Robotic Sensor Systems

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1, +) **Future Applications:**

- Industrial Robots: more complex tasks
  wider / broader range of manufacturing

- Service Robots: excluding industrial automation application

- Application: logistics, medical, field, defense

+) **Key abilities:** CIMMPC

- Configurability
- Interaction ability
- Motion Ability
- Manipulation ability
- Perception ability: suitable choice of sensing modality
- Cognitive ability: reduction of programming & configuration effort

+) **Key technologies:**

Advances in sensors → control theory
→ safety (sensor based)
→ navigation

Object/Process → Sensor → Amplifier → Filter
↓
ADC → Filter → Micro controller / Computer → Output
Control loop ↑ Object/Process

L2) Control & feedback control systems

1) Introduction to industrial robots:

can be equipped with

- several driven axes, freely programmable, tools, gripper, sensers..
  high-payload, large werking area

Components of robotic system

- Mechanical structure & end effector + Controller & Drive Modules + Sensers
- Main vs minor axes & different coordinate system

2) Internal metrology of industrial robot:
(the sciencific study of measurement)

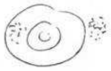
internal measuring sensors

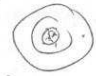
+) Control variables:

- Current measurement: current transfermers, anmeters
- Velocity measurement: tachogenerators
- Position measurement: encoders

+) Accuracy of industrial robots:

Repeatability vs Accuracy





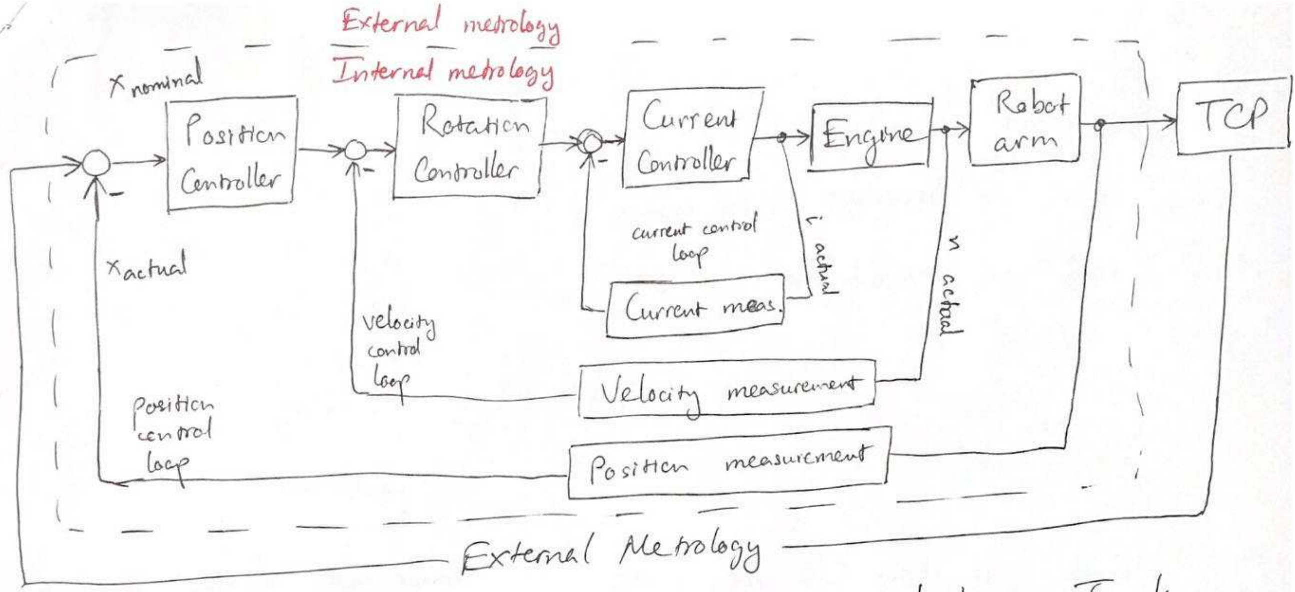
+) Position uncertainty:

+) ISO 9283: standards on how performance should be tested
characteristics ______ specified

3) External metrology..

external measuring sensors

- Poor position accuracy can be compensated with external metrolog



+)

	Indoor GPS	Laser Radar	Laser Tracker
	Transmitter & receiver	Scan arbitrary surfaces	Dynamic measurements
Range	1,5 – 30 m	2-30 m	2-80 m
Uncertainty:	0,2 mm	0,1 mm	0,035 mm
Example.	Assembly on moving main part		

+) Open-loop vs closed-loop

ex: Delta robot, pick & place
small, acceptable errors

+)

	Full Automization	Human-Robot-Collaboration
workspace	separated	shared
work flow	decoupled	coupled
Physical contact necessary	no	yes
Speed	maximum	reduced

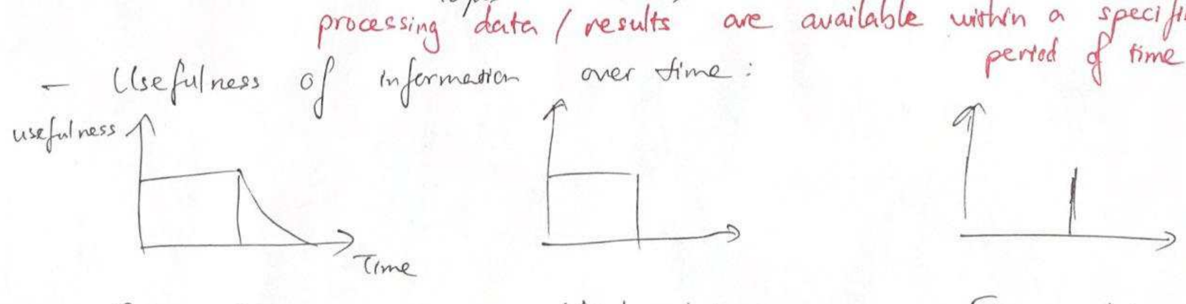
4) Communication between sensors & robots via industrial ethernet & 5G:

– Real time: for Machine Tools, Industrial Robot Applications:

10 μs → 10 ms

processing data / results are available within a specified period of time

– Usefulness of information over time:



Soft real-time Hard-real-time Firm real-time

+) Fieldbus protocol — 5G

Fieldbus protocol	5G
used for distributed control systems	wireless
real-time capabilities	high data rates
	ultra-low latency
	security
	scalability

real-time

Both: to share & use data

connect more devices, more data
ultra-reliable
ultra low latency → real time

Requirements

Enhance IT structure
Development of new wireless systems
Close the loop in real application
Prove the added value
Universal real-time capable connectivity

Electromagnetic Sensor

L3, Electromagnetic Sensers for robot control:

+) Proprioceptive Sensor

Proprioceptive Sensor	Encoders	Tachometer	Gyroscope
Position / Pose	✓		
Velocity	↓ ✓	✓	✓
Acceleration	↓ ✓	↓ ✓	

If you can measure x
$\Rightarrow$ can derive $\dot{x}, \ddot{x}$

1, Principles of Electromagnetism: Maxwell's equations

- Gauss' law :

electric flux $\Phi_E = \oint \vec{E} . d\vec{A} = \frac{Q_{encl}}{\varepsilon_0}$; $\varepsilon_0 = const \Leftrightarrow \vec{\nabla} . \vec{E} = \frac{\rho}{\varepsilon_0}$

$\Leftrightarrow \oint \vec{D} . d\vec{A} = \int \rho dV = Q_{encl}$; $\vec{D} = \varepsilon \vec{E} \Leftrightarrow \boxed{\vec{\nabla} . \vec{D} = \rho}$

- Gauss' law for magnetism:

magnetic flux $\Phi_B = \oint \vec{B} . d\vec{A} = 0 \Leftrightarrow \underbrace{\boxed{\vec{\nabla} . \vec{B} = 0}}_{\text{divergence}}$ $\Rightarrow \vec{B}$ is solenoidal vector fields

$\Rightarrow$ { no source, no sink

there is no magnetic monopo

- Maxwell - Faraday equation

$\boxed{\underset{\text{curl}}{\vec{\nabla} \times} \vec{E} = -\frac{\partial \vec{B}}{\partial t}}$; $U = \oint \vec{E} . d\vec{s} = - \iint \frac{\partial \vec{B}}{\partial t} . d\vec{A}$

Varying magnetic fields $\vec{B}$ induce electric fields $\vec{E}$

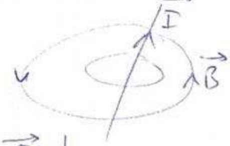
- Ampère's circuital law

$\boxed{\vec{\nabla} \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}}$; $\oint \vec{H} . d\vec{s} = \iint \vec{j} . d\vec{A} + \iint \frac{\partial \vec{D}}{\partial t} . d\vec{A}$

$\vec{H} = \frac{\vec{B}}{\mu_0}$, $\mu_0 = const$

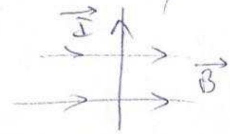
$$\oint \vec{B}\, d\vec{l} = \mu_0 I_{encl} + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$$

+) Magnetic field



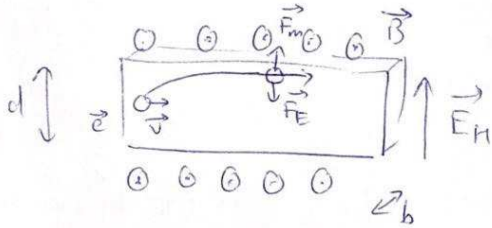
$B = \frac{\mu_0 I}{2\pi R}$; $\mu_0 = 4\pi.10^{-7}$

- Magnetic force



Lorentz force
- for current $\vec{F} = \vec{I} \times \vec{B}.l$
- for moving charge $\vec{F} = q.\vec{v} \times \vec{B}$

+) Hall effect:



$\vec{F_m} = \vec{F_E}$

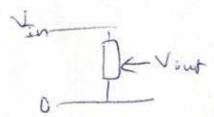
$\Leftrightarrow q\vec{v}\vec{B} = q\vec{E_H} = q\frac{U_H}{d}$

$\Leftrightarrow \vec{U_H} = \vec{v_D}\vec{B}d$ Hall emf

$= \frac{\vec{I}}{n.Q}\frac{\vec{B}}{b}$ (cause current density $\vec{v_D} = \frac{1}{n.Q}\frac{\vec{I}}{b.d}$)

$= R_H . \frac{\vec{I}\vec{B}}{b}$ (R_H : Hall constant)

2) Positioning sensors:



+) Potentiometer: works according to Ohm's law

- Turning
- Sliding

Potentiometer when joint rotate, the gear turns the potentiometer..

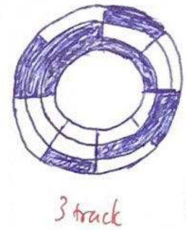
+) Induction-based Sensors:

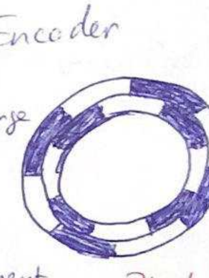
- Resolver ..
- Inductive Transducer
- Tranverse Armature Transducer : based on Maxwell bridge
- Differential Transducer
- Inductosyn

+) Rotary Encoders:

- Absolutely Encoder vs Incremental Encoder

Absolutely Encoder	Incremental Encoder
maintain info when power is removed	immediately report pos change
pos info available immediately	doesn't keep track
relationship encoder value & physical pos. set at assembly	have to go back to fixed point to init measurement


3 track


2 track

- Magnetic Encoder vs Optical Encoder

	Magnetic Encoder	Optical Encoder
Components:	Disk, conditioning circuit & Hall / magnetoresistive sensor	Code disk, LED, Scanner

- Number of track ⇒ resolution:

n track ⇒ resolution: $\frac{2\pi}{2^n}$

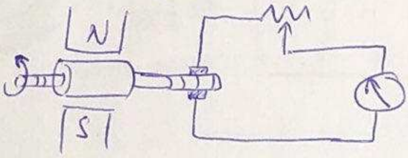
	Advantages	Disadvantages
Potentiometer	Simple low cost	Limited range Accuracy limited Wear out (due to contact)
Resolver	Non-contact	Analog Requires decoding circuit Expensive
Inductive Transducer	Non-contact High accuracy	Limited range Analog
Magnetic Encoder ⊗ (For Robots)	Non-contact Robust	Decoding required usually lower reso
Optical Encoder (For Robots)	Non-Contact	Gray decoding required Complex wiring

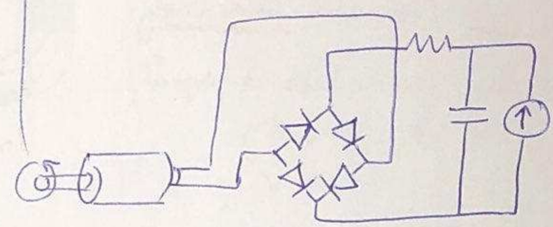
3, Speed Sensors:

Maxwell-Faraday equations $\frac{\partial \vec{B}}{\partial t} \Rightarrow \frac{\partial \vec{E}}{\partial t}$

/ta'kɒmɪtə/ Tachometer based on DC machine | Tachometer using AC generator

$$V = \frac{\vec{B} p n Z}{60a} = K.n$$





4, Acceleration Sensors:

+) Mechanical Gyroscopes (conservation of angular momentum)

$$C_y = -I\Omega\omega_z$$
$$C_z = I\Omega\omega_y$$

Torques lead to displacement

+) Micro Electro-Mechanical System Gyroscope (MEMS)

$$\vec{a}_{Coriolis} = 2(\vec{v}' \times \vec{\omega})$$

Change in capacitance $\Rightarrow$ proportional to Coriolis force

Capacitive & Piezoelectric Sensors

/pʌi zə/

L4,

+) Motivation for Robotics: capacitive collision avoidance

1, Electrotechnical Basis of Capacitance

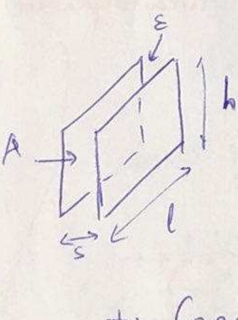
- $U_{AB} = \int_A^B E.ds$; $U_{AB} \sim Q$
- 1st Maxwell's equation: $\frac{Q}{\varepsilon_0} = \oint \vec{E}.d\vec{A} = \Phi_E$;

  If E = const over Area A: $\frac{Q}{\varepsilon_0} = E.A = \Phi_E$
- $Q = C.U$

2, Capacitive Sensors:

+) $C = \varepsilon_r \varepsilon_0 \frac{a.b}{d}$

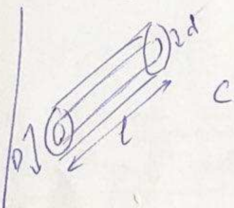
C : capacitance
ε_0 : absolute dielectric constant of vacuum
ε_r : relative dielectric constant
a, b: electrode lenghth, width . ab = A
d : distance between electrodes



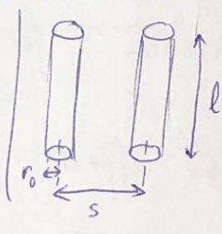
$C = \frac{\varepsilon_0 \varepsilon_r A}{s}$

$A = h.l$

⊗ Exercise



$C = \frac{2\pi\varepsilon_0\varepsilon_r l}{\ln\frac{D}{d}}$



$C = \frac{\pi \varepsilon_0 \varepsilon_r l}{\ln \frac{s}{r_0}}$

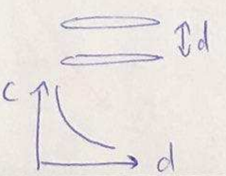
$s >> r_0$

+) Capacitive Transducers:

- Distance Sensors

  - non-contact
  - wear-free

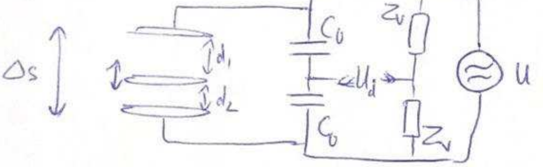
  distace determination



- Surface Transducers

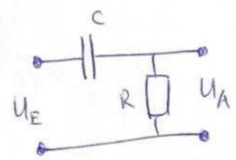
  - Determination of object displacements

- Simple Differential Arrangement

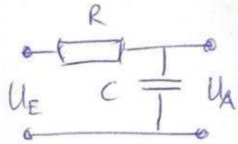


Ex: Capacitive Pressure Sensor

- High pass / Low pass filter



High pass



Low pass

+) Accelerometer: change $\vec{a} \Rightarrow \vec{F} \rightarrow$ change position of electrode

Ex: Airbag Deployment
Capacitive Touch Screen
Capacitive Gyroscope
Accelerometer-based Control

Pros & Cons:

(+)
Non-contact - wear-free
Simple, low power consumption
Penetrate insulating materials
Low temperature dependence
Extreme temp. range
Resolution sub nm

(−)
Required AC voltage
Disturbance of measuring power
Impairment by insulating walls
dust & moisture

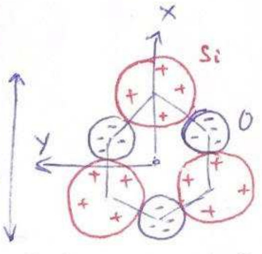
3) Electrotechnical Basics of Piezo Effect

+) Motivation for robotics

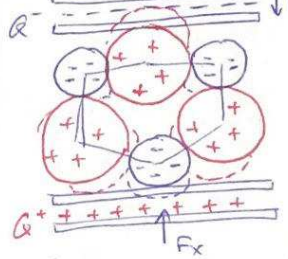
+) Piezo effect: deformations of crystal lattice of certain ion crystals
$\Rightarrow$ cause electric charges on surfaces

$d_{12} = -d_{11}$

area dependent

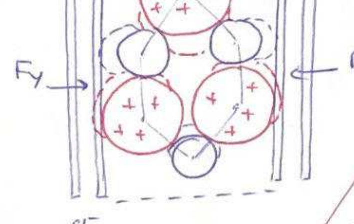


Unloaded Crystal Structure
- Here quartz (SiO_2)
- An asymmetrical charge dist.



Longitudinal Piezo effect.
- Area independent

$Q_x = d_{11} \cdot F_x$

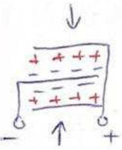


Transversal Piezo effect

$Q_x = d_{12} \dfrac{l_y}{l_x} F_y$

+) Basic Principles

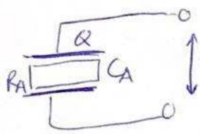
- Increase charge



$Q_G = n \cdot Q$ (parallel connection)

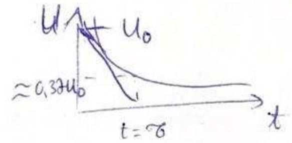
$Q = d \cdot F = C_A \cdot U_A$

- Capacitive properties
Discharge will drop U



$\Rightarrow U_A = \dfrac{d \cdot F}{C_A}$ with $\begin{cases} d\text{: piezo coeff.} \\ F\text{: mecha. force} \\ C_A\text{: inherent capacitance} \end{cases}$

- Discharge func: $U(t) = U_0 e^{-t/\tau}$
$\tau = R \cdot C$



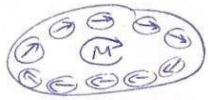
⊗ Exercise
- Double element

$C = 2C_0$ $\quad$ $\tau = \tau_0$
$R = R_0/2$ $\quad$ $U = U_0$
$d = 2d$

4) Piezoelectric sensors

+) Force & Torque Measurement

- Pairs of piezo plates $\Rightarrow$ longitudinal piezo effect $\Rightarrow F_z$
- Multi component force transducers $\Rightarrow$ shear effect $\Rightarrow F_y, F_x$
- For torque, arrange sensor to capture tangential in circuit & electrically switched



+) Pressure Measurement

- Accelerations can falsify pressure measurement
$\rightarrow$ Thus, use seismic mass in ~~the~~ the acceleration-compensated pressure transducers

- Spring mass oscillator

∘ An indirect measurement of acceleration $\Rightarrow$ from measuring $\begin{cases} \text{deflection } r \text{ of the mass } m \\ \text{spring force } F_c \end{cases}$

+) Reciprocal Piezo Effect: typical range: 10 – 200 μm

Apply electric field ⇒ a piezo electric element ⇒ generate mechanical stresses

Ex. ⇒ Piezo electric drive

Ex: Piezo electric actuator as Injector for Diesel Engine

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Electromagnetic Sensors for Robot Vision

L5) 1) Electromagnetic sensors for robot vision:

- Exteroceptive senser: info from environment
- Wave-particle duality:

2) Photo sensors

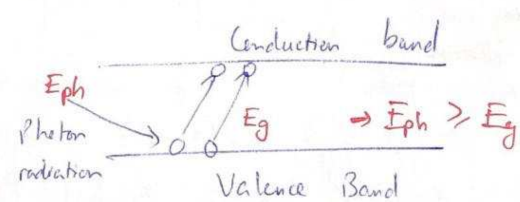
- Black body: produce a special type of light, continuous light
  - there is connection between light intensity, temperature and wavelength
  - absorb all incoming radiations
- Planck's law: energy spectrum of a black body with temp. T

$$E_\lambda = \frac{C_1}{\lambda^5} \cdot \frac{1}{e^{\frac{C_2}{\lambda T}} - 1}$$

- External photo electric effect $\underbrace{E_\lambda}_{\text{Planck energy}} = \underbrace{h}_{\text{Planck const}} \cdot \underbrace{f}_{\text{freq}} = h \cdot \frac{c}{\lambda}$

$$E_{kin} = E_{ph} - W_A = h \cdot f - W_A$$

- Inner photo electric effect



*) Inner photo electric effect:
- Photon diode
- Image senser
- CMOS
- CCD (Charged Coupled Device)

  - UV to near IR
  - Fast response time
  - small build size

External photo electric effect
- Photo multiplier
- Photo tube

  - UV to near IR
  - High sensitivity
  - large receiving surfaces

3) Electromagnetic waves:

Derivation of the wave equation:

time dependent, non-homogeneous wave equa.

$$\vec{\nabla} \times \vec{E} = -\dot{\vec{B}}$$

$$\vec{\nabla} \times \vec{H} = \vec{j} + \dot{\vec{D}}$$

$$\Rightarrow \Delta \vec{E} - \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = \mu_0 \left(\dot{\vec{j}} + \ddot{\vec{P}} \right)$$

time-dependent, homogeneous wave equa.

$$\vec{j} = \dot{\varepsilon} = 0, \quad \vec{P} = (\varepsilon - 1)\varepsilon_0 \vec{E}$$

$$\Rightarrow \Delta \vec{E} = \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2}$$

$$c = \frac{c_0}{n}, \quad n = \sqrt{\varepsilon}$$

$\Rightarrow$ Solution: $\vec{E}(\vec{x}, t) = \vec{E}_0 \cos(\vec{k}\vec{x} - \omega t)$

wave no. vector $\vec{k}$, $|k| = \frac{2\pi}{\lambda}$

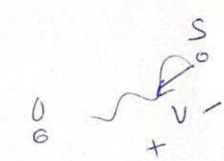
$$E = \frac{E_0}{r} \cos(kr - \omega t)$$

Optical Doppler effect

moving source
fix observer

$$f_0 = \frac{f_s}{1 - \frac{v}{c}}$$

f_0 - freq of the observed
f_s - freq when sended



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$$f_0 = f_s \left(1 - \frac{v}{c}\right)$$

+) GPS (Global Positioning System)

- civil L1 - signal wave 1575,42 MHz
- Triangulation with several satellites

+) iGPS: transmitter rotates with unique freq 40-50 Hz, ~~fixed~~ fixed receiver

$\Rightarrow$ Application: large volume positioning

+) LiDAR (Light Detection and Ranging)

- Time-of-flight measurement principle $d = \frac{c \cdot t}{2}$

- Phase shift measurement principle : $d = \frac{\lambda_{mod} \cdot \phi}{4\pi}$

(complex sensor design required)

$\phi = \tan^{-1}\left(\frac{s_0 - s_2}{s_1 - s_3}\right)$

- Application:
  - Robot navigation (SLAM)
  - Autonomous driving
  - Geodesy

+) Wave properties: Interference

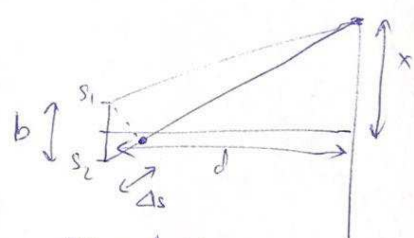
- Intensity $\boxed{I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\delta}$; $\delta = \varphi_2 - \varphi_1$

- Prerequisites
  - constanct phase
  - appropriate polarization (not perpendicular)

- Young - experimente:

min intensity: $\Delta s = \left(n + \frac{1}{2}\right)\lambda$ $\quad n \in \mathbb{N}$

max —— $\Delta s = n\lambda$



$\Delta s \approx b \frac{x}{d}$

+) Interferometry for distance measurements

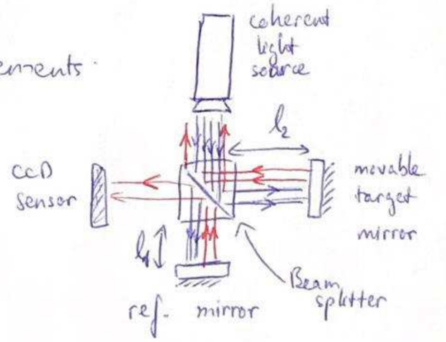
for smallest geometric deviations

- Michelson Interferometry $\Delta s = 2(l_1 - l_2)$

- At CCD sensor:

$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\delta$, $\delta = \left(\frac{2\pi}{\lambda}\right) \cdot 2(l_2 - l_1)$

$I_1 = I_2 = \frac{I_0}{4}$



+) Laser Tracker - range 30-70 m
- uncertainty 10 µm/m

highly accurate 6D position tracking

+) Laser Radar : - freq. of signal modulated in range 100 GHz
- reflected signal is phase shift modulation of ref. signal

3D scanning of | parts
| environments

texture mapping

4, Electromagnetic waves for communication:

- Antenna: open oscillating circuit
- Electro-magnetic (EM) waves enable wireless data / transmission / communication

RSS

Thermoelectric & Ultrasonic Sensors

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1, Thermo electric Sensors

+) Heat transfer & Temperature Measurement

for liquid, gas - Convection (Heat flux density) $j_Q = \alpha \Delta T$

for solid - Conduction $j_Q = -\lambda \nabla T$

- Heat radiation $P = A \sigma T^4$

+) General overview of instruments:

Mechanical Contact Thermometers	Electronic contact Thermometers	Radiation Thermometers
-200 - 630°C	-220 - 1500°C	-100 - 3500°C
- Liquid in glass thermometer - Bimetallic thermometers	- Resistance thermo. - Metal resistance thermo. - Semi conductor rest. thermo. - Thermocouples	- Radiation pyrometer - Thermography (infrared camera)

we will go into these 1 by 1

+) Laws of Thermodynamics

+) Temperature scales : T_K , T_C , T_F
Kelvin, Celsius, Farenheit

$T_C = T_K - 273,15$

$T_F = T_C \cdot 1,8 + 32$

+) Liquid in glass Thermometers:

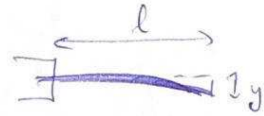
$\Delta V = V_0 \cdot \beta \cdot \Delta T$, $S = \frac{dh}{dT} = \frac{V_0 \beta}{\pi r^2}$

mercury range [-35, 30...
lower temp. ⇒ pentane alcohol..

+) Bimetallic Thermometers [-50, 400°C]

$y = \alpha \cdot \frac{l^2}{d} \Delta T$

deflection coeff. thickness



+) Resistance Thermometers. R ↑ as T ↑

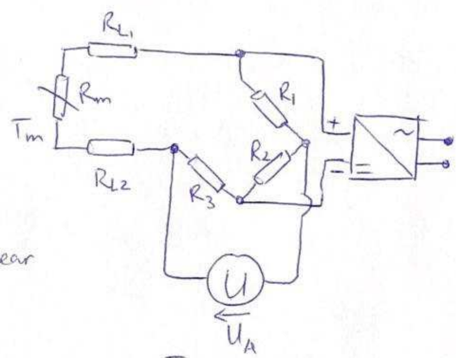
- Platinum [-200, 850°C] (Pt)
- NTC Thermistor (Negative temp coeff) : Silicon, zinc oxide
- PTC Thermistor (Positive ———) : Selenium

} semi conductor resistance thermometer

With Wheatstone's Bridge

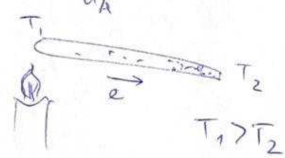
$U_A \sim R_m + R_{L1} + R_{L2} - R_1$

With Pt, resistance curve almost linear



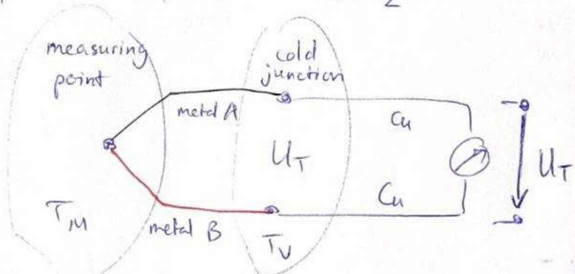
+) Thermocouple: Seebeck effect

$U_{seebeck} = \alpha \cdot \Delta T$



$U_T = K_{A/Pt} \cdot (T_M - T_V) + K_{B/Pt}(T_V - T_M)$

$U_T = K_{AB} (T_M - T_V)$



- Preferred thermocouples: iron - constantan
  nickel - chromium - nickel
  platinum - rhodium - platinum

+) Radiation thermometers : infrared detection

Pyrometer	1 spot
Thermography	an image

	Mechanical Contact Thermometer		Elektronic Contact Thermometer		Radiation Thermometor			
Sensers	Liquid in glass Thermometer	Bimetallic Thermometer	Resistance Thermometers	Thermocouple	Pyrometer	Thermogrephy	Quatz Thermometer	DTS
Temperature Range	[-35, 300°C]	[-50, 400°C]	[-200, 850°C]	[-200, 1700°C]	[-100, 3000°C]	[-50, 1500°C]	[-80, 300]	[-200, 350]
↑ Pros	No additional equipment required Small uncertainty	Robust (shock vibration)	Versatile applicability High penetration rate Cheap Relatively accurate Cheap Accurate Small delay	Better accuracy Active sensor	Wider range	Moving object	Very accurate	
↓ Cons	No remote measurement possible	Limited accuracy Time delay to expand / contract	Passive sensor (Need power source)	Need cold junction compensation			Complex	
Scope			Industrial temperature monitoring		High temp monitoring	Construction industry	Precision measurement	Monitoring cables & pipeline

+) Quatz Thermometer:

- Resonance freq of quatz crystal depends on temp.
- Resolution: 10E-3 ~ 10E-6 K
- Complex

+) DTS (Distributed Temperature Sensing)

+) Pulse echo method vs through-transmission method

Pulse echo method	through-transmission method
(+) one side accessibility	pass through material once
(−) pass through 2 times	must align sender & receiver access from both side can't determined depth of defect

+) Fibre Bragg Grating:

+) Noise Thermometer:

+) A-scan → { B-scan, C-scan }

2) Ultra sonic Sensors: waves as movement of matter

- Piezo electric effect
- Use AC current ⇒ deform a Piezo element

⇒ Measuring thickness...

- Velocity depends on temp., direction of wave, physical state, static pressure,...

+) Acoustic Impedance Z

$Z = c \times \rho$, ρ: density

$R = \dfrac{Z_2 - Z_1}{Z_2 + Z_1}$ (sound pressure reflection coeff.)

$R^2 = \rho = \dfrac{I_r}{I_0}$ (sound power reflection coeff.)

$T = \dfrac{2Z_2}{Z_2 + Z_1}$ (transmission coeff.) $= 1 - \rho$

+) $\rho_{vacuum} = 0 \rightarrow R_{vacuum} = 1 \rightarrow$ total reflection

RSS

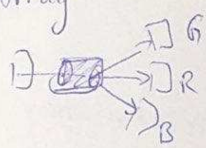
Machine Vision

L7)

1) Image Acquisition

+) Sensor: photo bucket

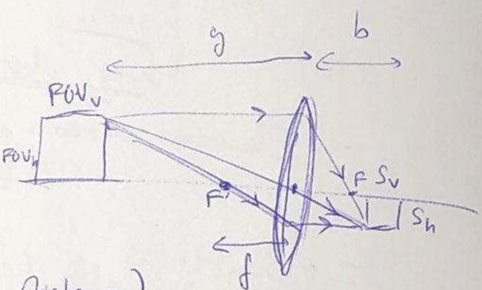
- The pixel and data transfer architecture [CCD / CMOS
- Filter color with: [Bayer Filter Array / Three Chip



- Image Resolution

FOV (Field of View)

Imaged Pixel Size = $\frac{FOV}{\text{Pixel count}}$



+) Optics: PMAG (Primary magnification)

- For desired FOV and WD (Working Distance)

$M = \frac{S_h}{FOV_h} = \frac{b}{g}$

M: magnification

$\frac{1}{f} = \frac{1}{g} + \frac{1}{b}$; $f = \frac{g \cdot S_h}{FOV_h + S_h}$

f: focal length

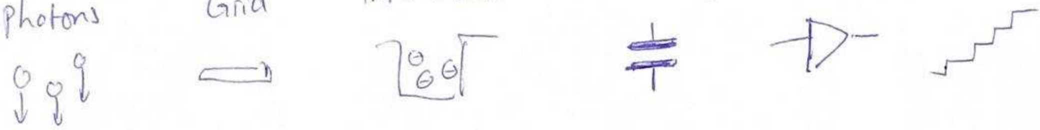
+) Lighting: [cameras & algorithm can not compensate bad illumination / designed for imaging, not human-viewing

Techniques: (8)

Direct / Diffuse bright field illumination
Direct / dark field illumination
Diffuse
Diffuse backlight
Structured light
On-axis illumination
Collimated illumination

+) Physical Model & Noise Sources:

Impenging photons ⇒ Pixed Grid ⇒ Transformation into Elections ⇒ Charge into Voltage ⇒ Amplification ⇒ Quantization ⇒ Digital Gray Values



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Photon noise

Dark noise

Readout noise

Amplifier noise
Quantization error

+) Interference and Mitigation measures: CHEVB

- Vibration:
  - reduce exposure time
  - utilize damping system
  - multiple inspection with image averaging
- Contamination: utilize
  - protective housing
  - air curtains, cleaning with compressed air
- Heat:
  - increase working distance / use endoscopy
  - cooling
  - heat-absorbing filter disks
- Electromagnetism:
  - shielding, fiber glass cable
  - use suitable signal conditioning
- Brightness:
  - flash controllers
  - mitigate ambient light
  - triggering of lighting through camera

2) Image Processing:

+) Machine Vision Software

+) General Machine Vision Algorithms:

- Geometric manipulation: ~~shf~~ shifting, rotating, sampling ..
- Content statistics: image histogram, threshlding ..
- Image enhancement: reduce noise, better contrast
- Connectivity: extraction & analysis of 2D shapes
- Edge detection:
- Correlation: model vs template
- Geometric search: locates features within an image
- OCR / OCV: optical character recognition / verification

- Convolution & Spatial Filter
- Canny Edge detector
- Hough transform

3) Integration & Application:

+)

	Classic Image Processing	Machine Learning
Pros	+ Rule-based feature extraction + Explicit relationship between input data and features	+ Implicit feature extraction + Unsupervised learning of data distribution + Few process knowledge needed for modelling + Simple integration of further process data
Cons:	- Expert / domain knowledge necessary - Mathematical formulation not always possible or very elaborate - A priori knowledge of features to be extracted necessary	- Extracted features typically not interpretable - Data annotation / time consuming / costly

RSS

Data Acquisition & Sensor Fusion

Ls)

1) Sensers within a Data Acquisition System and Signal Processing

+) Definition:
- Stimulus
- Trans ducer: one type energy → another
- Senser: ______ electrical signal

- Sensor includes transducer(s)

+) Classification: sensors
- direct vs hybrid (one or more transducer)
- contact (directly positioned on or inside object) vs noncontact
- active (require energy supply) vs passive

+) The signal chain in digital signal processing

$$\underbrace{\text{Analog Input Signal} \Rightarrow \text{Anti Aliasing Filter} \Rightarrow \text{A/D Converter}}_{\text{Digitalization}} \Rightarrow \underbrace{\text{Digital Signal Processing}}_{\text{Filtering}} \Rightarrow \underbrace{\text{D/A Conversion} \rightarrow \text{Reconstruction Filter} \Rightarrow \text{Analog Output signal}}_{\text{Reconstruction}}$$

+) Sampling: time - continuous → discrete signal

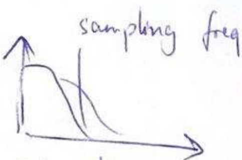
Quantization: continuous - value signal → series of discrete-value signal

Encoding: discrete value and time signal → another digital (binary digital)

+) Ideal Sampling vs Realistic Sampling

Ideal Sampling	Realistic Sampling
narrow Dirac impulse	mean signal value over sampling duration

- Shannon - Nyquist sampling theorem:
  sampling freq must > 2x max freq.



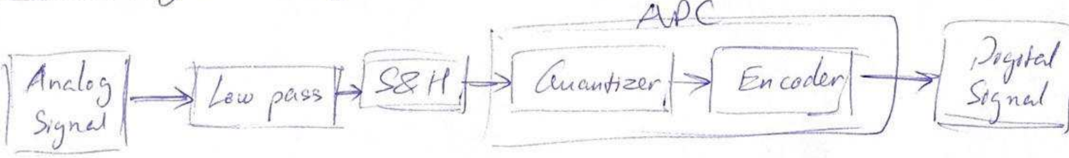
- Anti - aliasing: analog low-pass filter

+) Quantization:
- equipvalent to a rounding operation
- rounding is a irreversable process
- subject to quantization error/ noise

Signal-to-noise ratio (SNR) $SNR_{dB} = 20 \cdot \log_{10}(2^n)$ n: #No bits

+) Binary encoding: # decision thresholds $L = 2^B - 1$
robust in transmission

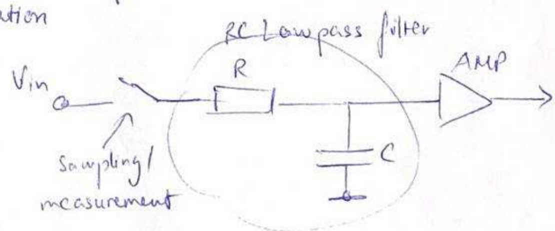
2) Analog-to-digital Converters



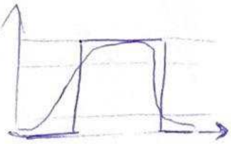
+) Different methods:

Velocity ↓ / Resolution ↑
- Counting method
- Iteration method
- Parallel method
- Parallel - Serial Transformation

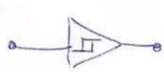
+) Sample and Hold:



+) Schmitt trigger

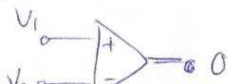


remove noise
well-defined level of signal



when input is between 2 levels ⇒ retain its value (hysteresis)

- Analog Comparator



1 if $V_1 > V_2$
else 0

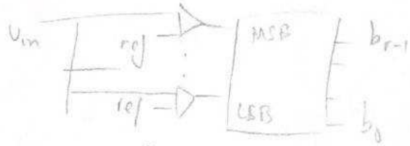
- V/F converter (Voltage-to-freq converter)

$f_{out} \propto V_{in}$: $f_{out} = \frac{V_{in}}{R_{in}} \cdot \frac{1}{t_{os} i}$

- PWM converter :

pulse duration $t_{PWM} \propto V_{in}$: $D = \frac{t_{PWM}}{T_0} = k \cdot V_{in}$

- Flash converter



- SAC converter (Successive-approximation converter)

3) Encoding & digital-to-analog converters

Input signal
↓
Source encoding ⟶ Channel encoding ⟹ Line encoding ⟶ (+) ← Disturbance
Source decoding ⟸ Channel decoding ⟸ Line decoding ⟵
⇓
Transmitted signal

- Source encoding : = data compression (reduce amount of data) ⟹ allow faster transmission
  (discretize, quantize, compress ..)
- Channel encoding : add redundant data, protect against tramission errors
- Line encoding : how data is transferred to binary signal

+) Line encoding

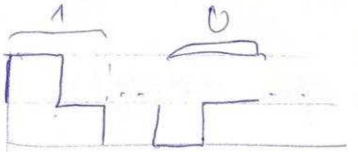
- encoded signals are analog transmitted via TTL (transistor-2 Logic)
  0 vs 1 is less susceptible to interference as continuous analog signals

each environment will influence the signal in different ways
→ thus we have different coding scheme

Binary line code	Block code
RZ (Return to Zero) code	Manchester coding
NRZ (Non ______) code	4B 5B
	Modified Monitored Sum 43 (MMS43)

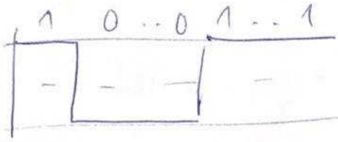
7

- RZ



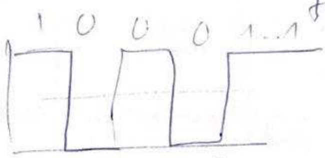
need 3 states
return to neutral state between pulse
self synchronizing
half data rate

- NRZ



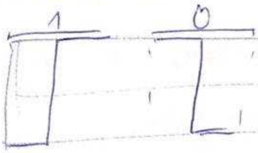
no neutral state
needs synchronization
capacitive problem
full data rate

- Differential NRZ



0: level change vs 1: no level change
full data rate
no probs for long sequences of 0s

- Manchester code



no neutral state
self synchronization
no capacitive prob
half data rate

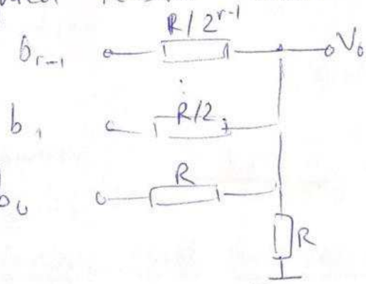
+) DAC

Velocity ↓ / Resolution ↑

Serial method
Serial Parallel Transformation
Parallel method
Parallel - Serial Transformation

- PWM

- Binary weighted resistor circuit



$$V_0 = V_{ref} \cdot \sum_{i=1}^{r} \frac{1}{2^i} b_{r-i}$$

4, Senser fusion techniques:

+) Definition: combining sensory | derived data → better than each individual sensor..

+) Motivation: senser deprivation, limited spatial / temporal coverage imprecision, uncertainty

Complementary fusion	Competitive fusion	Cooperative fusion
not directly depend on other → resolve incompleteness	independent, same property → fault tolerance, robustness	2 independent sensors → info that not available from 1
robot skin & overhead camera	indoor GPS & odometry	Stereo - camera

Signal Preprocessing
Filtering & noise removal

L9/

1) Motivation

- Main / raw signal is mixed with unwanted intefering signal → signal filtering
- How can noise be described & ideally attenuated → noise removal
- Extract relevant characteristics of signal for the task → signal feature extraction

2) Signal Filtering

+) Purpose: - separate useful / relevant signal, - attenuate unwanted part } improve signal quality

+) Types

- Passive filters vs Active filters
  - without power supply — require external power supply
  - just passive elements such as capacitors, coils, resistors, crystals — also active elements (amplifiers / transistors)
- Analog filters vs Digital filters
  - time continuous — time discrete
  - components: [passive, active] — logic components / processors (adder, multiplier, time lags)

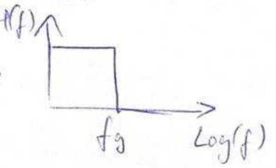
⊕ Analog filters

+) Passive filters | Active filters

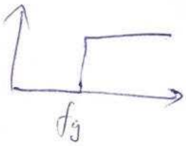
Passive filters	Active filters
high quality requires high effort	high quality factor
×	← amplification

+) Ideal filters:

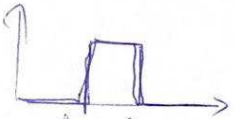
- Low pass: (speaker)



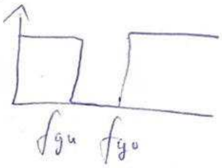
- High pass (pedometer) (sudden events)



- Bandpass (Microphone)

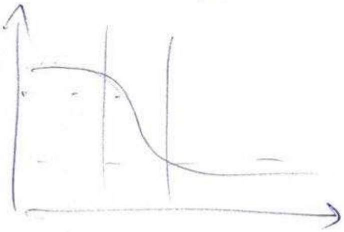


- Bandstop (net hum)

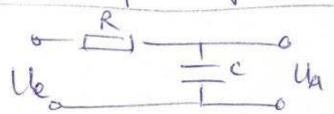


+) Real filters:

- pass band
- filter attenuation band
- transition band
- phase angle φ_g



Passive 1st order low pass filter



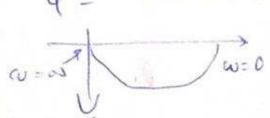
$$H(j\omega) = \frac{1}{1 + j\omega RC}$$

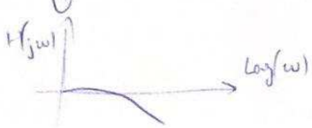
$$= \frac{1}{1 + (\omega RC)^2} - j\frac{\omega RC}{1 + (\omega RC)^2}$$

$$A = |H| = \frac{1}{\sqrt{1 + \omega^2 R^2 C^2}}$$

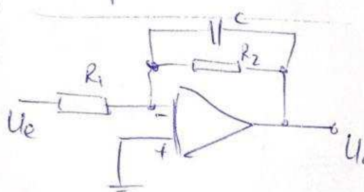
$$\omega_g = \frac{1}{RC}$$

$$\varphi = -\arctan(\omega RC)$$





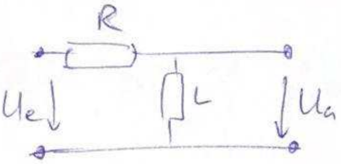
Active low-pass filter



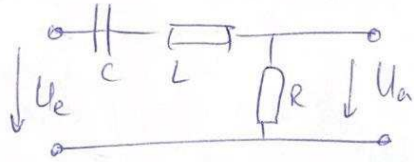
$$H(j\omega) = -\frac{R_2}{R_1} \cdot \frac{1}{1 + j\omega R_2 C}$$

$$= -\frac{R_2}{R_1} \cdot \frac{1}{1 + (\omega R_2 C)^2} + j \cdot \frac{R_2}{R_1} \cdot \frac{\omega R_2 C}{1 + (\omega R_2 C)^2}$$

+) High pass



→ +) Band pass



$$H(j\omega) = \frac{j\omega RC}{1 + j\omega RC - \omega^2 LC}$$

⊗ Digital filters

input 10011000 ..
output 0110011 ..

- Higher reproducibility, precision, flexibility, robustness towards disturbances

+) IIR (Infinite Impulse Response Filter)

- Feedback might cause instabilities

$$y(n) = \sum_{k=0}^{M} b_k \cdot x(n-k) + \sum_{l=1}^{N} a_l \, y(n-l)$$

+) FIR (Finite Impulse Response) Filter

- Never instable

$$y(n) = \sum_{k=0}^{M} b_k \cdot x(n-k)$$

3) Noise

- Signal + Intrinsic noise ⇒ Sensor + Electronics noise

- Stationary noise vs Non-stationary noise
  fixed probability distribution — time-varying distribution

1

+) Some distribution:

- Normal / Gauss
- Uniform
- Maxwell
- Poisson

+) - Mean $E(X) = \mu = \sum x_i p_i = \int x \cdot p(x) . dx$

- Variance: $Var(X) = \sigma_X^2 = E(X^2) - (E(X))^2$

$$= \sum (x_i - E(X))^2 p(x_i)$$

$$= \int (x - E(X))^2 p(x) dx$$

- Standard deviation: $\sigma_X = \sqrt{Var(X)}$
- Properties: $Var(aX+b) = a^2 Var(X)$

$$Var(X+Y) = Var(X) + Var(Y) - 2 . Cov(X, Y)$$

$$Cov(X, Y) = E(X.Y) - E(X) . E(Y)$$

(= 0 if X, Y not correlated)

+) Correlation integral: whether 2 signals are correlated

$$\rho(\tau) = K \int s(t)\ m(t+\tau)\, dt$$

→ $s(t)$ signal func

$m(t)$ reference signal

$$K = \begin{cases} 1 & \text{non-periodic signals} \\ 1/2T & \\ \lim_{t \to \infty} 1/2T & \text{random integrals} \end{cases}$$

- Auto correlation $m(t) = s(t)$
- Usual integral $m(t) = 1$
-
- -

+) Description & Detection of Noise

- Power spectral density $S(\omega)$

$$S(\omega) = \langle F_x(\omega)^2 \rangle = \langle F_x(\omega) F_x^*(\omega) \rangle$$

- Power spektrum

$$S_{xx}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} r_{xx}(t) \cdot e^{-i\omega t} \, dt \,, \qquad r_{xx}(t) = \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{T/2} f(\tau) f(\tau + t) \, d\tau$$

- White noise $\frac{d S_{xx}(\omega)}{d\omega} = \text{const}$

  Colored noise $\frac{d S_{xx}(\omega)}{d\omega} \neq \text{const}$, if $\propto \frac{1}{f} \Rightarrow$ "Pink noise"

  $\propto \frac{1}{f^2} \Rightarrow$ "red noise"

4) Signal extraction techniques

- strategies depend on noise type
- some are unavoidable

+) Bandpass require a priori knowledge

+) Lock-in amplification use reference signal

+) Sensor fusion : Kalman- Filter

- Prediction stage:
$$\hat{x}_k^- = F.\hat{x}_{k-1}^+ + B.u_{k-1}$$
$$P_k^- = F P_{k-1}^+ F^T + Q$$

- Correction stage
$$\tilde{z}_k = y_k - H\hat{x}_k^-$$
$$K_k = P_k^- H^T (R + H P_k^- H^T)^{-1}$$
$$\hat{x}_k^+ = \hat{x}_k^- + K_k \tilde{z}_k$$
$$P_k^+ = (I - K_k H) P_k^-$$

+) RMS (Root Mean Square) to calculate power

$$RMS = \sqrt{\frac{1}{\sqrt{t_2 - t_1}} \int_{t_1}^{t_2} f^2(t)\, dt}$$

$\Rightarrow$ SNR (Signal to Noise Ratio) $= \frac{P_{signal}}{P_{noise}} = \frac{RMS^2_{signal}}{RMS^2_{noise}}$

$$= 20 \log_{10} \frac{RMS_{signal}}{RMS_{noise}}$$

RSS

Communication & Signal Transmission

40)

1) Challenges in data transmission:

- Different forms (text, speech, pics ..)
- Large distances, limited time
- Certain band width

2) Information Systems & Data Transmission principles

- Source → Transmitter → Channel → Receiver → Sink

- Source → Source Encoding → Channel Encoding → Line encoding → Modulation : assignment of | carrier signal to the message / custom physical transmitter

- Classification Modulation
  - Continuous in time
    - Continuous values: analog modulation
    - Discrete values: digital modulation
    - } Carrier signal: Sinusoidal oscillation
  - Discrete in time
    - Discrete values
    - Continuous values
    - } Pulse - carrier process

+) Amplitude Modulation (AM)

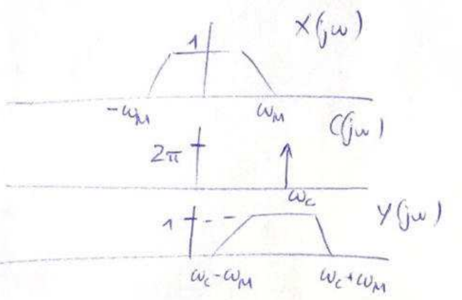
- AM using complex exponential carrier

$c(t) = e^{j(\omega_c t + \theta_c)}$

If $\theta_c = 0 \Rightarrow y(t) = x(t) \cdot e^{j\omega_c t}$

$Y(j\omega) = X(j\omega - j\omega_c)$

$C(j\omega) = 2\pi\, \delta(\omega - \omega_c)$



- Sinusoidal carrier: $c(t) = \cos(\omega_c t + \theta_c)$

If $\theta_c = 0 \Rightarrow C(j\omega) = \pi\left[\delta(\omega-\omega_c) + \delta(\omega+\omega_c)\right]$

$$Y(j\omega) = \frac{1}{2}\left[X(j\omega - j\omega_c) + X(j\omega + j\omega_c)\right]$$

Synchronous Demodulation of AM signals: $w(t) = y(t) \cdot \cos(\omega_c t)$

$$= \frac{1}{2}x(t) + \frac{1}{2}x(t)\cos(2\omega_c t)$$

$\Rightarrow$ low pass filter for $\frac{1}{2}x(t)$

- Asynchronous demodulation of AM: envelop detector
- Multiplexing
- Single - side band AM: $H(j\omega) = \begin{cases} -j & \omega > 0 \\ +j & \omega < 0 \\ 0 & \omega = 0 \end{cases}$

+) Frequency Modulation (FM)

- Require larger bandwidth
- Not linear
- More effort required to be analyzed

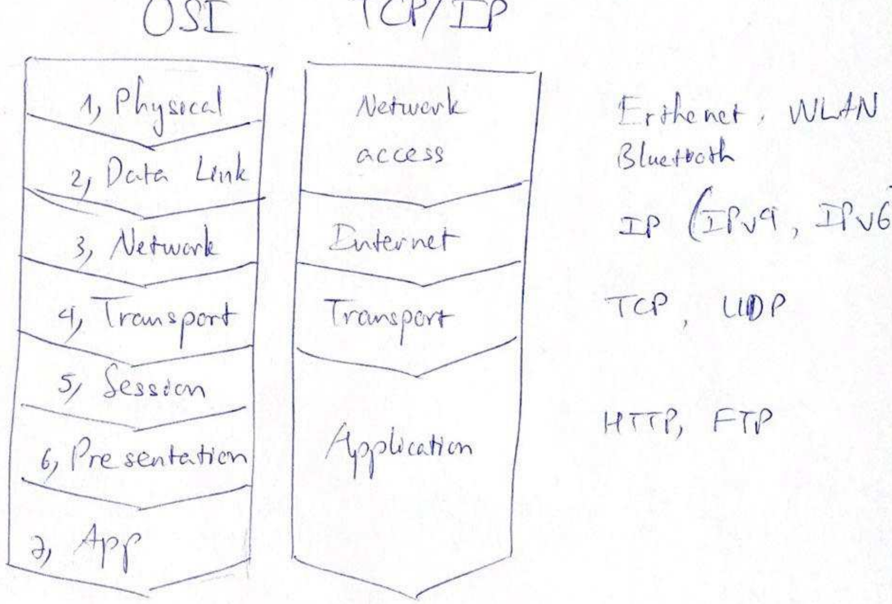
3) Transmission Media

- Cable-based Transmission
- Wireless: Antenna
- Mobile communications standards
- 5G

4) Network topologies & data transmission protocols

⊕) Topologies:
- P2P
- Bus
- Field buses

⊗ Protocols



5, Robot communication with ROS

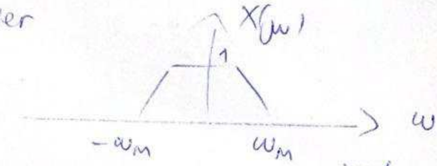
- Publisher node – subscriber node

- ROS messages

+) AM using complex exponential carrier

$c(t) = e^{j(\omega_c t + \theta_c)}$

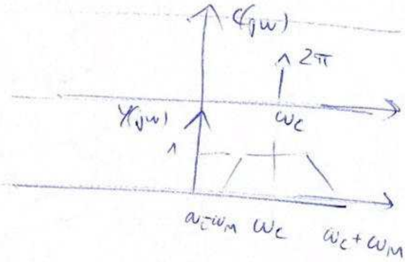
$y(t) = x(t).c(t)$



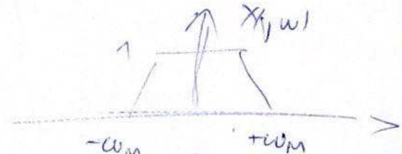
- If $\theta_c = 0 \Rightarrow y(t) = x(t).e^{j\omega_c t} \Rightarrow x(t) = y(t)e^{-j\omega_c t}$

- $C(j\omega) = 2\pi\delta(\omega-\omega_c)$

  $Y(j\omega) = X(j(\omega-\omega_c))$



+) AM using sinusoidal carrier signal.

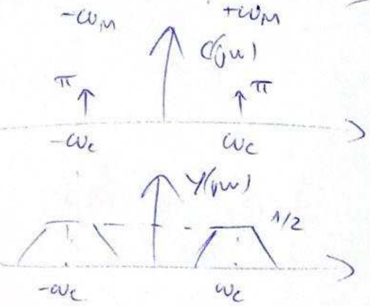


. $c(t) = \cos(\omega_c t + \theta_c)$

- If $\theta_c = 0 \Rightarrow y(t) = x(t).\cos(\omega_c t)$

- $C(j\omega) = \pi\left[\delta(\omega-\omega_c) + \delta(\omega+\omega_c)\right]$

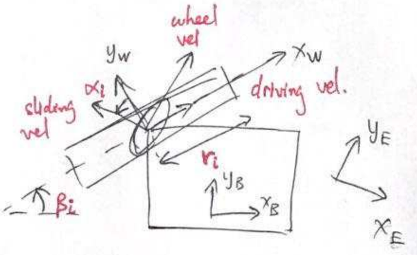
  $Y(j\omega) = \frac{1}{2}\left[X(j(\omega-\omega_c)) + X(j\omega+j\omega_c)\right]$



$\omega_c > \omega_M$, else leads to overlap

RSS Formulas

2) $u_i = \frac{1}{r_i} \begin{bmatrix} 1 & \tan\alpha_i \end{bmatrix} \begin{bmatrix} c\beta_i & s\beta_i \\ -s\beta_i & c\beta_i \end{bmatrix} \begin{bmatrix} -p_{y,i} & 1 & 0 \\ p_{x,i} & 0 & 1 \end{bmatrix} \begin{bmatrix} \omega_z \\ v_x \\ v_y \end{bmatrix} = H_i v$



$1 \to 2$: ${}^{1}T_2$ (2 in coord. 1) $\quad {}^{B}T_W \quad {}^{W}T_{v_B} \quad {}^{E}v_B$

3) Gauss law $\quad \Phi_E = \oint \vec{E}\, d\vec{A} = \frac{Q_{end}}{\varepsilon_0}$; $\vec{D} = \varepsilon \vec{E}$, $\vec{\nabla}\vec{E} = \frac{\rho}{\varepsilon_0}$, $\vec{\nabla}\vec{D} = \rho$

$\Phi_B = \oint \vec{B}\, d\vec{A} = 0$; $\vec{H} = \frac{\vec{B}}{\mu_0}$, $\vec{\nabla}\vec{B} = 0$ (div)

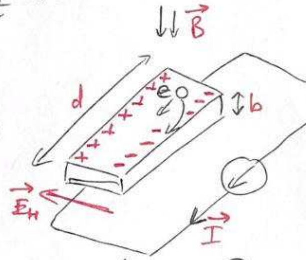
MF $\quad \vec{\nabla} \times \vec{E} = \frac{-\partial \vec{B}}{\partial t}$ (curl) , $\oint \vec{E}\, d\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} d\vec{A}$

Ampere circuital law $\quad \vec{\nabla} \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}$, $\oint \vec{H}\, d\vec{s} = \iint \vec{j}\, d\vec{A} + \iint \frac{\partial \vec{D}}{\partial t} d\vec{A}$

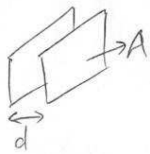
Lorentz force $\quad \vec{F} = q\vec{v}\vec{B} = \vec{I}\vec{B}\, l$

Hall effect: $\quad q\vec{E}_H = q\vec{v}\vec{B} = q\frac{\vec{U}_H}{d}$, $\quad \vec{v}_D = \frac{1}{n.Q} \cdot \frac{\vec{I}}{b.d}$

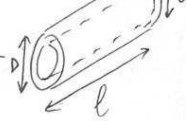
$U_H = \vec{v}_D \vec{B}\, d = \frac{\vec{I}}{nQ} \frac{\vec{B}}{b} = \underset{\text{Hall const}}{R_H} \cdot \frac{\vec{I}\vec{B}}{b}$



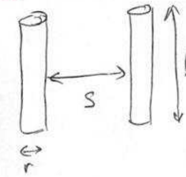
4) $C = \frac{\varepsilon_0 \varepsilon_r A}{d}$



; $\frac{2\pi \varepsilon_0 \varepsilon_r l}{\ln \frac{D}{d}}$



; $\frac{\pi \varepsilon_0 \varepsilon_r l}{\ln \frac{s}{r_0}}$ $\quad s \gg r_0$



$Q = d.F = C_A . U_A \Rightarrow U_A = \frac{d.F}{C_A}$ $\quad$ (d - piezo coeff.)

$\tau = R.C \Rightarrow U(t) = U_0 . e^{-t/\tau}$

$\underset{\text{longitudinal}}{Q_x = d_{11} . F_x}$, $\underset{\text{transversal}}{Q_y = d_{12} \frac{l_y}{l_x} F_y}$, $d_{12} = -d_{11}$

5) $c_0 = f.\lambda$ $\quad$, $c_0 = 3.10^8$ m/s $\approx 1{,}079e^9$ km/h

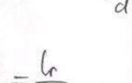
$E_\lambda = h.f = h.\frac{c}{\lambda}$, h Planck const.

$E_{kin} = hf - W_A$

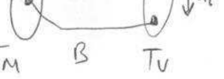
$f_{obs} = \frac{f_{send}}{1 - \frac{v}{c}}$ (sour $\leftrightarrow$) , $f_{obs} = f_{send}\left(1 - \frac{v}{c}\right)$ (obs $\leftrightarrow$)

$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\delta$, $\quad \delta = \varphi_2 - \varphi_1$

6) $\Delta V = V_0 . \beta . \Delta T$, $\quad S = \frac{dh}{dT} = \frac{V_0 \beta}{\pi r^2}$; $\quad y = \alpha \frac{l^2}{d} \Delta T$



$U_T = K_{A/Pt}(T_M - T_V) + K_{B/Pt}(T_V - T_M)$
$= K_{AB}(T_M - T_V)$



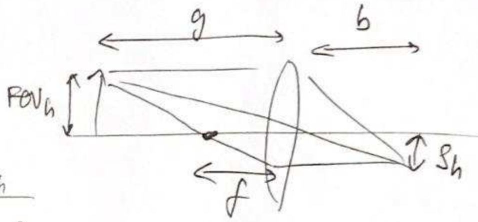
$Z = c.\rho$

$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \Rightarrow R^2 = \rho = \frac{I_r}{I_v}$

$T = 1 - R^2$

7) $M = \frac{S_h}{FOV_h} = \frac{b}{g}$ (magnification)

$\frac{1}{f} = \frac{1}{b} + \frac{1}{g} \Rightarrow f = \frac{g \cdot S_h}{FOV_h + S_h}$



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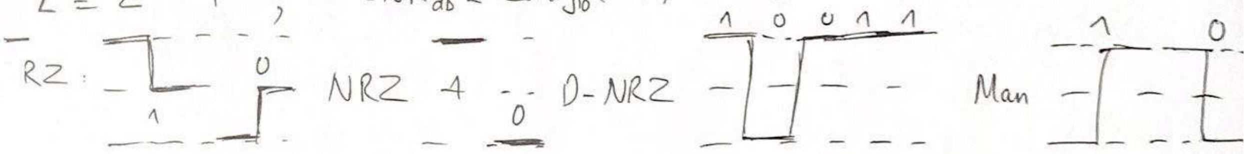
$r = x \cdot \cos\theta + y \cdot \sin\theta$ | $g(x,y) = \sum_{s=-a}^{a} \sum_{t=-b}^{b} \omega(s,t) \cdot f(x+s, y+t)$

8) $L = 2^B - 1$; $SNR_{dB} = 20 \cdot \log_{10}(2^n)$, n: #No. bits



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$V_0 = V_{ref} \sum_{i=1}^{r} \frac{1}{2^i} b_{r-i}$

9) $\omega_c \Leftrightarrow A = \frac{1}{\sqrt{2}}$

—

FIR: $y(n) = \sum_{k=0}^{M} b_k \, x(n-k)$

—

~~$r_{xx}(\tau) = K \int s(t) \cdot s(t+\tau)\, dt$~~

$r_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} s(t)\, s(t-\tau)\, dt$ auto correlation

$\rho(\tau) = K \int s(t)\, m(t+\tau)\, dt$ cross-corr.

$K = \begin{cases} 1 & \text{non-periodic} \\ 1/2\text{-}T & \text{———} \\ \lim_{T\to\infty} 1/2T & \text{random} \end{cases}$

10) $c(t) = e^{j(\omega_c t + \theta_c)}$

$y(t) = x(t) \cdot c(t)$

$C(j\omega) = 2\pi \cdot \delta(\omega - \omega_c)$

$Y(j\omega) = X(j\omega - j\omega_c)$

$c(t) = \cos(\omega_c t + \theta_c)$

$y(t) = x(t) \cdot \cos(\omega_c t)$

$C(j\omega) = \pi\left[\delta(\omega-\omega_c) + \delta(\omega+\omega_c)\right]$

$Y(j\omega) = \frac{1}{2}\left[X(j\omega - j\omega_c) + X(j\omega + j\omega_c)\right]$

Ng Huu Duc