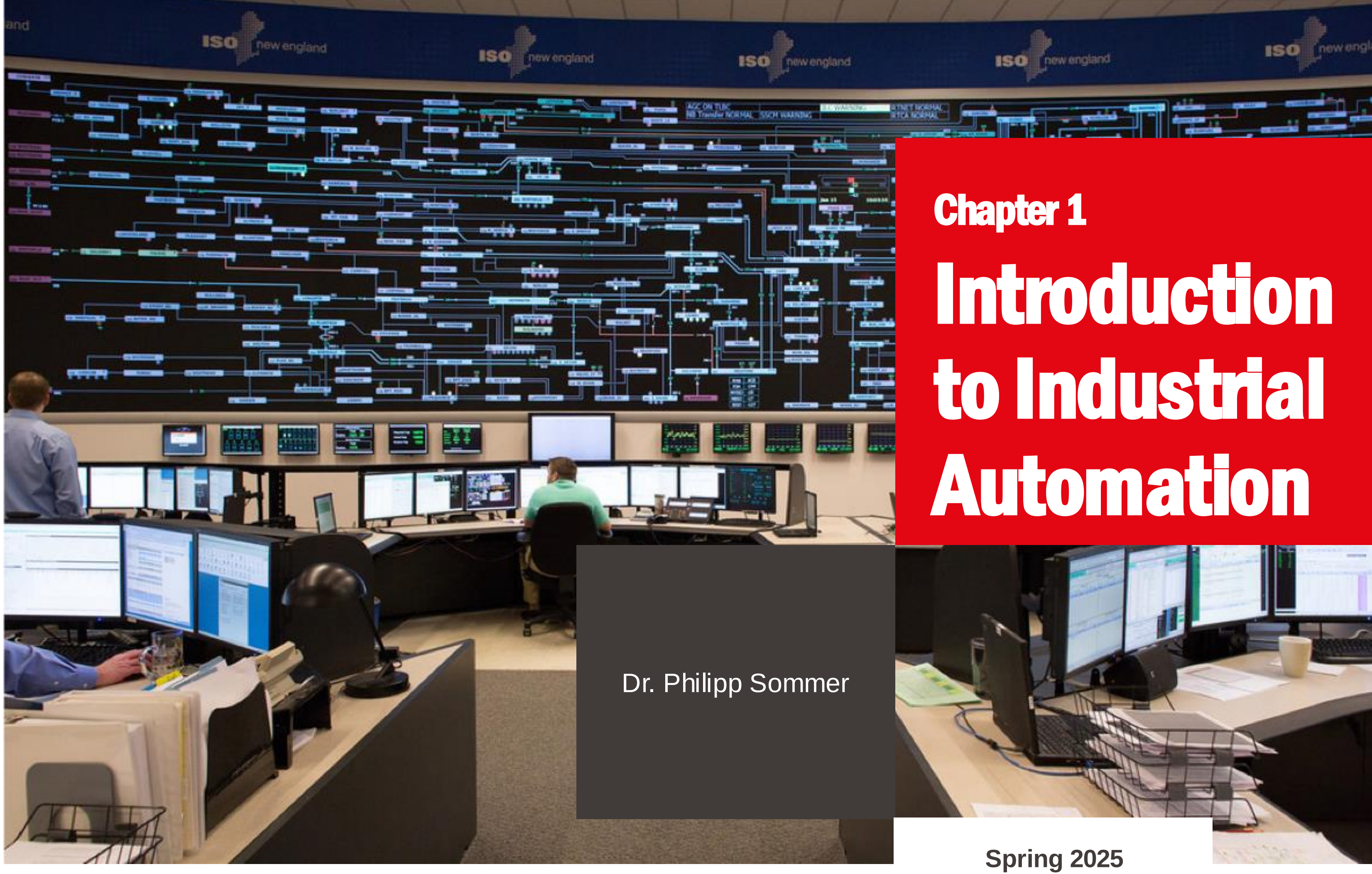
EPFL



Chapter 1

Introduction to Industrial Automation

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Spring 2025

The material of this course has been initially created by Prof. Dr. H. Kirrmann and adapted by Dr. Y-A. Pignolet, J-C. Tournier & Philipp Sommer.

Definition: What is Industrial Automation?

- Industrial automation systems use machines, sensors, actuators, communication networks & controllers to automate industrial processes.
- The process of replacing human work through machines is called automation.
- Industrial plant: facility designed for production, assembly or processing.

Expectations: Why do we want Automation?

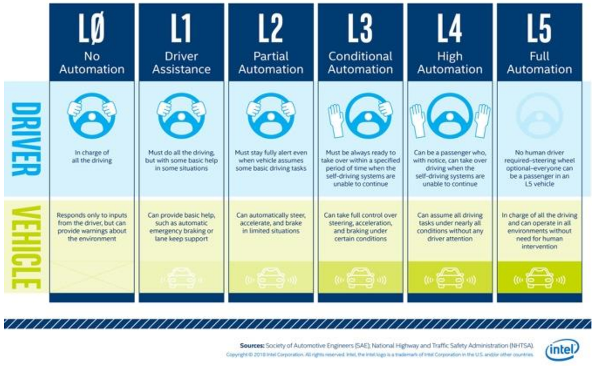
- **Process Optimisation** → Acquisition of large number of “process variables”, data mining
  - Energy, material and time savings, quality improvement
  - Reduction of waste, pollution control
  - Compliance with regulations and laws, product tracking
  - Increase availability, safety, fast response to market
- **Personnel costs reduction** → Human-Machine-Interface (HMI)
  - Simplify interfaces, assist decision
  - Require data processing, displays, data base, expert systems
- **Asset Optimisation** → Engineering Tools
  - Automation of engineering, commissioning and maintenance
  - Life-cycle control, maintenance support

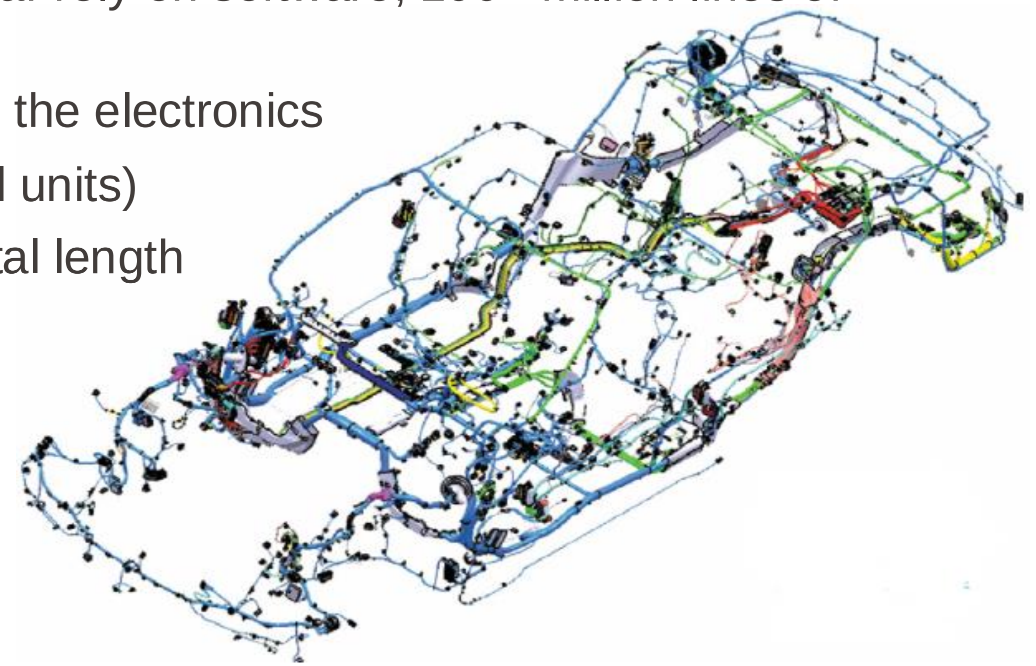
Automation Systems: Examples

EPFL

Cars

- > 90% of the functions of a car rely on software, 100+ million lines of code
- >40% of the costs stem from the electronics
- >100 ECU (electronic control units)
- >1500 wires with >5km of total length





Airplanes

- "Avionics" (electronic systems used on aircrafts):
  - flight control (safe flight envelope, autopilot, "engineer")
  - flight management
  - flight recording (black boxes, turbine supervision
  - diagnostics
  - "fly-by-wire"

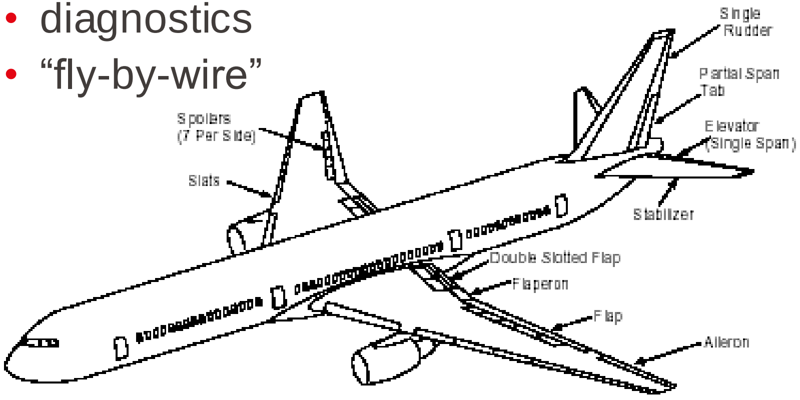
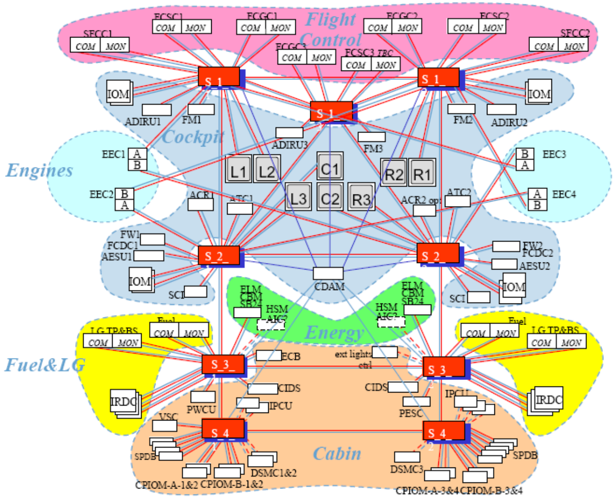


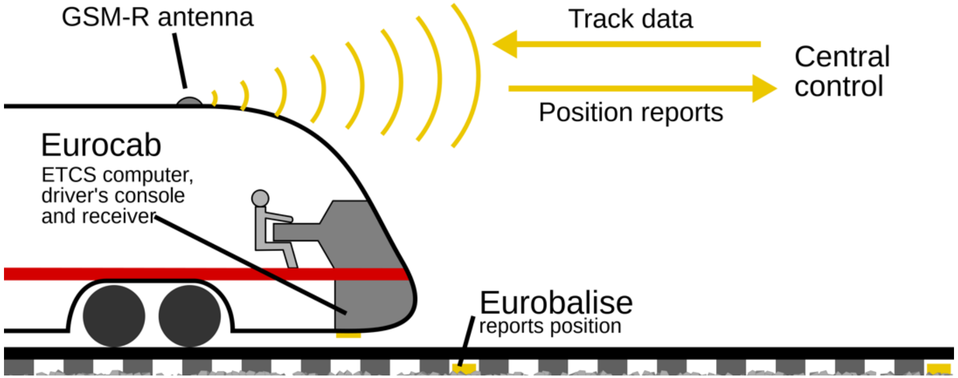
FIGURE 1 777 FLIGHT CONTROL SURFACES



Airbus A380 – Data network

Train Networks

- Signaling and control, railroad switches, customer information systems
- From legacy systems to European Train Control System (ETCS)



Source: https://en.wikipedia.org/wiki/European_Train_Control_System

Flexible Factory Automation

Source: B&R Automation

Source: ABB

- Equipment: Numerous conveyors, robots, CNC machines, paint shops, logistics
- Connected to production management

Manufacturing: Collaborative Robots (Cobots)

Source: ABB

- Can work in close proximity of human co-workers
- frequent reprogramming for new tasks, tool changes
- Smaller payload than larger industrial robots

Autonomous Mobile Robots

Source: ABB

Source: ANYbotics

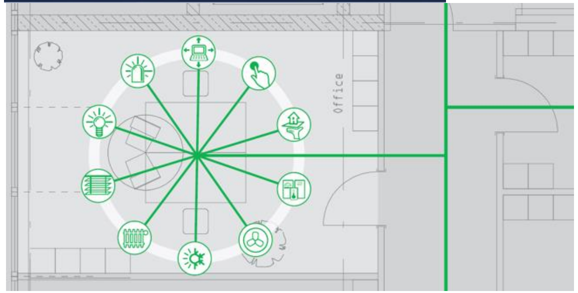
- Can navigate autonomously in industrial environments
- Used for logicstics applications and inspection tasks
- Increased flexibility in warehouses, offload routine inspection tasks in dangerous environments

Oil & Gas, petrochemicals

- **Upstream**: from the earth to the refinery down-sea control
  - special requirement: high pressure, saltwater, inaccessibility explosive environment with gas.
- **Midstream** / Distribution:
  - special requirement: environmental protection
- **Downstream**: from the oil to derived products
  - special requirement: extreme, explosive environment

Building Automation

- Automation tasks:
  - fire, intrusion, climate, energy management
- HVAC = Heat, Ventilation and Cooling
- visitors, meeting rooms, catering
- low price tag



Ports & Logistics

- From ship planning to crane manipulation and stock control

Water treatment

- Fresh and waste water treatment: manage pumps, tanks, chemical composition, filters, movers, quality

https://flickr.com/photos/youbelonginlongmont/6359258189

https://www.stadt-zuerich.ch/dib/de/index/wasserversorgung.html

Power Plants & Electrical Grid

- **Protection** of lines, transformers, generators: very high speed response
- **Control** (remote or local) to guarantee power flow, safe operation (interlocking)
- **Measurement** (local and remote), electricity bill, power flow in grid

Automation System Architecture

Automation as a hierarchy of services

5 Planning, Statistics, Finances

4 Production planning, orders, purchase

3 Workflow, order tracking, resources

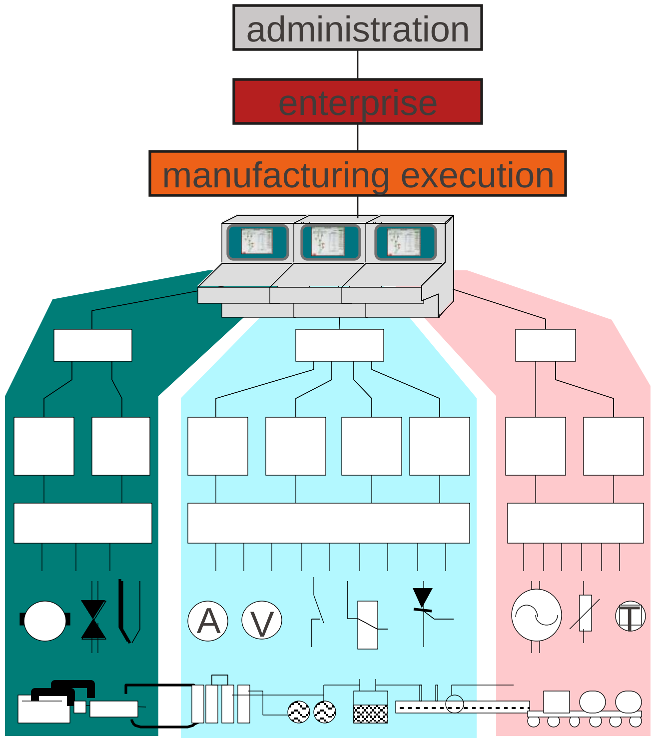
2 Supervision

SCADA =
Supervisory Control
And Data Acquisition

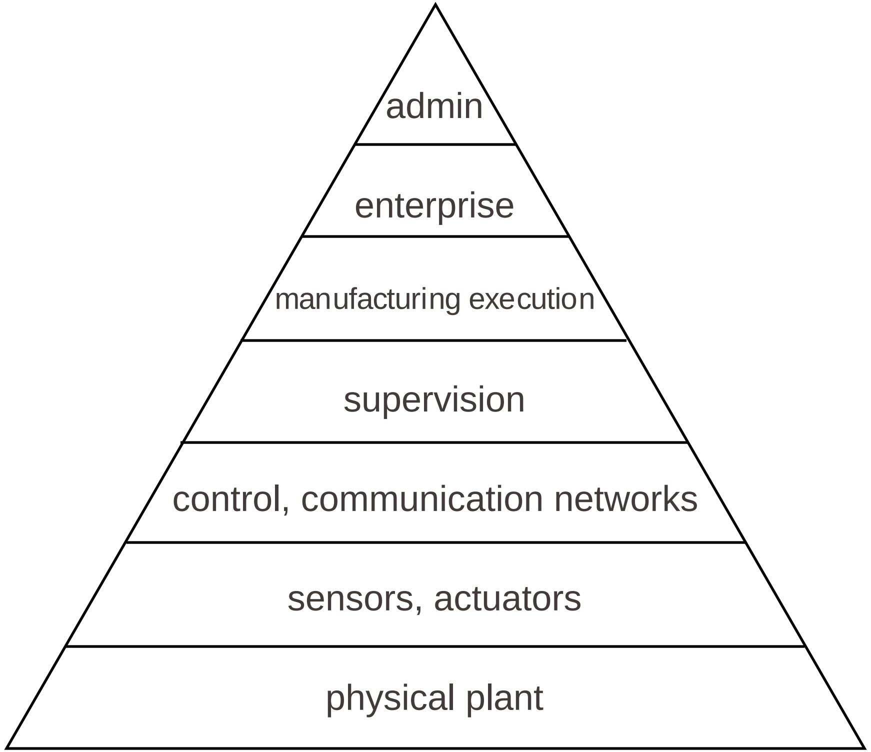
1 Control
Group control
Unit control

Field
Sensors
& actuators

0 Primary technology



Automation Pyramid



Details of control system hierarchy

Administration	Finances, human resources, documentation, long-term planning
Enterprise	Set production goals, plan resources, coordinate sites, manage orders
Manufacturing /Execution	Manages execution, resources, workflow, quality supervision, production scheduling, maintenance.
Supervision	Supervise production and site, execute operations, visualization, store process data, log operations, history (open loop control)
Control	Group (Area) Control: Responsible for well-defined part of plant (closed loop, except for intervention of an operator) - Coordinate units - Adjust set-points and parameters Unit (Cell) Control: Regulation, monitoring and protection of group part (closed loop except for maintenance) - Measure: Sampling, scaling, processing, calibration. - Control: regulation, set-points and parameters - Command: sequencing, protection and interlocking
Field	data acquisition (sensors, actors), data transmission no processing except measurement correction and built-in protection.

Field level

today

- The **field level** is in direct interaction with the plant's hardware (primary technology)

Control

Week 2+7

- **Group control** coordinates activities of several **unit controls**
- Typically hierarchical, can be peer-to-peer
- Set-points, parameters, sequencing, interlocking
- Note: "Distributed Control Systems" (DCS) commonly refers to a hardware and software infrastructure to perform Process Automation

Supervisory level: SCADA

Week 3

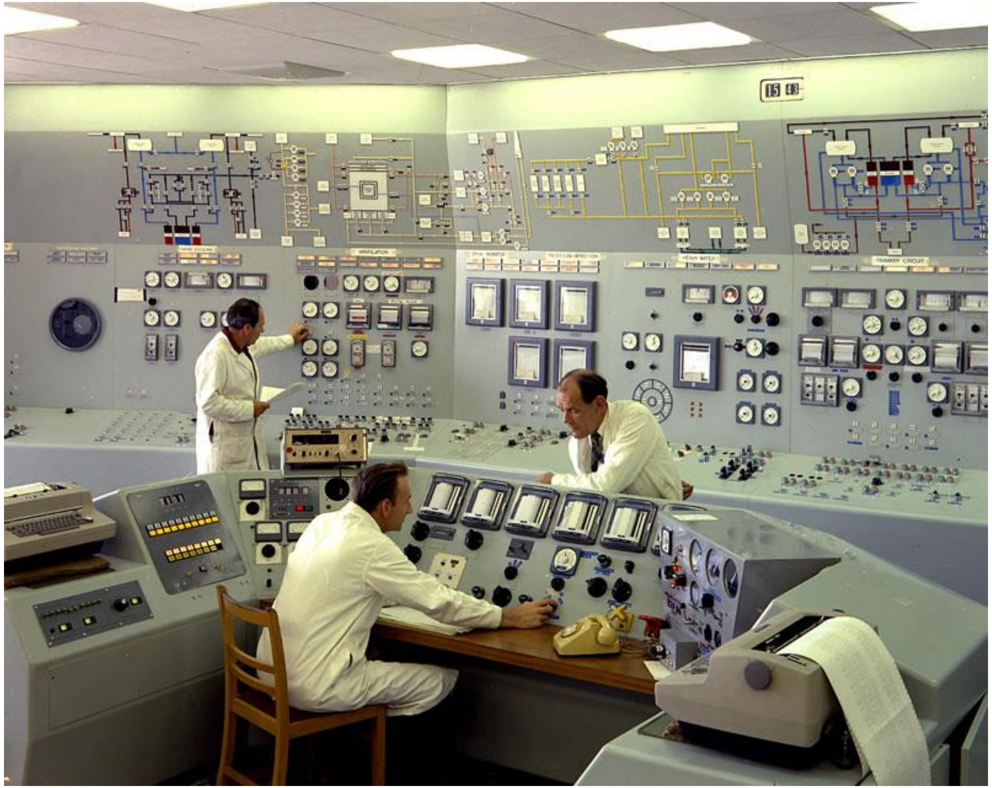
- SCADA = Supervisory Control and Data Acquisition
  - displays the current state of the process (**visualization**)
  - display the alarms and events (**alarm log, logbook**)
  - display the trends (**historians**) and analyse them
  - display handbooks, data sheets, inventory, expert system (**documentation**)
  - allows communication and data synchronization with other centres

Picture: ABB

Control Room Example From the 1950s

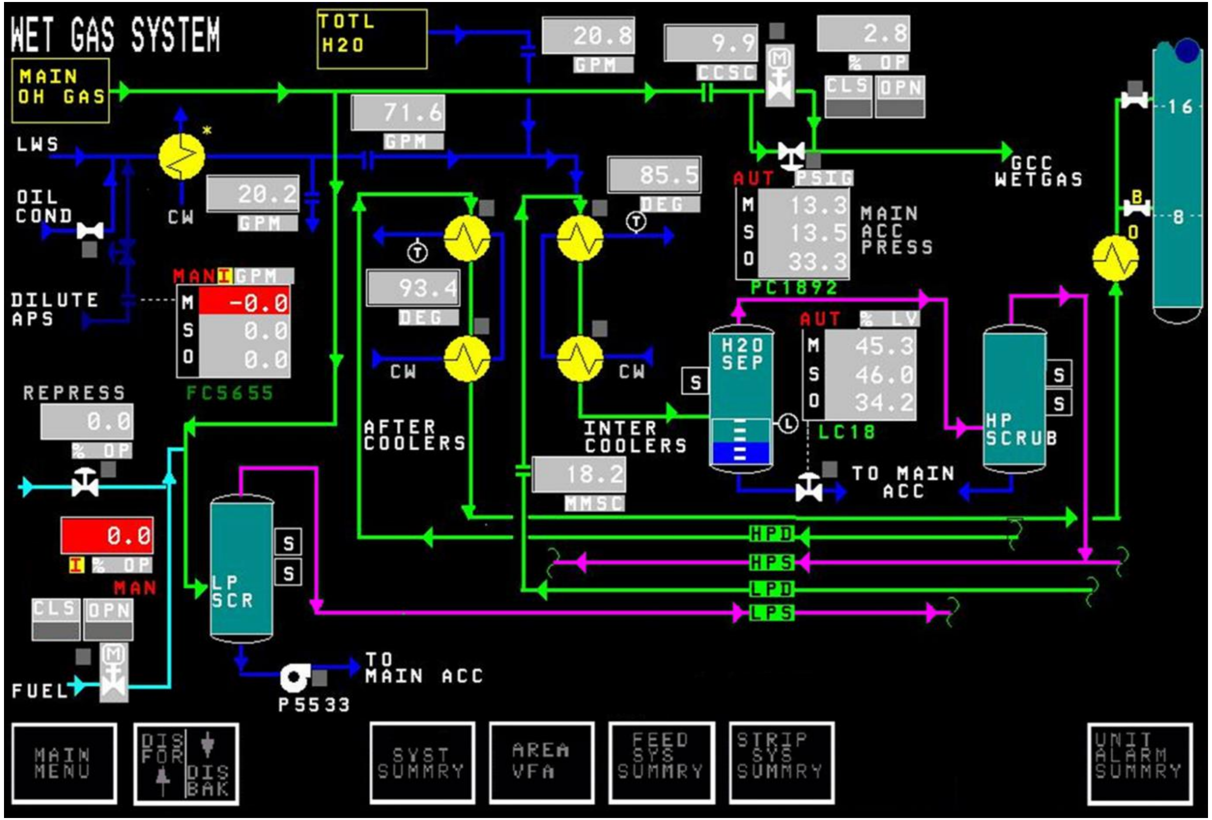
Coal-Fired Battersea Power Station – South London, UK – 1950s
Photo: Fox Photos/Getty Images

Control Room Example From the 1970s



Steam Generating Heavy Water Reactor – (Water Cooled Nuclear Reactor) - Dorset, UK - 1970s

Control Room Example From the 1990s



Control Room Example From the 2010s

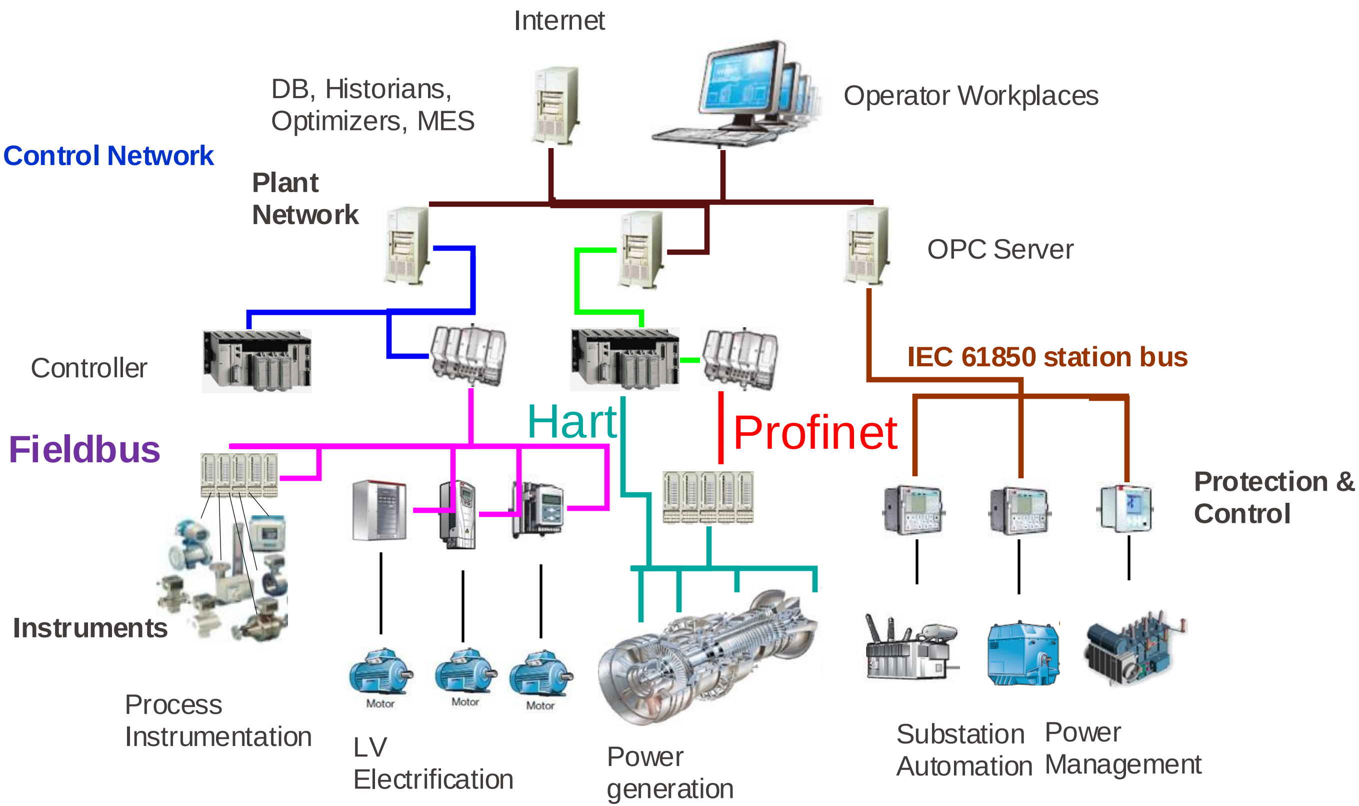
ISO New England Control Room

Next User Interface?

Source: Apple

Automation as a computer network

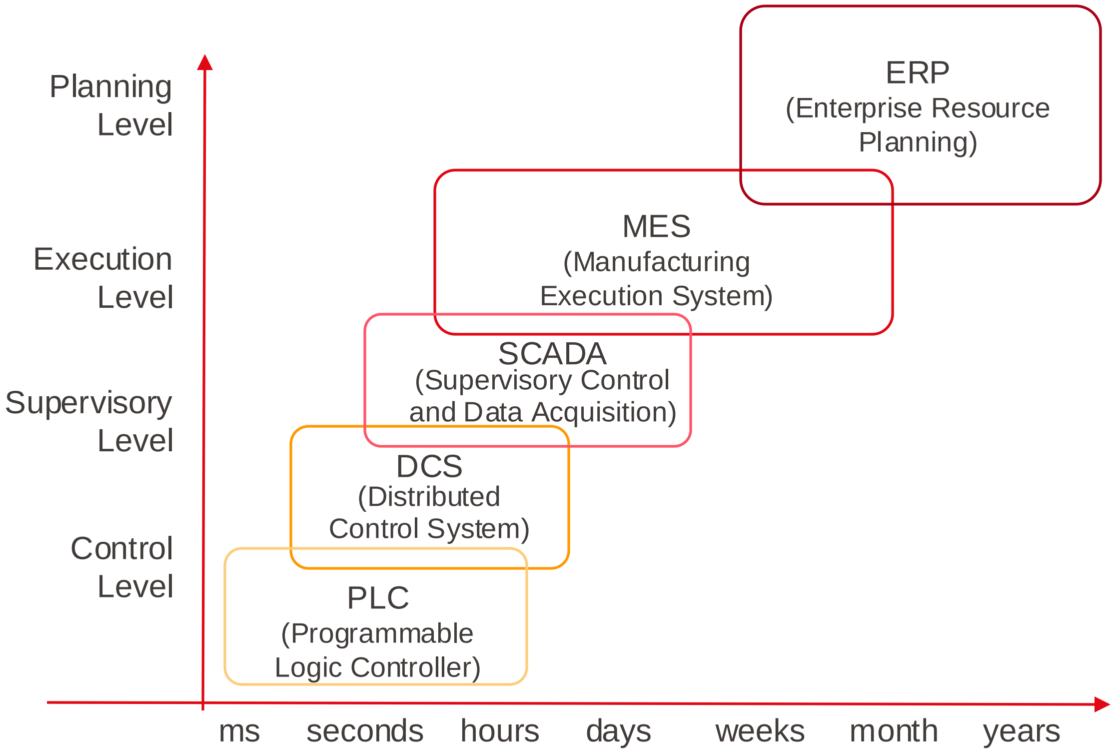
Weeks 5+6



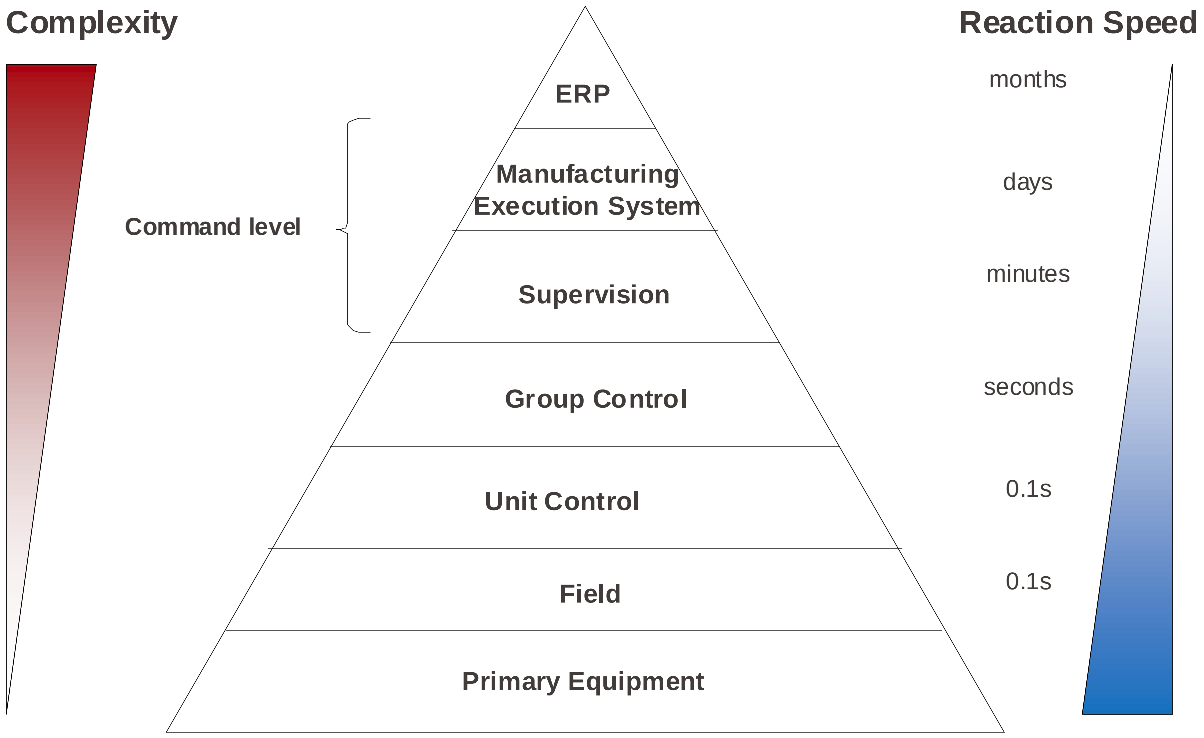
Data Quantity & Quality and Hierarchical Level

- Higher Levels
  - Data reduction / summary information
  - Complex processing and decisions (requires models)
  - Timing requirements are slackened. Historical data are stored
- Supervisory Control and Data Acquisition (SCADA) level
  - Presentation of complex data to operator
  - Help to make decisions (expert system) and maintenance
  - Require knowledge database in addition to plant database
- Lower Levels
  - Closest to plant, most demanding response time
  - Quantity of raw data very large (e.g. sensor readings)
  - Processing is trivial (formerly realized in hardware)
  - Under computer control, except in emergency situations, for maintenance or commissioning.

Response time and hierarchical level



Complexity and Hierarchical level



Assessment

- Describe the levels of a hierarchical control system.
- What is the relationship between hierarchical level, the response time, data quantity and complexity?
- What does SCADA stand for?
- What is a group control used for?

Plant Categories

Plant categories

- Diverse applications, but principles are always the same.
- A few basic categories of plants
- Control system hardware and software shared by most applications.
- Distinction depends on point of view, domain-specific vocabulary and marketing.

Discrete and continuous plants

discrete control
(binary)

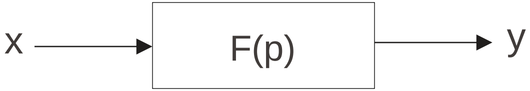
continuous control
(analog)

Continuous plants

Week 2

- States described by continuous (analog) variables (temperature, voltage, speed,...)
- Input/output relation: transfer function, described by differential equations

Examples: drives, ovens, chemical reactors

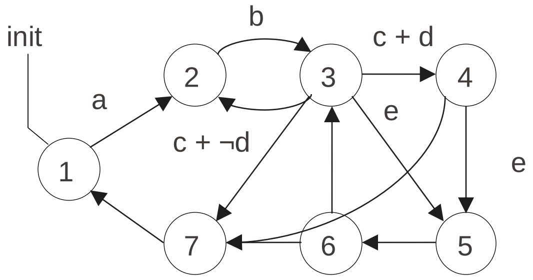


Principal control task: ***regulation***
(maintain the state on a determined level or trajectory)

Discrete plants

Week 7

Examples: lifts, robots, …



- Well-defined non-overlapping states, abrupt transitions caused by events
- Described by Finite State Machines, Petri Nets, Flow Charts.

Principal control task: ***command*** (control state transitions)

Mixed plants

- Most plants consist of discrete and of continuous processes.
  - Example 1: Motor control of a cable-car with speed control and stop at stations
  - Example 2: A bottle-filling line is in principle a continuous process, but each step consists of a sequence of operations
- Processes can be described as continuous within a discrete state or as non-linear, continuous process.
  - Example: Time-triggered set-point temperature for an oven
- Most processes have some continuous and some discrete behavior. Description depends on point of view.
- All parts must de described individually.

Industrial processes

discrete

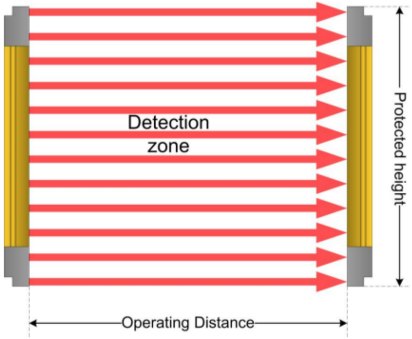
Automotive Manufacturing
Electronics
Machinery
Textiles
Pharmaceuticals
Fine Chemical
Food & Beverage
Metals & Mining
Water & Waste
Pulp & Paper
Vehicles
Petrochemicals
Oil & Gas
Electrical Power

continuous

source: ARC

Sensors & Actuators

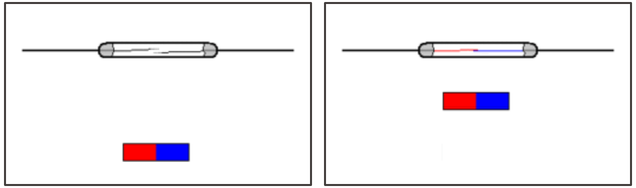
Binary Sensors



Binary sensors:

- micro-switch
- optical sensor
- magnetic sensor

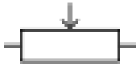
https://www.ecm-france.com/domaines-dactivite/pesee-en-mouvement/piezolor/

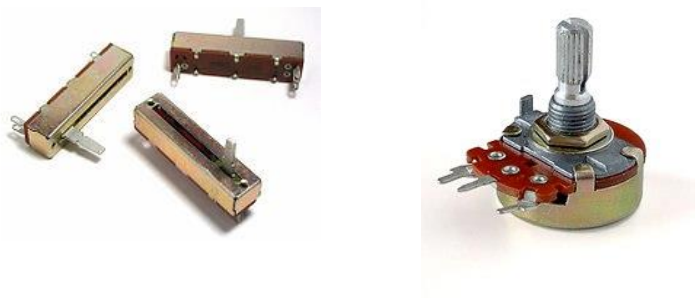


https://fr.wikipedia.org/wiki/Interrupteur_reed

Analog mechanical position sensors

- Potentiometer
  - Resistance based on position

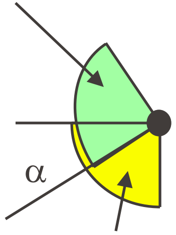




https://de.wikipedia.org/wiki/Potentiometer

+cheap, -wear, bad resolution

- Capacitive angle/position measurement

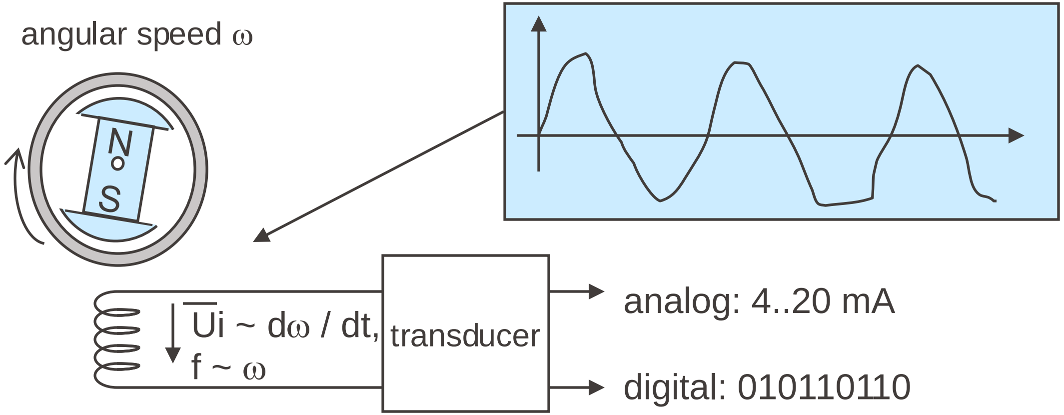


$$C = \frac{\varepsilon A}{d} \approx \alpha$$

Movable part is either rotating or displacing vertically

+cheap, -bad resolution

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
- Mainly used to measure engine RPM (cars, planes, boats, etc.)

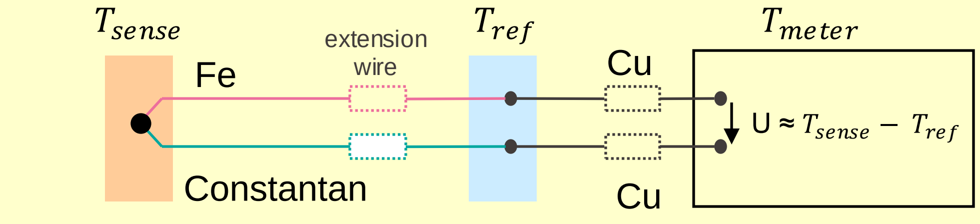
Temperature measurements

Thermo-element
(*Thermocouple*)

two
dissimilar
electrical
conductors

Fe-Const

also: Pt/Rh - Pt



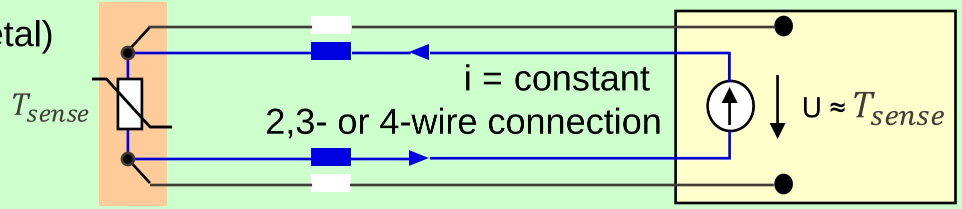
measured temperature
(hot junction)

reference temperature
(cold junction)

Thermoresistance
(semiconductor or metal)

Platinum (Pt 100)

one material
whose
resistance is
temperature-
dependent

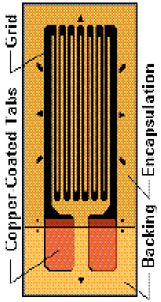


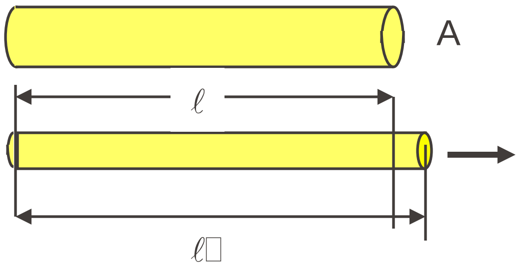
2 or 4 wire connection (to compensate voltage drop)

Small position measurement: strain gauges

+reliable, very small displacements

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

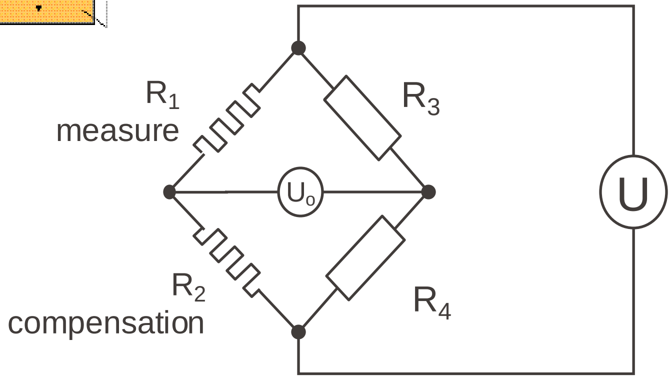




ρ = resistivity

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

volume = constant, ρ = constant

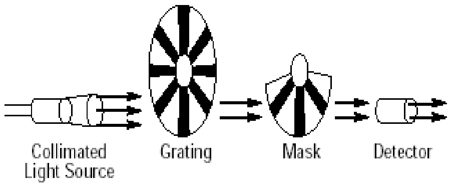


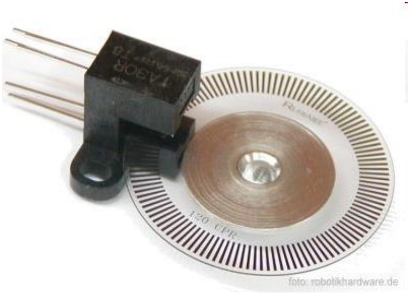
measurement using a Wheatstone bridge (if $U_0 = 0$: $R_1 R_4 = R_2 R_3$)

temperature compensation by "dummy" gauges

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

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.
- 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 several 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.

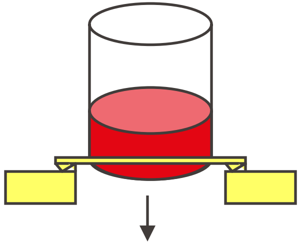
courtesy Parker Motion & Control

Level measurement

- Measure the level of a liquid inside a vessel/tank
- Measurement principles:
  - load cell
  - pulsed laser
  - pulsed microwave (radar)
  - ultrasonic (40-60 kHz)

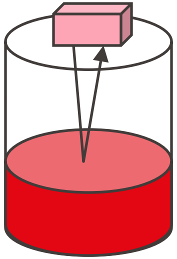
Source: VEGA

Load cell

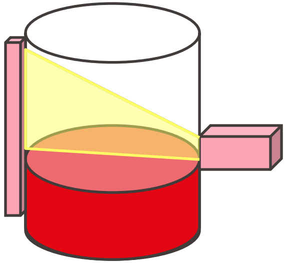


F = mg

Sensor at top



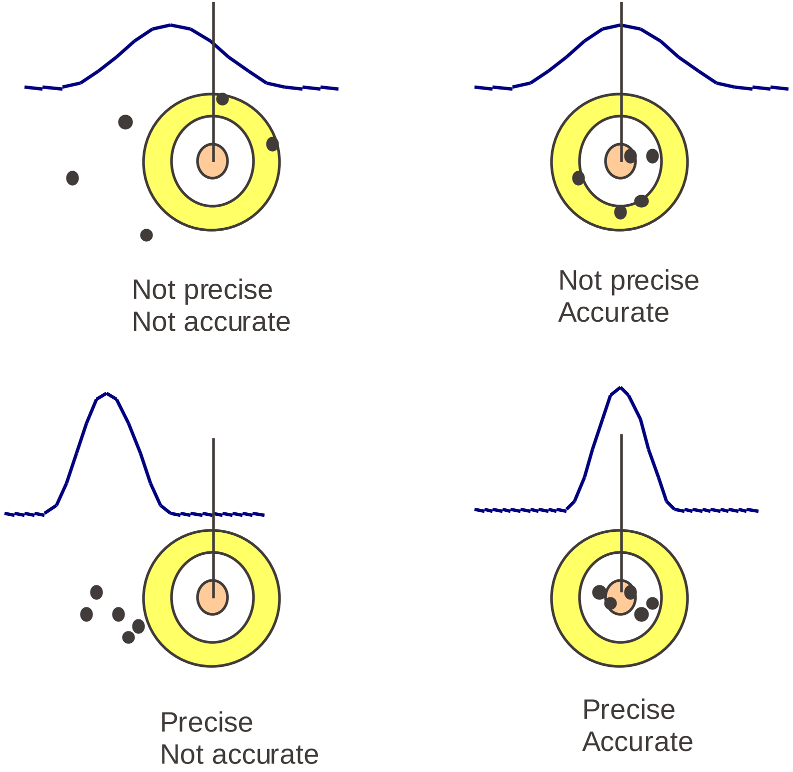
Sensor on side



Other sensors

- Flow
- Mass Flow
- Pressure
- Conductivity
- pH-Sensor
- Viscosity
- Humidity
- and many others…

Precision (repeatability) and accuracy (deviation)



- Accuracy is a consequence of systematic errors (or bad calibration)
- accuracy and precision may depend on time (drift)

Resolution

- Resolution expresses how many different levels can be distinguished
  - resolution is the smallest meaningful number that can be displayed or recorded by the measurement device.

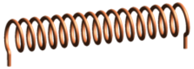
- Example:
  - A reading device that has a specified accuracy of ±0.015% will give a reading that is between 0.99985 and 1.00015 times the actual value.
  - measuring 1 Volt within ±0.015% accuracy requires a 6-digit instrument capable of displaying five decimal places.
    - The fifth decimal place represents 10 microvolts, giving this instrument a resolution of 10 microvolts.
    - Every digit displayed after the 5^{th} decimal is just noise

Precision, Accuracy and Resolution

- Precision:
  - How reproducible or close identical measurements will be reported as a percentage of full scale
- Accuracy:
  - The ability of the instrument to measure a quantity to the absolute true and correct value.
- Resolution:
  - The smallest unit of measure or the smallest meaningful change that can be displayed or recorded by an instrument (sometimes referred to as granularity)

Electric Motors

- Solenoids



- DC motor
- Asynchronous Motors (Induction)
- Synchronous motors
- Step motors

Source: ABB

Variable-Speed Drives

- Variable speed drives control speed & acceleration
- Protect the motor: over-current, torque, temperature.
- High-power drives can feed back energy to the grid when braking (inverters).

simple motor control

cabinet for power of > 10 kW

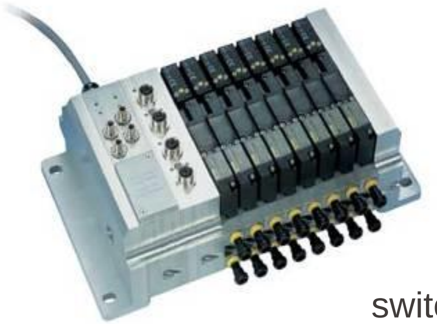
small drive control < 10 kW (Rockwell)

Hydraulics and fluidics

Pumps, valves, rods, …

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

fluidic switches



switchboard

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

source: www.bachofen.ch

Assessment

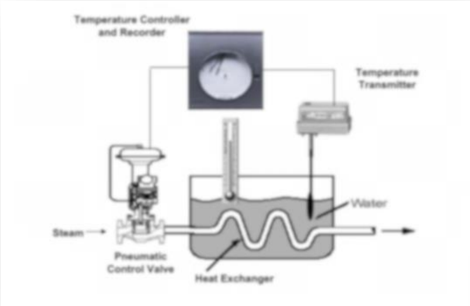
- What is the difference between precision and accuracy for sensors?
- What is the difference between analog and digital sensors?
- Name a few selection criteria for sensors in an industrial application.

Instrumentation Diagrams

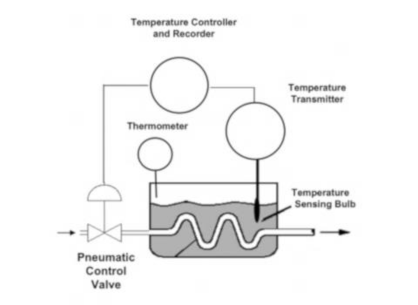
Instrumentation Diagrams: P&ID

- Similarly to electrical schemas, the control industry (especially the chemical and process industry) describes its plants and their instrumentation by a **P&ID** (pronounced P.N.I.D.) (Piping aNd Instrumentation Diagram)
- 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.

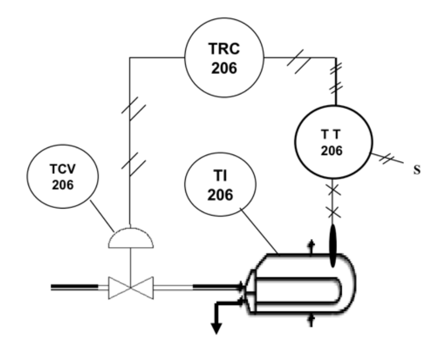
Principles



Pictorial Representation
- Good for small plant
- Not practical for computer processing



Use symbols and circle for each instrument and devices and show how they are connected

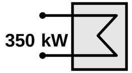
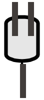
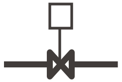
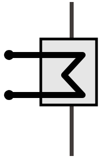


Name the different parts and identify the function

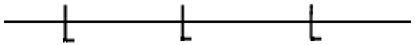
P&ID: Symbols

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:

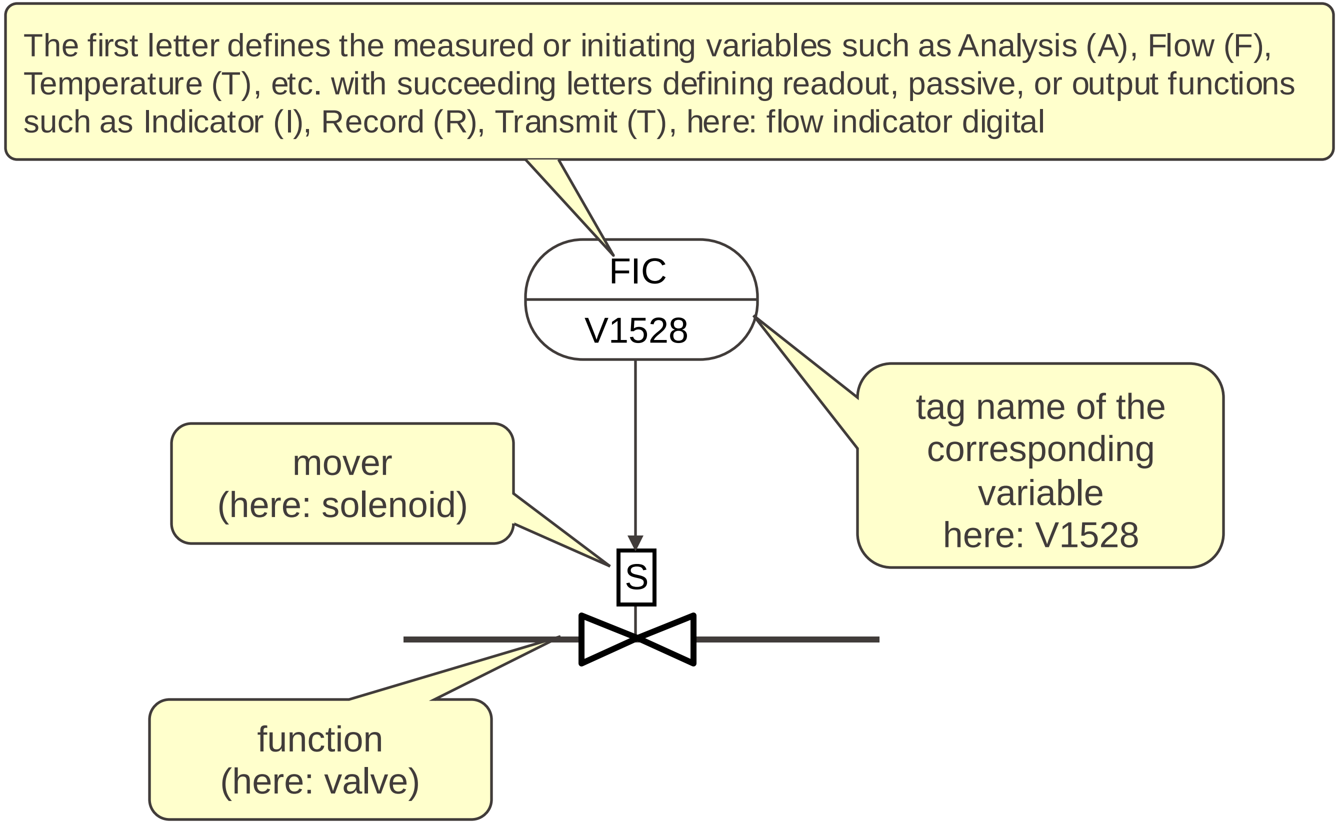
pipe		pump	
valve		heater	
one-way valve ("diode")		vessel / reactor	
binary (or solenoid) valve (on/off)		heat exchanger	
analog valve (continuous)			

P&ID: 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

Instrumentation identification



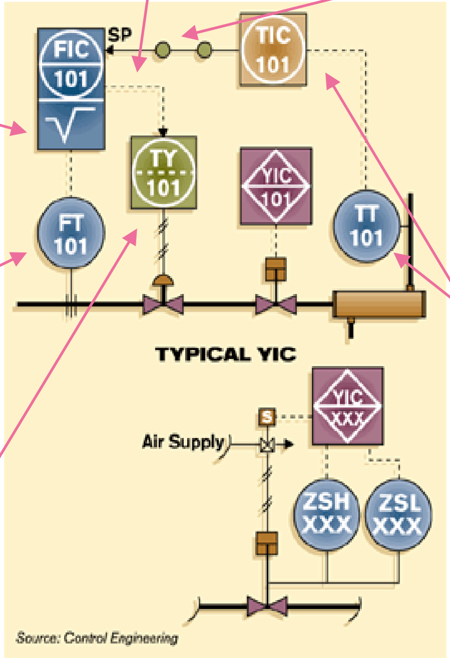
P&ID Example

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

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

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



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

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)

Another P&ID Example