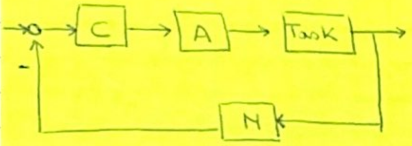
INTRODUCTION

- Industry 4.0 paradigm | • Data: production, exchange and management
- Enabling technologies — robotics IoT
  big data

Automation: science and tech. whose aim is design automatic control systems.
able to perform tasks wich are diff. for hum.

M	C	A
Measurement	Control	Actuation
cómo van los cosas	dados los medidos decide q acción hacer	ejecuta la acción



Automation and productivity growth

- → Aut. of activities can enable → businesses to improve performance { ↓ errors and improving ↑ quality and speed
- → contributes to productivity
- → needed boost to economic growth

AUT. could raise↑ productivity growth globally 0'8 - 1'4 % annually

→ 60% of occupations have at least 30% of their activities that could be automated

Activities most susceptible to automation involve: physical activities in highly structured and predictable environments Prevalent → manufacturing

Automation and workforce
personal

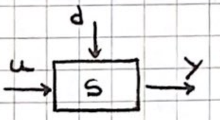
- → People will need to continue working alongside machines to produce growth GDP
- → Creation new types of work

Automation and policy-makers
responsables polit.

- Put in place policies to encourage investment → continued progress, innovation
- Innovate policies that help workers and institutions, adapt to impact enploym
- Workforce will need to engage with machines, acquire new skills.

PROCESS AUTOMATION

Control, automate a system
Make the sistem behave how we want.



SYSTEM UNDER CONTROL

Elements of a control problem

CONTROL PROBLEM:
wherever we want to impose a behaviour to a system

$\xrightarrow{y^\circ}$

DESIRED BEHAVIOUR
of the controlled variables
how we want the variables to be

u: control variables, to make syst. behave
d: posible disturbances
y: controlled variables, represent beh. of syst.

Setting a control problem

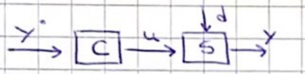
CONTROL PROBLEM
determine the value of the control variables u

CONTROLLER
the object that determines the control action

CONTROL LAW
the principle with wich the controller works

OPEN LOOP CONTROL

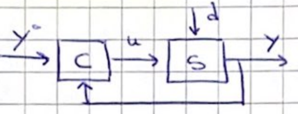
No measurements are used



feedforward

CLOSED LOOP CONTROL

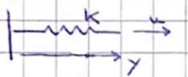
applied based on measurements of variables that depends on variable u



feedback

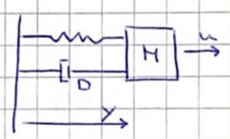
Modelling the system undercontrol

STATIC MODEL



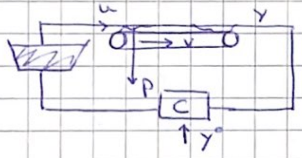
$\boxed{u=Ky}$

DINAMIC MODEL



$\boxed{u=Ky+D\dot{y}+M\ddot{y}}$

Role of the dinamics



$u=K(\dot{y}^\circ-\dot{y})$

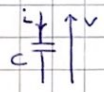
INPUTS: variables with wich the behaviour of the syst. is influenced from

OUTPUTS: ones that charactenze the behaviour of the syst.

DINAMIC SYSTEM Series of variables inputs and outputs

The order of the system

$\xrightarrow{u}\boxed{S}\xrightarrow{y}$



input $u=i$
outp. $y=V$

$$C\dot{y}(t)=u(t)\rightarrow y(t)=\overset{1}{y(t_0)}+\frac{1}{C}\overset{2}{\int_{t_0}^{t}u(\tau)d\tau}$$

The state

$x=\begin{bmatrix}x_1\\ \vdots\\ x_n\end{bmatrix}$ state variables

$u=\begin{bmatrix}u_1\\ \vdots\\ u_m\end{bmatrix}$ m: n° of inputs variables

$y=\begin{bmatrix}y_1\\ \vdots\\ y_p\end{bmatrix}$ p: output variables

Definition of dinamic system

$$f(x,u)=\begin{bmatrix}f_1(x_1,x_2\ldots x_n,u_1,u_2\ldots u_m)\\ \vdots\\ f_n(\text{"}\quad\text{"},\text{"}\quad\text{"})\end{bmatrix}\quad g(x,u)=\begin{bmatrix}g_1(x_1,x_2\ldots x_n,u_1\ldots u_m)\\ \vdots\\ g_p(\text{"}\quad\text{"},\text{"}\quad\text{"})\end{bmatrix}$$

Vector → $\dot{x}(t)=f(x(t),u(t))$ $\quad y(t)=g(x(t),u(t))$] State equations

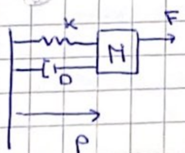
EXAMPLES

MECHANICAL OSCILLATOR

$F(t)=M\dot{v}(t)+Dv(t)+Kp(t)$

i: $u=F$
o: $y=p$

state var. $x_1=p$ $x_2=V$



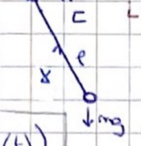
$\dot{x}_1(t)=x_2(t)$

$\boxed{\dot{x}_2(t)=\frac{1}{M}(-Kx_1(t)-Dx_2(t)+u(t))}$

$y=x_1(t)$

PENDULUM

$I(t)=ml^2\dot{\omega}(t)+mgl\sin(\vartheta(t))$



i: $u=C$ o: $y=\vartheta$ S.V. $x_1=\vartheta$ $x_2=\omega$

$\dot{x}_1=x_2(t)$

$\boxed{\dot{x}_2(t)=-\frac{g}{l}\sin(x_1(t))+\frac{1}{ml^2}u(t)}$

$y(t)=x_1(t)$

pendullum equilibrium $f(\bar{x}, \bar{u}) = 0$

if $\bar{u} = 0$ the following equilibria exist:

$$\begin{cases} \bar{x}_1 = 0 \\ \bar{x}_2 = 0 \end{cases} \qquad \begin{matrix} \bar{x}_1 = \pi \\ \bar{x}_2 = 0 \end{matrix}$$

$$\begin{cases} \bar{x}_2 = 0 \\ -\frac{g}{\ell} \sin(\bar{x}_1) + \frac{1}{m\ell^2} \bar{u} = 0 \end{cases}$$

Siso (single input, single output)

Mimo (multiple '' , multiple '')

Linear $\rightarrow ax + b = 0 \rightarrow \boxed{a \neq 0}$

Mechanical oscillator. $\dot{p}(t) = v(t)$

$$\dot{v}(t) = \frac{1}{M}\left(-Kp(t) - Dv(t) + F(t)\right)$$

siso, linear

Pendullum $\omega(t) = \gamma(t)$

$$\dot{\omega}(t) = -\frac{\cancel{m}g\ell}{\cancel{m}\ell^2} \sin(\theta(t)) + \frac{1}{m\ell^2} \tau(t)$$

siso, nonlinear

Dinamic equations

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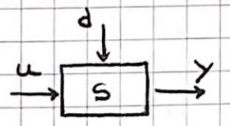

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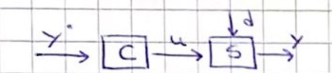

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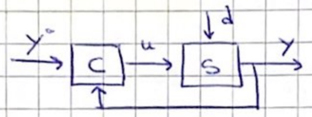


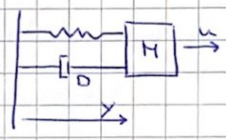
feedback

Modelling the system under control

STATIC MODEL

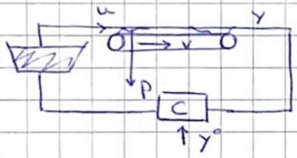
$$\boxed{u = Ky}$$

DINAMIC MODEL



$$\boxed{u = Ky + D\dot{y} + M\ddot{y}}$$

Role of the dinamics



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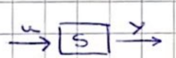

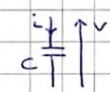

input u = i
outp. y = v

$C\dot{y}(t) = u(t) \rightarrow y(t) = \overset{1}{y(t_0)} + \overset{2}{\frac{1}{C}\int_{t_0}^{t} u(\tau)\,d\tau}$

The state

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Definition of dinamic system

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Vector $\longrightarrow$ $\dot{x}(t) = f(x(t), u(t)) \quad y(t) = g(x(t), u(t))$] State equations

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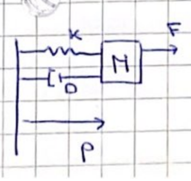
$F(t) = M\dot{v}(t) + Dv(t) + Kp(t)$ i: $u = F$ o: $y = p$

state vars. $x_1 = p$ $x_2 = v$

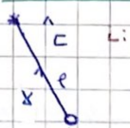


$\dot{x}_1(t) = x_2(t)$

$\boxed{\dot{x}_2(t) = \frac{1}{M}(-Kx_1(t) - Dx_2(t) + u(t))}$

$y = x_1(t)$

PENDULUM $C(t) = m\ell^2\dot{\omega}(t) + mg\ell\sin(\gamma(t))$



i: $u = C$ o: $y = \gamma$ S.V. $x_1 = \gamma$ $x_2 = \omega$

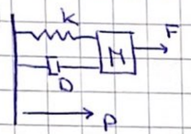
$\dot{x}_1 = x_2(t)$

$\boxed{\dot{x}_2(t) = -\frac{g}{\ell}\sin(x_1(t)) + \frac{1}{m\ell^2}u(t)}$

$y(t) = x_1(t)$

LINEAR SYSTEM $\left\{ \dot{x}(t) = Ax(t) + Bu(t) \; ; \; y(t) = Cx(t) + Du(t) \right.$

Mechanical oscillator



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$y = x_1(t)$

$\longrightarrow \quad A = \begin{bmatrix} 0 & 1 \\ -\frac{K}{M} & -\frac{D}{M} \end{bmatrix} \quad B = \begin{array}{c|c} & u \\ \hline \dot{x}_1 & 0 \\ \dot{x}_2 & \frac{1}{M} \end{array}$

$C = \underset{y}{[1 \quad 0]}$

Stability $\dot{\delta x}(t) = \mathbf{A}\,\delta x(t)$, $\delta x(0) = \delta x_0$

Linear dinamic system (A matrix)
- → Asymptotically stable: all **A** have a real negative part
- → Stable: **A** have real negative or null parts
- → Unstable: **A** positive real part

Transfer function

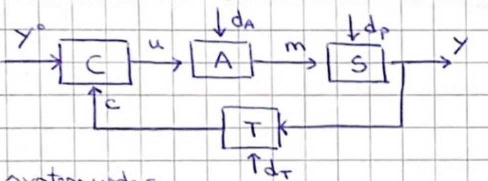
Consider linear system: $\dot{x}(t) = Ax(t) + Bu(t)$

$y(t) = Cx(t) + Du(t)$

$$\begin{tikzcd} u(t) \arrow[r, "\text{transform}"] \arrow[d, bend right] & U(s) \arrow[d, bend left] \\ y(t) & Y(s) \arrow[l, "\text{inverse}", "\text{transform}"'] \end{tikzcd}$$

$$\boxed{G(s) = \frac{Y(s)}{U(s)}}$$

ELEMENTS OF A CONTROL SYSTEM.



y controlled variable

y° set point

c measurement

u control variable

m actuation variable

d_A disturbance on the actuator d_P " " process

d_T " " transducer

S system under control

A actuator

T transducer

C controller

The role of feeback Feedback control means to take decisions based on measurements of some variables and some optimization criterion

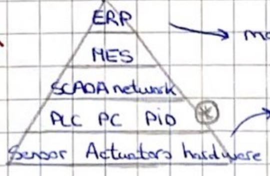
DISCRETE AUTOMATION

Evolves in time

Discrete events system Dynamic system, where:
- state takes values only in a discret set of values
- Evolution of the state is always related to the current of some events

EXAMPLE: line of people at a counter, where state is numbers of people queuing

Hierarchical automation systems rather common organized that way



ERP → management systems that gathers all the functions at company level (reune)

⊛ → one or more digital control systems controlling the execution of each action

⊛ control of the sequences of action

PROGRAMABLE LOGIC CONTROLLER

PLC ⟹ device (dispositivo), introduced in automation to replace older relay circuits, that were incharge to actually govern the logistics of the production plan

Able to implement some logic functions, can re-program

Ladder Diagram

Sequential Function Charts

GANANCIA $\mu = \frac{1}{K}$

FRECUENCIA NAT $\omega_n = \sqrt{\frac{K}{M}}$

AMORTIGUACIÓN $\xi = 0'5 \frac{D}{\sqrt{KM}}$

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = \frac{1}{M}(-Kx_1(t) - Dx_2(t) + u(t)) \\ y \overset{(t)}{=} x_1(t) \end{cases}$$

$$\begin{cases} \boxed{Sx_1(S) = x_2(S)} \\ Sx_2(S) = \frac{1}{M}(-Kx_1(S) - Dx_2(S) + U(S)) \\ Y(S) = X_1(S) \end{cases}$$

$$S^2 x_1^{(S)} + \frac{D}{M} S x_1(S) + \frac{K}{M} x_1(S) = \frac{1}{M} U(S)$$

$$G(S) = \frac{Y(S)}{U(S)} = \frac{1}{MS^2 + DS + K}$$

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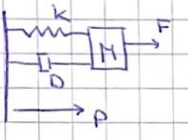

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y

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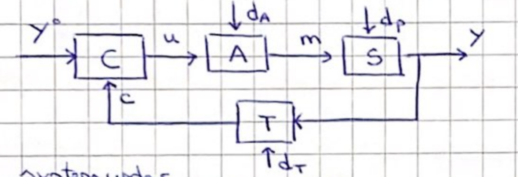
$$u(t) \xrightarrow{\text{transform}} U(s) \qquad y(t) \xleftarrow[\text{transform}]{\text{inverse}} Y(s)$$

$$\boxed{G(s) = \frac{Y(s)}{U(s)}}$$

ELEMENTS OF A CONTROL SYSTEM.



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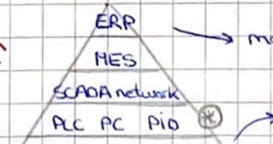

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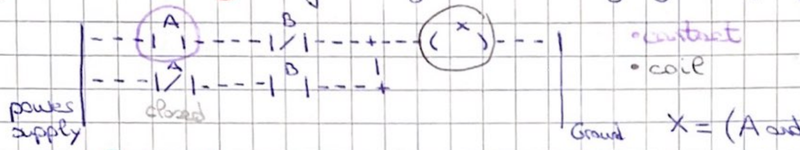
PLC is executed repeatedly, following steps: • The status of physical inputs are stored in a certain part of the memory. • The user program is run from the begging to the end. • Operating system services are executed.

• The status of outputs is copied. Tc → cycle time

→ If any inputs changes during the cycle, PLC is not aware of any variations of its inputs within the cycle when its operating, so it checks inputs only at begging.

(LD) Ladder diagram first graphical language to program PLC

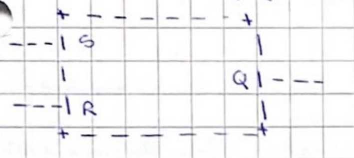


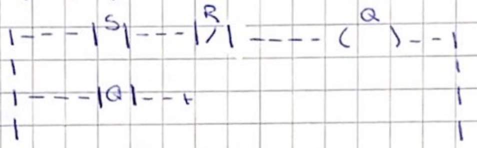
• contact
• coil

A → true - contact closed
A → false - " open
} A, B inputs true or false

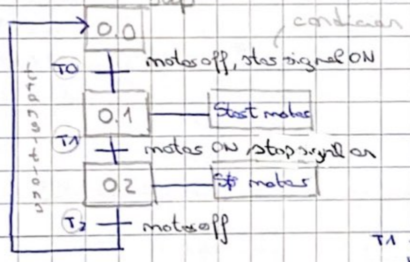
X = (A and (not B)) or ((not A) and B)

Example: Q = (not R) and (Q or S)



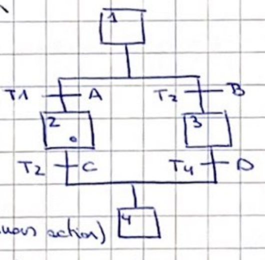


(SFC) SEQUENTIAL FUNCTION CHART graph. programing language, used to program processes that can be split into dif execution steps



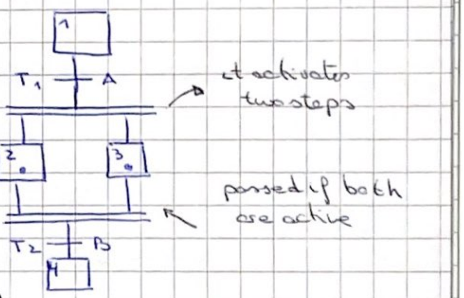
Controlled to start after a signal is received (start s ON)

and to stop when another signal is received (stop signal ON)



if-then-else

Parallelism and rendezvous



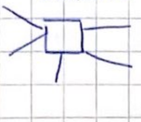
Types of actions
- **N** normal (continuous action)
- **L** time limited
- **D** delayed
- **P** pulse (executed once)

REAL TIME SYSTEMS react to an event exactly at a certain time, extremely precise

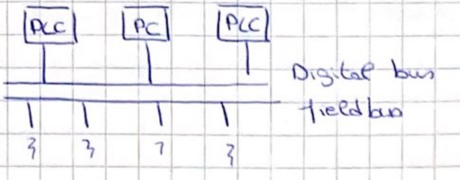
Distributed control system

Point-to-point connections

Centralized architecture



Bus architecture



PID controllers In industrial application, PID (with Proportional, Integral and Derivate action) are used extensively. The PID control law:

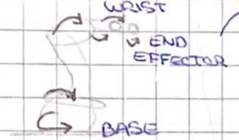
$$u(t) = K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \frac{de(t)}{dt}$$

INDUSTRIAL ROBOTICS

What is a robot? An automatically controlled, reprogrammable, multipurpose <u>manipulator</u> (objetivo) programmable in three or more axes (ejes)

THE MECANICAL SYSTEM

series of rigid bodies connected by joints



→ where the gripper or tool is mounted (agarre)

Usually have <u>six links</u>:

- 3 make the positioning
- last 3 (wrist) orientation

6 degrades of freedom

RIGID AUTOMATION (neumáticos)
- Sequences operations fixed
  - ↳ simple operations
- Producción larga, poca variación

PROGRAMMABLE AUTOMATION
- Seq. operat. can be changed
- ~-↓ production batches (lotes)
- Between batches production plan has to be reconfigured (PLC) red amplificadas

FLEXIBLE AUTOMATION (Robot)
- Production can be varied without idle times for conversion (muertos)
- Machine characterized by ↑ flexibility and configurability

ROBOTS IN THE AUTOMATION SYSTEM

Countries in wich sold < China ⊕ / Japón

Robot density < Singapore / Rep. of Korea

USED FOR < automotive / electrical

Problems in robotics: 1. Kinematics 2. Motion planning 3. Control

TCP (TOOL CENTER POINT) The task the robot has to acomplish is usually expressed in terms of the TCP

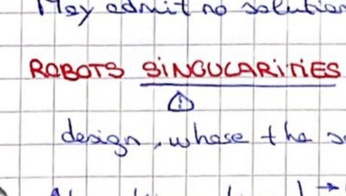
Can be expressed in different cordinate systems

The base cordinator system: Located in the base

Joints: each joint allow for 1 degree of freedom between 2 links

Direct Kinematics problem is:

Find the position and orientation of the TCP frame, the base frame



$$p_x = a_{1x} + a_{2x} = a_1 \cos(\theta_1) + a_2 \cos(\theta_1 + \theta_2)$$

$$p_y = a_{1y} + a_{2y} = a_1 \sin(\theta_1) + a_2 \sin(\theta_1 + \theta_2)$$

Inverse Kinematics problem is: find joint variables given position and orientation of the tool frame, base frame

May admit no solution, numerical techniques used, infinite, multiple sol.

ROBOTS <u>SINGULARITIES</u> ⚠ particular configurations of the robot, related to its mechanical design, where the same robot position can be obtained with an ∞ n° of joint configrations

At a kinematics singularity we have
- → Loss of mobility
- → ∞ solutions
- → high velocities in joint spaces

Singularities may happen:

Manipulator work-space < at the borders / inside

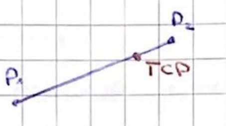
<u>Dangerous</u>

THE GENERATION OF THE MOTION

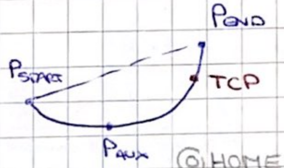
how the robot has to move

Operational space

LINEAR PATH



CIRCULAR PATH



Motion control of a robot is performed with feedback controllers

Program example

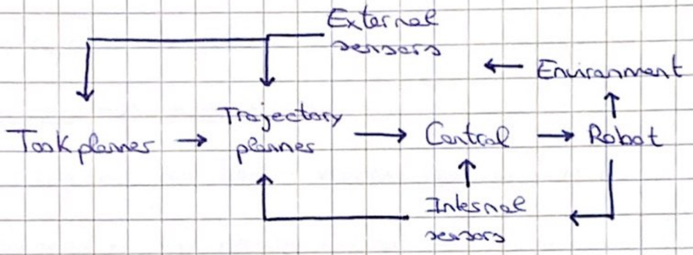
⓪ HOME

1. Feeders (alimentadores)
2. Robot
3. Discard bin (desechos) ①
4. Table ②

Control with force sensors

A general scheme for the robot controller

composed of several functional units:



To control the interaction with the environment we need sensors

Force Sensors

Vision Sensors (cameras)

JOINT SPACE	OPERATIONAL SPACE
• Singularities don't create problems	• Task description is natural
• interest when we want axes move from an initial to a final pose	• Constraints on the path can be accounted for
	• Singularities generate problems
• Online Kinem. inversion not needed	• Online Kinematics inversion needed

---

Delay contributions involved packet switched comm.

Four types
- Processing
- Queuing
- Transmission
- Propagation

Is amount of time required to push all the packet's bits into the wire

COLLABORATIVE ROBOTICS.

collaborating same task

New paradigm in industrial robotics, where humans and robots share the same environment and collaborate at the same tasks

- Protective fences no needed
- Particularly interested for SMEs (reduced cost, reduced footprint)
- Dual arm, low inertia and payload
- Still good precision
- Good potential for assembly of electr. part
- New programming interfaces
- Decrease of the deployment time
- High potencial for SME's

Why robot-human collaboration? → High flexibility High productivity

COST Trad. 15% (35% purchased parts) C. 50% (engineering, purchased parts.)

C. ROBOTICS & INDUSTRY 4.0 • Collaborative robotics is considered one of the enabling technologies of the industry 4.0 paradigm. • Humans and machines are expected to actively cooperate in the smart factory

Safety standards → Collaborative operation: robots work in direct cooperation with human

→ Collaborative workspace: workspace within safeguarded space where r and h can perform tasks.

INTRODUCTION TO IoT

- Devices
- Communication protocols
- Cloud-based resources

} technologies

IoT Buildings blocks and techical challenges

- Security Bio-sensor detects heart attack and calls 911
- Reliability / Robustness

HARDWARE LEVEL

- Data collected must be reliable
- Device must live in harsh environment

SOFTWARE LEVEL

- Communications protocols must be robust to failures, interferences...
- Self healing, self configuration needed

- Management platform:

THINGS

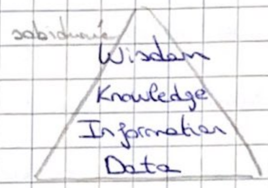
Cost reduction
Miniaturization
Energy effiency
Resiliency
Design

CONNECTIVITY

Comm. technol. | energy efficiency

Comm protocols | "classic" not suited
"Integration issue"

DATA/ANALYTICS



FIELD DEVICES IoT AND IIoT

INDUSTRIAL

mgmt

HARDWARE (IIoT) Dedicated hardware: edge devices, local data bases (MES, ERP), gateways.

- MGMT
- Planning → Control and supervision hardware: SCADA
- Supervisory
- Control → Control hardware: PLC, DCS
- Measurement command → Sensors / Actuators

SENSOR'S TASK:

- Sensing the industrial process
- Processing / storing information
- Communicating with other sensors

ACTUATOR'S TASK:

- Receiving input signals from control devices
- Processing / storing information
- Acting on the industrial process

Wire-free Sensor: Energy efficiency becomes a MUST

Sensor node has limited power source, lifetime depends on battery lifetime

Goal: Provide as much energy as possible at smallest.

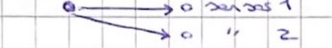
Network topologies supported by the IEEE 802.11

- Basic service set: star topology with the access point at the very center
- Ad Hoc: meshed networks with cross-traffic allowed
- Extended service set: multiple BSSs interconnected via a Distribution system

COMMUNICATIONS TECH. FOR THE IoT

Traffic in I.4.0 Cyclic (sensor measures.) Acyclic (unpredictable events) Multimedia Backhand (aggregated flows, enterprise level)

MINIMUM CYCLE TIME (MCT) minimum time required to execute a cycle in a control loop



$\boxed{MCT} = T_{PLC-S_1} + T_{S_1-PLC} + T_{PLC-S_2} + T_{S_2-PLC}$

$T = \frac{L}{R} + \frac{d}{v}$ transmission time, propagation delay

2 sensors
1 controller
PLC polls s1, s1 sends back reading
PLC same s2

Wireless is gaining momentum (wired connectivity)

NETWORKING FUNDAMENTALS

Communicating technology 1) Physical infrastructure. 2) Network architect/topologies 3) A set of communications protocols.

Network topologies 1) Ring T. 2) Tree T. 3) Linear Chain 4) Star T. intermediate devices field devices

Communication protocols • Message format • Connection set up procedures • Connection tear down • Semantics

(CAN Bus) FIELDBUS GENERALITIES • Mainly targeting the interconnection of control devices and field dev.

• Short frequently-exchanged messages • Tight requirements in terms of delay and determinism

DISGRESSION ON CHANNEL ACCESS PROBLEM: To share a single communication medium

SOLUTIONS

① SCHEDULED ACCESS (polling schemes, centralized scheduling)

PROS • "Guaranteed" performance (bounded delay/throughput)

CONS • Coordination required (central node, synchronization) Bluetooth Prof. BUS

② RANDOM ACCESS (wifi CanBus) Transmission can overlap

PROS • Easy to implement • Opportunistic access to the resources

CONS • Only "statical" guarantees on performance • Poor performance under heavy traffic

Bus arbitration: • Each message has a priority • Each station monitors its own transmission and the status of the BUS. • If transm. station overhears another on the channel at higher priority, then quits

Topologies HUB SWITCH

Ethernet/IP - Bringing the internet to the industry. - Automation/Enterprise information to converge

Wifi Standardized within IEEE working group 802.11. It's a "wireless ethernet". Different dialects at the physical and upper layers ARCHIT. Extended Basic Service Set, centralized interconnection Access Point, distributed ad hoc mode

Types of devices 802.15.4

FULL FUNCTION DEV.	REDUCED F. DEV.	PAN Coordinator
- Can send beacons	- Cannot route frames	- Responsible of Personal Area Netw
- " communicate with others	- Cannot comm. others	- Manages PAN association
- " route frames	- Can comm with FFD	
- Power supply	- Batteries	

MAC: Funtional Description two operations modes are defined:

Beacon enabled
- PAN coordinator transmits beacons
- Usually adopted in star topologies
- Slotted CSMA/CA + scheduled transmissions

Non beacon enabled uncoordinated access through unslotted CSMA/CA

5G comming to industry

Nice features
- mmWave access, massive MIMO
- Network Densification
- Slicing
- Mobile Edge Computing (MEC)

- High access speed
- Low latency

Enabled applications
- Immersive virtual reality - Autonomous vehicles - Collaborative robotics

→ Cellular IoT operators → Mobile Radio Networks → Capillary multi-hop networks

MESSAGE TRANSPORT PROTOCOLS FOR IoT

Application design lines

- CLIENT - SERVER (web browsing)
  - clients very many, can only issue requests
  - Servers are few
- PEER TO PEER (torrent)
  - Every body can act as clients and servers
- IBRIDA (skype)
  - A mixture

HTTP communication client/server architecture

Client: issues HTTP requests for specific resources (URIs)

Server answers back with the required resource

Constreined Application (COAP) Protocol

GOAL to enable web-based services in constrained wireless networks → 8bit micro-controllers → Limited memory → Low-power networks

PROBLEM: Web solution are hardly applicable

SOLUTION re-design web-based services for constrained networks -- COAP

Coap observation: P: → rest paradigm is often "pull" type, that is, data is obtained by issuing an explicit request. → Data in WSN is often periodic / triggered

S: use observation on COAP resources

The message queuing telemetry transport (MQTT)

Is a client server publish messaging transport protocol.
- Simple to implement - QoS support - Lightweight and bandwidth effic.
- Data agnostic - Session awareness

Components
- Clients don't know each other - One-to-many paradigm

Communication Pattern
- Every client publishes and subscribes - PUSH information paradigm compared to PULL's one in COAP

MQTT-SN

Main differences
- Extended architecture with Gateways - New gateway discovery procedures
- Some messages are more "compresse" - Extended Keepalive procedures