Sensors

Robotics 1

Robot components:
Introduction, Actuators, Transmissions

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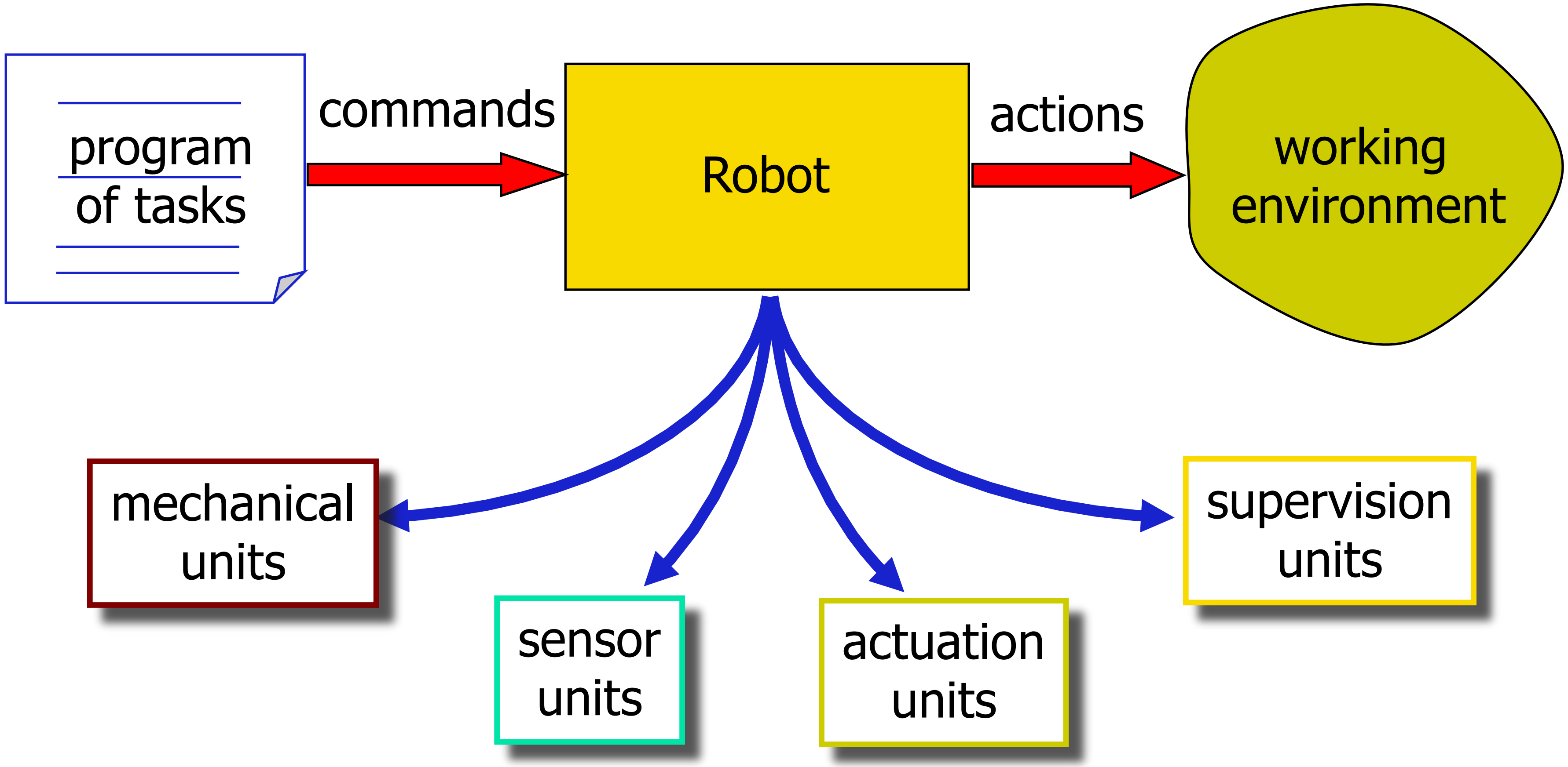
Robot as a system

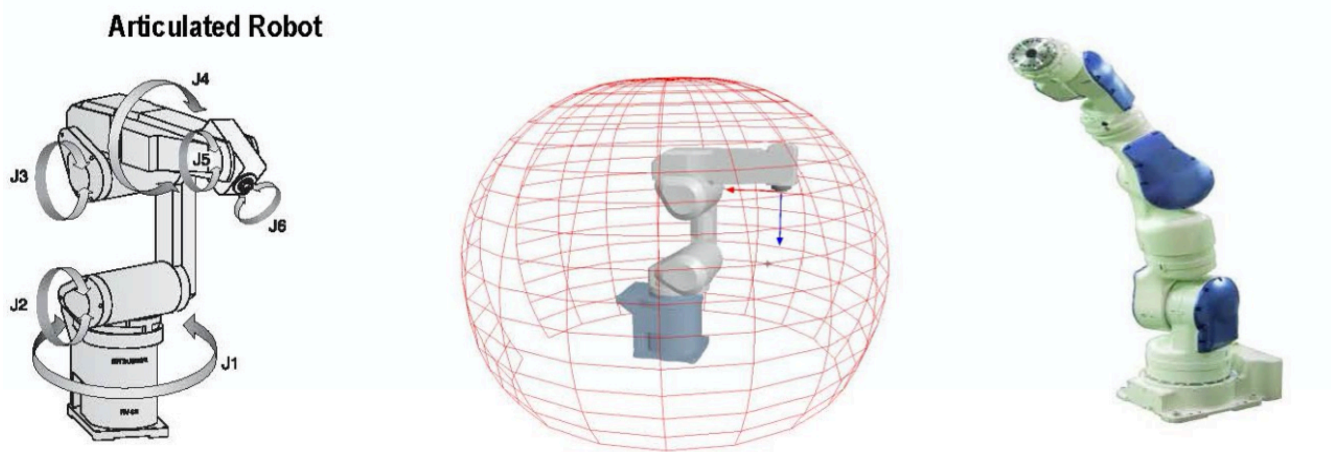


Functional units of a robot

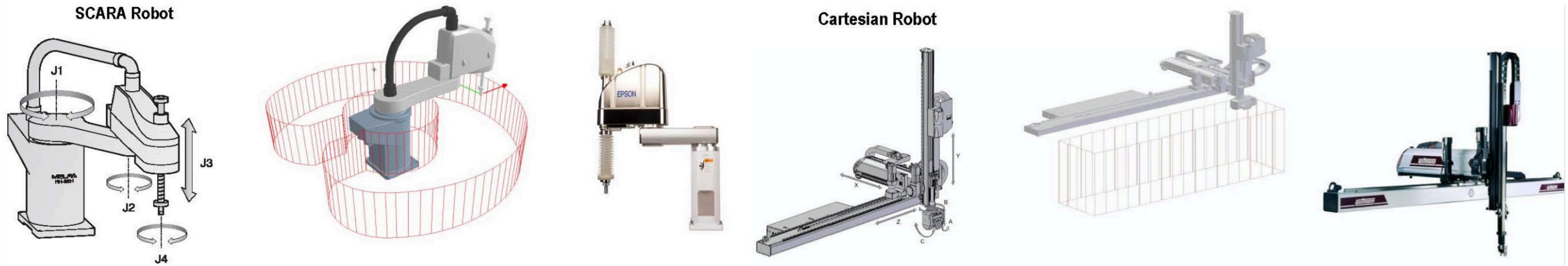
- mechanical units (robot arms)
  - serial manipulators: rigid links connected via rotational or prismatic joints (each giving 1 degree of freedom = DOF)
  - supporting structure (mobility), wrist (dexterity), end-effector (for task execution, e.g., manipulation)
- actuation units
  - motors (electrical, hydraulic, pneumatic) and transmissions
  - motion control algorithms
- sensor units
  - proprioceptive (internal robot state: position and velocity of the joints)
  - exteroceptive (external world: force and proximity, vision, …)
- supervision units
  - task planning and control
  - artificial intelligence and reasoning

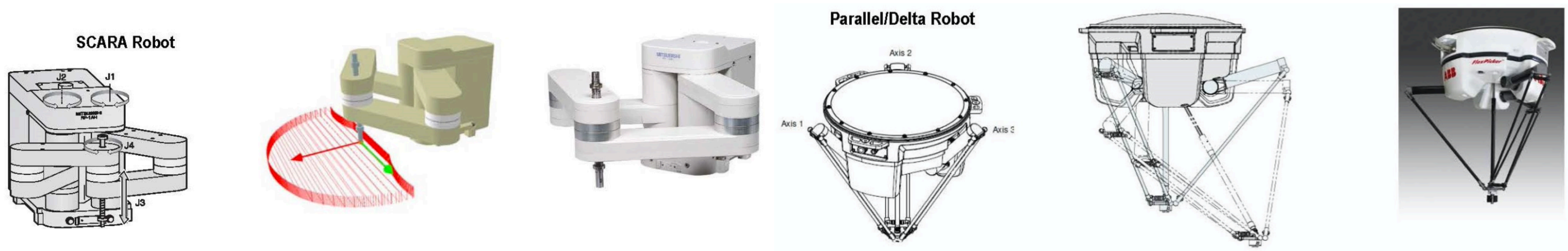
Arrangement of mechanical links

4, 5, or 6 joints (DOFs)



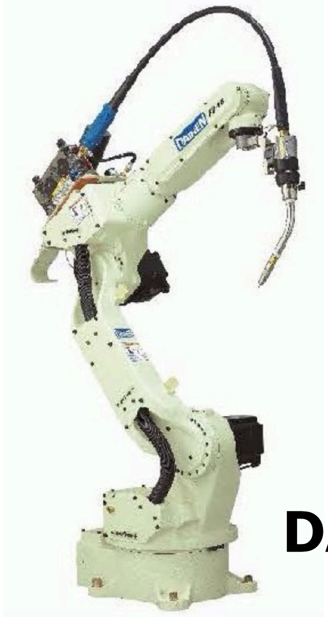
different kinematic types of robot arms





Examples of industrial robots
with brands

ABB



DAIHEN

EPSON

FANUC

KUKA

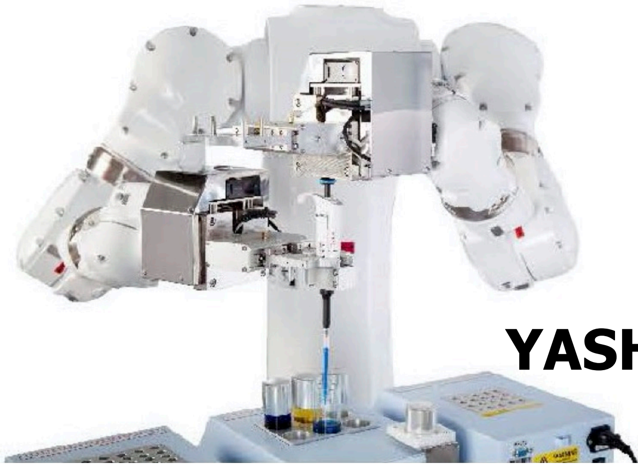
NAICHI

Bi-manual industrial robots
with brands

ABB

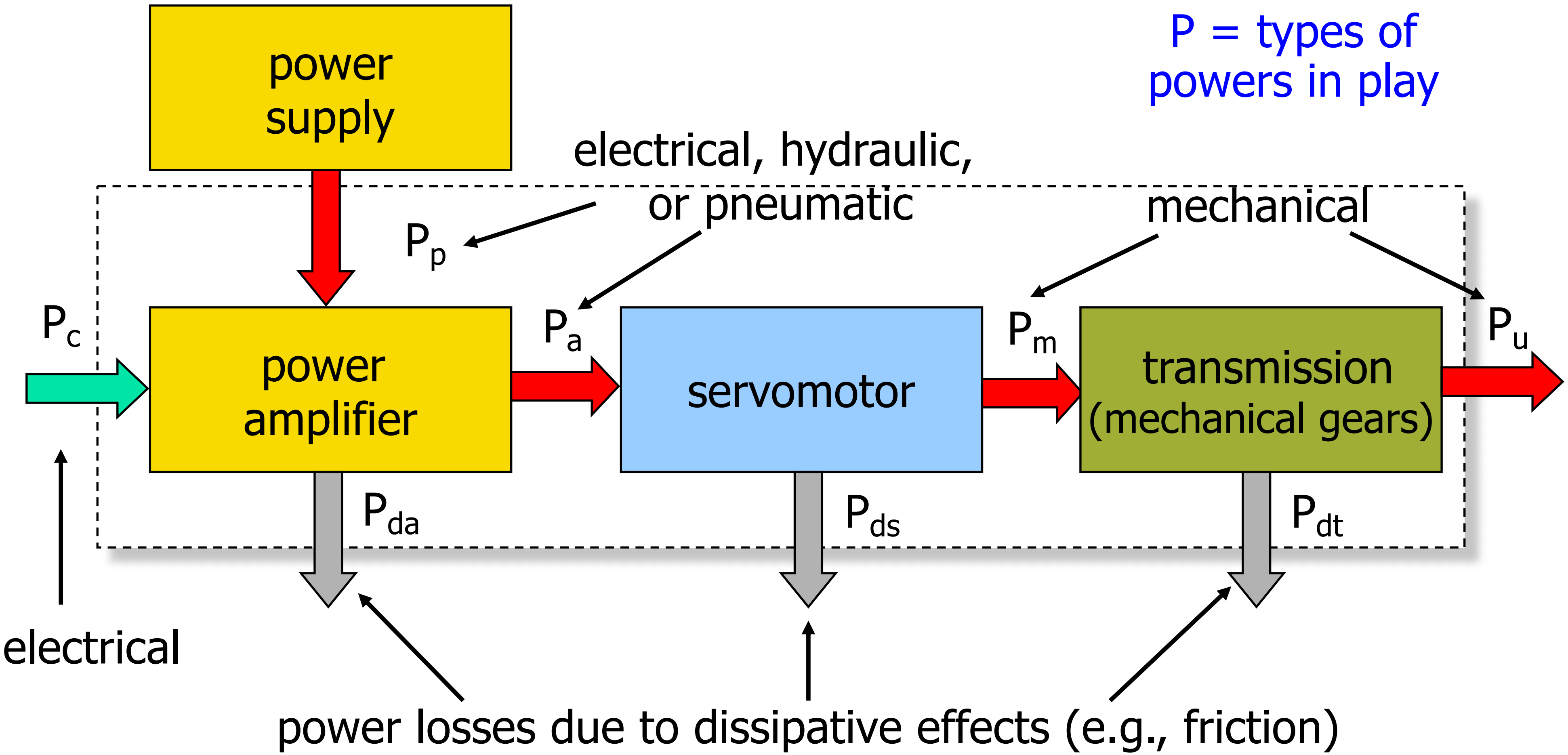
COMAU

UNIVERSAL ROBOTS



YASHKAWA

Actuation systems

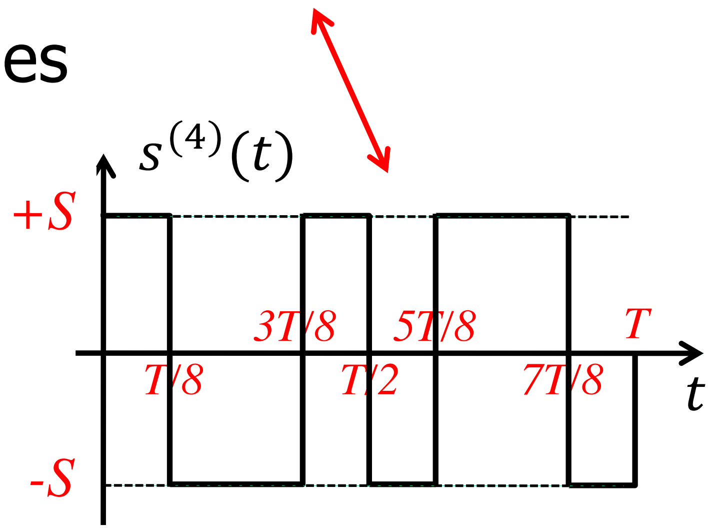


power = voltage · current = pressure · flow rate = force · speed = torque · angular speed [W, Nm/s]

efficiency = power out/power in [%] energy ~ work = power · time [kWh, Nm, J]

Desired characteristics for robot servomotors

- low inertia
- high power-to-weight ratio
- high acceleration capabilities
  - variable motion regime, with several stops and inversions
- large range of operational velocities
  - 1 to 2000 rpm (round per min)
- high accuracy in positioning
  - at least 1/1000 of a turn
- low torque ripple
  - continuous rotation at low speed
- power: 10 W to 10 kW



Servomotors

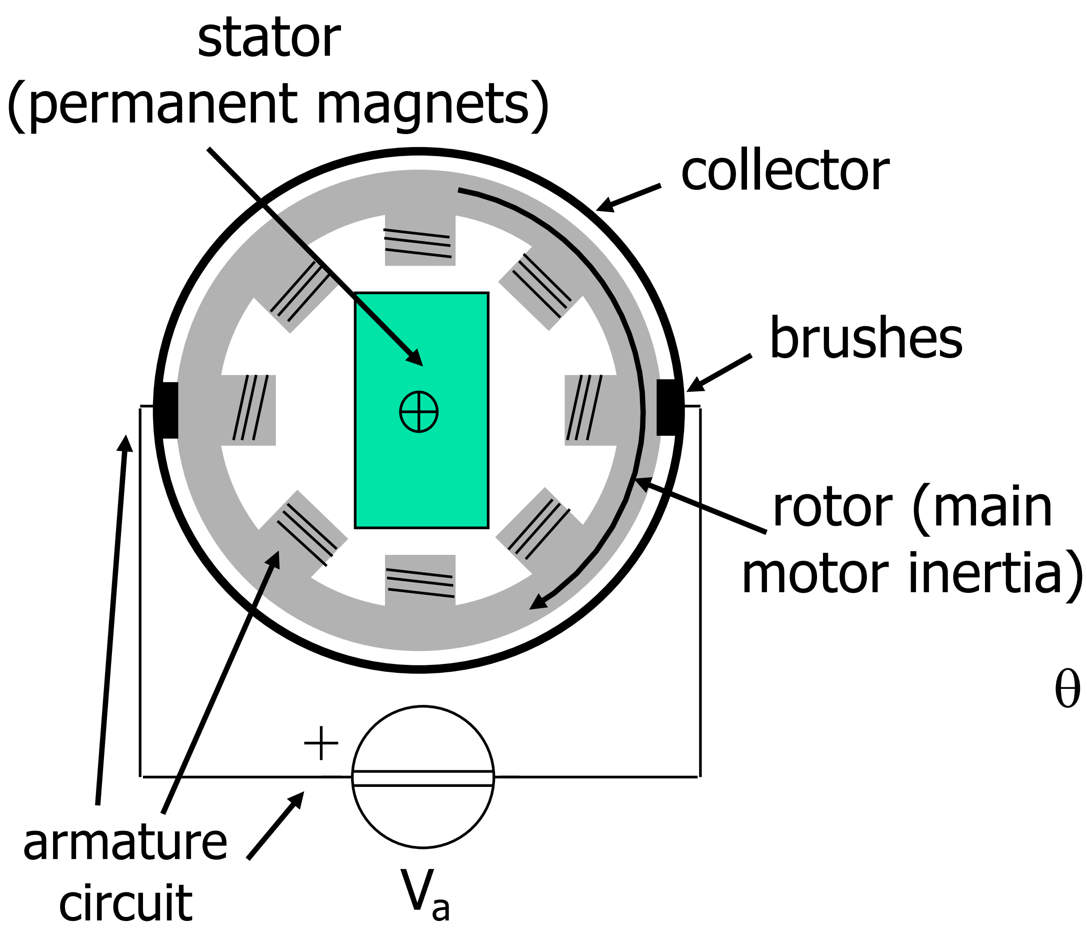
- pneumatic: pneumatic energy (compressor) $\rightarrow$ pistons or chambers $\rightarrow$ mechanical energy
  - difficult to control accurately (change of fluid compressibility) $\rightarrow$ no trajectory control
  - used for opening/closing grippers
  - ... or as artificial muscles (McKibben actuators)

- hydraulic: hydraulic energy (accumulation tank) $\rightarrow$ pumps/valves $\rightarrow$ mechanical energy
  - advantages: no static overheating, self-lubricated, inherently safe (no sparks), excellent power-to-weight ratio, large torques at low velocity (w/o reduction)
  - disadvantages: needs hydraulic supply, large size, linear motion only, low power conversion efficiency, high cost, increased maintenance (oil leaking)

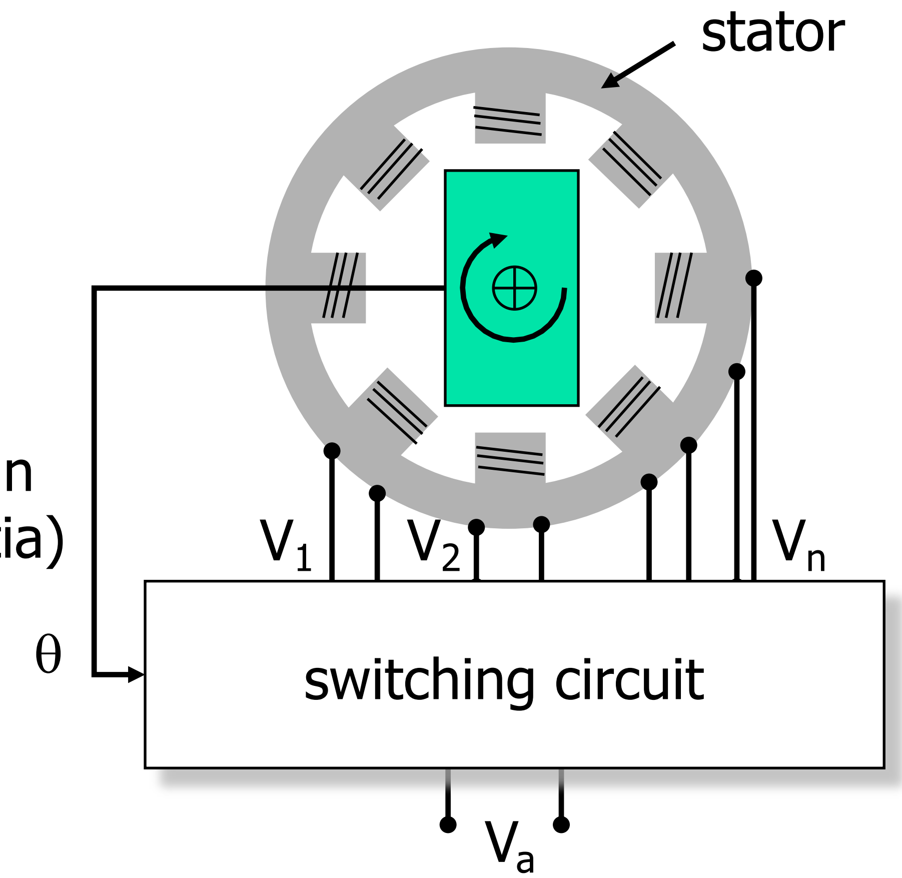
Electrical servomotors

- advantages
  - power supply available everywhere
  - low cost
  - large variety of products
  - high power conversion efficiency
  - easy maintenance
  - no pollution in working environment
- disadvantages
  - overheating in static conditions (in the presence of gravity)
    - use of (emergency) brakes
  - need special protection in flammable environments
  - some advanced models require more complex control laws

Electrical servomotors for robots



direct current (DC) motor



with electronic switches (brushless)

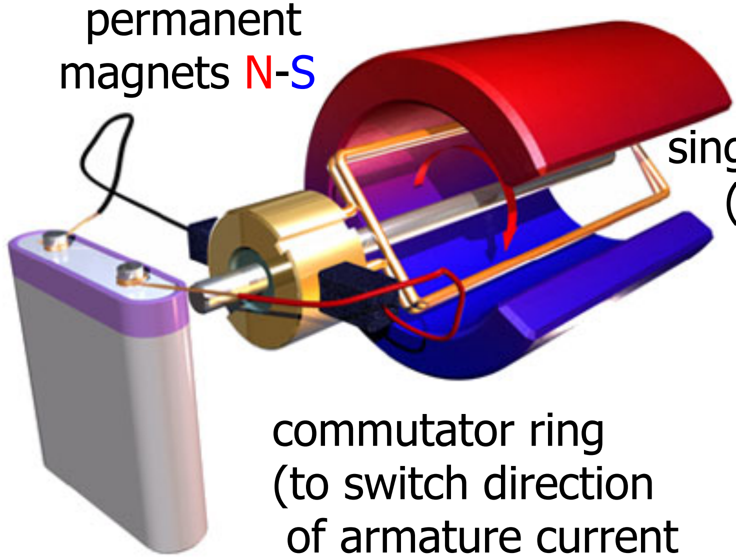
Advantages of brushless motors

- reduced losses, both electrical (due to tension drops at the collector-brushes contacts) and mechanical (friction)
- reduced maintenance (no substitution of brushes)
- easier heat dissipation
- more compact rotor (less inertia and smaller dimensions)

… but indeed a higher cost!

Principle of operation of a DC motor

permanent
magnets N-S

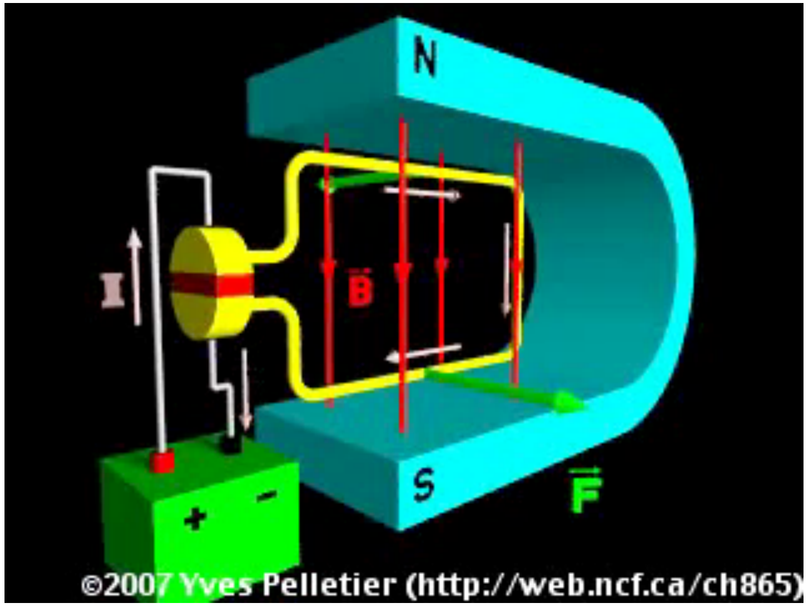


single coil
(armature)

commutator ring
(to switch direction
of armature current
every half round)

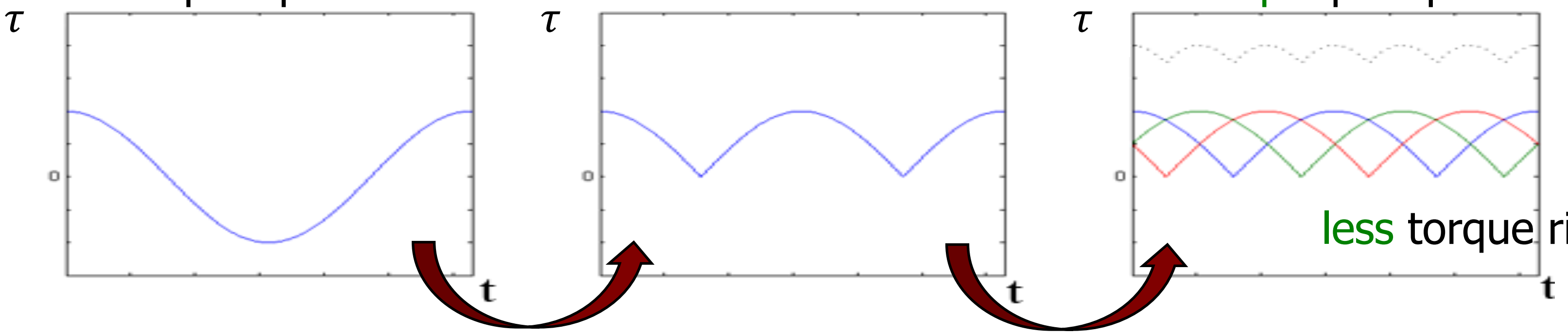
DC supply
v_a

video



$$\vec{F} = L(\vec{\imath} \times \vec{B}) \qquad \tau = d\left|\vec{F}\right|$$

1 pole pair ... ... + commutator multiple pole pairs



less torque ripple!

see also other video at https://www.youtube.com/watch?v=LAtPHANEfQo

DC electrical motor

mathematical model (in the time domain)

electrical balance
(on the equivalent armature circuit)

$$v_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + v_{emf}(t)$$

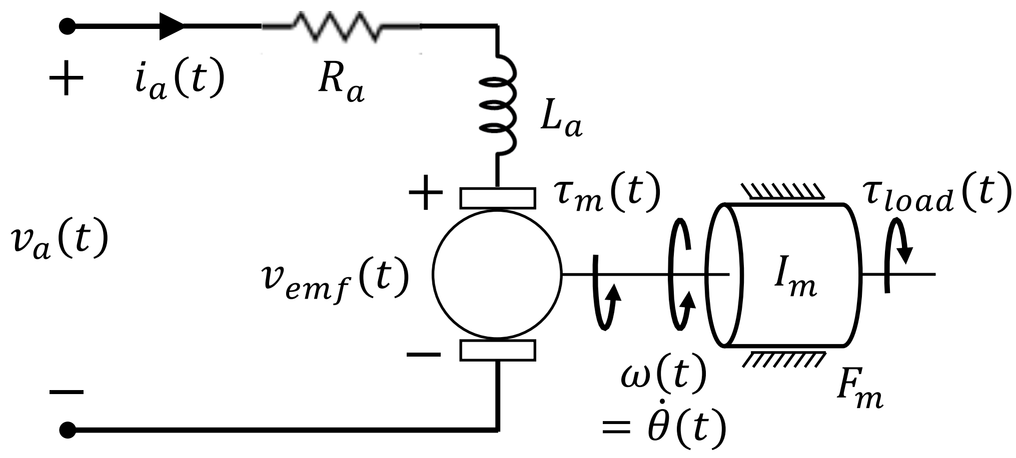
$$v_{emf}(t) = k_v \omega(t)$$

(back emf)

in the absence of losses, conservation of power holds in energy transformations

$$P_{elec} = v_{emf} i_a = \tau_m \omega = P_{mecc}$$

$$\Longrightarrow \quad k_v = k_t \qquad \text{(in SI units)}$$



mechanical balance
(Newton law on torques)

$$\tau_m(t) = I_m(t) \frac{d\omega(t)}{dt} + F_m \omega(t) + \tau_{load}(t)$$

$$\tau_m(t) = k_t i_a(t)$$

(motor torque)

using Laplace transform, differential equations become algebraic relations!

$$X(s) = \mathcal{L}[x(t)] = \int_0^\infty x(t) e^{-st}\, dt$$

DC electrical motor

mathematical model for command and control

electrical balance

$$V_a = (R_a + sL_a)\, I_a + V_{emf}$$

$$V_{emf} = k_v\, \Omega$$

Laplace domain (transfer functions)

$$\tau_{elec} = \frac{L_a}{R_a} \ll \frac{I_m}{F_m} = \tau_{mecc}$$

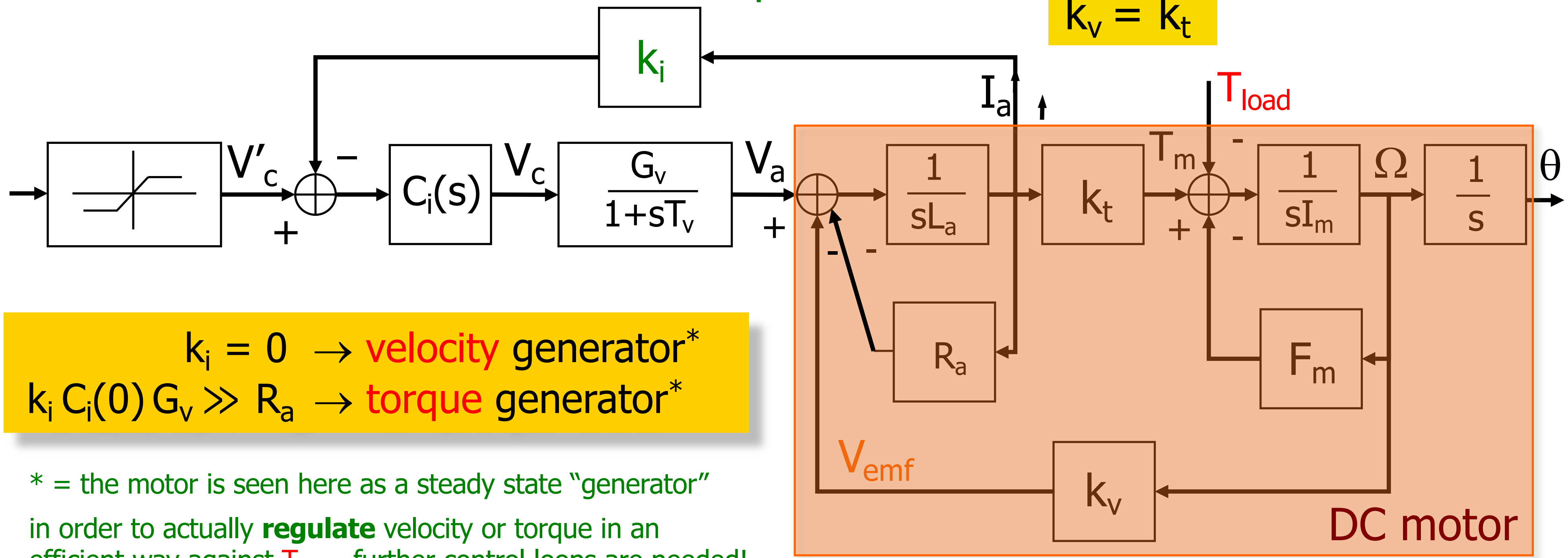
mechanical balance

$$T_m = (sI_m + F_m)\, \Omega + T_{load}$$

$$T_m = k_t\, I_a$$

current loop

$k_v = k_t$



$k_i = 0 \;\rightarrow$ velocity generator*

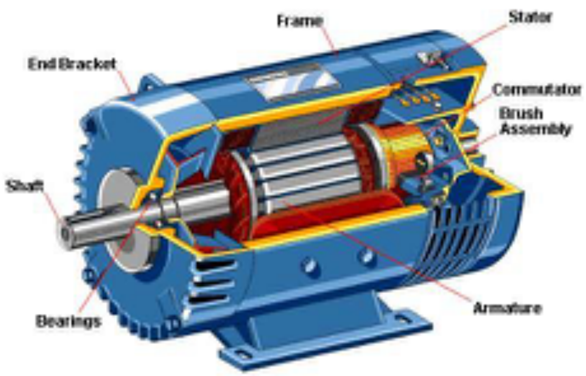
$k_i\, C_i(0)\, G_v \gg R_a \;\rightarrow$ torque generator*

* = the motor is seen here as a steady state "generator"

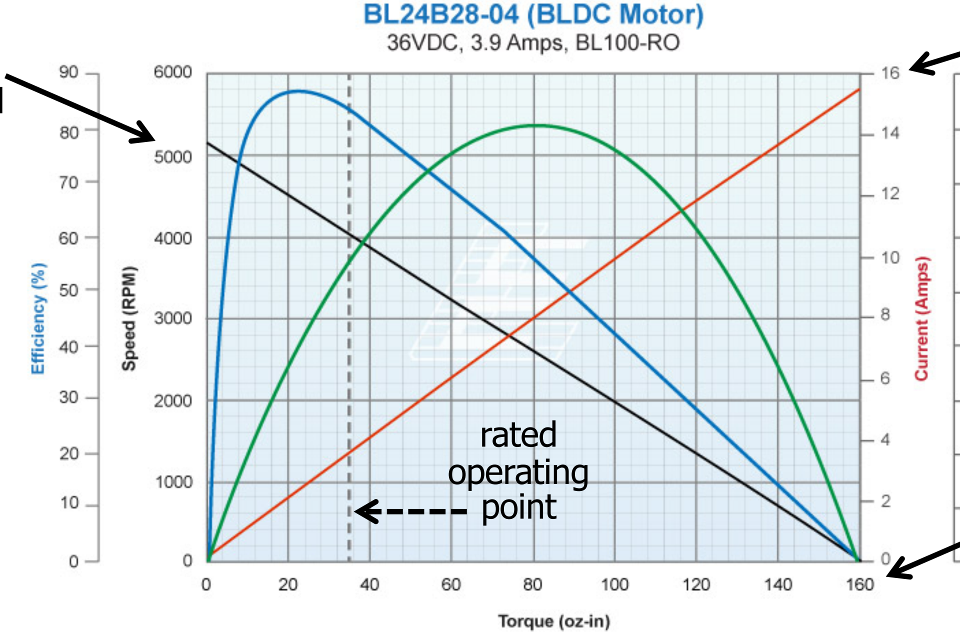
in order to actually **regulate** velocity or torque in an efficient way against T_{load}, further control loops are needed!

Characteristic curves of a DC motor

at steady-state,
for constant
applied tension v_a



no-load
max speed

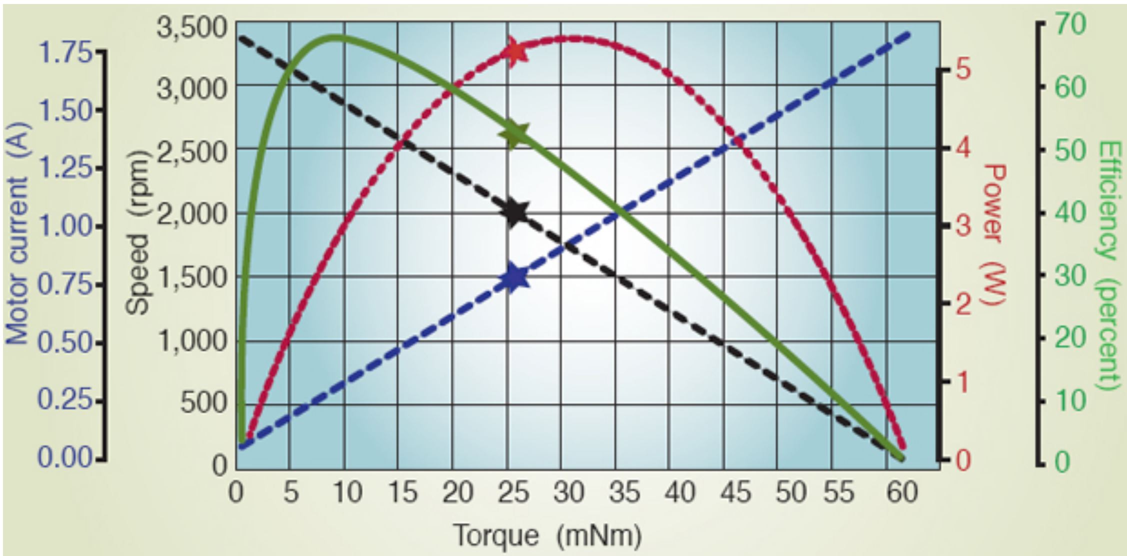


stall current

stall
load torque

medium
size
motor
160 W

conversion SI ⇔ US
unit systems (!!)
1 Nm = 141.61 oz-in
100 oz-in = 0.70 Nm



small
size
motor
5.5 W

Data sheet electrical motors

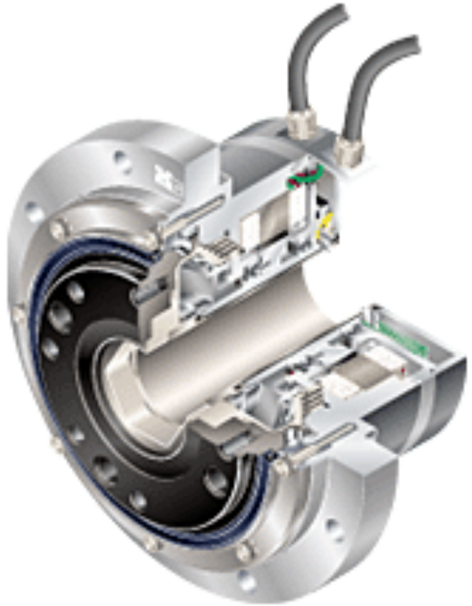
- DC drives

Model of actuator		RHS-14		RHS-17		RHS-20/RFS-20				RHS-25/RFS-25				RHS-32/RFS-32			
		6003	3003	6006	3006	6007	3007	6012	3012	6012	3012	6018	3018	6018	3018	6030	3030
Rated Torque	Inlb	48	69	87	177	106	212	177	266	177	354	266	531	266	531	443	885
	Nm	5.4	7.8	9.8	20	12	24	20	30	20	40	30	60	30	60	50	100
Rated Speed of Rotation	rpm	60	30	60	30	60	30	60	30	60	30	60	30	60	30	60	30
Max. Instant. Torque	Inlb	159	248	301	478	504	743	504	743	885	1416	885	1416	1947	3009	1947	3009
	Nm	18	28	34	54	57	84	57	84	100	160	100	160	220	340	220	340
Max.Speed of Rotation	rpm	100	50	80	40	80	40	80	40	80	40	80	40	80	40	80	40

nominal/peak torques and speeds

Data sheet electrical motors

- AC drives



	unit	HKM-20-60	HKM-20-30	HKM-25-60	HKM-25-30
Rated Power	Watts	100		200	
Rated Torque	in-lb	115	223	233	440
	N-m	13	26	26	50
Maximum Torque	in-lb	345	700	830	1330
	N-m	39	79	94	150
Rated Speed	r/min	60	30	60	30
Maximum Speed	r/min	80	40	80	40
Current Rated	A	1.8	1.4	4.8	3
Current Max	A	5	4	14	9
Thermal Time Constant	min.				
Gear Reduction Ratio	R:1	50	100	50	100
Output Resolution	P/rev	50,000	100,000	75,000	150,000
	arc sec	26	13	17	9
Absolute Accuracy	+/- arc sec	75	40	60	40

- for applications requiring a rapid and accurate response (in robotics!)
- induction motors driven by alternate current (AC)
- small diameter rotors, with low inertia for fast starts, stops, and reversals

Motion transmission gears

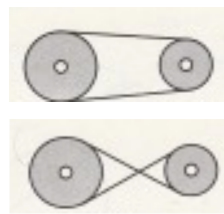
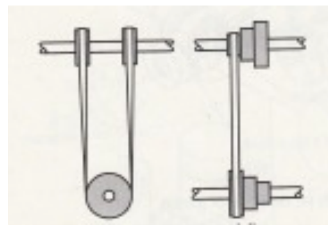
- optimize the transfer of mechanical torque from actuating motors to driven links
- quantitative transformation (from low torque/high velocity to high torque/low velocity)
- qualitative transformation (e.g., from rotational motion of an electrical motor to a linear motion of a link along the axis of a prismatic joint)
- allow improvement of static and dynamic performance by reducing the weight of the actual robot structure in motion (locating the motors remotely, closer to the robot base)

Transmissions in robotics

- spur gears: modify direction and/or translate axis of (rotational or translational) motor displacement
  - problems: deformations, backlash


- lead screws, worm gearing: convert rotational into translational motion (prismatic joints)
  - problems: friction, elasticity, backlash


- toothed belts and chains: dislocate the motor w.r.t. the joint axis
  - problems: compliance (belts) or vibrations induced by larger mass at high speed (chains)

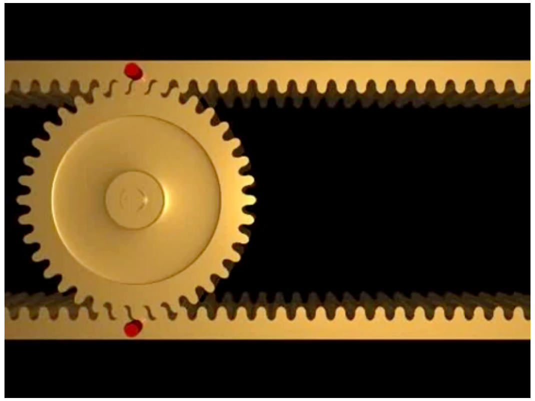



- harmonic drives: compact, in-line, power efficient, with high reduction ratio (up to 150-200:1)
  - problems: elasticity

- transmission shafts: long, inside the links, with flexible couplings for alignment

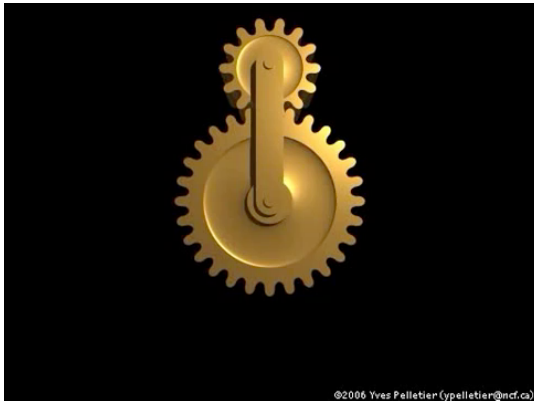

Transmission gears in motion

- racks and pinion
  - one rack moving (or both)



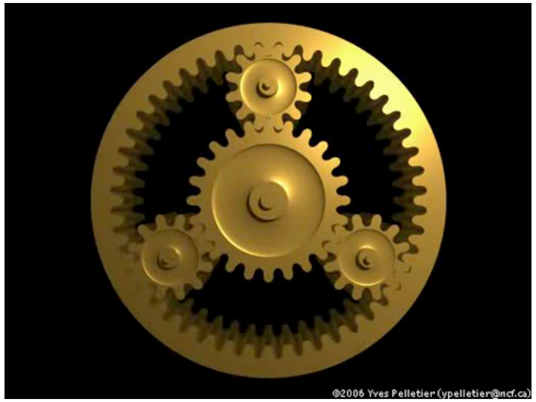
video

- epi-cycloidal gear train
  - or hypo-cycloidal (small gear inside)



video

- planetary gear set
  - one of three components is locked: sun gear, planet carrier, ring gear



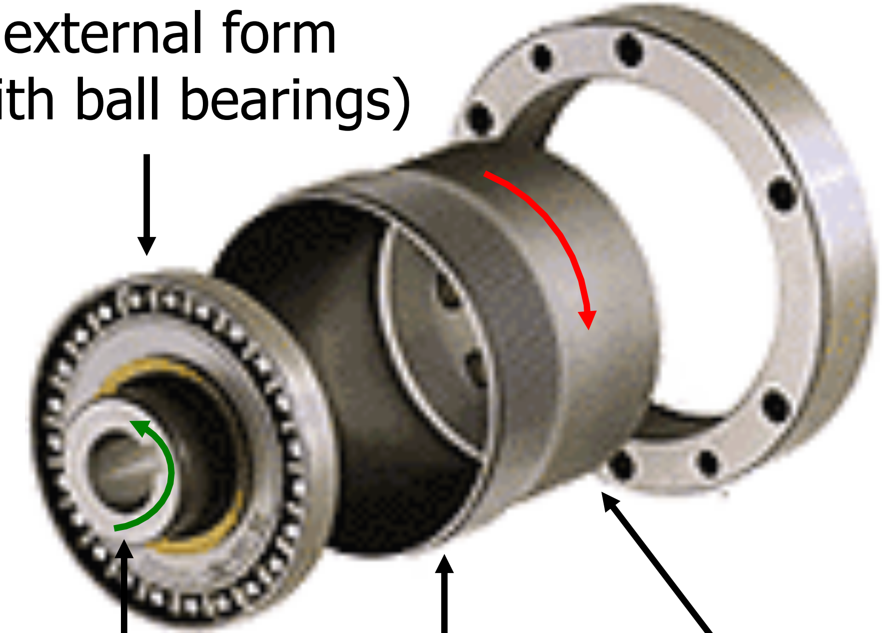
video

Harmonic drives

video

Wave Generator
of slightly elliptic
external form
(with ball bearings)

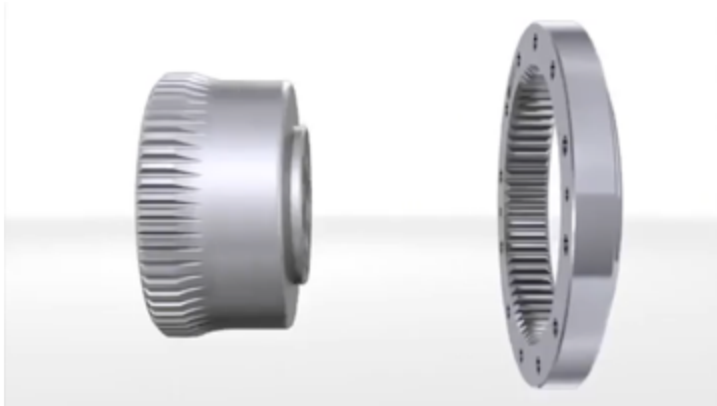
Circular Spline



FlexSpline
(two contact points)

input from motor

output to load



inner #teeth CS = outer #teeth FS + 2

reduction ratio

n = #teeth FS / (#teeth CS - #teeth FS)
= #teeth FS / 2

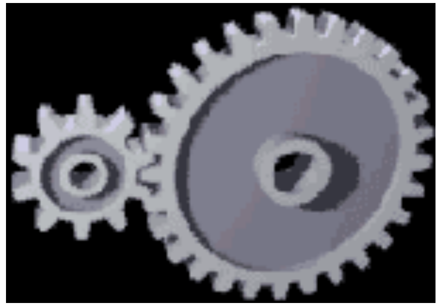
Operation of an harmonic drive

commercial video by Harmonic Drives AG
(https://www.youtube.com/watch?v=bzRh672peNk)

Optimal choice of reduction ratio

motor $\xrightarrow{P_m}$ transmission gear $\xrightarrow{P_u}$ link

$\downarrow P_{dt}$ power dissipated by friction



ideal case (no friction)

$$P_m = T_m\, \dot{\theta}_m = T_u\, \dot{\theta}_u = P_u$$

torque × angular speed

n = reduction ratio ($\gg$1) $\qquad \dot{\theta}_m = n\, \dot{\theta}_u \quad \Rightarrow \quad T_u = n\, T_m$

to have $\ddot{\theta}_u = a$ (thus $\ddot{\theta}_m = n\, a$), the motor should provide a torque

$$T_m = J_m\, \ddot{\theta}_m + 1/n\, (J_u\, \ddot{\theta}_u) = (J_m\, n + J_u/n)\, a$$

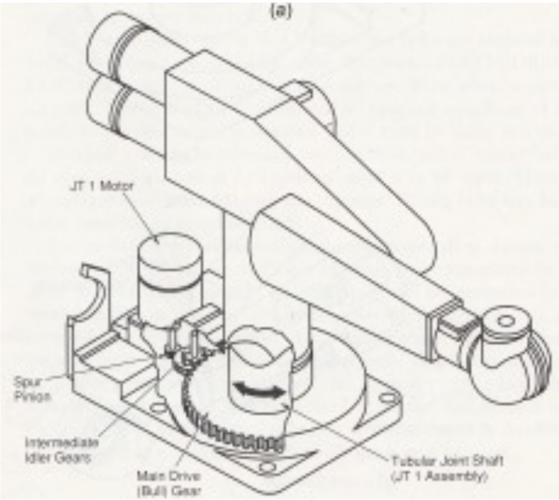
inertia × angular acceleration

for minimizing T_m, we set: $\quad \dfrac{\partial T_m}{\partial n} = (J_m - J_u/n^2)\, a = 0$

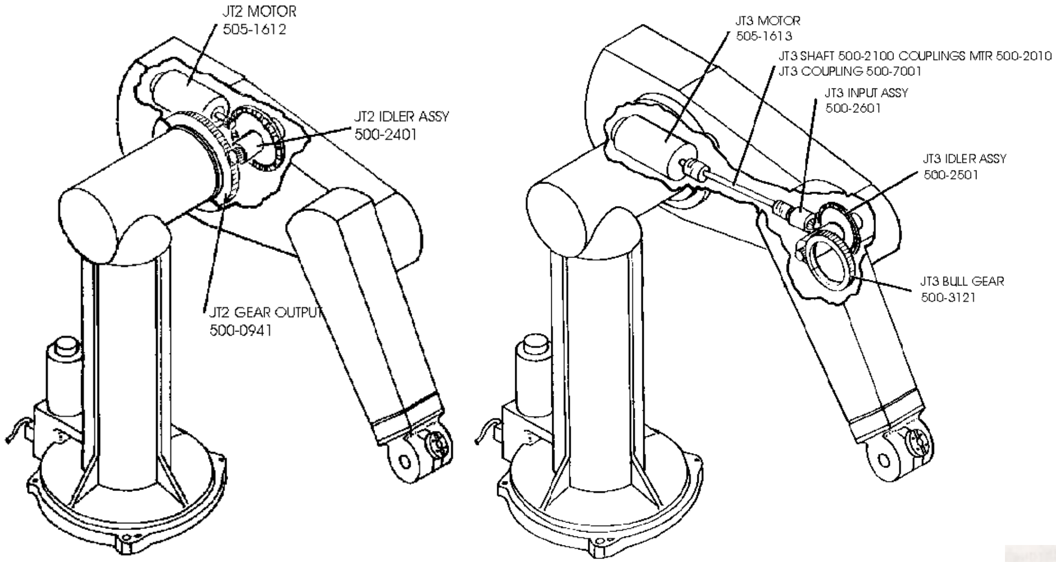
$\Rightarrow \quad \boxed{n = (J_u / J_m)^{1/2}}$ "matching" condition between inertias

Transmissions in industrial robots

- transmissions used (inside) 6-dof Unimation industrial robots with serial kinematics

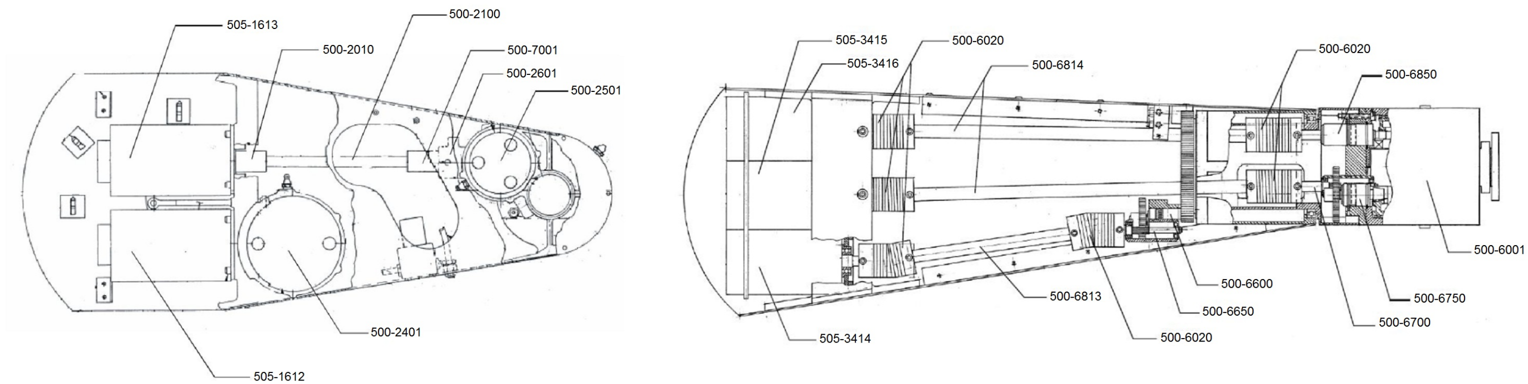


PUMA 260: 1st axis

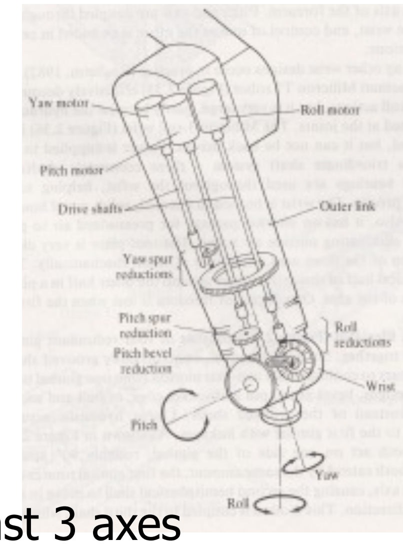


PUMA 560: 2nd and 3rd axes

PUMA 560



PUMA 560: inner and outer links

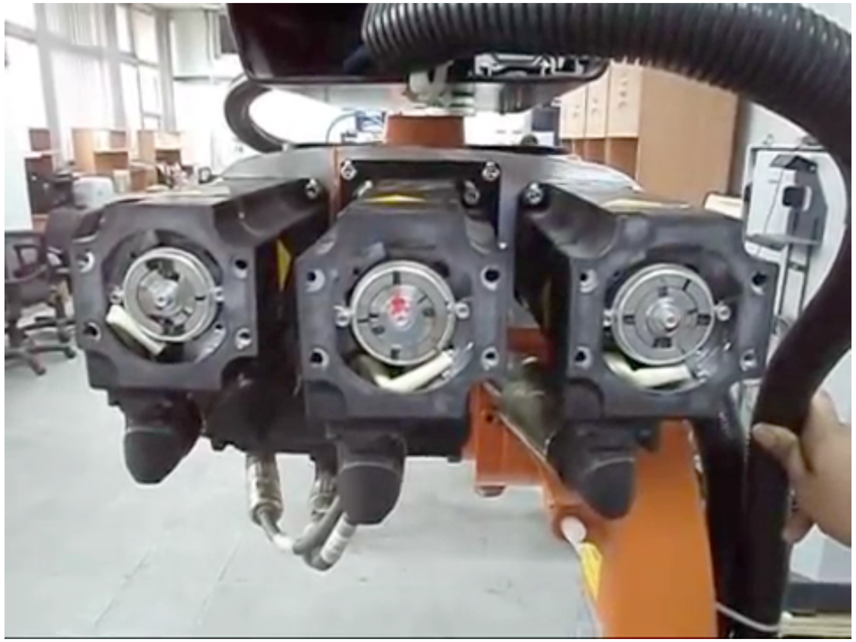


PUMA 560: last 3 axes

Inside views on joint axes 4, 5 & 6 of an industrial KUKA robot

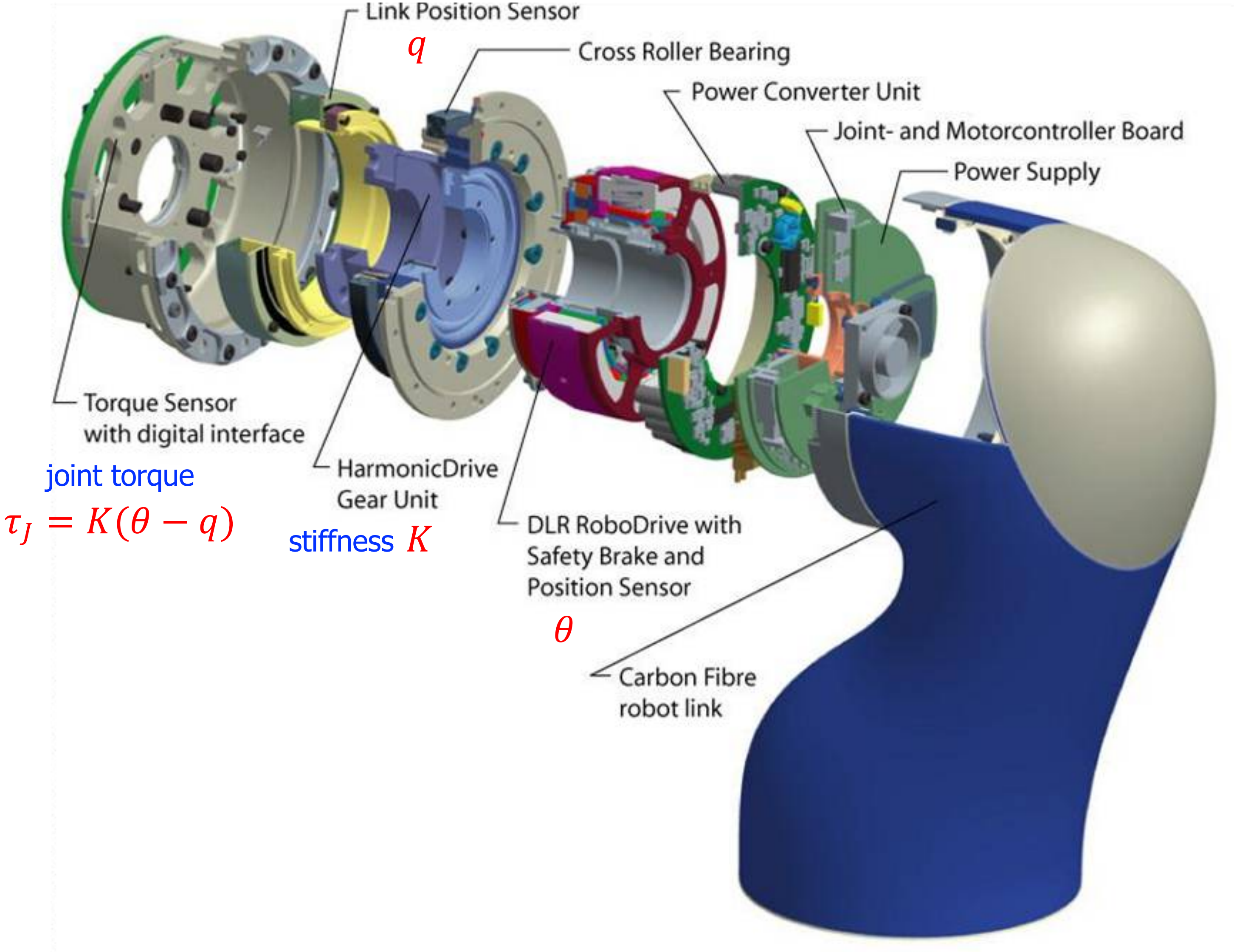
- looking inside the forearm to see the transmissions of the spherical wrist
- motor rotation seen from the encoder side (small couplings exist)

video



video

Exploded view of a joint
in the DLR-III robot



Robotics 1

Robot components:
Proprioceptive sensors

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Properties of measurement systems - 1

- accuracy

  agreement of measured values with a given reference standard (e.g., ideal characteristics)

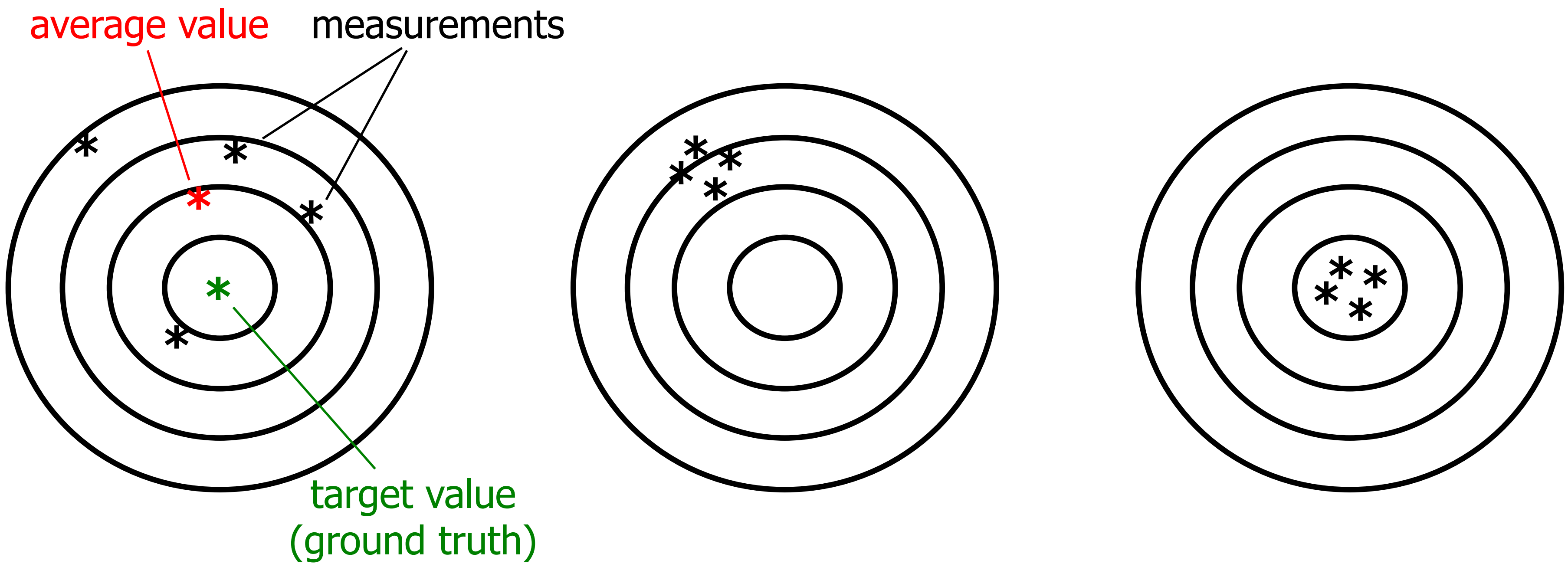
- repeatability

  capability of reproducing as output similar measured values over consecutive measurements of the same constant input quantity

- stability

  capability of keeping the same measuring characteristics over time/temperature (similar to accuracy, but in the long run)

Accuracy and Repeatability



low accuracy
low repeatability

low accuracy
high repeatability

high accuracy
high repeatability

better components!

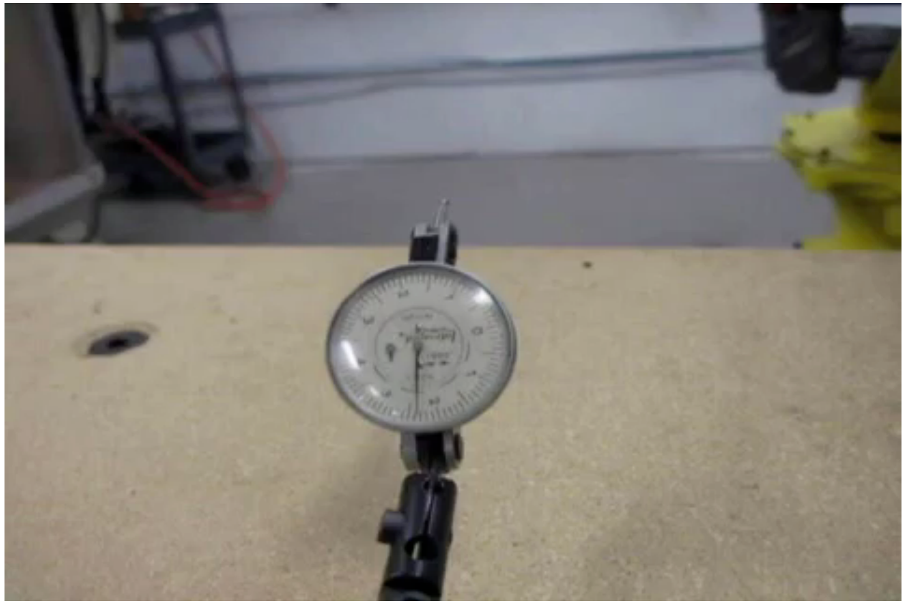
calibration!

Accuracy and Repeatability
in robotics

- accuracy is how close a robot can come to a given point in its workspace
  - depends on machining accuracy in construction/assembly of the robot, flexibility effects of the links, gear backlash, payload changes, round-off errors in control computations, ...
  - can be improved by (kinematic) **calibration**
- repeatability is how close a robot can return to a previously taught point
  - depends only the robot controller/measurement resolution

video

- both may vary in different areas of the robot workspace
  - standard ISO 9283 defines conditions for assessing robot performance
  - limited to static situations (recently, interest also in dynamic motion)
  - robot manufacturers usually provide only data on "repeatability"



simple test on repeatability of a Fanuc ArcMate100i robot (1.3 m reach)

Properties of measurement systems - 2

- linearity error

  maximum deviation of the measured output from the straight line that best fits the real characteristics

  - as % of the output (measurement) range

- offset error

  value of the measured output for zero input

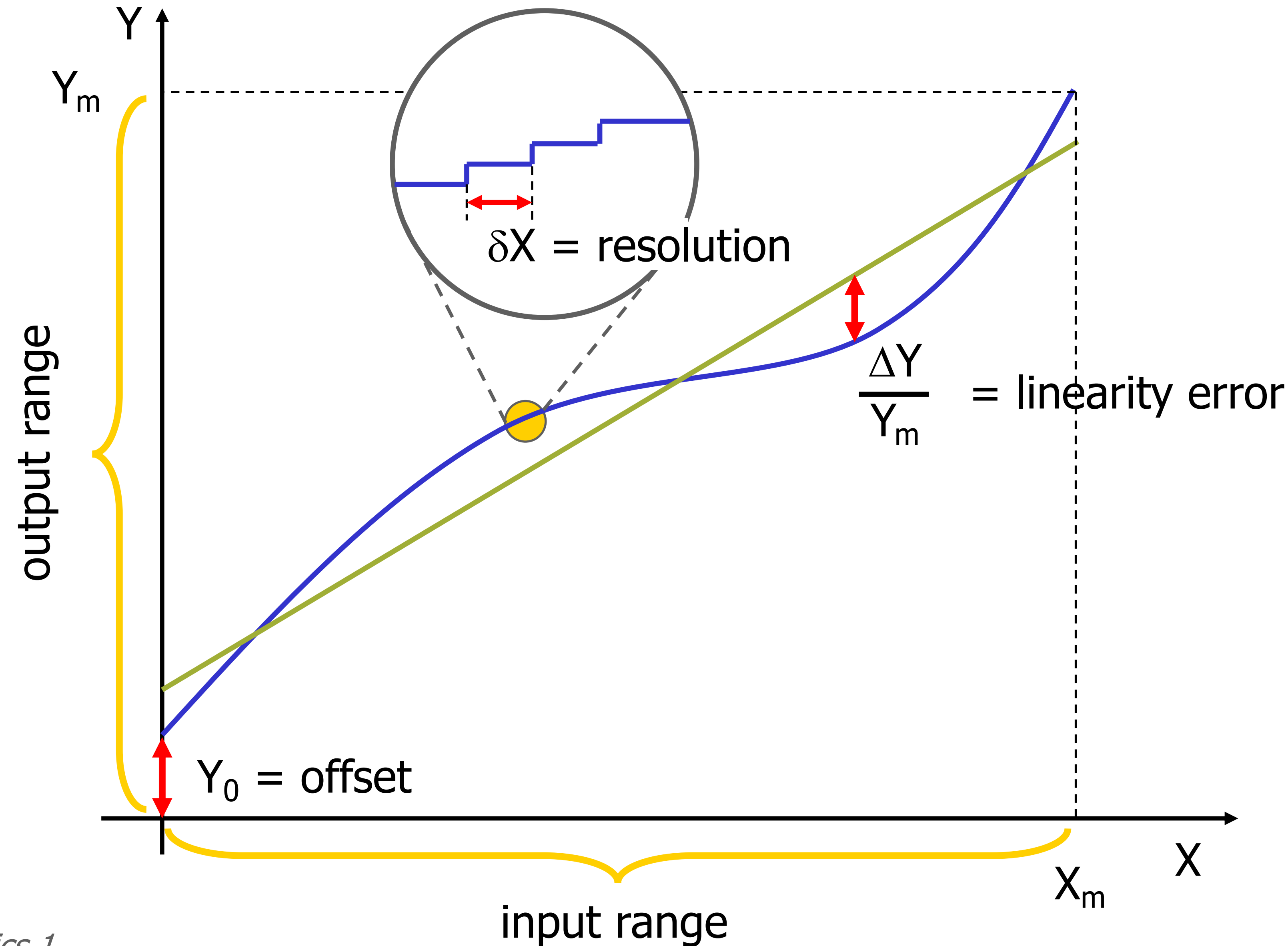
  - sometimes not zero after an operation cycle, due to hysteresis

- resolution error

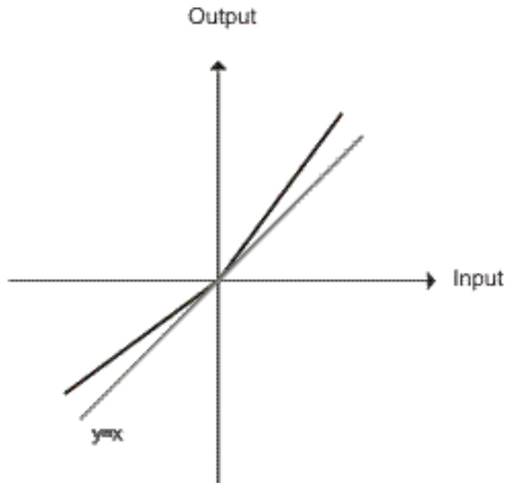
  maximum variation of the input quantity producing no variation of the measured output

  - in absolute value or in % of the input range

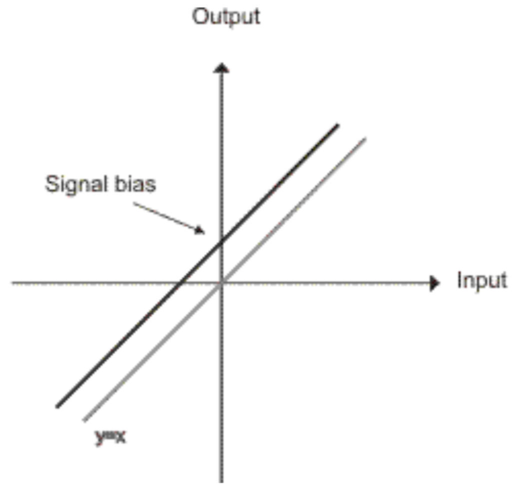
Linearity, Offset, Resolution



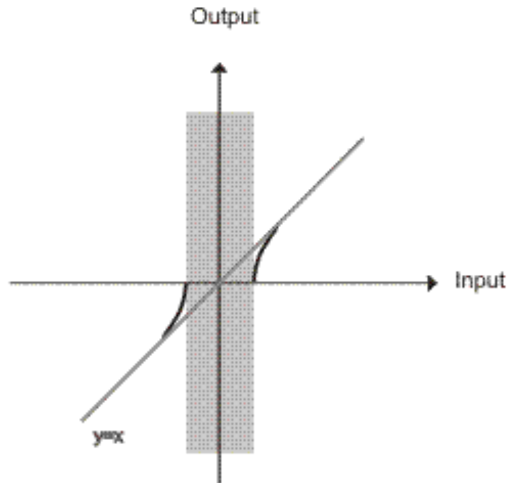
Sensor measurements
some non-idealities



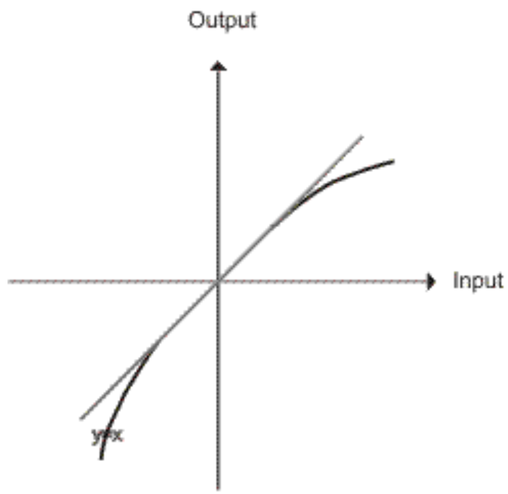
Asymmetry



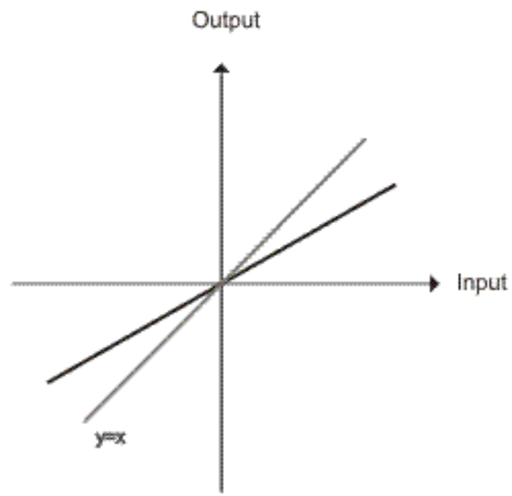
Bias



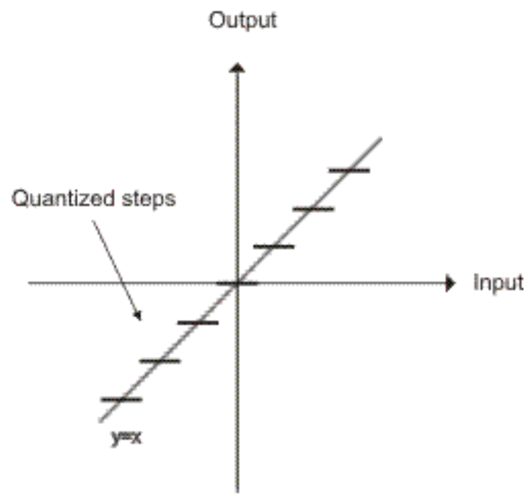
Dead zone



Nonlinearity



Scaling factor



Quantization

Classes of sensors for robots

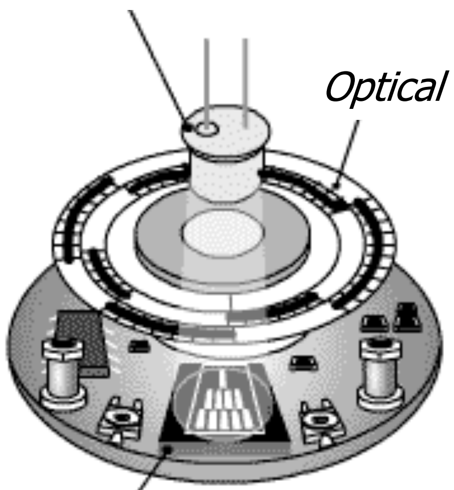
- proprioceptive sensors measure the internal state of the robot (position and velocity of joints, but also torque at joints or acceleration of links)
  - kinematic calibration, identification of dynamic parameters, control
- exteroceptive sensors measure/characterize robot interaction with the environment, enhancing its autonomy (forces/torques, proximity, vision, but also sensors for sound, smoke, humidity, …)
  - control of interaction with the environment, obstacle avoidance in the workspace, presence of objects to be grasped, …
  - mobile-base robots: localization in a map, navigation in unknown environments, …

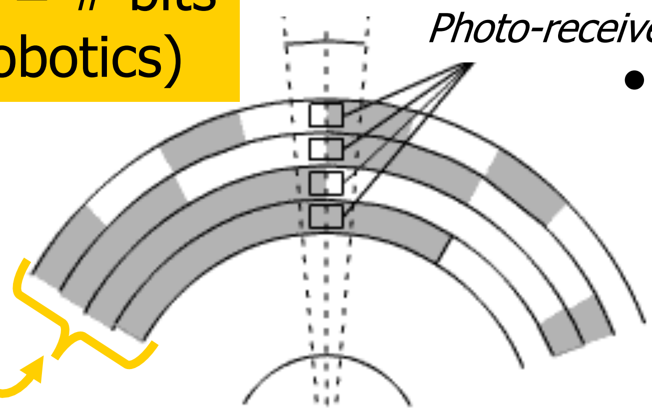
Position sensors

- provide an electrical signal proportional to the displacement (linear or angular) of a mechanical part with respect to a reference position
- linear displacements: potentiometers, linear variable-differential transformers (LVDT), inductosyns
- angular displacements: potentiometers, resolvers, syncros (all analog devices with A/D conversion), optical **encoders (digital)**, Hall sensors, ...

the most used in robotics, since also linear displacements are obtained through rotating motors and suitable transmissions

Absolute encoders





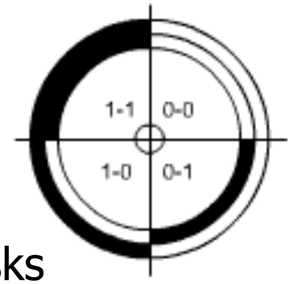
N_t = # tracks = # bits
(min 12 in robotics)

- rotating optical disk, with alternate transparent and opaque sectors on multiple concentric tracks
- (infrared) light beams are emitted by leds and sensed by photo-receivers
- light pulses are converted into electrical pulses, electronically processed and transmitted in output
- resolution = $360^{\circ} / 2^{N_t}$
- digital encoding of absolute position

when the optical disk is rotating fast, the use of binary coding may lead to (large) reading errors, in correspondence to multiple transitions of bits

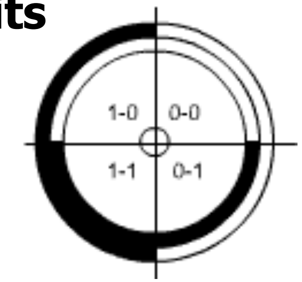
Absolute encoding

binary coding

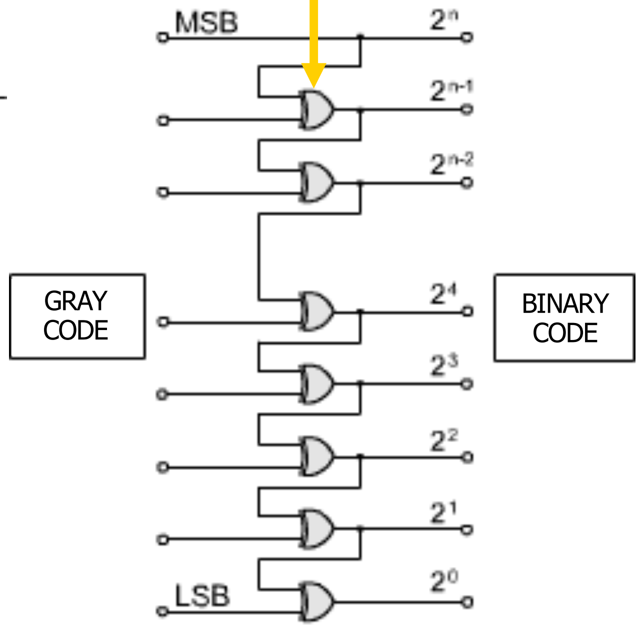


optical disks with **2 bits**

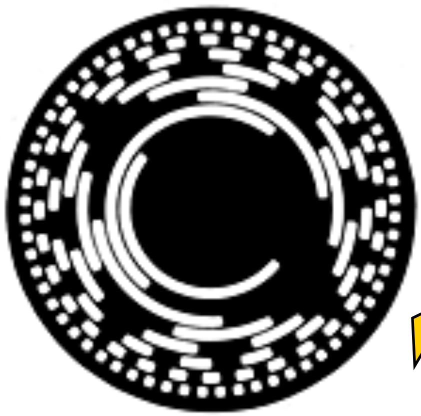
Gray coding



XOR



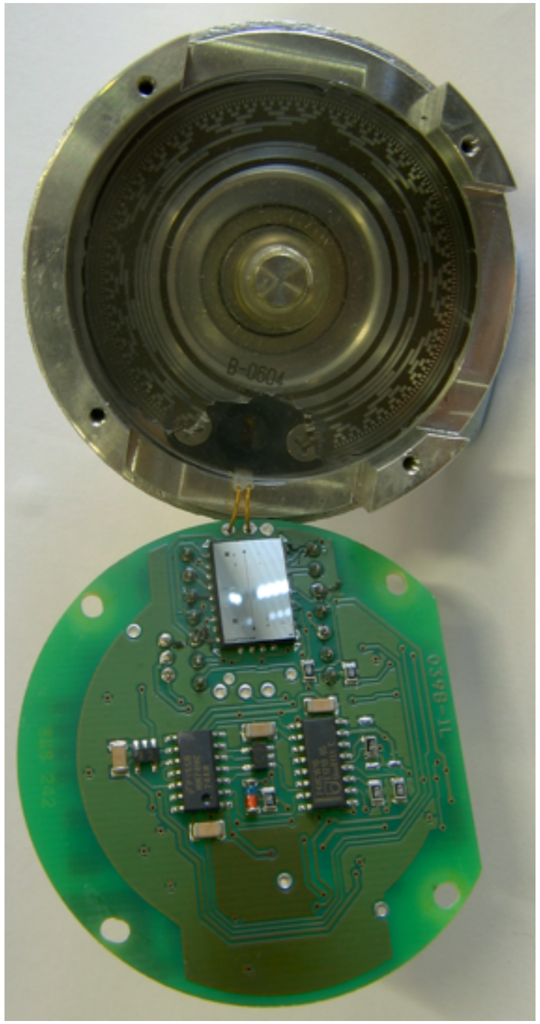
DECIMAL	BINARY	GRAY
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100
9	1001	1101
10	1010	1111
11	1011	1110
12	1100	1010
13	1101	1011
14	1110	1001
15	1111	1000



8-bit Gray-coded absolute encoder

adjacent codes differ by just one bit

Use of absolute encoders



13-bit absolute encoder opened: Gray-coded disk and electronics

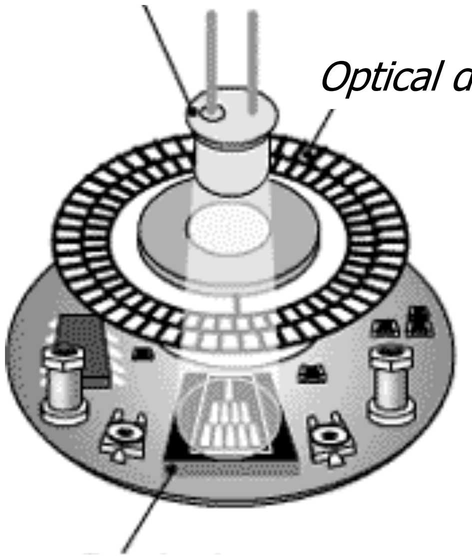
- ready to measure at start (no "homing")
- two modes for permanent operation
  - when switching off the drive, position parameters are saved on a flash memory (and brakes activated)
  - battery for the absolute encoder is always active, and measures position even when the drive is off
  - data memory > 20 years
- single-turn or multi-turn versions, e.g.
  - 13-bit single-turn has $2^{13} = 8192$ steps per revolution (resolution = 0.044°)
  - 29-bit multi-turn has 8192 steps/revolution + counts up to $2^{16} = 65536$ revolutions
- aluminum case with possible interface to field bus systems (e.g., CANopen or PROFIBUS)
- typical supply 5/28V DC @1.2 W

hollow shaft

round flange

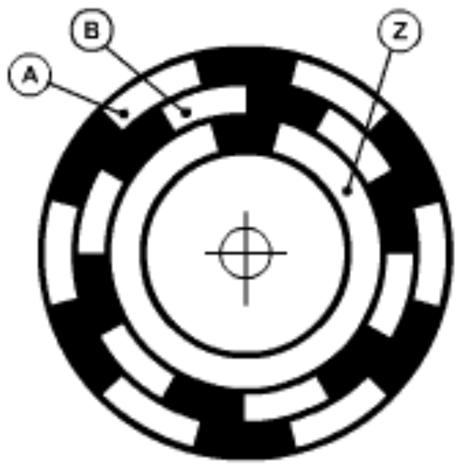
multi-turn

Incremental encoders



- optical rotating disk with three tracks, alternating transparent and opaque areas: measures incremental angular displacements by counting trains of N_e pulses ("counts") per turn ($N_e = 100 \div 5000$)

- the two A and B tracks (channels) are in quadrature (phase shift of 90° electrical), allowing to detect the direction of rotation



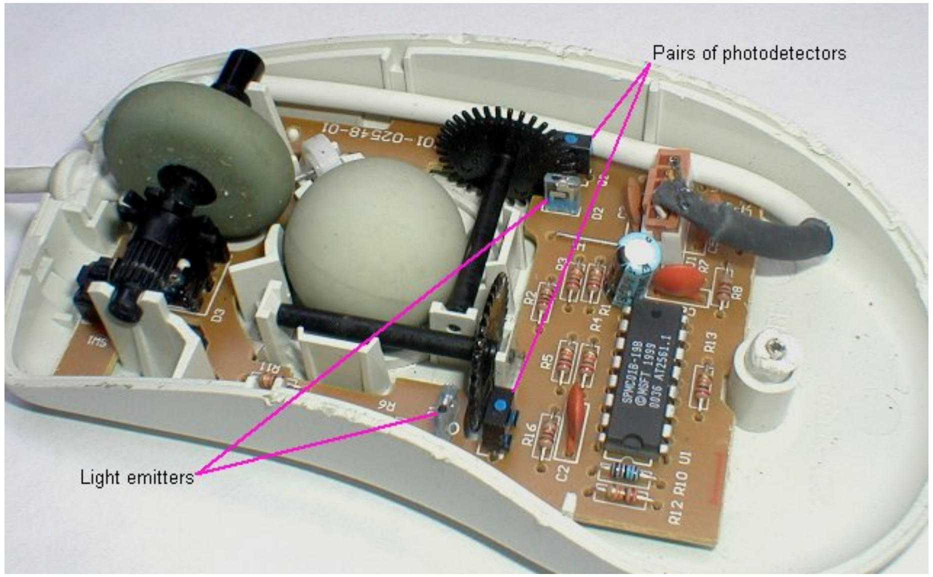
The three tracks on an optical disk (here N_e = 6)

- a third track Z is used to define the "0" reference position, with a reset of the counter (needs "homing" at start)

- some encoders provide as output also the three phases needed for the switching circuit of brushless motors

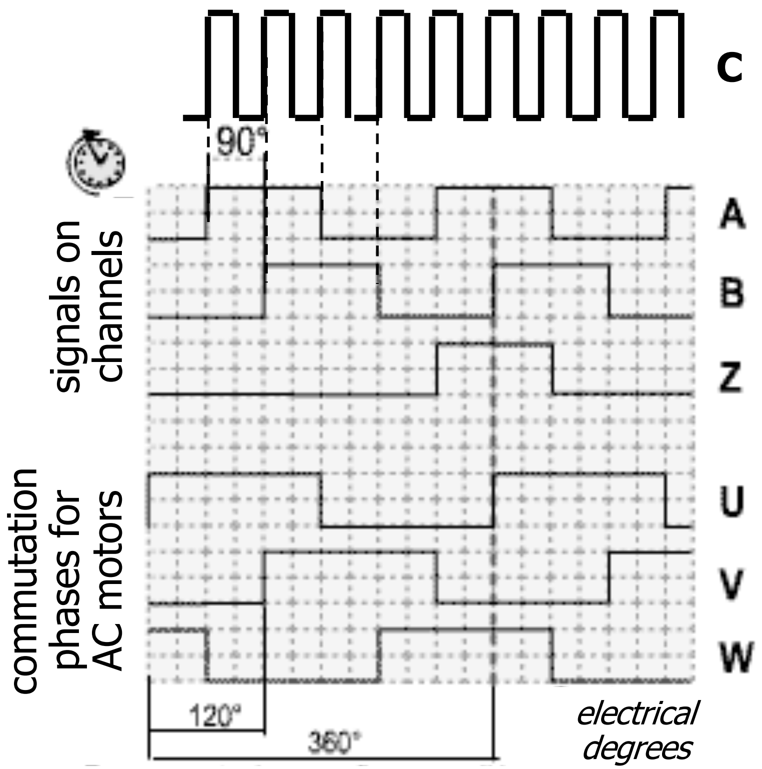
Incremental encoders

- two (cheap) incremental encoders inside a mouse
- a OMRON incremental encoder with 2000 pulses/turn

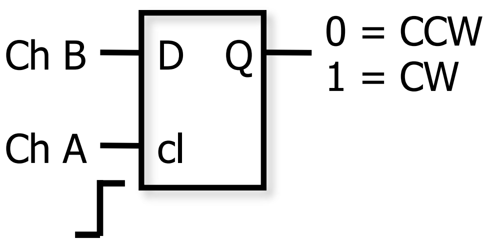


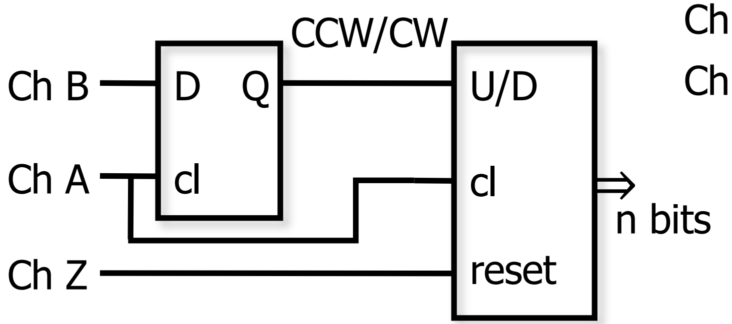
diameter Ø 40 mm
mass m ≈ 100 g
inertia $J = 1 \cdot 10^{-6}$ kg m^2

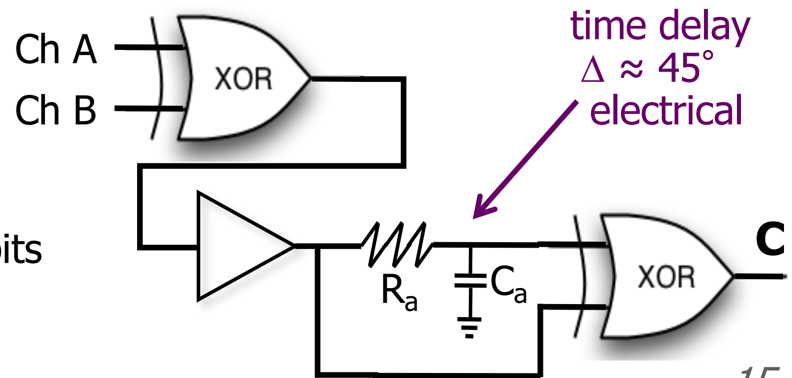
Signal processing



- "fractions of a cycle" of each pulse train are measured in "electrical degrees"
- 1° electrical = 1° mechanical/N_e
  360° mechanical = 1 turn
- signals are fed in a digital counter, with a D-type flip-flop to sense direction + reset
- to improve resolution (4 ×), the leading and trailing edges of signals A and B are used
- the sequence of pulses C will clock now the counter (increments or decrements)

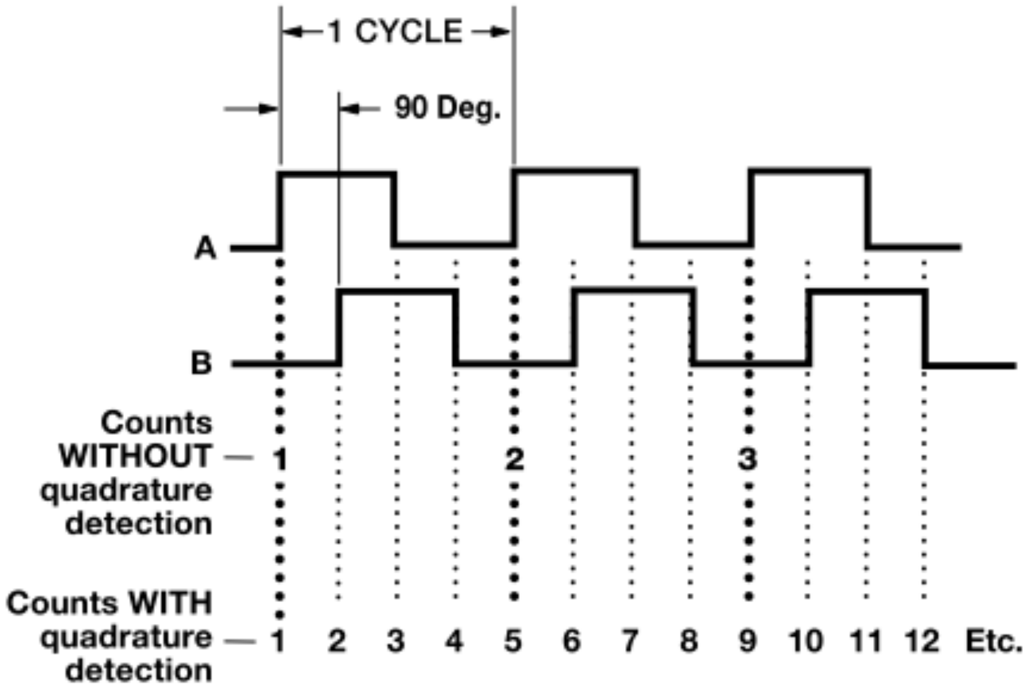






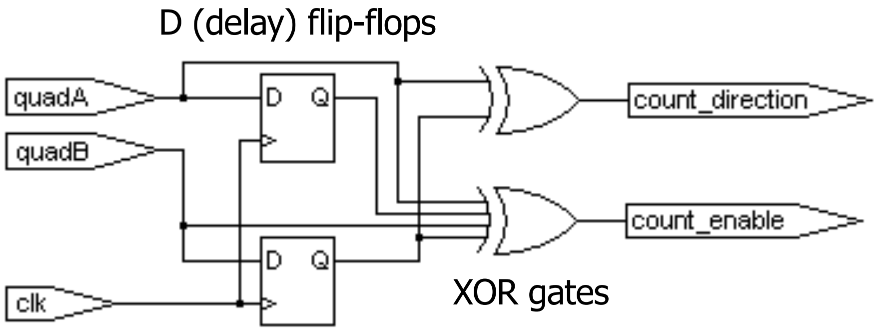
Count multiplication

example of quadrature detection

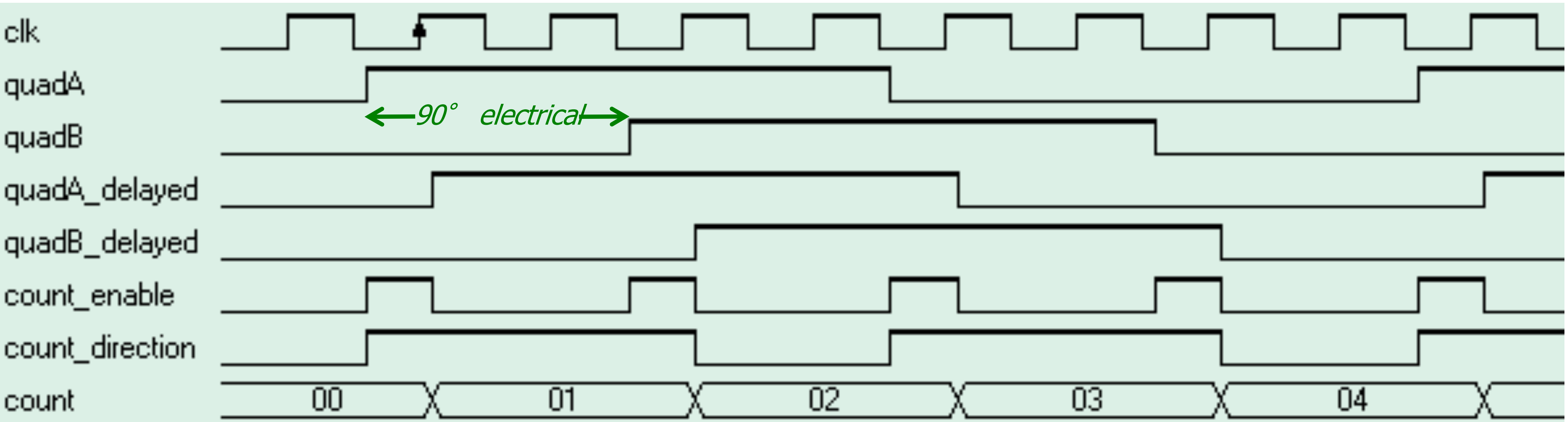


- an incremental encoder with N_e = 2000 (electrical) cycles provides a count of N = 8000 pulses/turn after electronic multiplication
- its final resolution is (mechanical) $360^\circ/8000 = .045^\circ$ (= $0^\circ\ 2'\ 42''$)
- needs a 13-bit counter to cover a full turn without reset ($2^{13} = 8192$)

Quadrature detection in incremental encoders
a more complete implementation

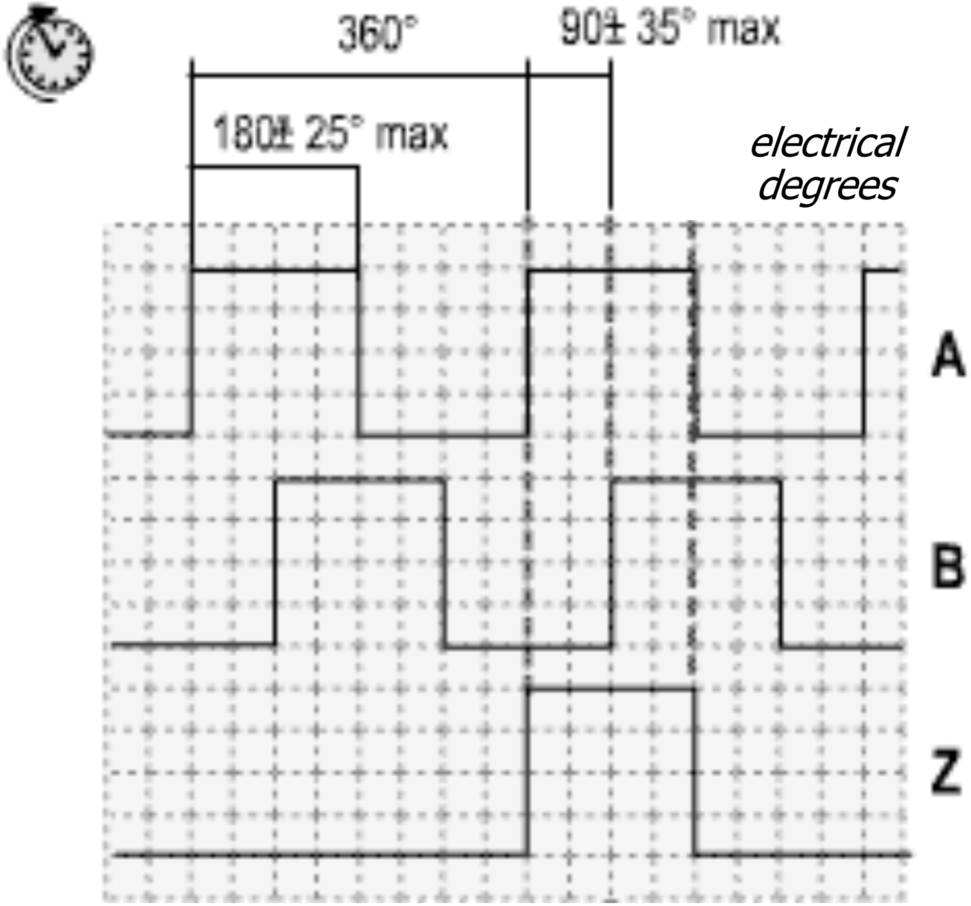


NOTE: since in practice A and B signals may **not** be synchronous to the clock signal, two extra D flip-flops per input should be used to avoid meta-stable states in the counters



- it is assumed that an oversampling clock "clk" (e.g., as provided by a FPGA) is available, which is faster than the two quadrature signals A and B
- the digital count output will have a resolution multiplied by 4

Accuracy in incremental encoders

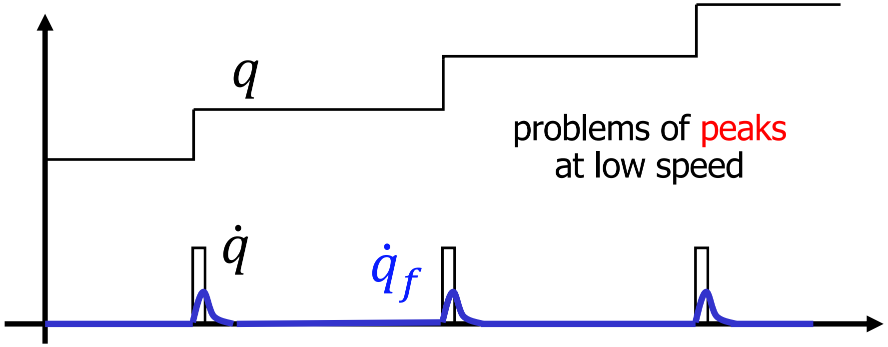


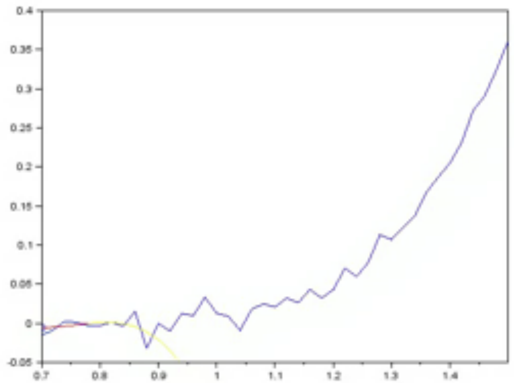
...apart from quantization errors

- division error: maximum displacement between two consecutive leading/trailing edges, typically within max $\pm$ 25° electrical
- the phase shift of the two channels, nominally equal to 90° electrical, is typically within max $\pm$ 35° electrical (quadrature error)

Indirect measure of velocity

- numerical differentiation of digital measures of position
  - to be realized on line with Backward Differentiation Formulas (BDFs)
  - 1-step BDF (Euler): $\dot{q}_k = \dot{q}(kT) = \dfrac{1}{T}(q_k - q_{k-1}) \iff \dot{q}_k = \dfrac{\Delta q_k}{T} \Longleftarrow$ directly from incremental encoder
  - 4-step BDF: $\dot{q}_k = \dfrac{1}{T}\left(\dfrac{25}{12}q_k - 4q_{k-1} + 3q_{k-2} - \dfrac{4}{3}q_{k-3} + \dfrac{1}{4}q_{k-4}\right)$
- convolution filtering is needed because of noise and position quantization
  - use of non-causal filters (e.g., Savitzky-Golay) helps, but introduces delays
- Kalman filter for on line state estimation (optimal, assuming Gaussian noise)





animation of Savitzky-Golay filter with cubic polynomials

Kinematic Kalman Filter
for velocity estimation

motion and sensing discrete-time model for estimation

$$\boldsymbol{\xi}(k) = \begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix} \boldsymbol{\xi}(k-1) + \boldsymbol{\mu}$$

$$z(k) = \begin{pmatrix} 1 & 0 \end{pmatrix} \boldsymbol{\xi}(k) + \nu$$

noisy position measure (encoder output)

zero mean Gaussian noises with (co)variances $\boldsymbol{Q}$ (a matrix) and R

T = sampling time

$$\boldsymbol{\xi}(k) = (x(k)\ \dot{x}(k))^T$$

actual state

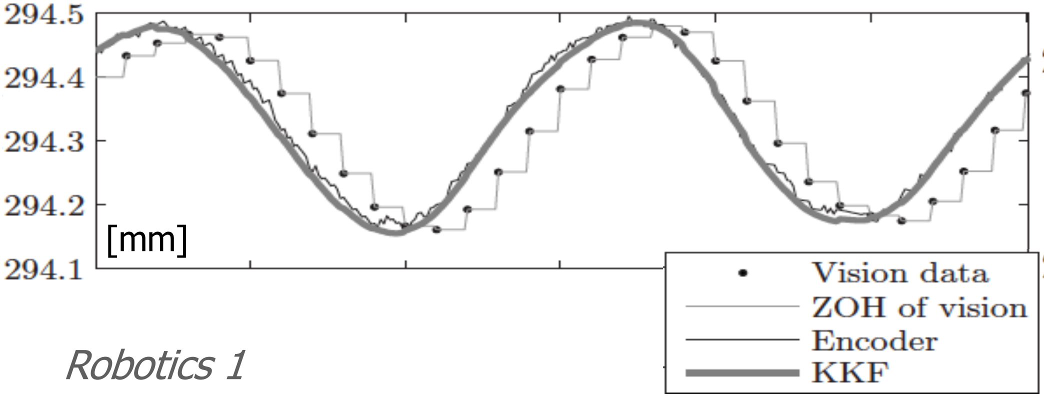
unmeasured velocity

design a (linear) Kalman filter providing an estimate $\hat{\boldsymbol{\xi}}(k)$ of the model state

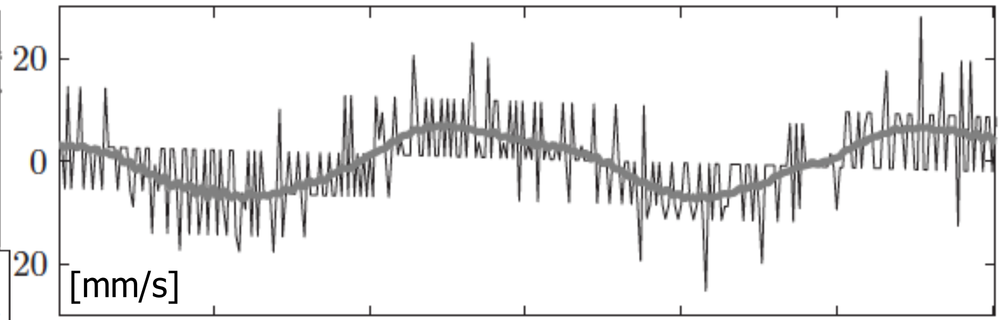
$$\hat{\boldsymbol{\xi}}(k) = \underbrace{\begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix} \hat{\boldsymbol{\xi}}(k-1)}_{\text{(a priori) prediction}} + \boldsymbol{K}_k \underbrace{\left(z(k) - \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix} \hat{\boldsymbol{\xi}}(k-1) \right)}_{\text{correction (based on the measured output)}}$$

using the optimal Kalman gain $\boldsymbol{K}_k$

position measure and its filtered version



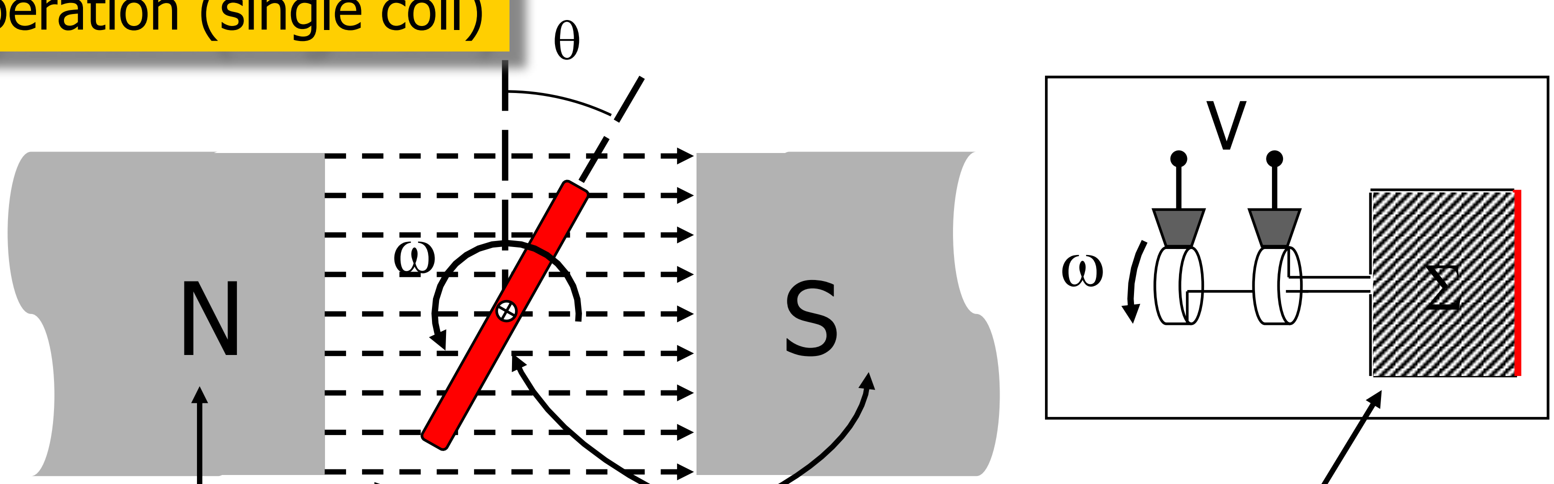
numerical velocity and its filtered estimate



Velocity sensor: Tachometer

always mounted on the (electrical) motor axis

principle of operation (single coil)



permanent magnet

coil with area Σ

magnetic field:

flux through the coil is $\Phi(\vec{B}) = |\vec{B}|\Sigma \cos\theta = |\vec{B}|\Sigma \cos\omega t$

$$V = -\, d\Phi/dt = |\vec{B}|\Sigma\, \omega \sin\omega t$$

amplitude $V \propto \omega$

⇒ to reduce ripples, use m coils rotated regularly by 180°/m

DC tachometer

an example

- Servo-Tek Tach Generator (B series)
- bi-directional
- output voltage 11÷24 V @1000 RPM
- low ripple: < 3% peak-to-peak of DC value (with 72 KHz filter)
- weight = 113 g, diameter = 2.9 cm
- linearity error < 0.1% (at any speed)
- stability 0.1% (w.r.t. temperature)

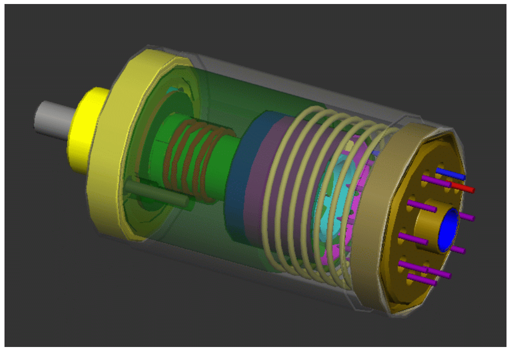
B-Series Specifications

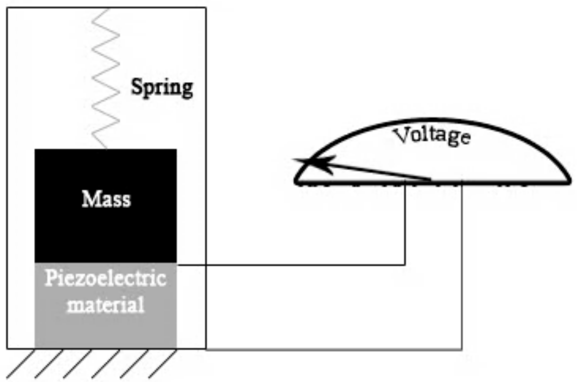
Model Number	Mounting	Weight (approx)	Inertia (approx) oz-in.-sec ^{2}	V/1,000 RPM	RPM (max)	Driving Torque (max)	Arm R (ohms dy-namic)	Arm Ind (h)
SA-740B-1*	Face	4.0 oz	2.27×10^{-4}	20.8 V	8,000	0.25 oz-in.	1000	0.56
SB-740B-1*	Flange	4.0 oz	2.27×10^{-4}	20.8 V	8,000	0.25 oz-in.	1000	0.56
SA-757B-1*	Face	4.0 oz	2.27×10^{-4}	20.8 V	8,000	0.25 oz-in.	1000	0.56
SB-757B-1*	Flange	4.0 oz	2.27×10^{-4}	20.8 V	8,000	0.25 oz-in.	1000	0.56

1.75 mNm (as a load)

Accelerometers

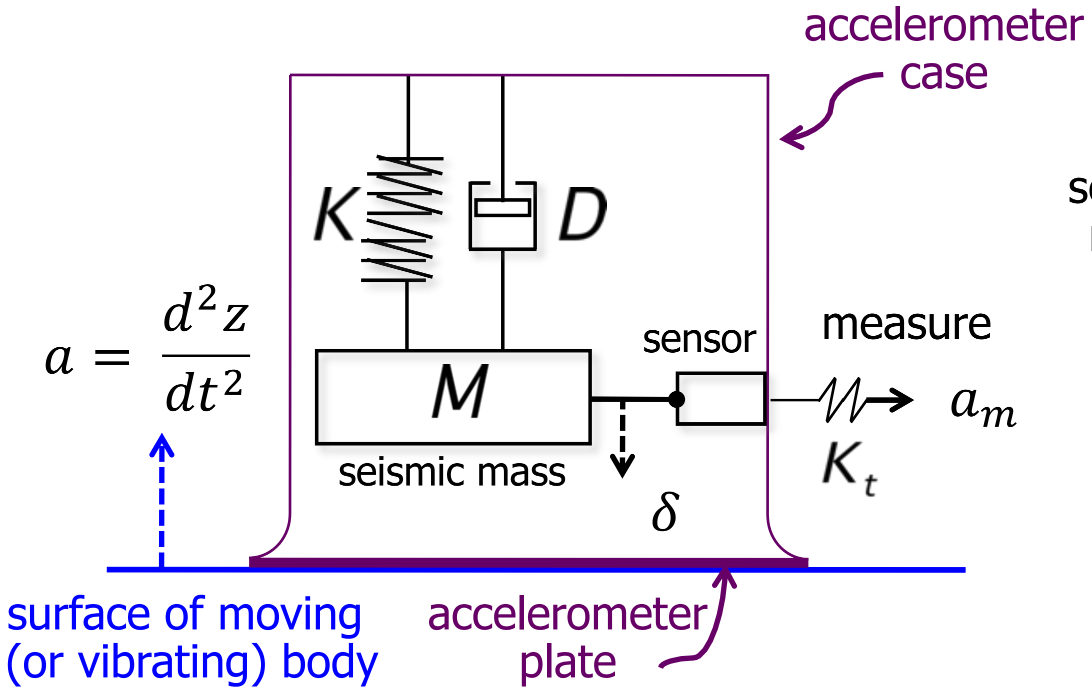
- measure of linear acceleration based on inertial forces (no "touch")
  - units: [m/s²] or gravitational acceleration [g] (non-SI unit: 1g ≈ 9.81 m/s²)
- different principles for converting mechanical motion in an electrical signal
  - piezoelectric: piezoceramics (PZT) or crystals (quartz), better linearity & stability, wide dynamic range up to high frequencies, no moving parts, no power needed
  - piezoresistive: for high-shocks, measures also static acceleration (g_0), needs supply
  - capacitive: silicon micro-machined sensing element, superior in static to low frequency range, can be operated in servo mode, cheap but limited resolution
  - modern solution: small MEMS (Micro Electro-Mechanical Systems)
- multiple applications: from vibration analysis to long range navigation

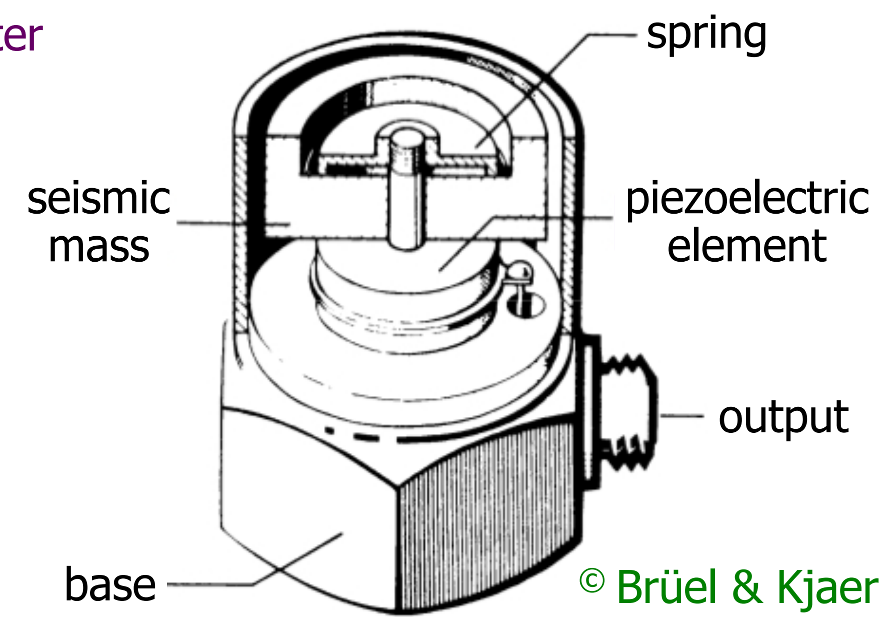




animation of measurement principle in a piezoelectric accelerometer

Operation principle
seismic accelerometer





$$Ma = M\ddot{\delta} + D\dot{\delta} + K\delta$$

$$a_m = K_t \delta$$

by Laplace transform

$$\frac{A_m(s)}{A(s)} = K_t \frac{M}{Ms^2 + Ds + K}$$

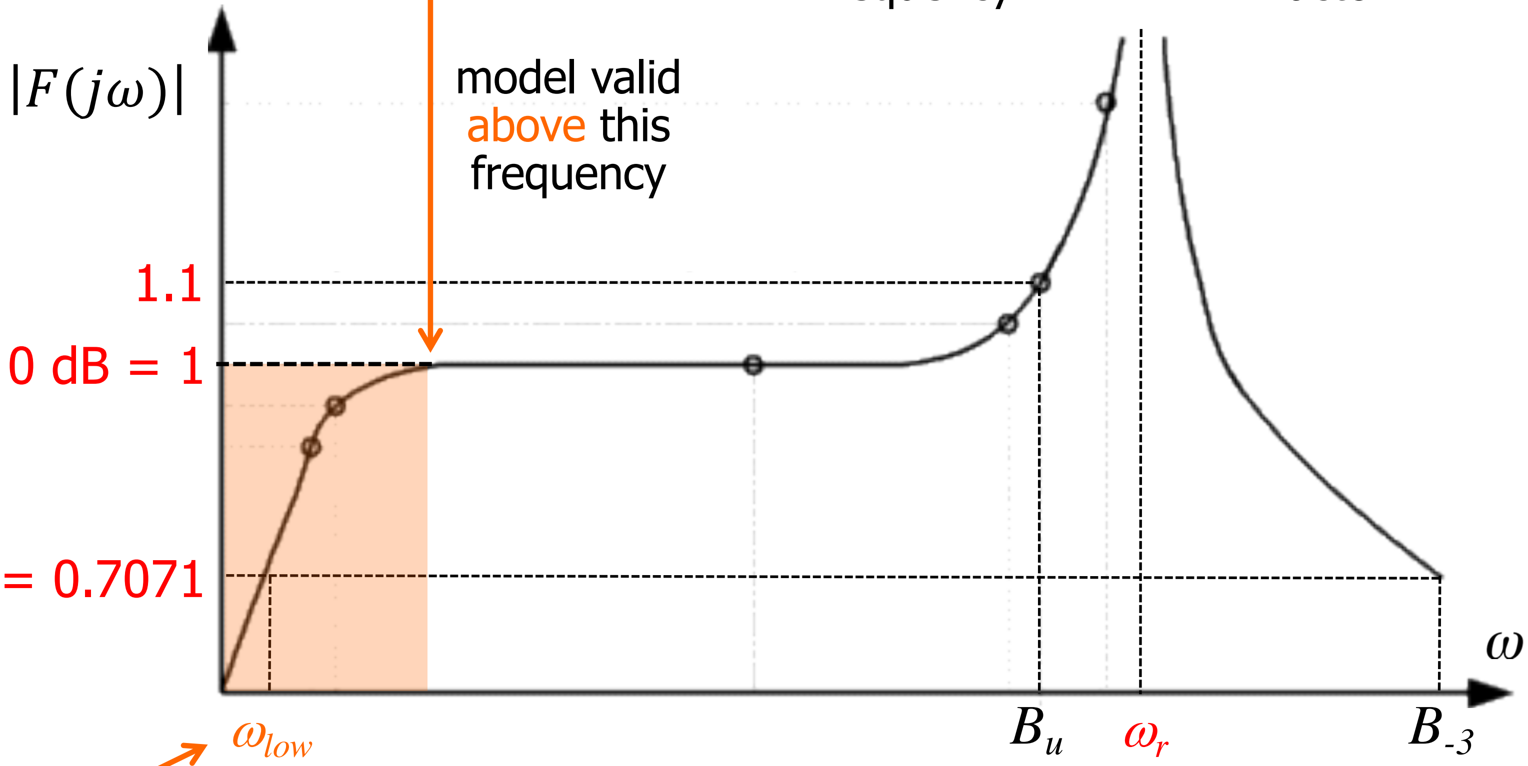
$$= \frac{K_t}{s^2 + (D/M)s + (K/M)}$$

Frequency characteristics
of a piezoelectric accelerometer

$$F(s) = \frac{A_m(s)}{A(s)} = \frac{K_t}{s^2+(D/M)s+(K/M)} \qquad \omega_r = \sqrt{K/M} \qquad \zeta = \frac{D}{2}\sqrt{1/KM}$$

resonance frequency

damping factor



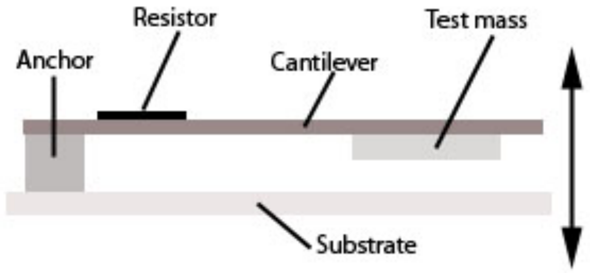
low frequency limit of piezoelectric use (≤ 1 Hz)

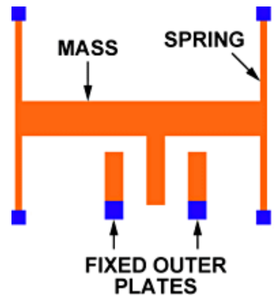
useful bandwidth $B_u \approx 0.3\omega_r$ for 10% error

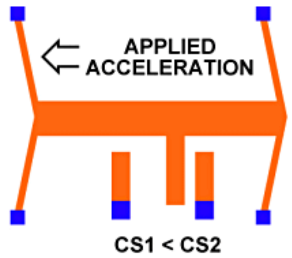
bandwidth

MEMS accelerometers

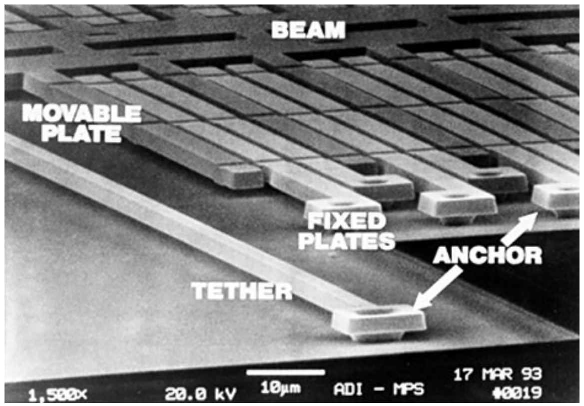
- very simple MEMS (a cantilever beam with a test mass, with damping from the residual gas sealed in the device), single- or tri-axial, very small and light
- cross-couplings among acceleration sensing directions should be limited ≤ 3%

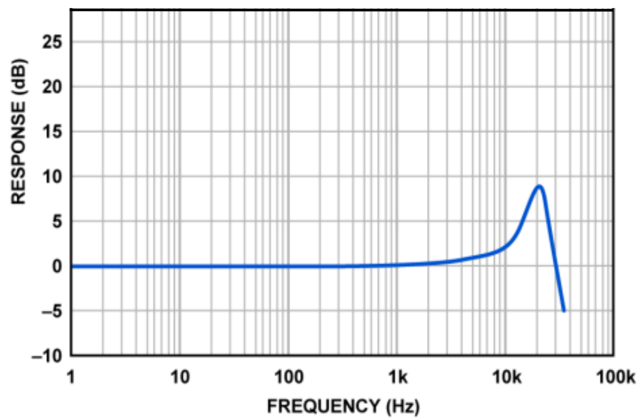


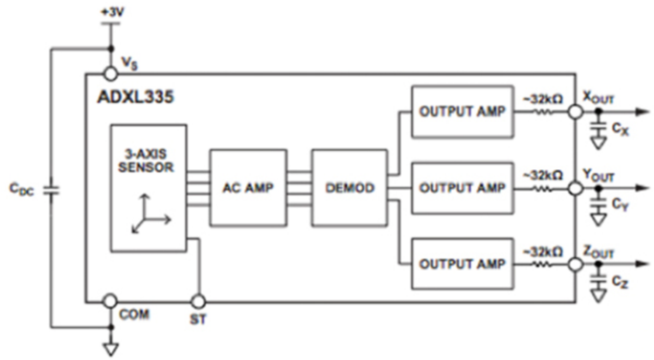




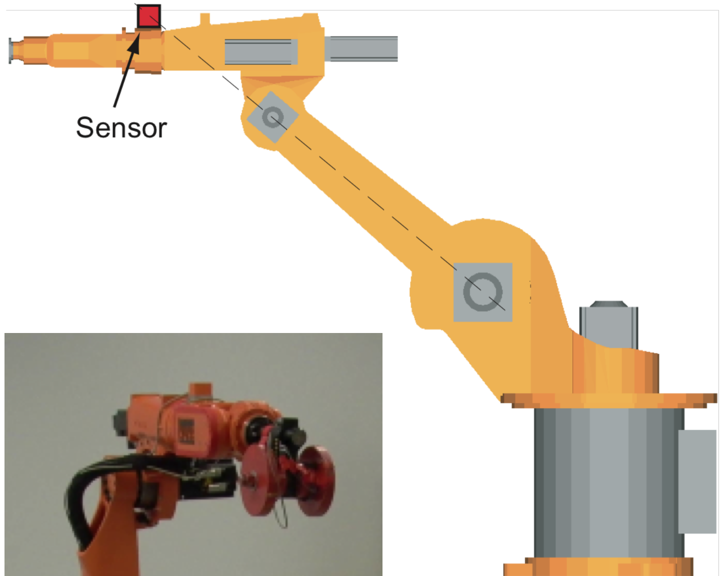
ADXL335 3-axis, small, low power, ±3g, with signal conditioned voltage outputs



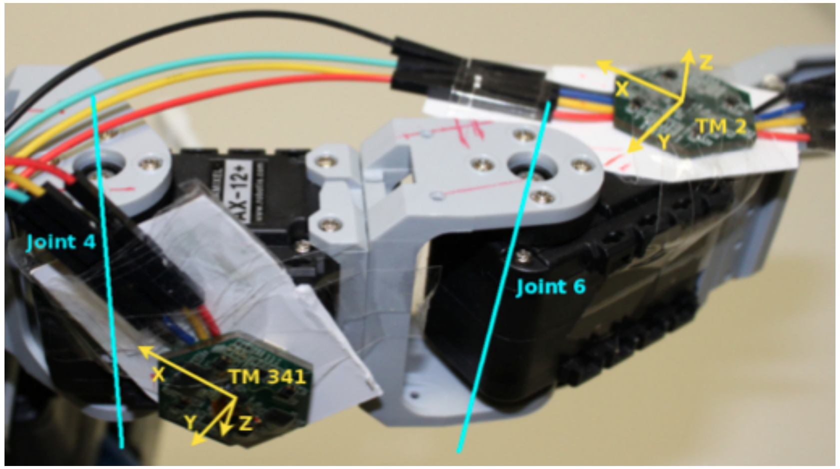




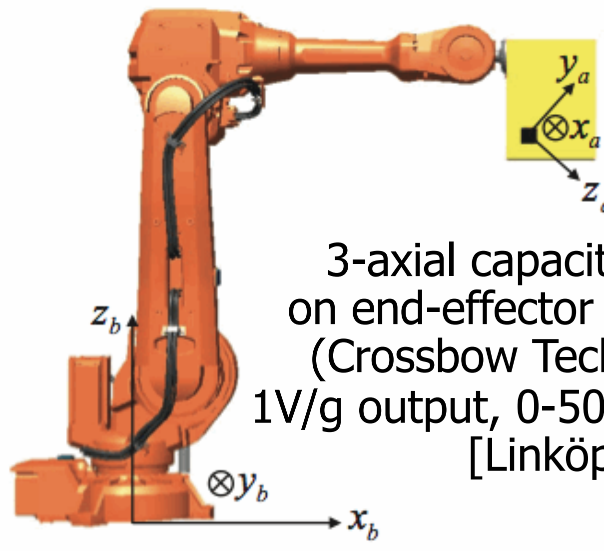
Mounting accelerometers on robots



3-axial MEMS accelerometer on the forearm of a KUKA KR15/2 [DLR/Sapienza, 2007]



Bosch BMA 150 3-axial accelerometers integrated in two larger Tactile Modules on the links of a Bioloid humanoid left arm [TUM, 2011]



3-axial capacitive accelerometer on end-effector tool of an ABB robot (Crossbow Technology: 2g range, 1V/g output, 0-50 Hz, $\pm 2°$ align error) [Linköping, 2012]

Robotics 1

Robot components:
Exteroceptive sensors

Prof. Alessandro De Luca

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AUTOMATICA E GESTIONALE ANTONIO RUBERTI

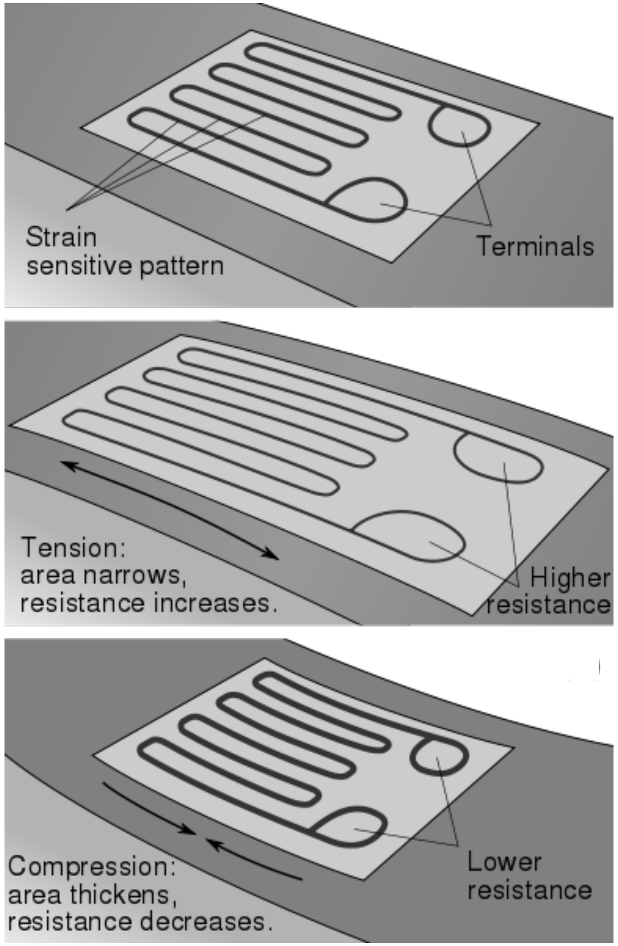
SAPIENZA
UNIVERSITÀ DI ROMA

Summary

- force sensors
  - strain gauges and joint torque sensor
  - 6D force/torque (F/T) sensor at robot wrist
  - RCC = Remote Center of Compliance *(not a sensor, but similar...)*
- proximity/distance sensors (⇒ moved to AMR course!)
  - infrared (IF)
  - ultrasound (US)
  - laser
  - with structured light
- vision
- examples of robot sensor equipment
- some videos intertwined, with applications

Force/torque and deformation

- indirect information obtained from the measure of deformation of an elastic element subject to the force or torque to be measured
- basic component is a strain gauge: it uses the variation of the resistance R of a metal conductor when its length L and/or cross-section S vary



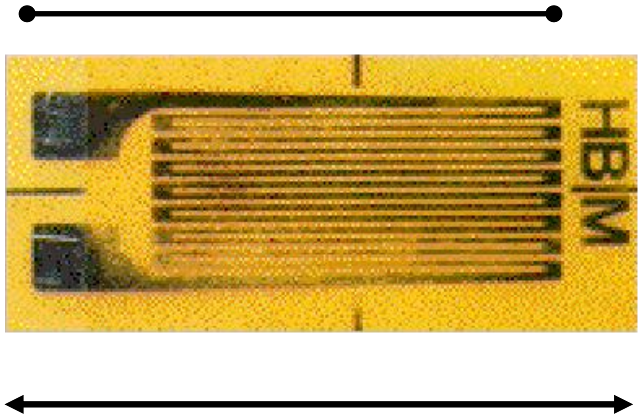
$$\frac{\partial R}{\partial L} > 0 \qquad \frac{\partial R}{\partial S} < 0$$

$$\frac{\partial R}{\partial T} \text{ small}$$

temperature

Strain gauges

10 mm

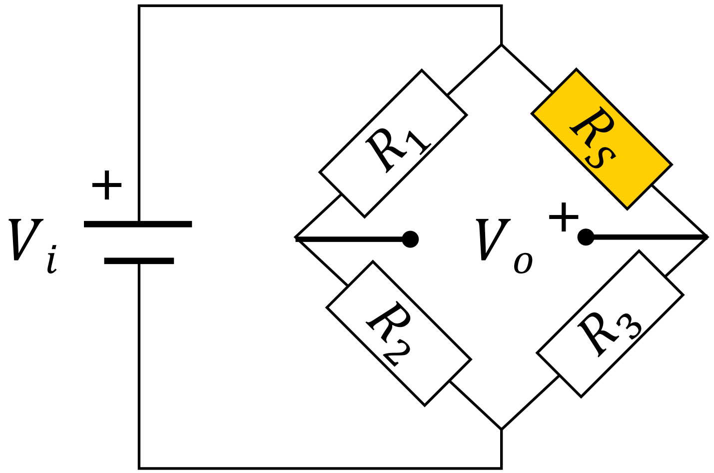


principal measurement axis

Gauge-Factor = GF = $\dfrac{\Delta R/R}{\Delta L/L}$ strain ε

(typically GF $\approx$ 2, i.e., small sensitivity)

Wheatstone single-point quarter-bridge
(for accurately measuring resistance)



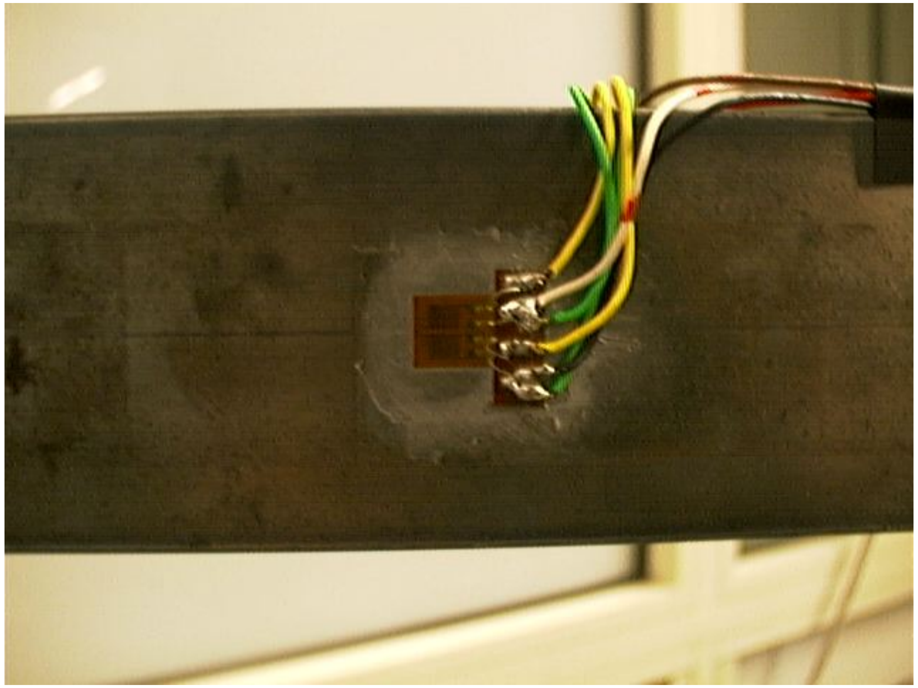
- R_1, R_2, R_3 very well matched ($\approx R$)
- $R_S \approx R$ at rest (no stress)
- two-point bridges have 2 strain gauges connected oppositely (↗ sensitivity)

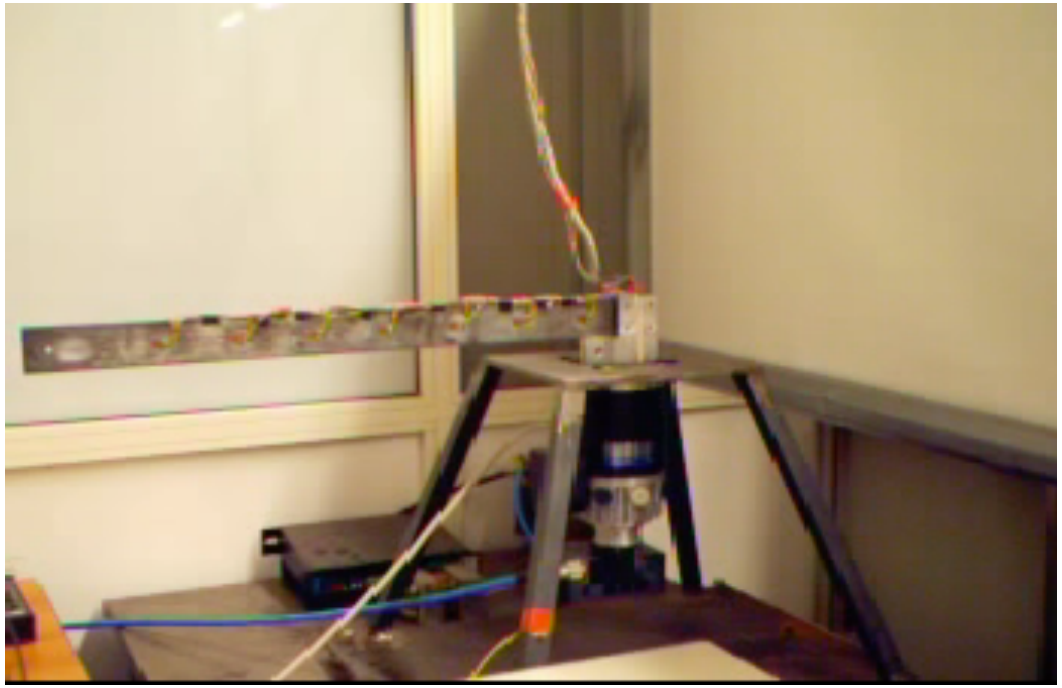
if R_1 has the same dependence on T of R_S thermal variations are automatically compensated

$$V_0 = \left(\frac{R_3}{R_3 + R_s} - \frac{R_2}{R_1 + R_2}\right) V_i$$

Strain gauges in flexible arms

video



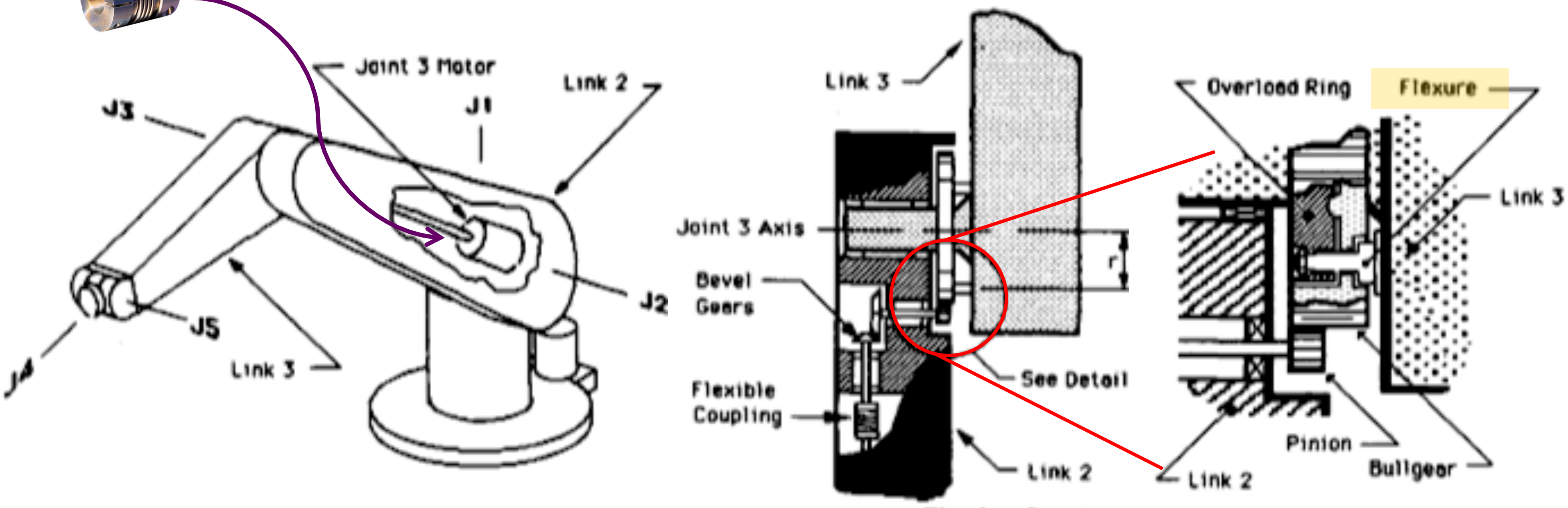


7 strain gauges glued[1] to a flexible aluminum beam (a robot "link") measuring its local "curvature" in dynamic bending during slew motions (a proprioceptive use of these sensors)

[1] by cyanoacrylic glue

Torque sensor at robot joints

use of flexible *bellow couplings*
for aligning motors and long shafts

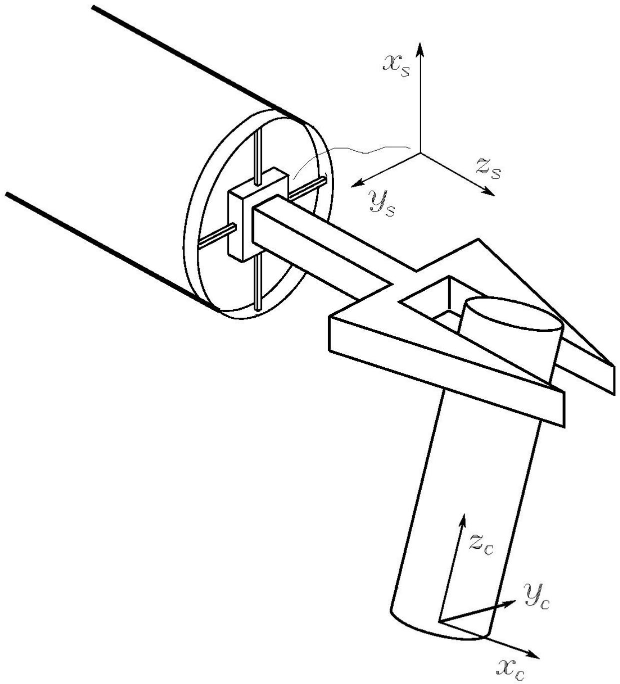


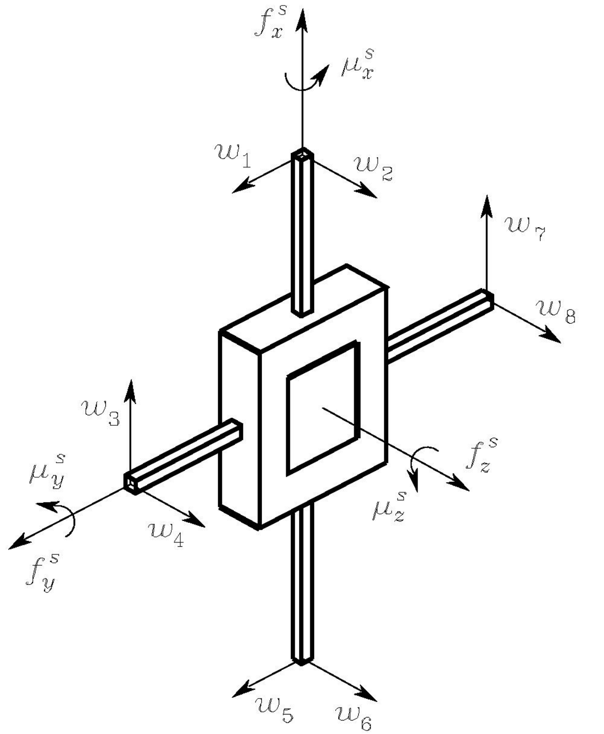
strain gauge mounted to “sense” the axial deformation
of the transmission shaft of joint #3 (elbow) in a PUMA 500 robot
(again, a proprioceptive use of this sensor)

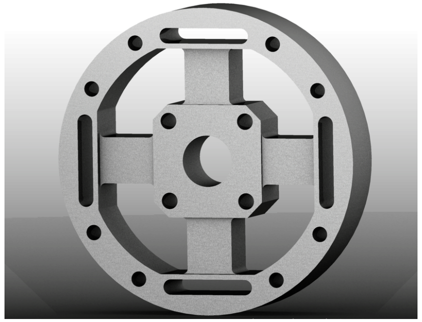
Force/torque sensor at robot wrist

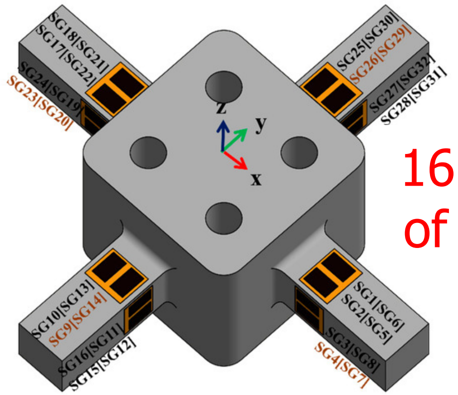
- a device (with the outer form of a cylinder), typically located between the last robot link and its end-effector
- top and bottom plates are mechanically connected by a number of deformable elements subject to strain under the action of forces and moments
- there should be at least one such element in any direction along/around which a force or torque measure is needed
- since a complete "decoupling" of these measurements is hard to obtain, there are $N \geq 6$ such deformable elements
- on each element, a pair of strain gauges is glued so as to undergo opposite deformations (e.g., traction/compression) along the main axis of measurement

Maltese-cross configuration









16 pairs of SG !!

- diameter ≈ 10 cm
- height ≈ 5 cm
- 50÷500 N (resolution 0.1%)
- 5÷70 Nm (resolution 0.05%)
- sample frequency ≈ 1 KHz

- 4 deformable elements
- two pairs of strain gauges (SG) mounted on opposite sides of each element (8 pairs)
- the two gauges of each pair are placed adjacent on the same Wheatstone bridge

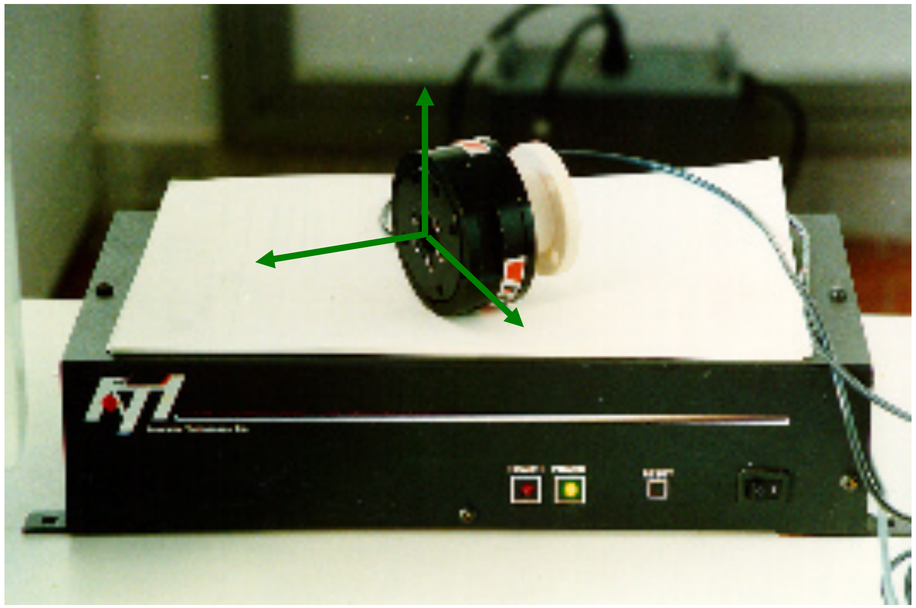
6D force/torque sensors

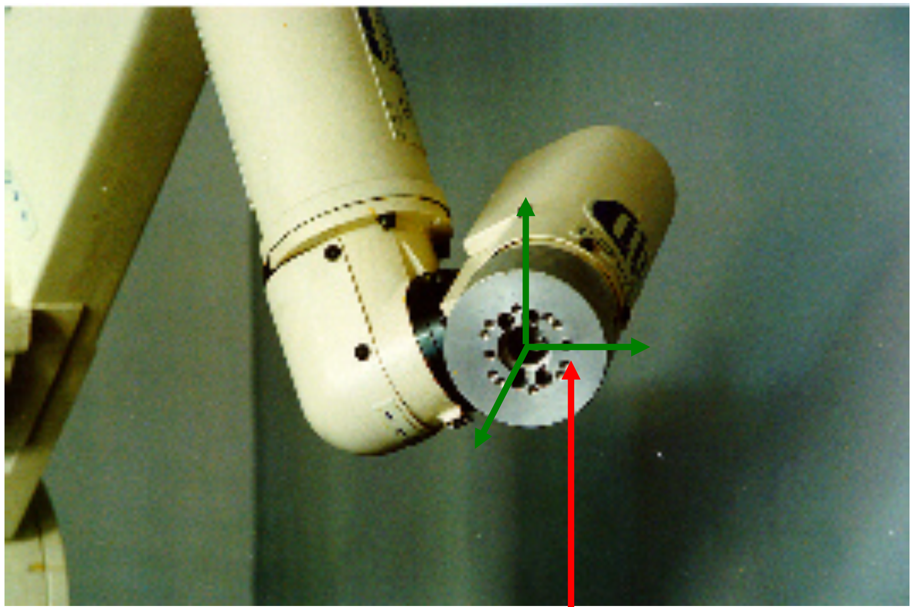
- ATI series
- cost (in 2016): about 6 K€ for Mini45 model + 700 € DAQ card

Model	Max Fx,Fy*	Max Tx,Ty*	Weight**	Diameter**	Height**
Nano17	±50 N	±500 N-mm	0.0091 kg	17 mm	14 mm
Nano25	±250 N	±6 N-m	0.064 kg	25 mm	22 mm
Nano43	±36 N	±500 N-mm	0.041 kg	43 mm	11 mm
Mini40	±80 N	±4 N-m	0.05 kg	40 mm	12 mm
Mini45	±580 N	±20 N-m	0.091 kg	45 mm	16 mm
Gamma	±130 N	±10 N-m	0.25 kg	75 mm	33 mm
Delta	±660 N	±60 N-m	0.91 kg	94 mm	33 mm
Theta	±2500 N	±400 N-m	5 kg	150 mm	61 mm
Omega160	±2500 N	±400 N-m	2.7 kg	160 mm	56 mm
Omega190	±7200 N	±1400 N-m	6.4 kg	190 mm	56 mm

6D force/torque sensor

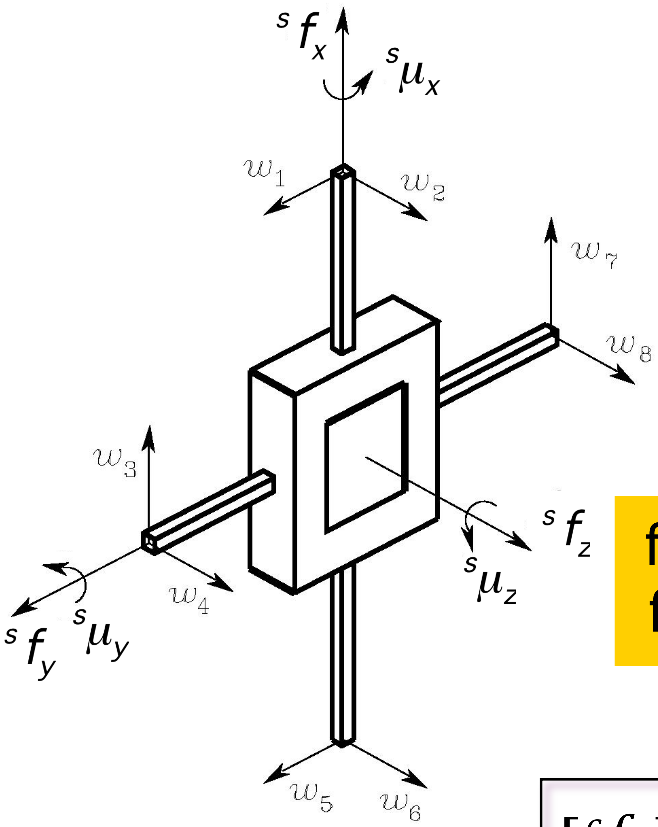
- electronic processing unit and mounting on an industrial robot (Comau Smart 3 robot, 6R kinematics)





mounting flange
(on link 6 of the manipulator arm)

6D F/T sensor calibration



$$\begin{bmatrix} {}^s f_x \\ {}^s f_y \\ {}^s f_z \\ {}^s \mu_x \\ {}^s \mu_y \\ {}^s \mu_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & c_{13} & 0 & 0 & 0 & c_{17} & 0 \\ c_{21} & 0 & 0 & 0 & c_{25} & 0 & 0 & 0 \\ 0 & c_{32} & 0 & c_{34} & 0 & c_{36} & 0 & c_{38} \\ 0 & 0 & 0 & c_{44} & 0 & 0 & 0 & c_{48} \\ 0 & c_{52} & 0 & 0 & 0 & c_{56} & 0 & 0 \\ c_{61} & 0 & c_{63} & 0 & c_{65} & 0 & c_{67} & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \\ w_6 \\ w_7 \\ w_8 \end{bmatrix}$$

force/torque measured in the frame attached to the sensor

calibration matrix

output of Wheatstone bridges

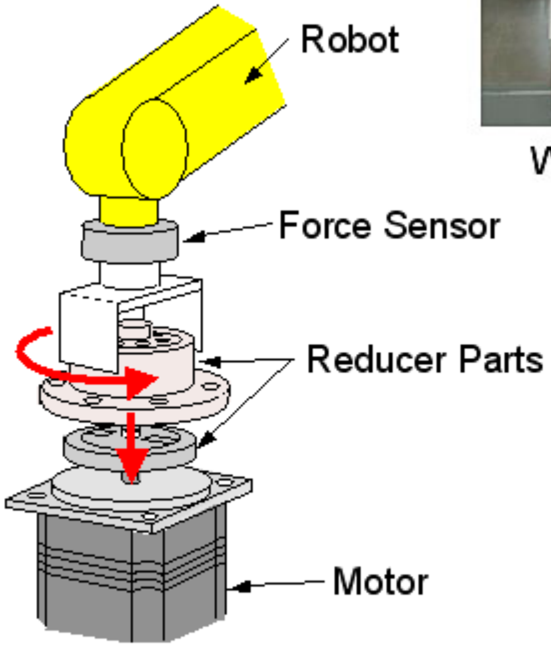
$$\begin{bmatrix} {}^c f_c \\ {}^c \mu_c \end{bmatrix} = \begin{bmatrix} {}^c R_s & O \\ S({}^c r_{cs})\,{}^c R_s & {}^c R_s \end{bmatrix} \begin{bmatrix} {}^s f_s \\ {}^s \mu_s \end{bmatrix}$$

transformation from the sensor frame to the load/contact frame (at TCP)

Typical uses of a F/T sensor

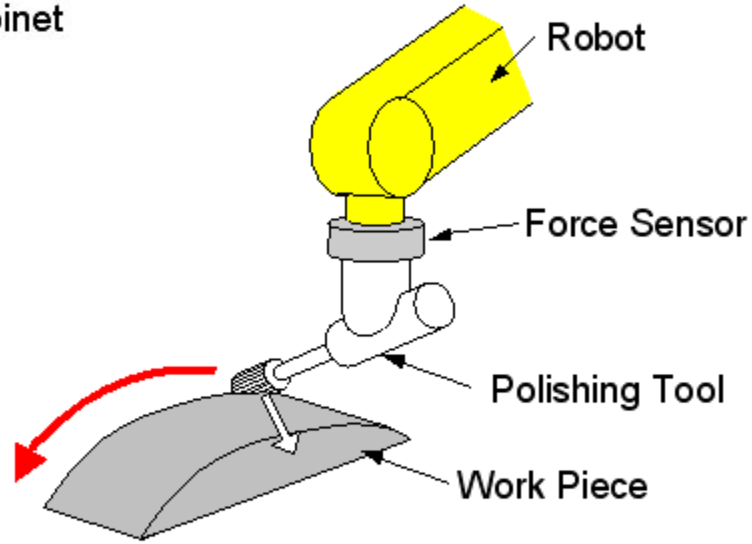
Washstand

Metal Cabinet



Phase matching by force sensing

Gear Parts



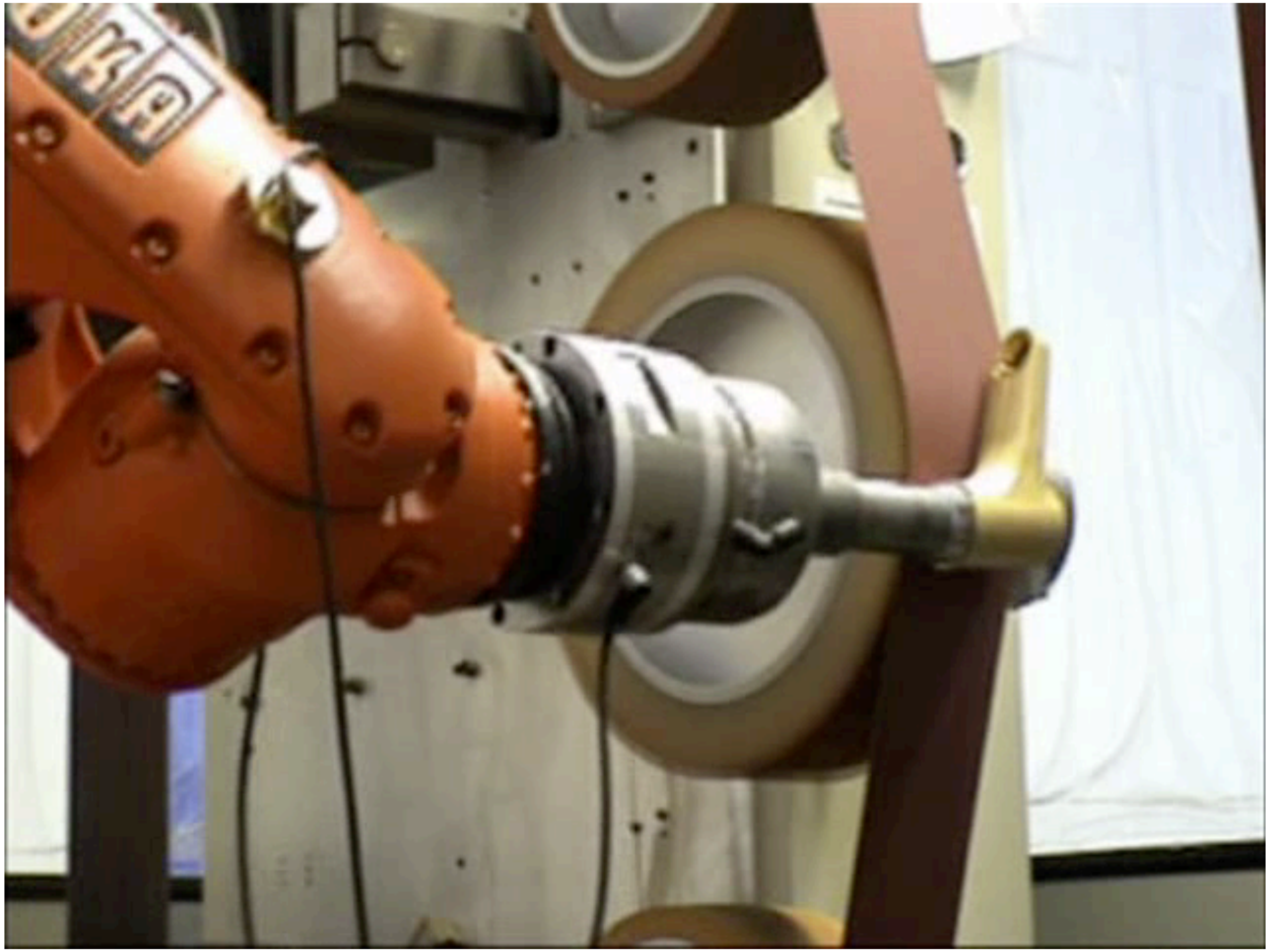
Following with constant pushing force

Active assembly with F/T sensor

video

ABB robot with ATI F/T sensor

Surface finishing with F/T sensor



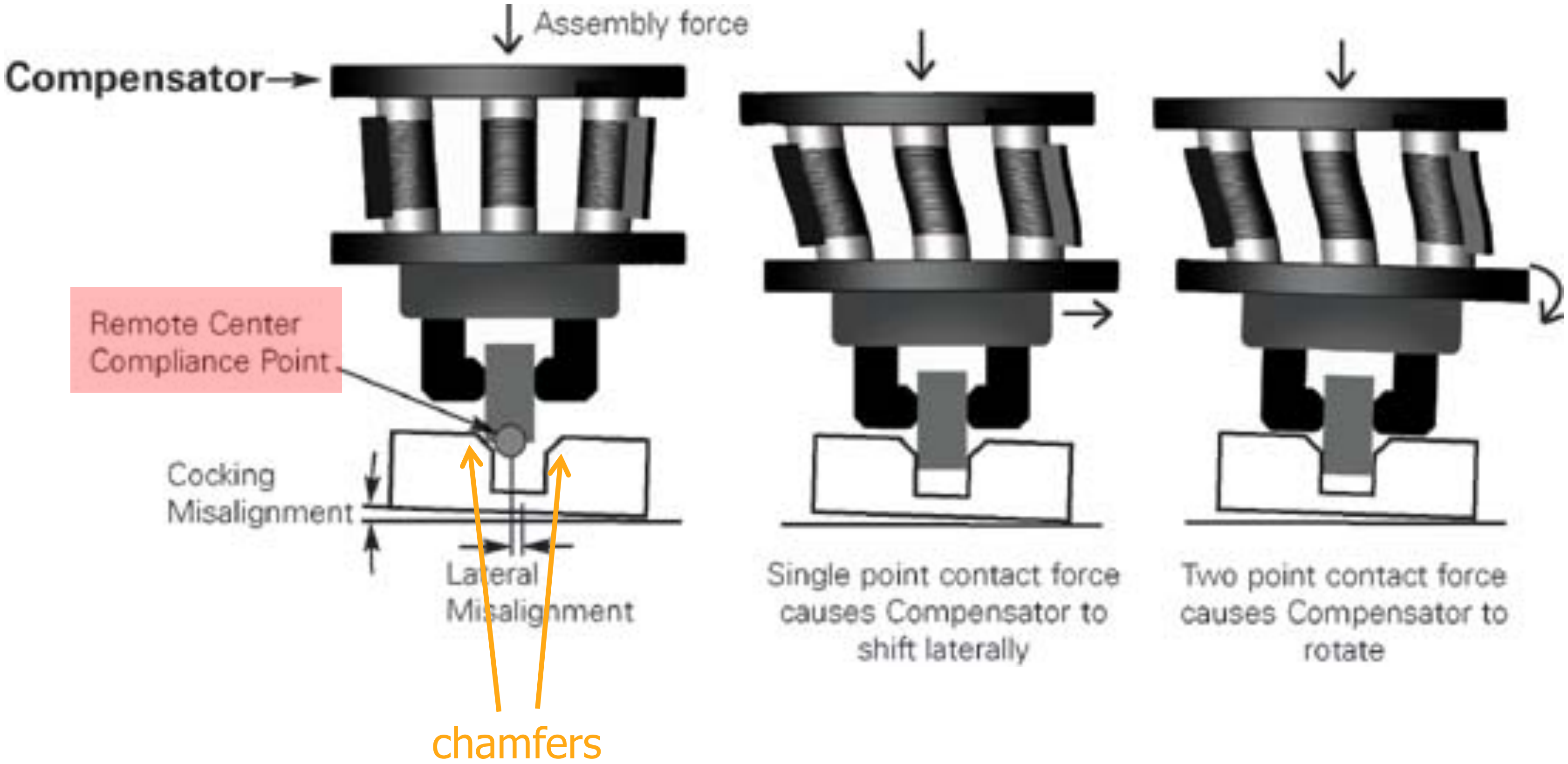
video

KUKA robot with F/T sensor

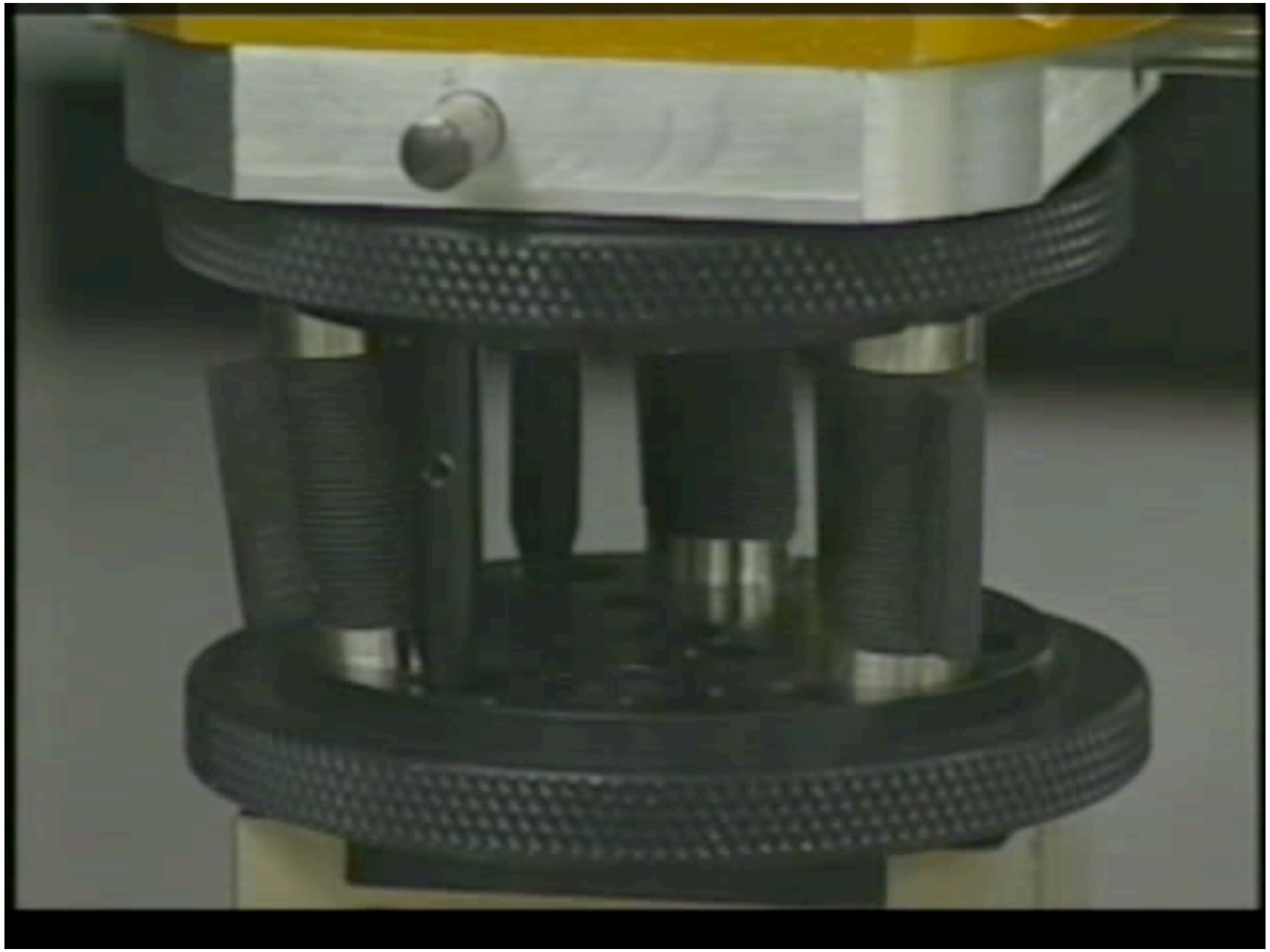
Passive RCC device

- RCC = Remote Center of Compliance
- placed on the wrist so as to introduce passive "compliance" to the robot end-effector, in response to static forces and moments applied from the environment at the contact area
- mechanical construction yields "decoupled" linear/angular motion responses if contact occurs at or near the RCC point

Assembly with RCC



Passive assembly with RCC

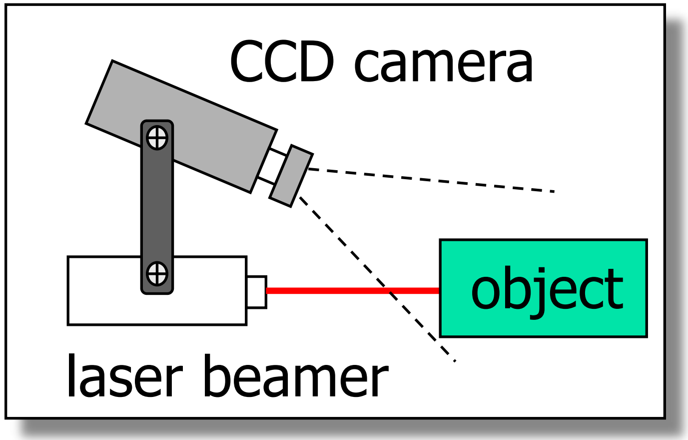


video

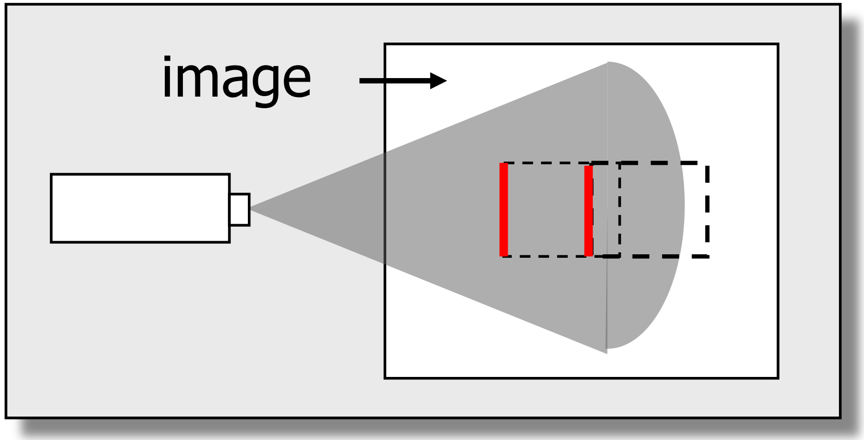
RCC by ATI Industrial Automation
http://www.ati-ia.com

Proximity/distance sensors - 4

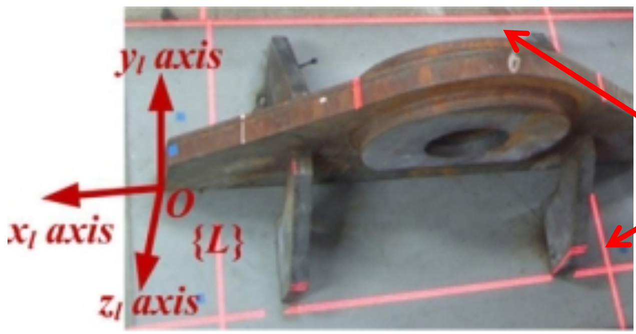
- structured light: a laser beam (coherent light source) is projected on the environment, and its planar intersection with surrounding objects is detected by a (tilted) camera
- the position of the "red pixels" on the camera image plane is in trigonometric relation with the object distance from the sensor



side view

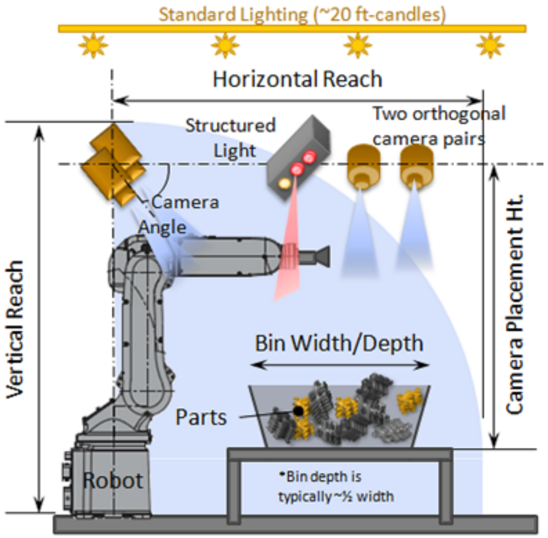


top view

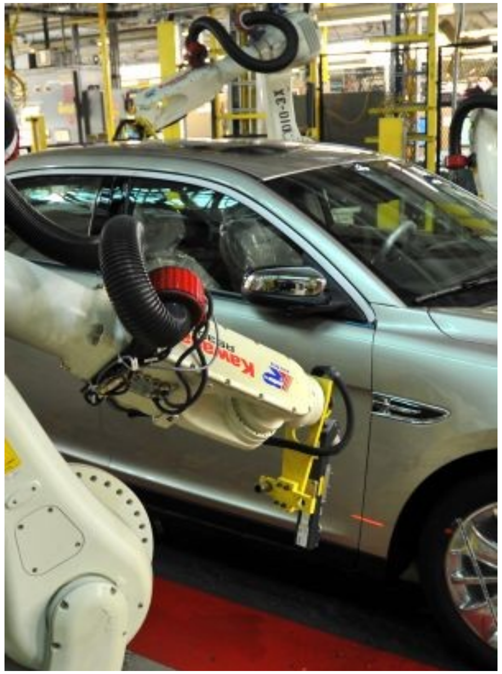


projected laser beams (2D in this case)

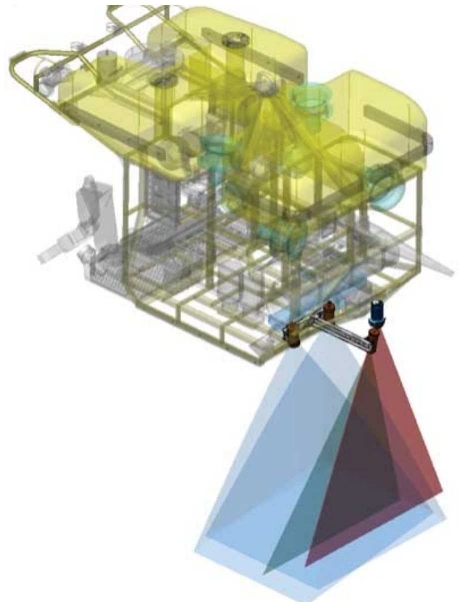
Use of structured light sensors

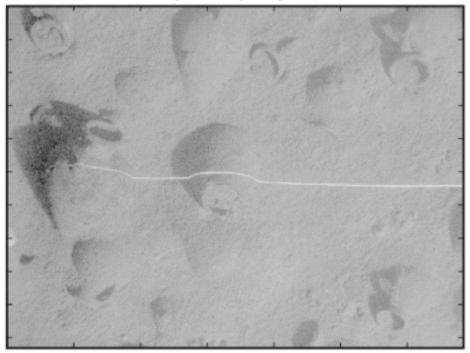


Random bin picking of 10-30 parts/minute (with surface inspection) with a 6R industrial robot, two pairs of cameras and a structured light sensor [Universal Robotics]



Structured light approach to best fit and finish car bodies (down to 0.1 mm) for reducing wind noise [Ford Motor Co.]





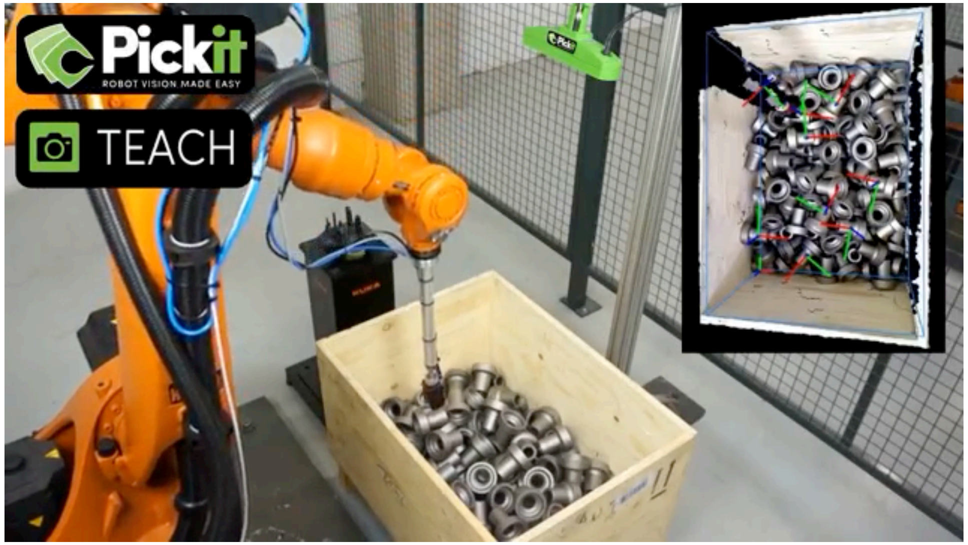
Hercules ROV + structured-laser-light imaging system for high-resolution bathymetric underwater maps [Univ. Rhode Island]

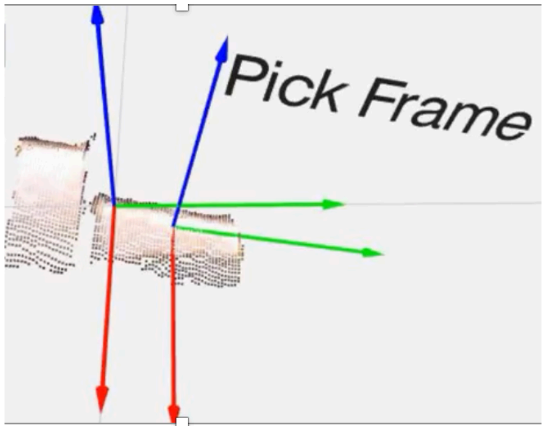
Virtobot system for post-mortem 3D optical scanning of human body & image-guided needle placement [Univ. Zürich]

Robotic bin picking
using vision and structured light

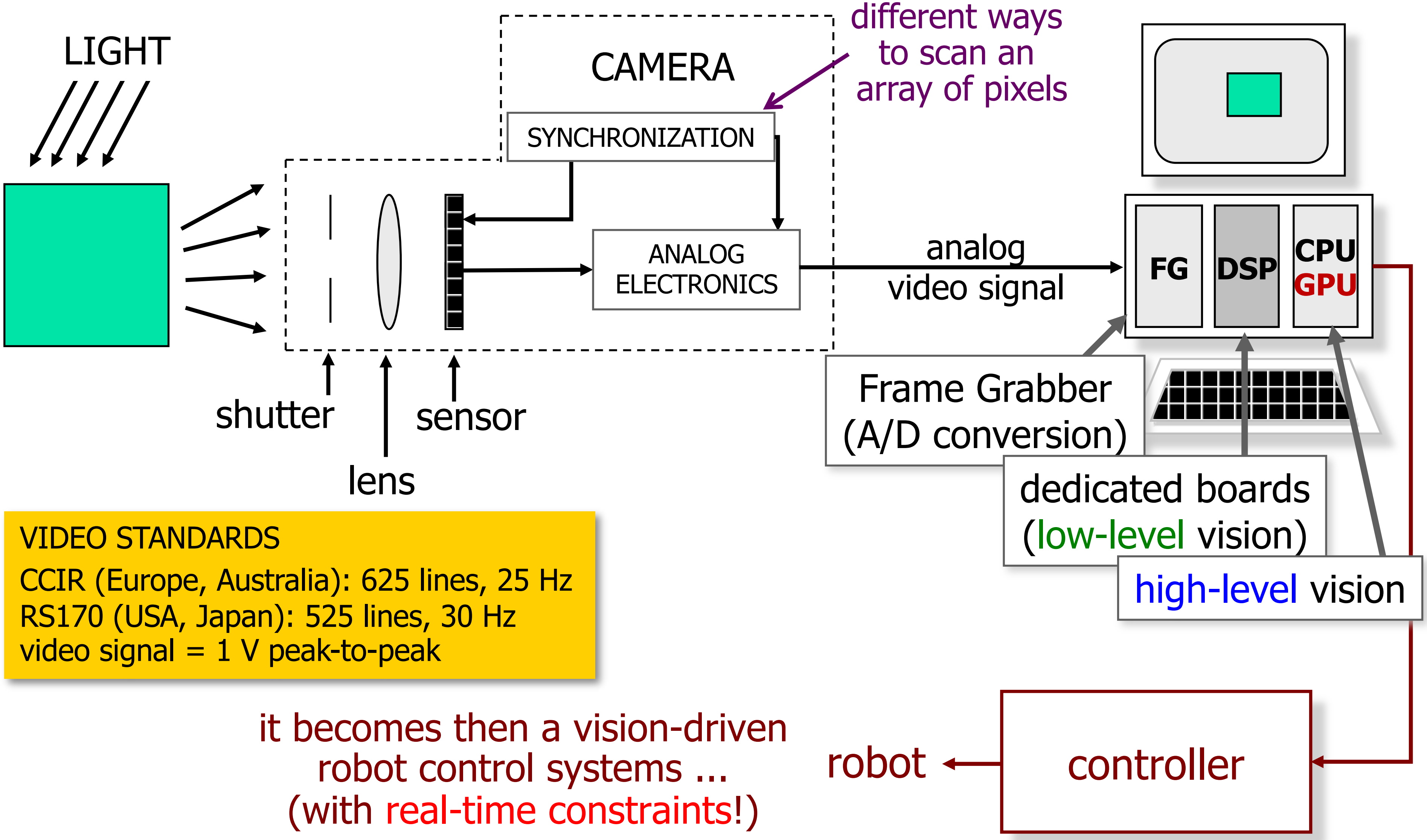
video

video





Vision systems

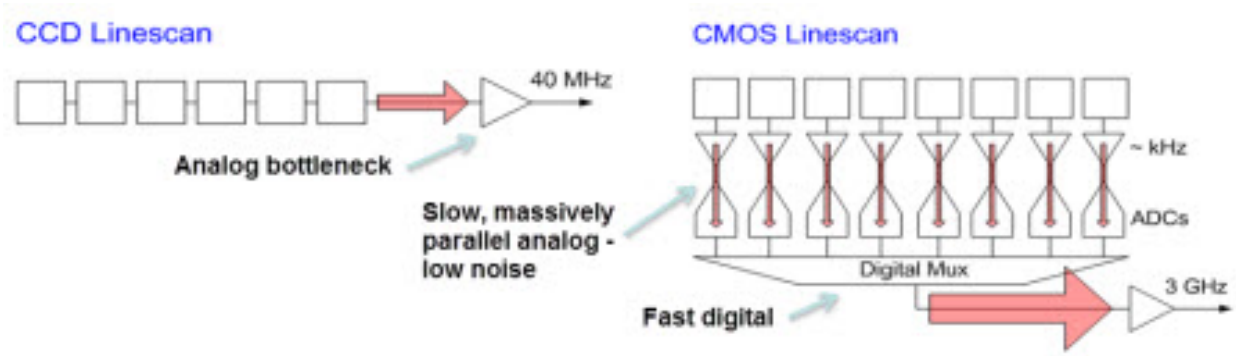


VIDEO STANDARDS
CCIR (Europe, Australia): 625 lines, 25 Hz
RS170 (USA, Japan): 525 lines, 30 Hz
video signal = 1 V peak-to-peak

it becomes then a vision-driven robot control systems ...
(with real-time constraints!)

Sensors for vision

- arrays (spatial sampling) of photosensitive elements (pixel) converting light energy into electrical energy
- CCD (Charge Coupled Device): each pixel surface is made by a semiconductor device, accumulating free charge when hit by photons (photoelectric effect); "integrated" charges "read-out" by a sequential process (external circuitry) and transformed into voltage levels
- CMOS (Complementary Metal Oxide Semiconductor): each pixel is a photodiode, directly providing a voltage or current proportional to the instantaneous light intensity, with possibility of random access to each pixel

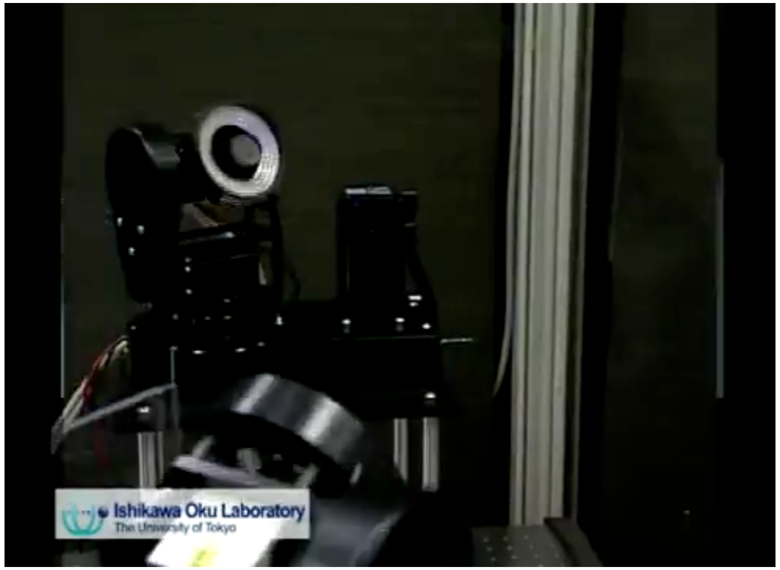


CMOS versus CCD

- reduction of fabrication costs of CMOS imagers
- better spatial resolution of elementary sensors
  - CMOS: 1M pixel, CCD: 768×576 pixel
- faster processing speed
  - 1000 vs. 25 fps (frames per second)
- possibility of integrating "intelligent" functions on single chip
  - sensor + frame grabber + low-level vision
- random access to each pixel or area
  - flexible handling of ROI (Region Of Interest)
- possibly lower image quality w.r.t. CCD imagers
  - sensitivity, especially for applications with low S/N signals
- customization for small volumes is more expensive
  - CCD cameras have been on the market since much longer time

Fast image processing for fast motion control

video



video

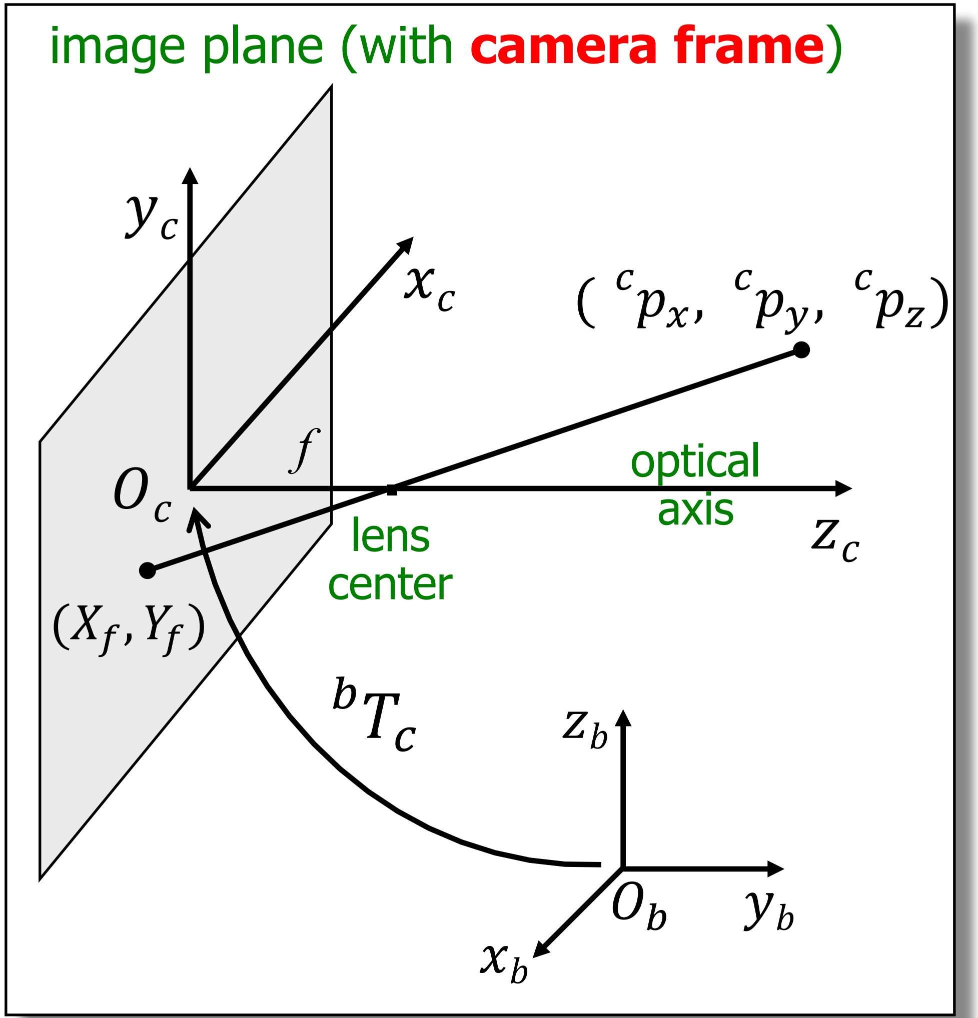
video

- 1 KHz vision frame rate
- 1 KHz robot control rate

  @ Ishikawa Lab – U Tokyo

  (2007-09)

Perspective transformation
with pinhole camera model



1. in metric units

$$X_f = \frac{f\ {}^c p_x}{f - {}^c p_z} \qquad Y_f = \frac{f\ {}^c p_y}{f - {}^c p_z}$$

2. in pixel

$$X_I = \frac{\alpha_x f\ {}^c p_x}{f - {}^c p_z} + X_0$$

$$Y_I = \frac{\alpha_y f\ {}^c p_y}{f - {}^c p_z} + Y_0$$

offsets of pixel coordinate system w.r.t. optical axis

pixel/metric scaling factor

3. LINEAR MAP in homogeneous coordinates

$$X_I = \frac{x_I}{z_I} \quad Y_I = \frac{y_I}{z_I} \quad \Rightarrow \quad \begin{bmatrix} x_I \\ y_I \\ z_I \end{bmatrix} = \Omega \begin{bmatrix} {}^c p_x \\ {}^c p_y \\ {}^c p_z \\ 1 \end{bmatrix}$$

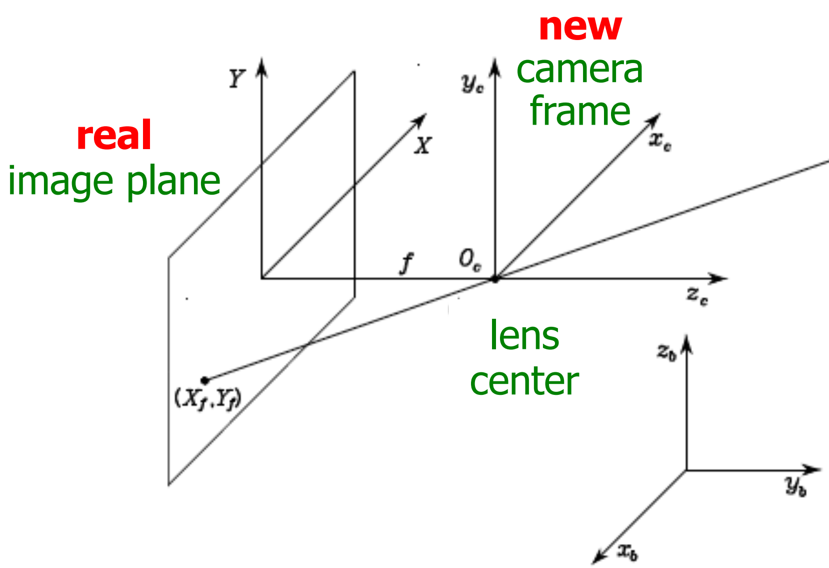
$$\Omega = \begin{bmatrix} \alpha_x & 0 & X_0 & 0 \\ 0 & \alpha_y & Y_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/f & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

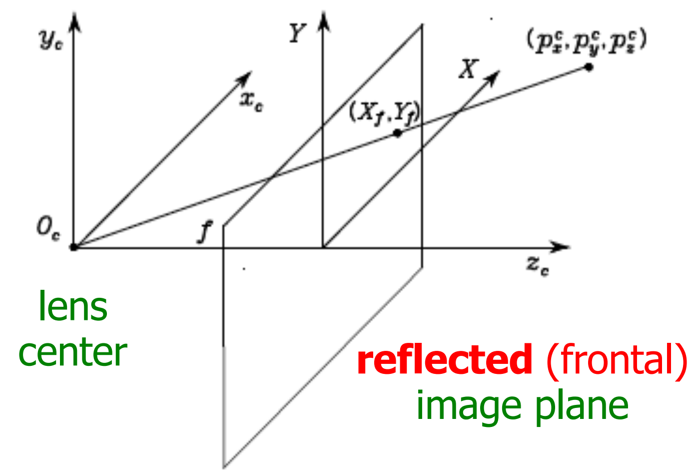
calibration matrix

$$H = \Omega \cdot {}^c T_b$$

intrinsic and extrinsic parameters

Perspective transformation
with camera frame at the lens center





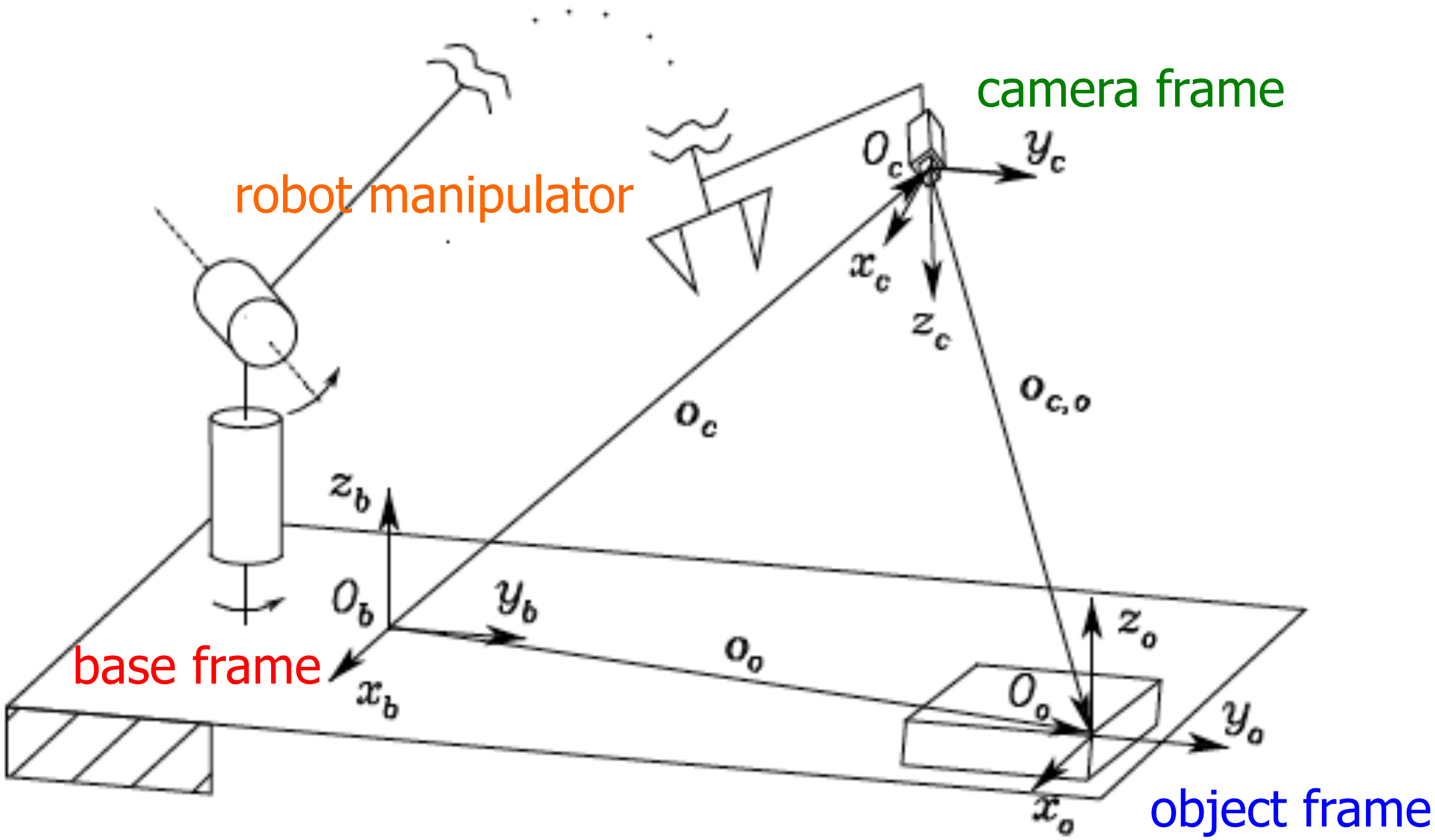
1. in metric units $\quad X_f = -\dfrac{f\ {}^c p_x}{{}^c p_z} \quad Y_f = -\dfrac{f\ {}^c p_y}{{}^c p_z} \quad \Rightarrow \quad X_f = \dfrac{f\ {}^c p_x}{{}^c p_z} \quad Y_f = \dfrac{f\ {}^c p_y}{{}^c p_z}$

2. in pixel $\quad \ldots \quad \Rightarrow \quad X_I = \dfrac{\alpha_x f\ {}^c p_x}{{}^c p_z} + X_0 \quad Y_I = \dfrac{\alpha_y f\ {}^c p_y}{{}^c p_z} + Y_0$

3. LINEAR MAP in homogeneous coordinates $\quad \ldots \quad \Rightarrow$

$$\begin{bmatrix} x_I \\ y_I \\ z_I \end{bmatrix} = \Omega \begin{bmatrix} {}^c p_x \\ {}^c p_y \\ {}^c p_z \\ 1 \end{bmatrix} \qquad \Omega = \begin{bmatrix} \alpha_x f & 0 & X_0 & 0 \\ 0 & \alpha_y f & Y_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

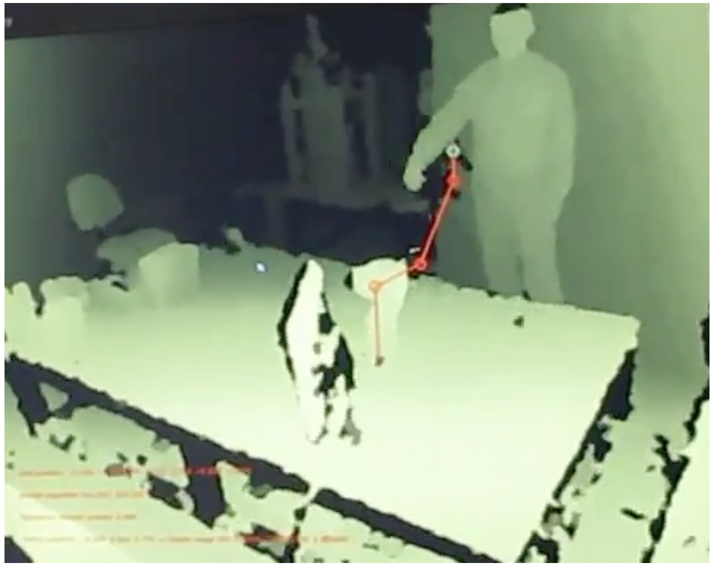
Eye-in-hand camera



Relevant reference frames for visual-based tasks

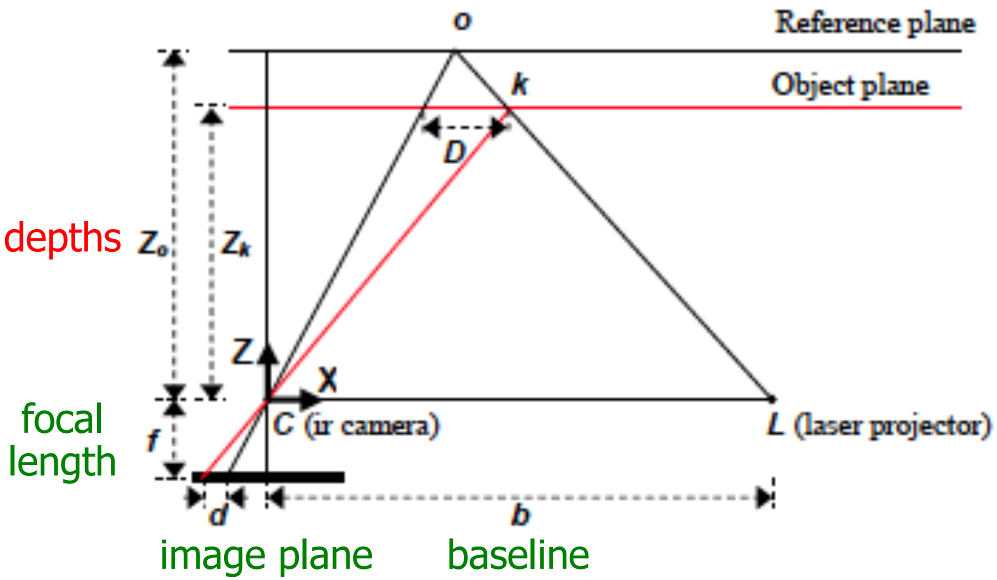
Kinect
camera + structured light 3D sensor

- RGB camera (with 640 × 480 pixel)
- depth sensor (by PrimeSense)
  - infrared laser emitter
  - infrared camera (with 320 × 240 pixel)
- 30 fps data rate
- range: 0.5 ÷ 5 m
- depth resolution: 1cm@2m; 7cm@5m
- cost: < 90 €



"skeleton" extraction and
human motion tracking

Kinect
Depth sensor operation



- stereo triangulation based on IR source emitting pseudo-random patterns
- reference pattern on IR camera image plane acquired in advance from a plane at known distance and coded in H/W
- correlating the disparity d (10 bits) of reference and received object patterns provides the object depth z_k

1. triangulation equations (by similarity of triangles)

$$\frac{D}{b} = \frac{z_0 - z_k}{z_0} \quad \& \quad \frac{d}{f} = \frac{D}{z_k} \quad \Rightarrow \quad z_k = \frac{z_0}{1 + \frac{d}{fb} z_0}$$

$$x_k = -\frac{z_k}{f}(X_k - X_0 + \delta X)$$

$$y_k = -\frac{z_k}{f}(Y_k - Y_0 + \delta Y)$$

2. accurate calibration of sensor

   baseline length b, depth of reference z_0 + camera intrinsic parameters (focal length f, lens distortion coefficients $\delta X, \delta Y$, center offsets X_0, Y_0)

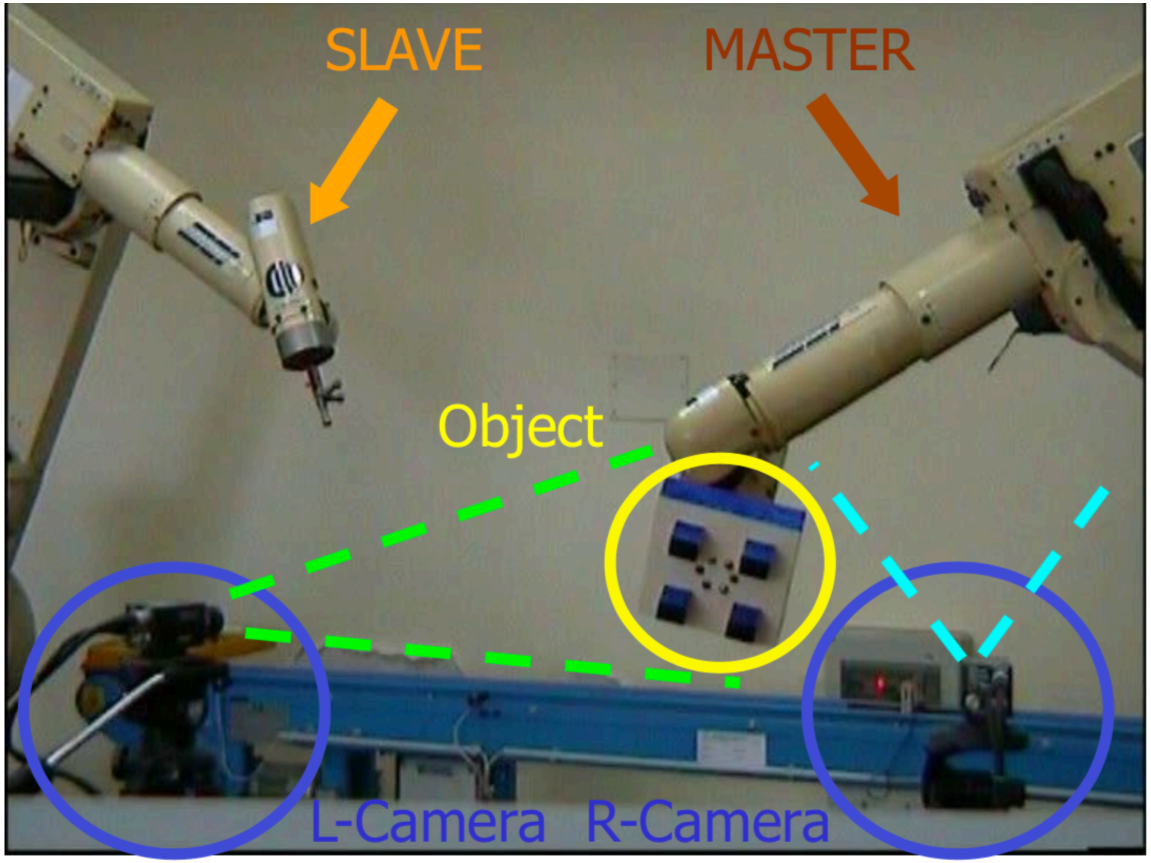
How Kinect works
(a 2-minute illustration...)

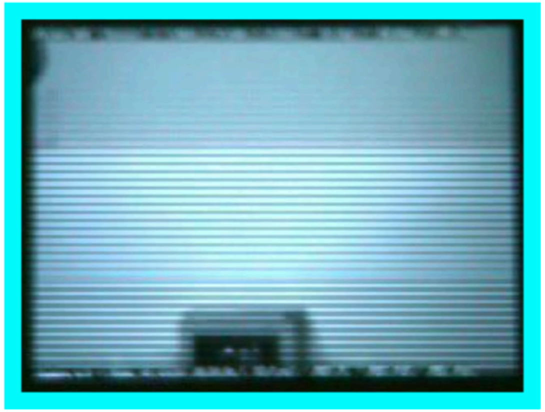
video

http://youtu.be/uq9SEJxZiUg

Manipulators and vision systems

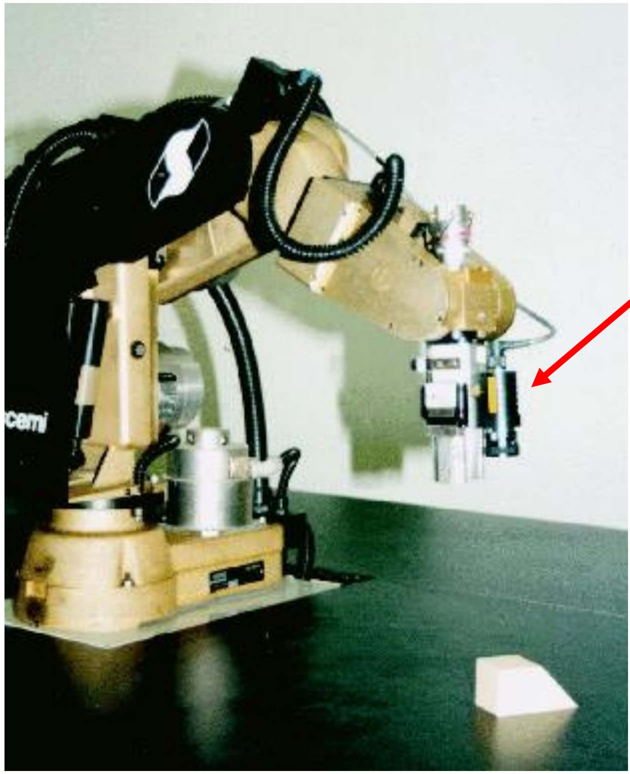
- stereovision with two external cameras, fixed in the environment (eye-to-hand)

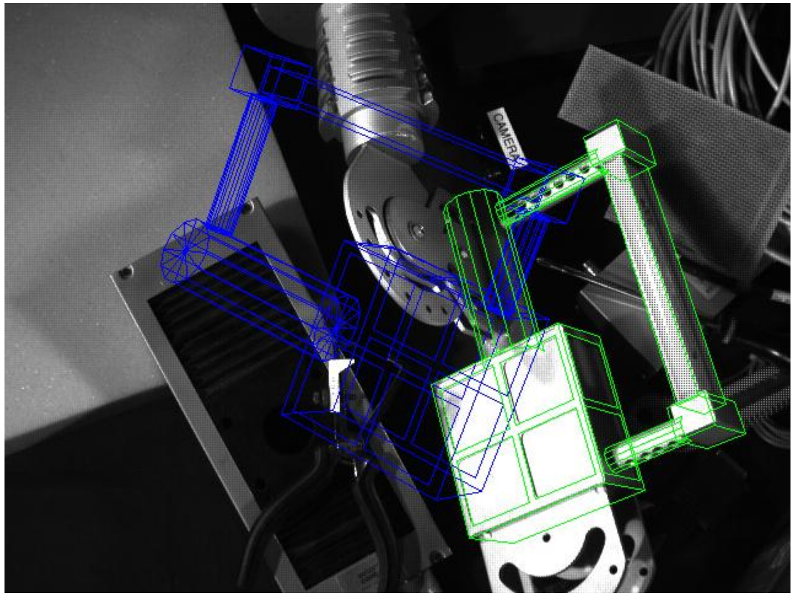




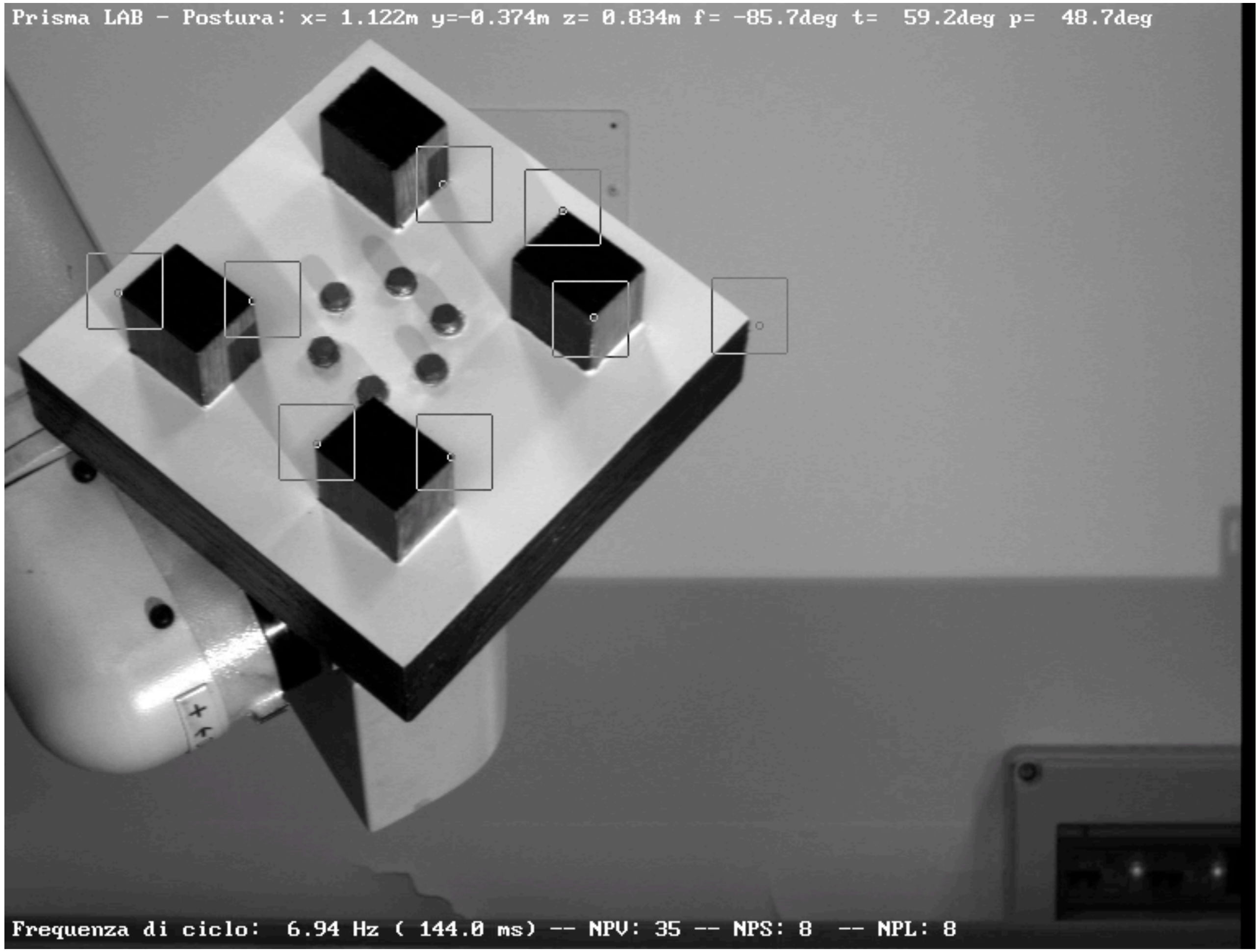
Manipulators and vision systems

- CCD camera mounted on the robot for controlling the end-effector positioning (eye-in-hand)





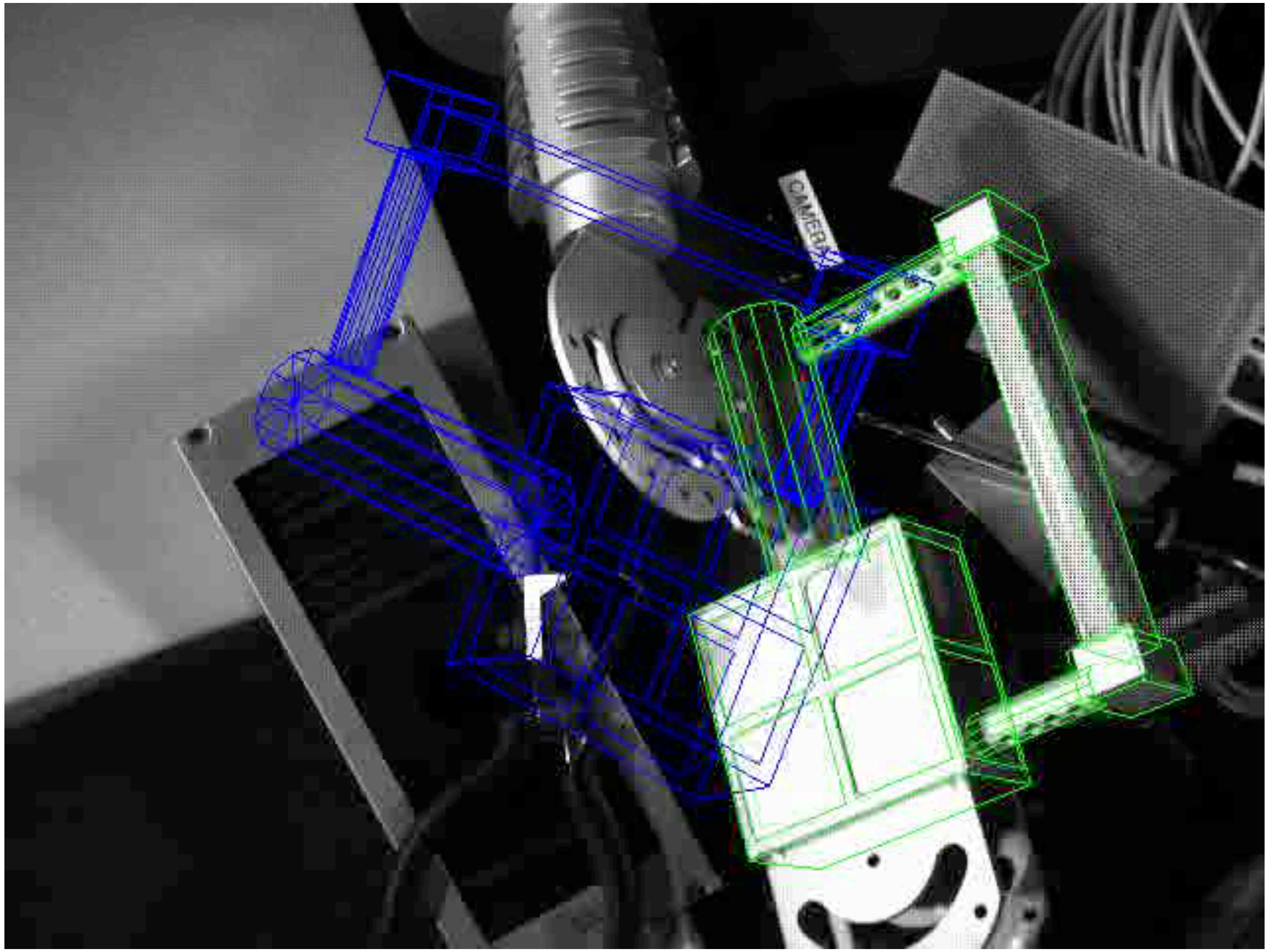
Visual tracking eye-to-hand



video

COMAU robot with position-based 6D tracking from external camera
(DIS, Università di Napoli Federico II)

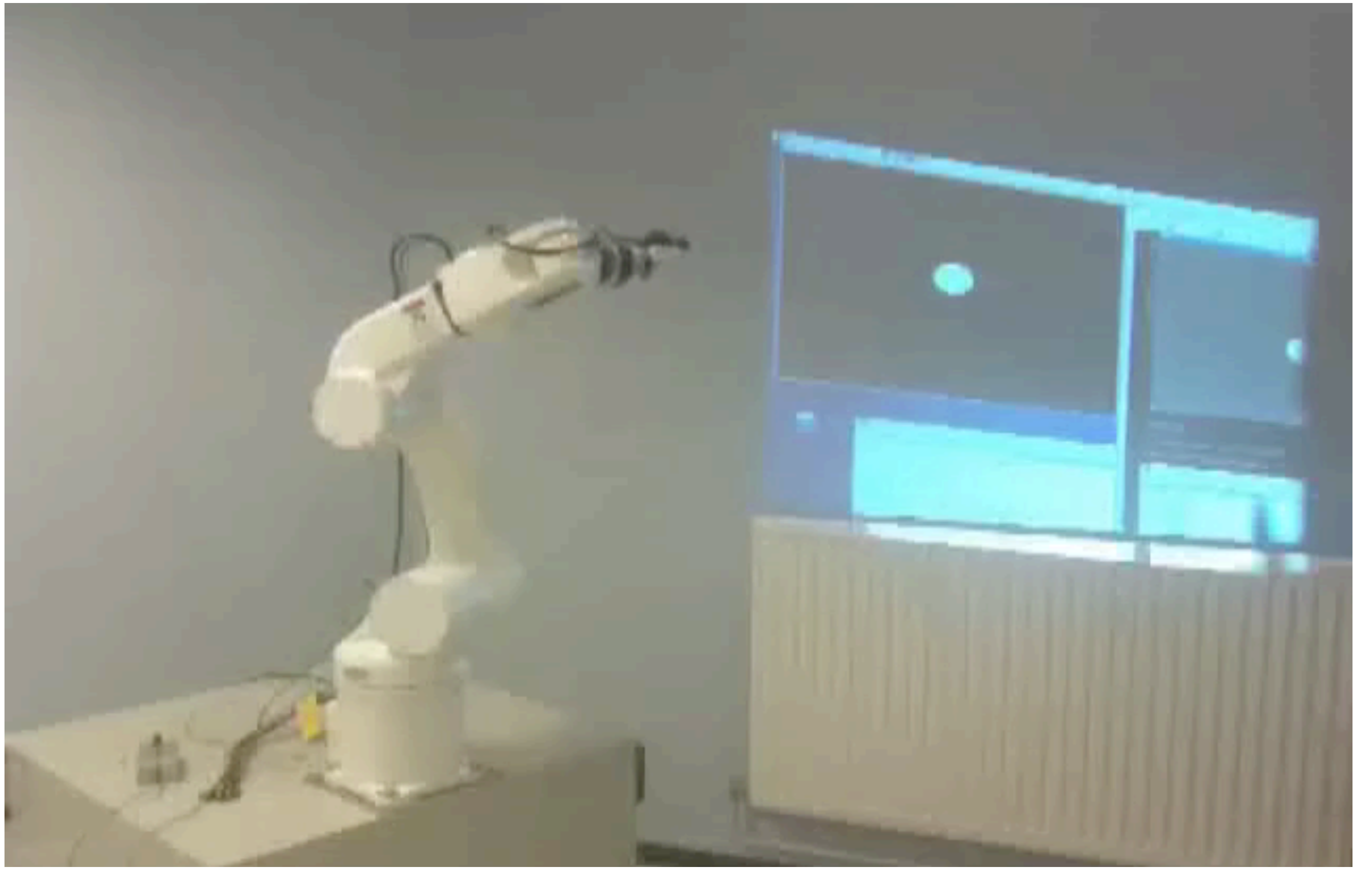
Visual servoing eye-in-hand



video

Image-based servoing with camera mounted on the robot end-effector
(IRISA/INRIA, Rennes)

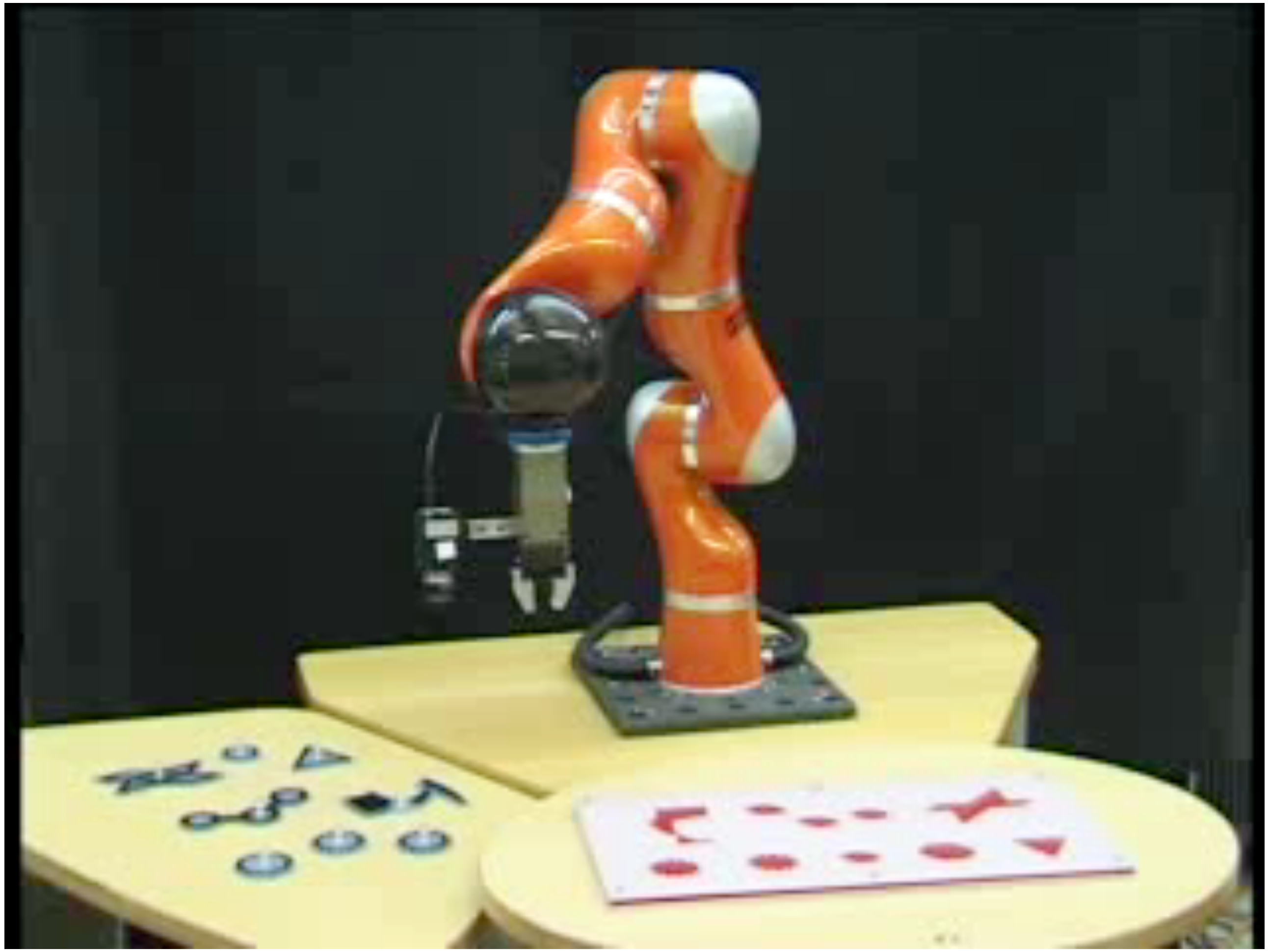
Visual servoing and redundancy



video

visual servoing of circle feature ($m = 3$: p_x, p_y, r) by Adept Viper robot ($n = 6$): redundancy is used for avoiding joint range limits (IRISA/INRIA, Rennes)

Combined visual/force assembly

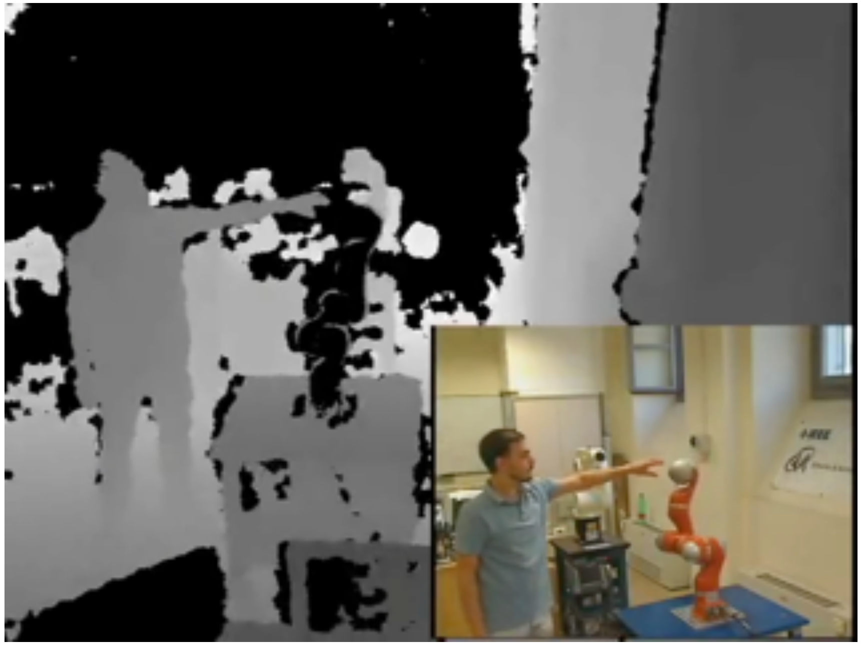


video

KUKA LWR with eye-in-hand camera and F/T sensor
(DLR, IEEE ICRA'07 demo in Roma)

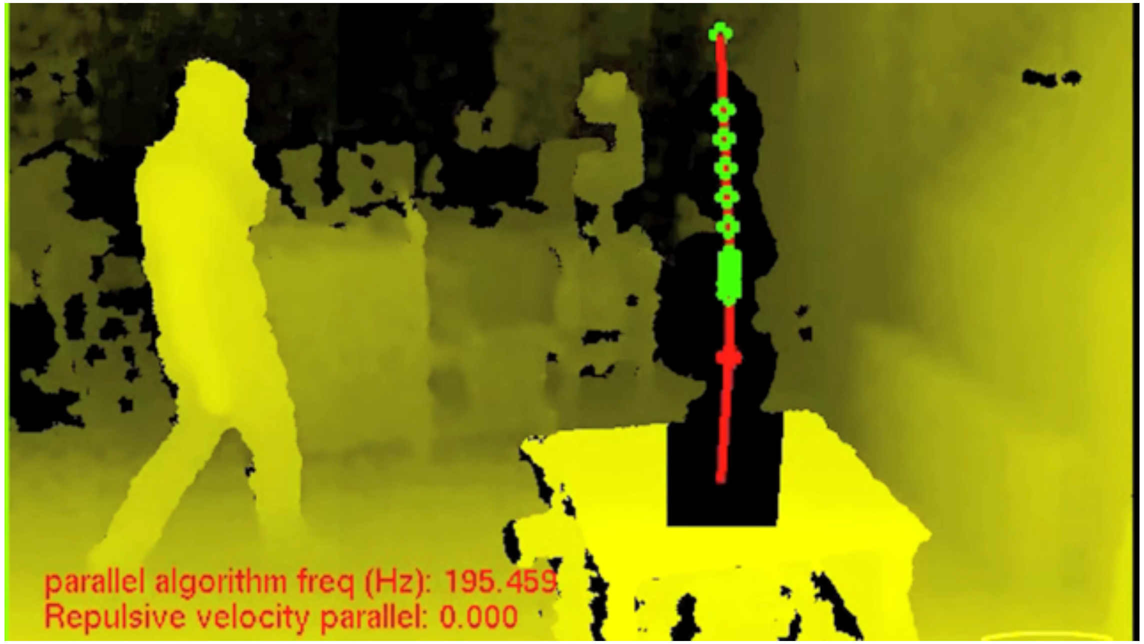
On-line distance computation and human-robot coexistence

video



monitoring left- and right-hand distance to the robot (at same time)

video



several control points on robot skeleton used to compute distances and control motion

KUKA LWR with a Kinect monitoring its workspace
(DIAG Robotics Laboratory, EU project SAPHARI, 2013)