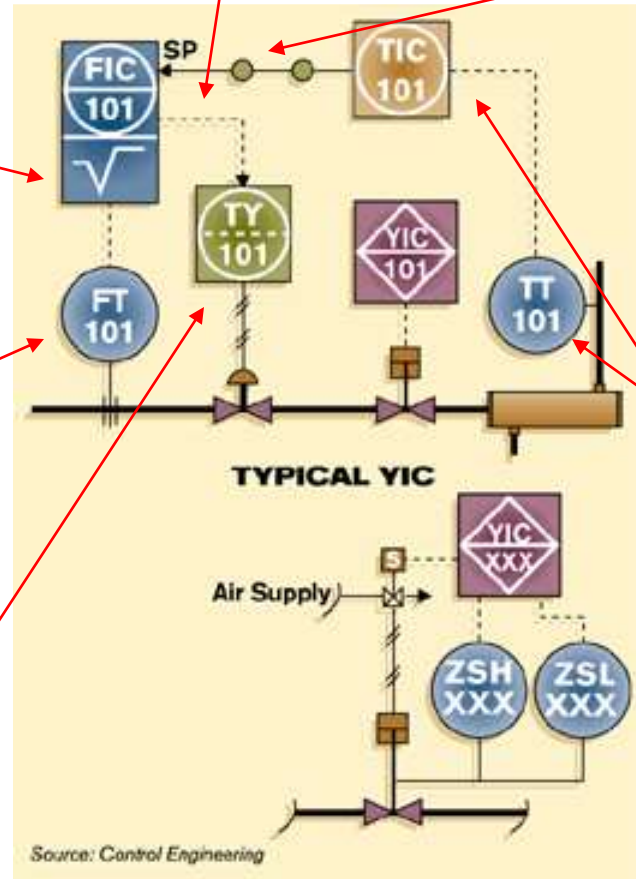
Example of P&ID

The output of FIC 101 is an electrical signal to TY 101 located in an inaccessible or behind-the-panel-board location.

Square root extraction of the input signal is part of FIC 101's functionality.

FT101 is a field-mounted flow transmitter connected via electrical signals (dotted line) to flow indicating controller FIC 101 located in a shared control/display device

The output signal from TY 101 is a pneumatic signal (line with double forward slash marks) making TY 101 an I/P (current to pneumatic transducer)



TIC 101's output is connected via an internal software or data link (line with bubbles) to the setpoint (SP) of FIC 101 to form a cascade control strategy

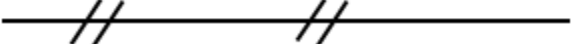
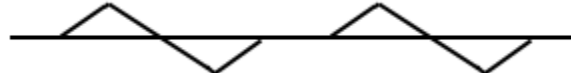
TT 101 and TIC 101 are similar to FT 101 and FIC 101 but are measuring, indicating, and controlling temperature

Source: Control Engineering

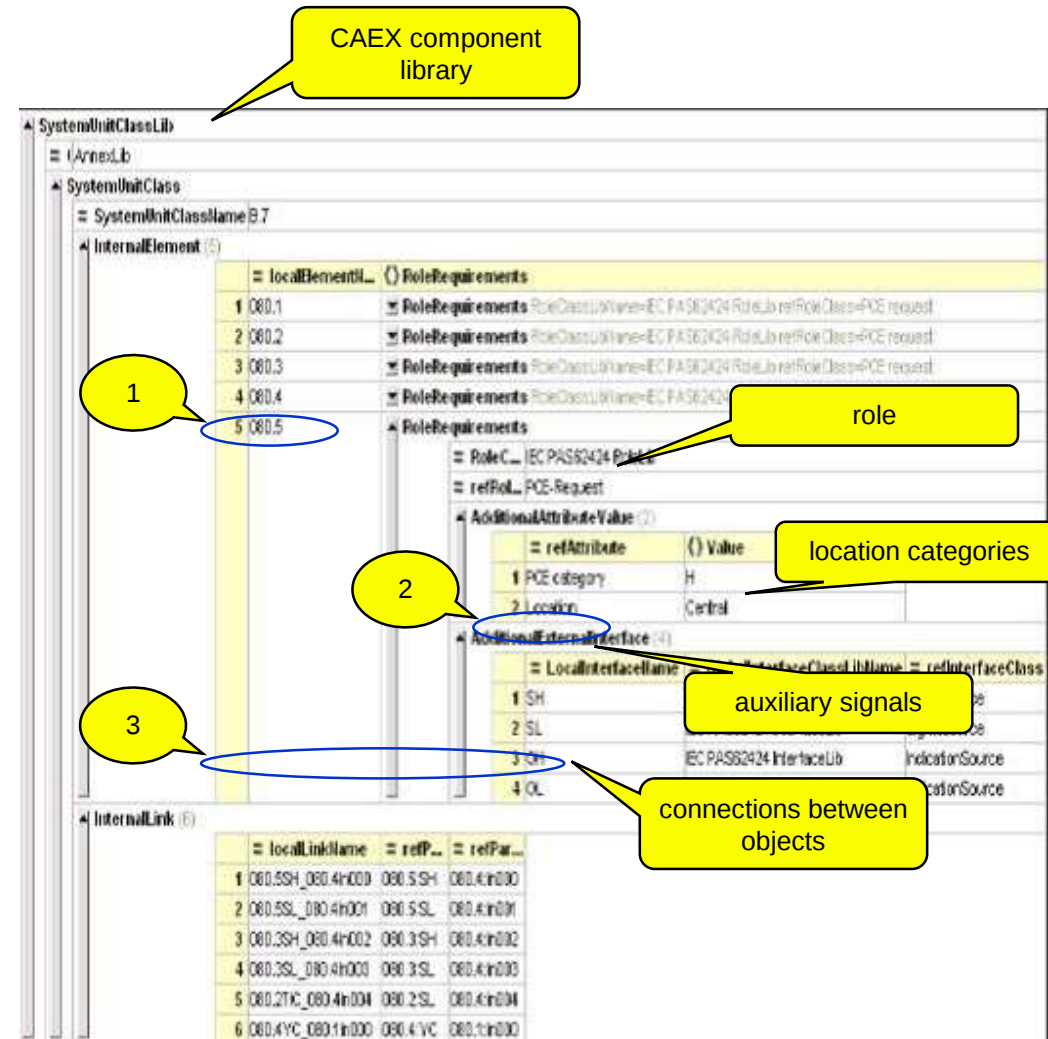
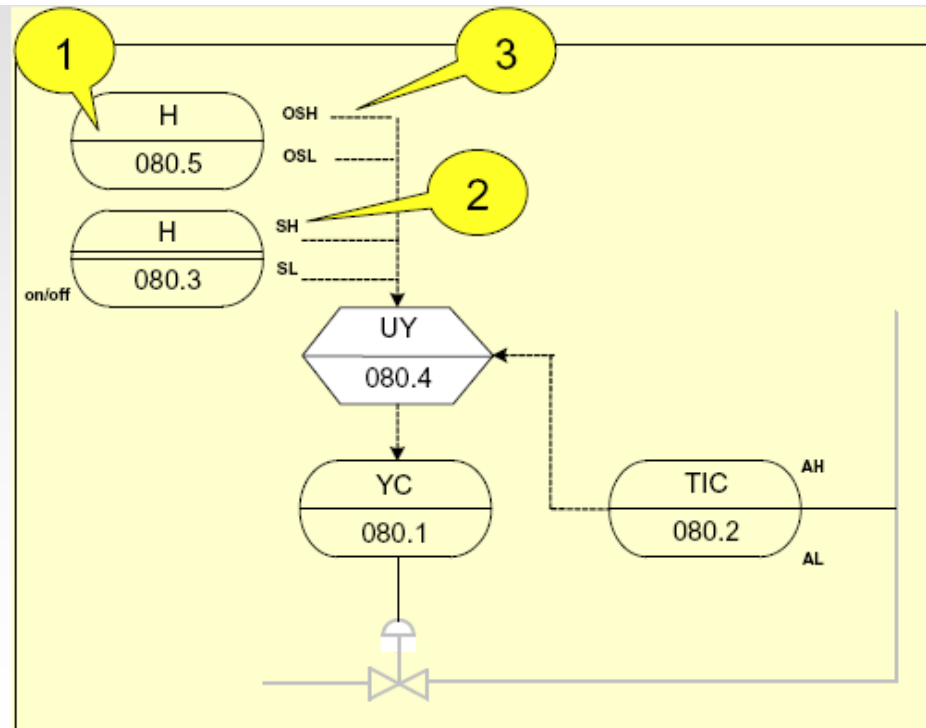
The ISA code for instrument type

	First letter	
	Measured or initiating variable	Modifier
A	Analysis	
B	Burner, combustion	
C	User's choice	
D	User's choice	Differential
E	Voltage	
F	Flow rate	Ration (fraction)
G	User's choice	
H	Hand	
I	Current (electrical)	
J	Power	Scan
K	Time, time schedule	Time rate of change
L	Level	
M	User's choice	Momentary
N	User's choice	
O	User's choice	
P	Pressure, vacuum	
Q	Quantity	Integrate, totalizer
R	Radiation	
S	Speed, frequency	Safety
T	Temperature	
U	Multivariable	
V	Vibration, mechanical analysis	
W	Weight, force	
X	Unclassified	X axis
Y	Event, state, or presence	Y axis
Z	Position, dimension	Z axis

Common connecting lines

Connection to process, or instrument supply	
Pneumatic signal	
Electric signal	
Capillary tubing (filled system)	
Hydraulic signal	
Electromagnetic or sonic signal (guided)	
Internal system link (software or data link)	
Source: Control Engineering with data from ISA S5.1 standard	

P&ID in computer readable form: IEC 62424



2.1.7 Protection Classes

2.1 Instrumentation

2.1.1 Market

2.1.2 Binary instruments

2.1.3 Analog Instruments

2.1.4 Actors

2.1.5 Transducers

2.1.6 Instrumentation diagrams

2.1.7 Protection classes

2.2 Control

2.3 Programmable Logic Controllers

German IP-Protection classes

1st digit	touching	objects	2nd digit	water
0	none		0	none
1	large body surface	object > 50 mm ø	1	vertically falling
2	finger	object >12.5 mm ø	2	vertically dropping, 15° from vertical
3	tools, wires	object > 2.5 mm ø	3	spraying, 60° from vertical
4	covered	object >1 mm ø	4	spraying, any direction
5	dust		5	jet, any direction
6	hermetical for dust		6	strong jet, any direction
			•	protection against temporary dipping (30 mn, 1 m)
			•	protection against permanent dipping
			•	9K water in high-pressure steam washing

e.g. IP 67 connector

Explosion protection

Instruments that operate in explosive environments (e.g. petrochemical, pharmaceutical, coal mines,...) are subject to particular restrictions.

e.g.

They may not contain anything that can produce sparks or high heat, such as electrolytic capacitors or batteries without current limitation.

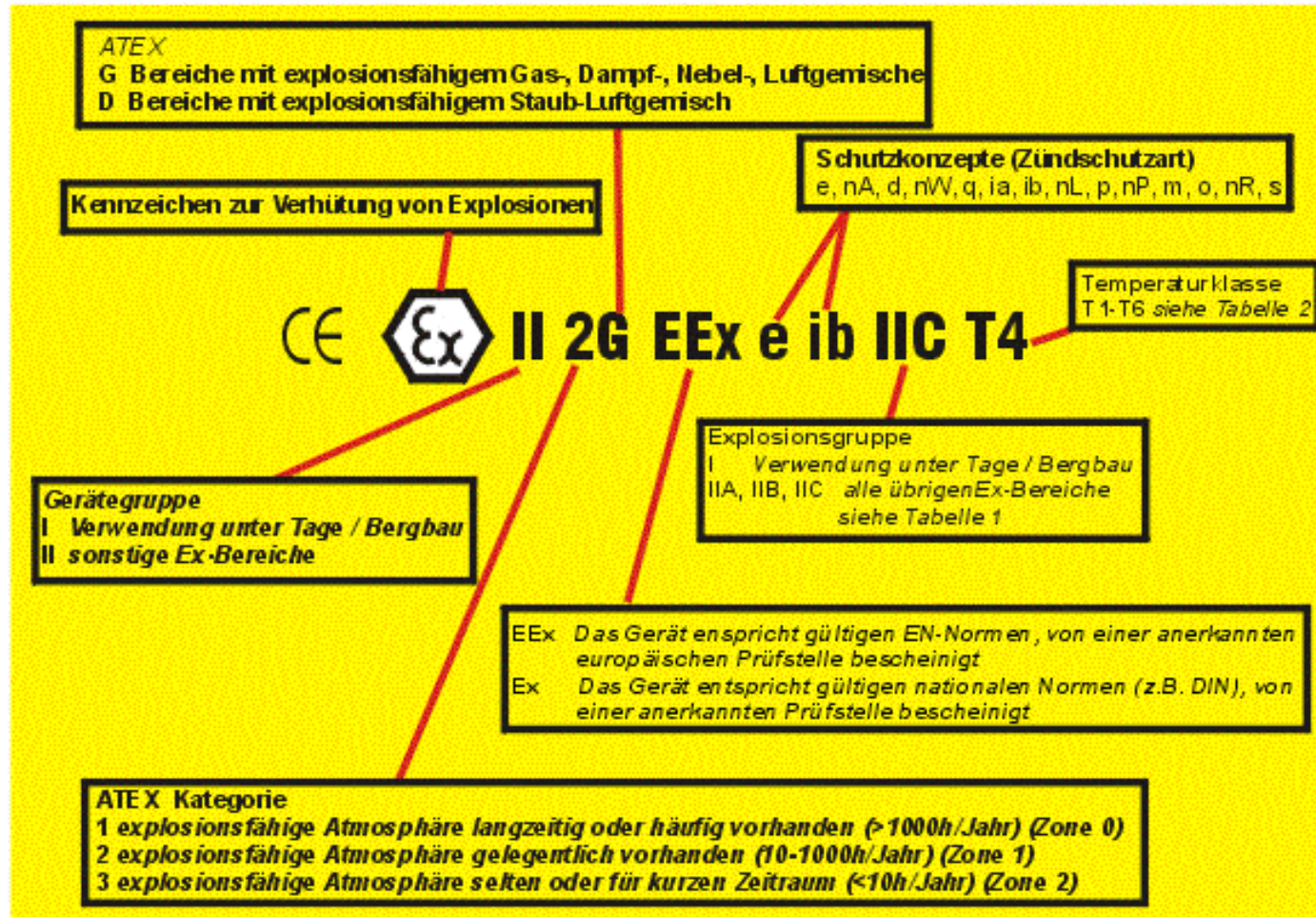
Their design or programming may not be altered after their acceptance.

Their price is higher than that of standard devices because they have to undergo strict testing (Typentest, type test) by a qualified authority (TÜV in Germany)

Such devices are called Eex - or "intrinsic safety devices" (*Eigensichere Geräte*, "Ex-Schutz", *protection anti-déflagrante*, "Ex") and are identified by the following logo:



European Explosion-Proof Code



Eex-devices are "safe" (certified) to be used in an explosive environment. They must have passed a type test at TÜF (Germany), UL (USA),...

Swiss Norm: "Verordnung über Geräte und Schutzsysteme in explosionsgefährdeten Bereichen"

Field Device: faceplate (movie)



Assessment

How are binary process variables measured ?

How are analogue process variables measured ?

How is temperature measured ?

What is the difference between a thermocouple and a thermoresistance ?

How is position measured (analog and digital) ?

What is a Grey encoder ?

How is speed measured ?

How is force measured ?

What is a P&ID ?

What is a transducer ?

How does a 4..20 mA loop operate ?

