Robotics 1

Robot components:
Introduction, Actuators, Transmissions

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AUTOMATICA E GESTIONALE ANTONIO RUBERTI

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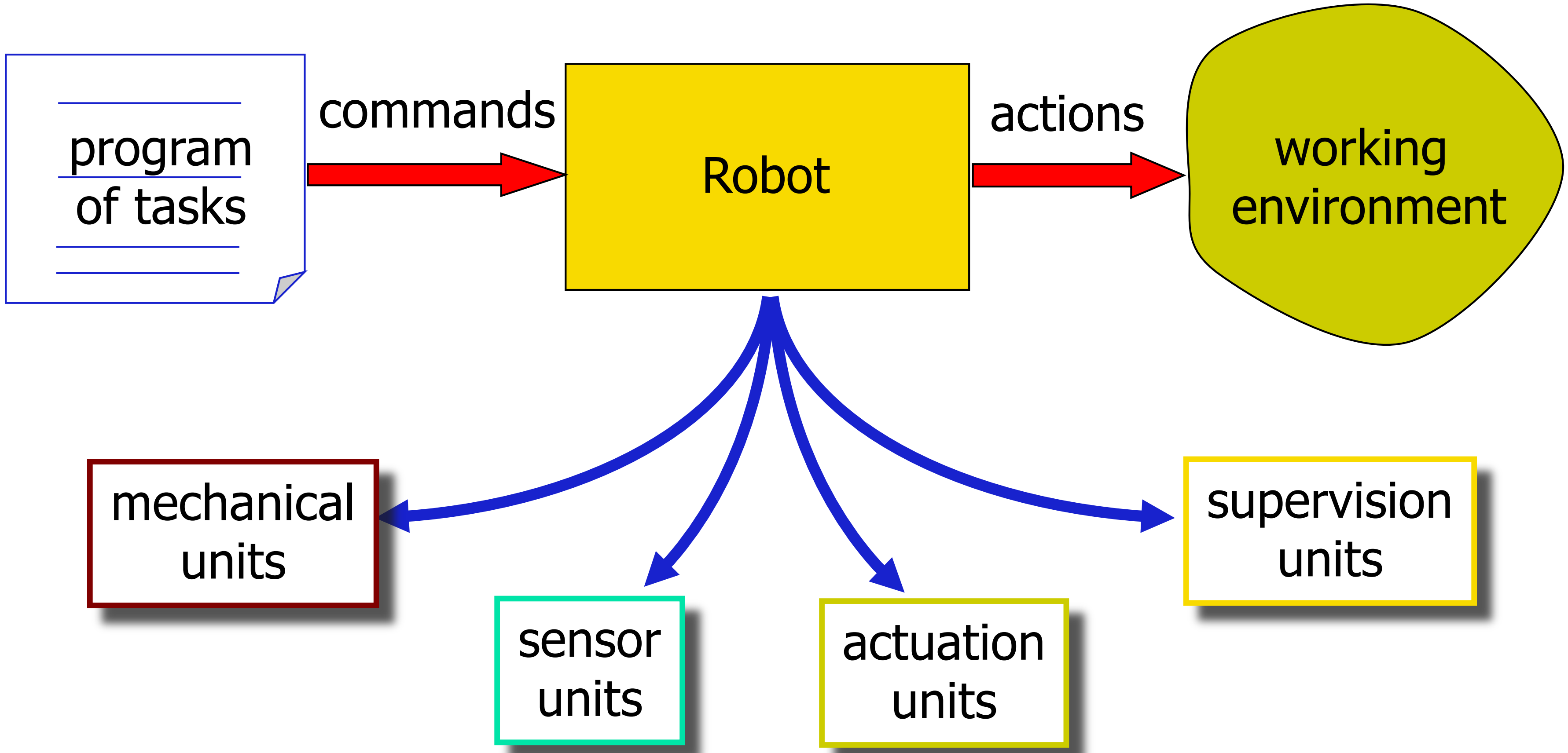
Robot as a system



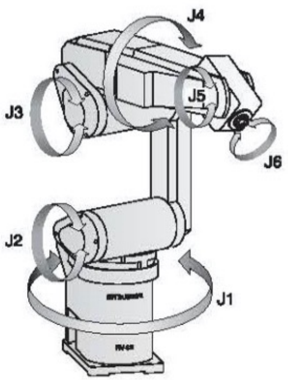
Functional units of a robot

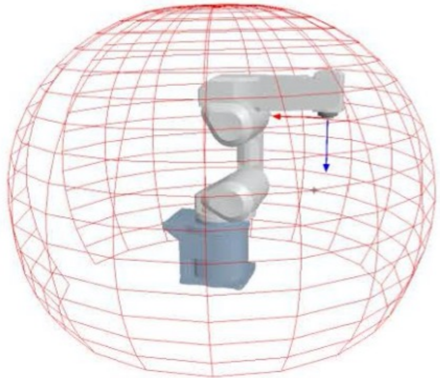
- mechanical units (robot arms)
  - serial manipulators: rigid links connected via rotational or prismatic joints (each giving 1 degree of freedom = DOF, R or P type)
  - supporting structure (mobility), wrist (dexterity), end-effector (for task execution, e.g., manipulation)
- actuation units
  - motors (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)

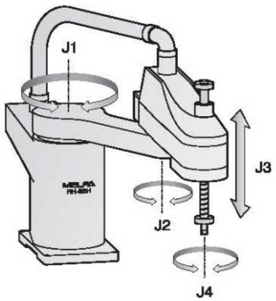
Articulated Robot

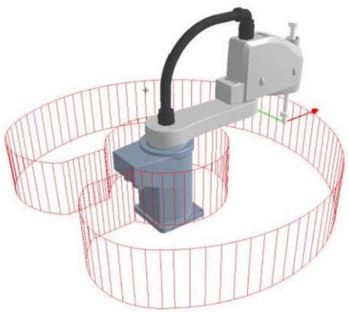




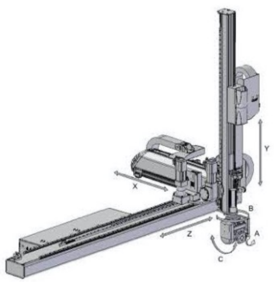
different kinematic types of robot arms

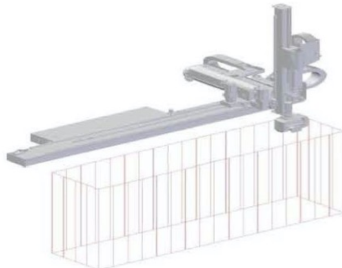
SCARA Robot



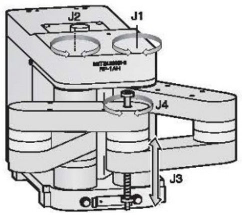


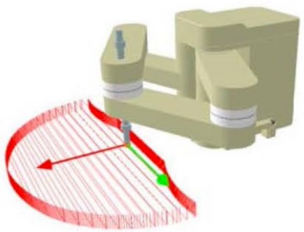
Cartesian Robot



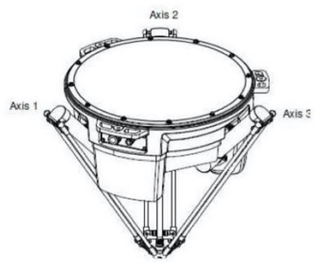


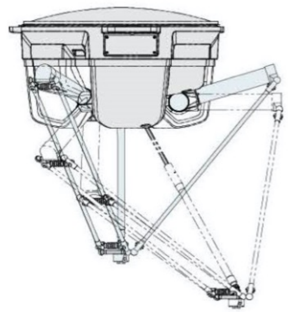
SCARA Robot





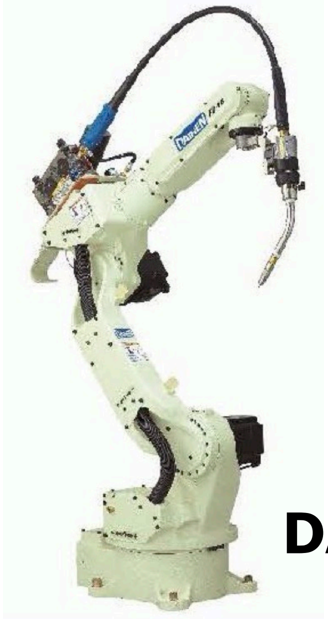
Parallel/Delta Robot





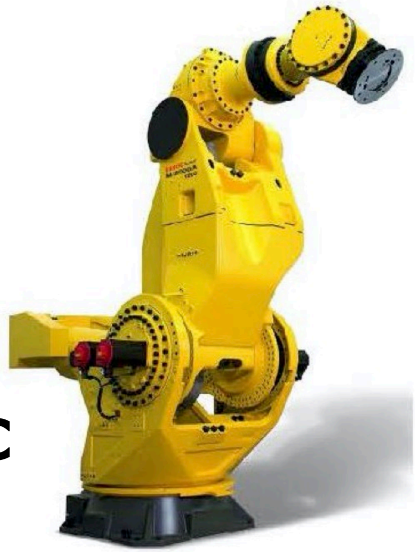
Examples of industrial robots
with brands

ABB



DAIHEN

EPSON



FANUC

KUKA

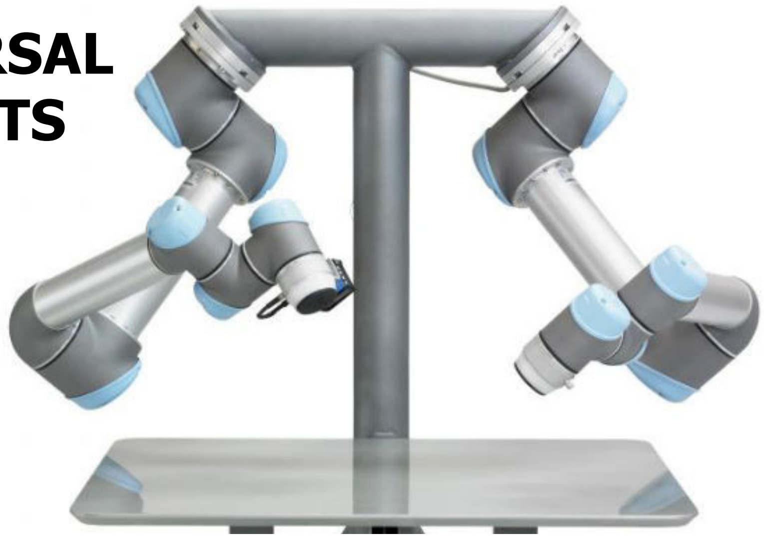
NAICHI

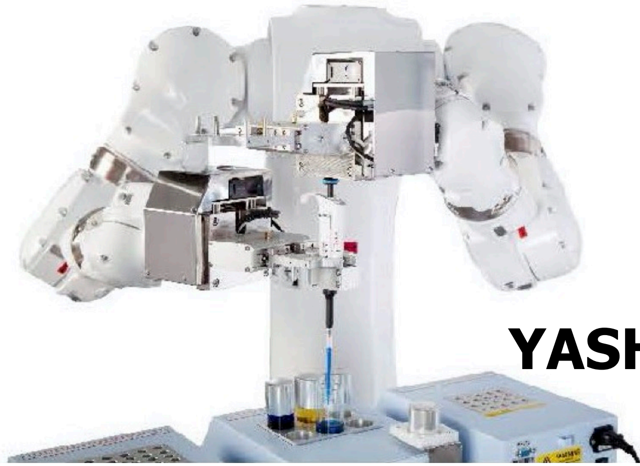
Bi-manual industrial robots
with brands

ABB

COMAU

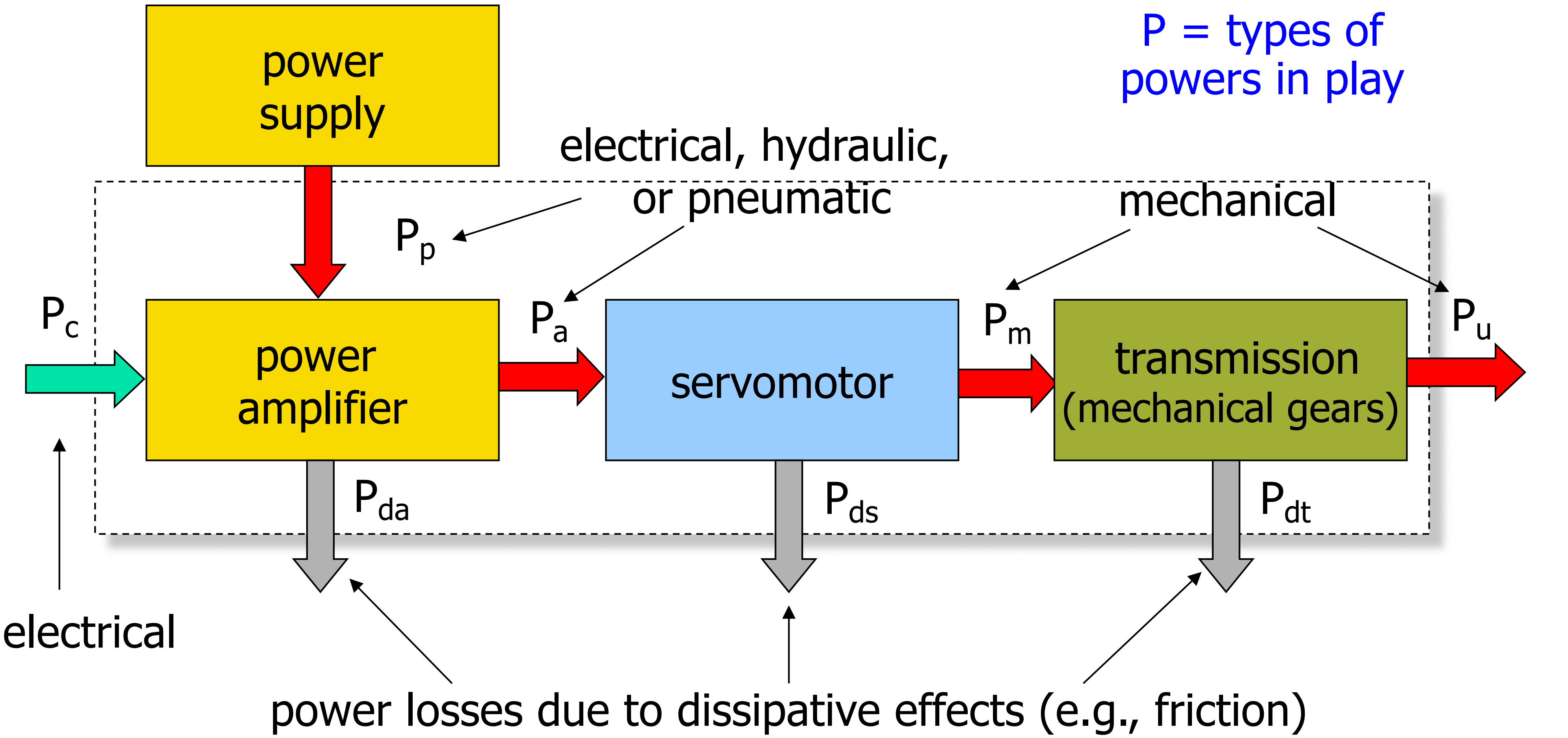
UNIVERSAL ROBOTS





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]

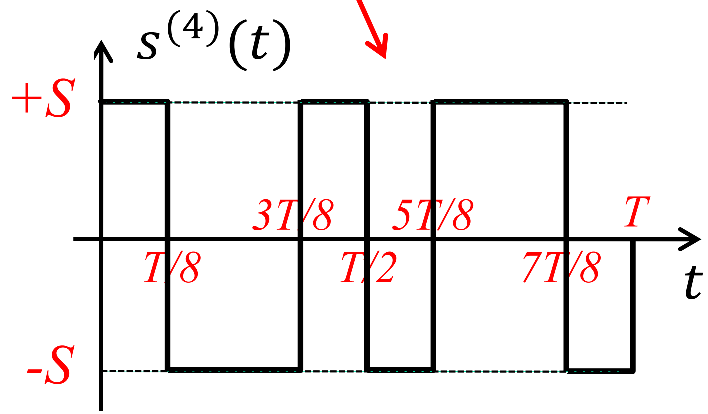
Desired characteristics for robot servomotors

examples of computations (with reduction ratio):

2000 rpm ~12500 rad/min = 210 rad/s → reduction ratio n_r = 50 → ~4 rad/s = 240 deg/s on link side

1/1000 turn ~ 6 mrad = 0.36 deg → reduction ratio n_r = 50 → 7.2 mdeg on link side

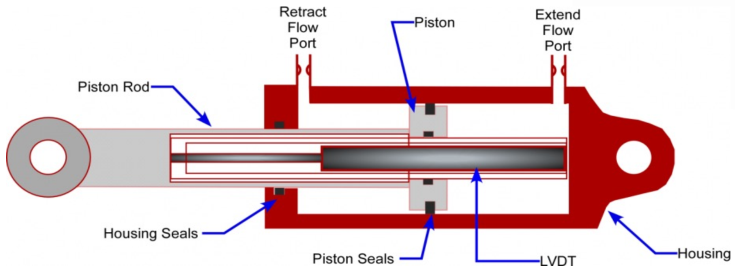
- low inertia
- high power-to-weight ratio
- high acceleration capabilities
  - variable motion regime, with several stops and inversions
- large range of operational velocities
  - 1 to 2000 rpm (round per min)
- high accuracy in positioning
  - at least 1/1000 of a turn
- low torque ripple
  - continuous rotation at low speed
- power: 10 W to 10 kW
  - max 80W for HRI applications



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)

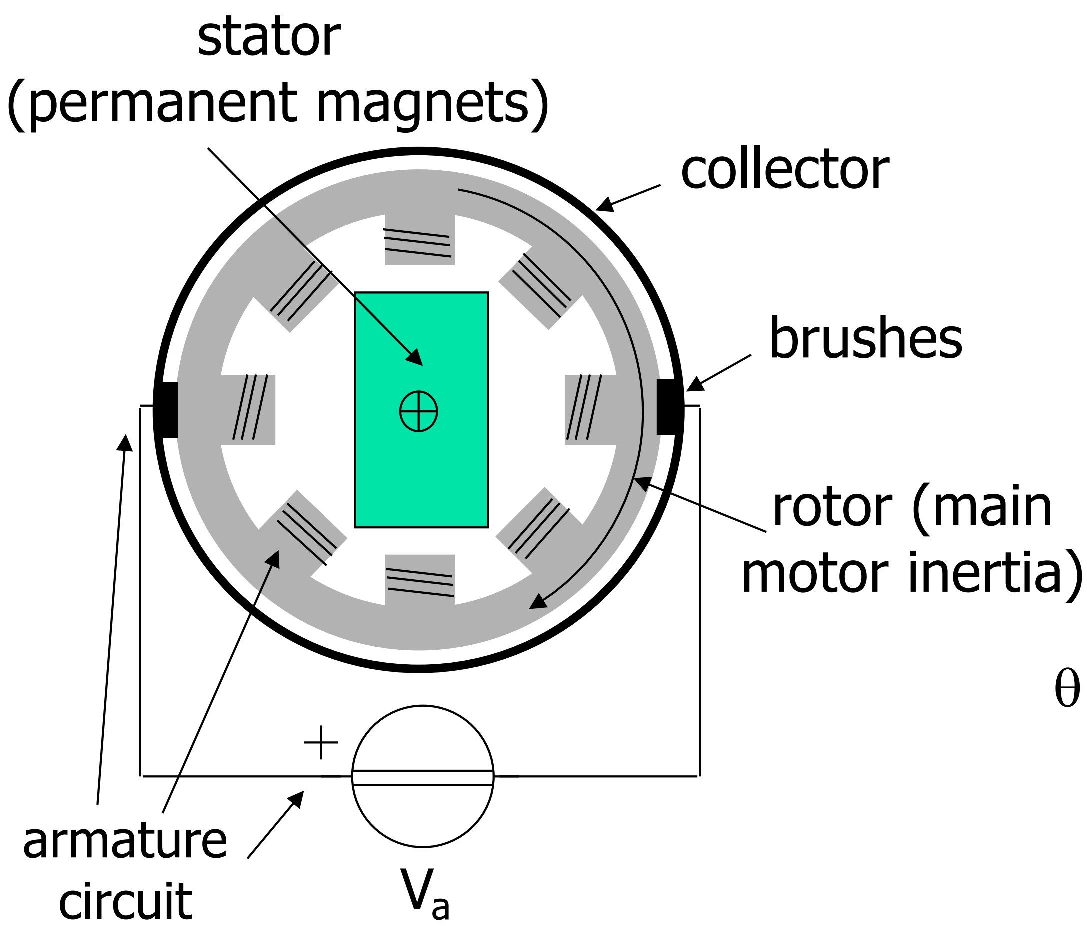
- hydraulic: hydraulic energy (accumulation tank) pumps/valves $\rightarrow$ mechanical energy
  - advantages: no static overheating, self-lubricated, inherently safe (no sparks), excellent power-to-weight ratio, large torques at low velocity (w/o reduction)
  - disadvantages: needs hydraulic supply,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



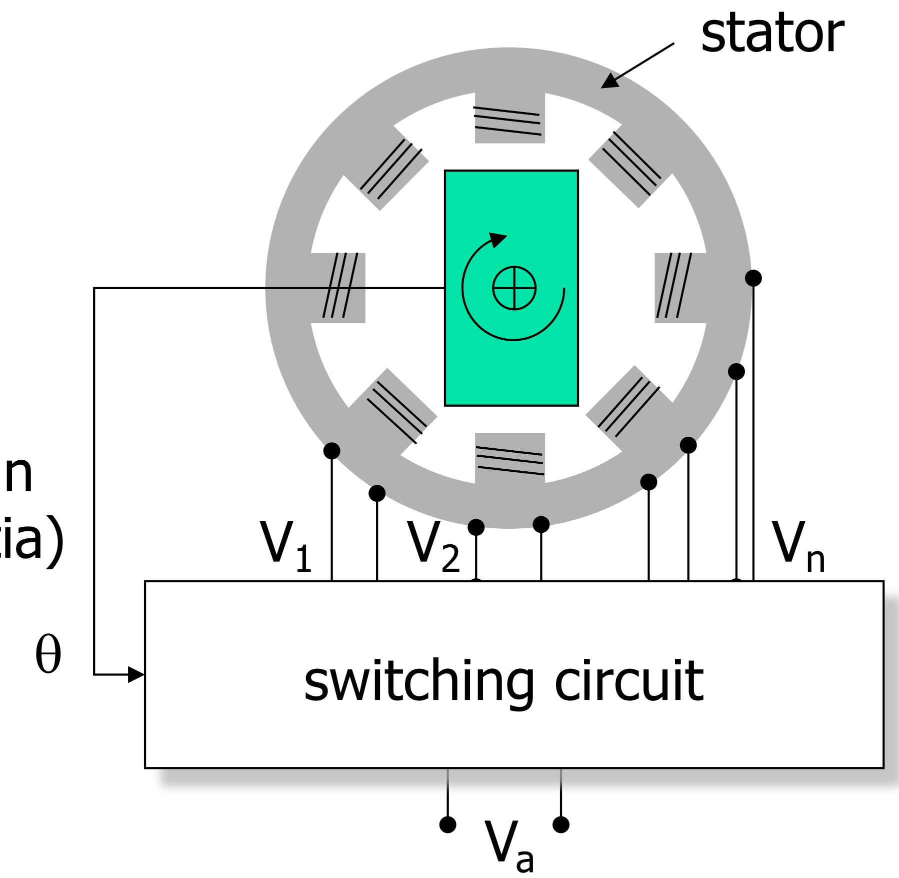
Electrical servomotors

- 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



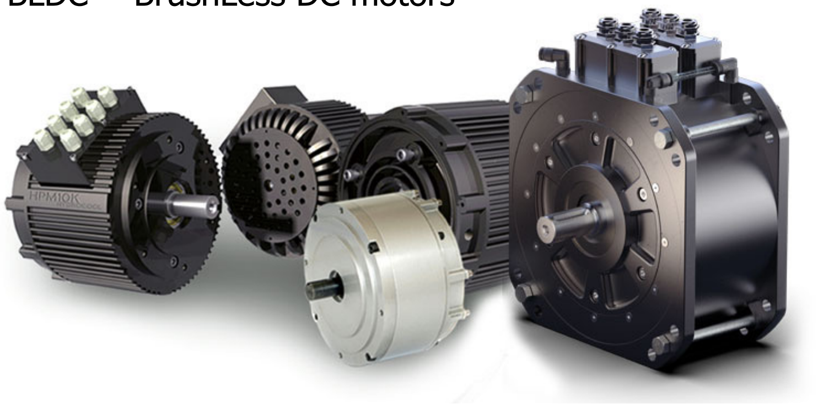
with electronic switches (brushless)

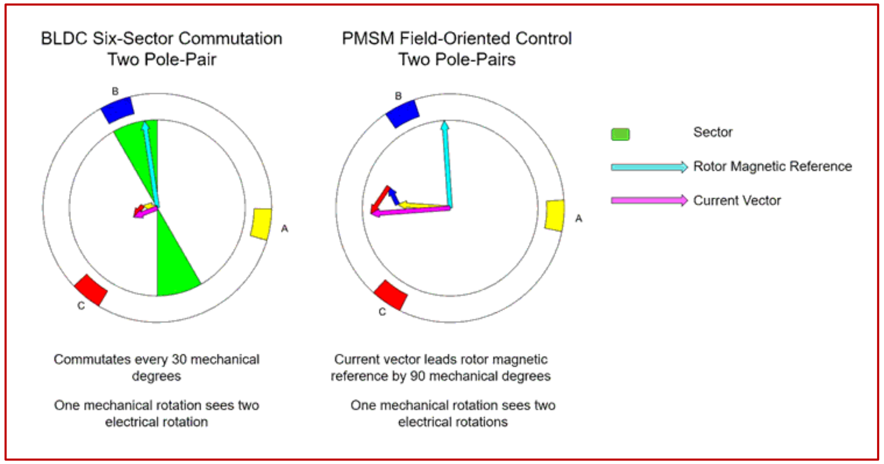
Advantages of brushless motors

- 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!

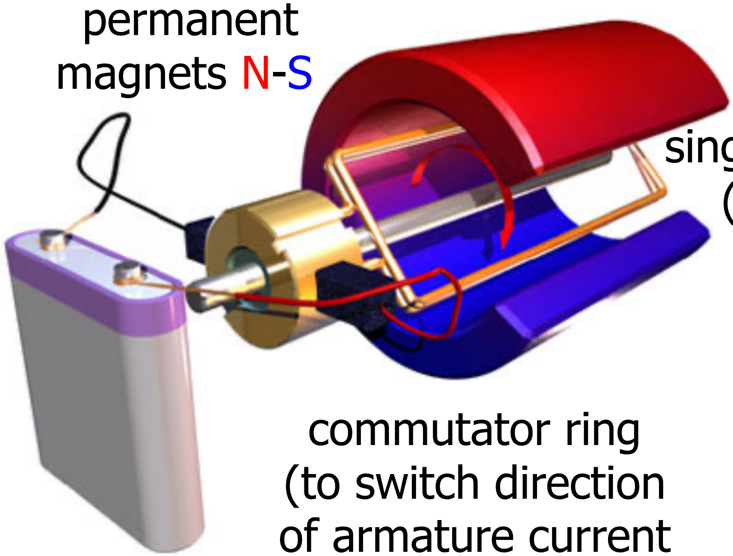
BLDC = BrushLess DC motors



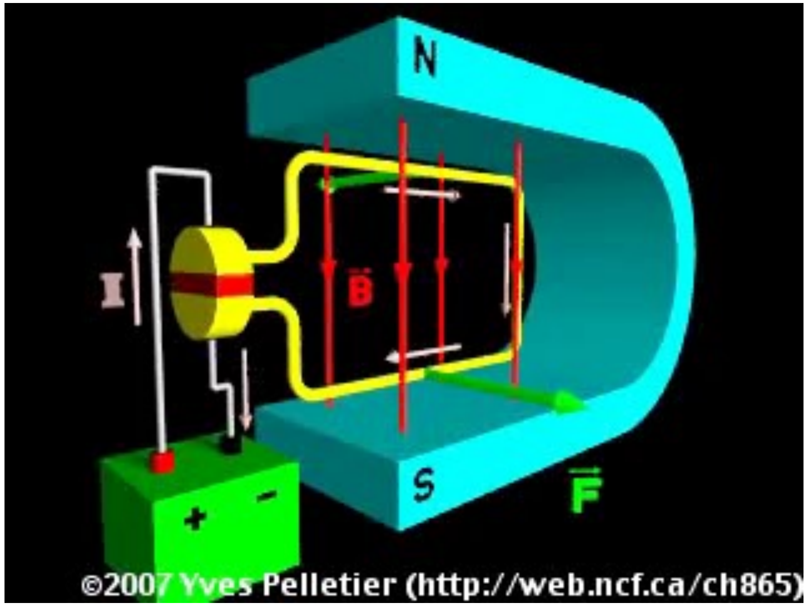


MATLAB animation

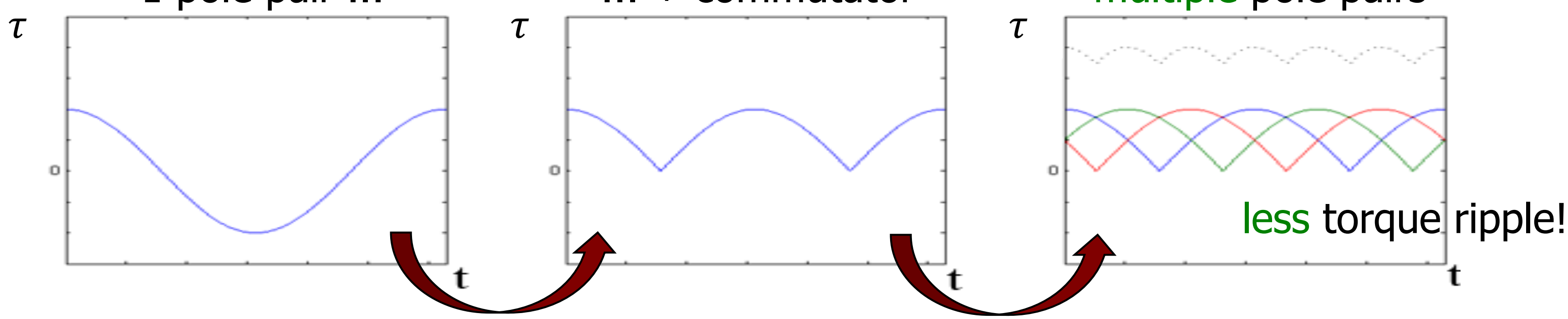
Principle of operation of a DC motor



video



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



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)

mechanical balance
(Newton law on torques)

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

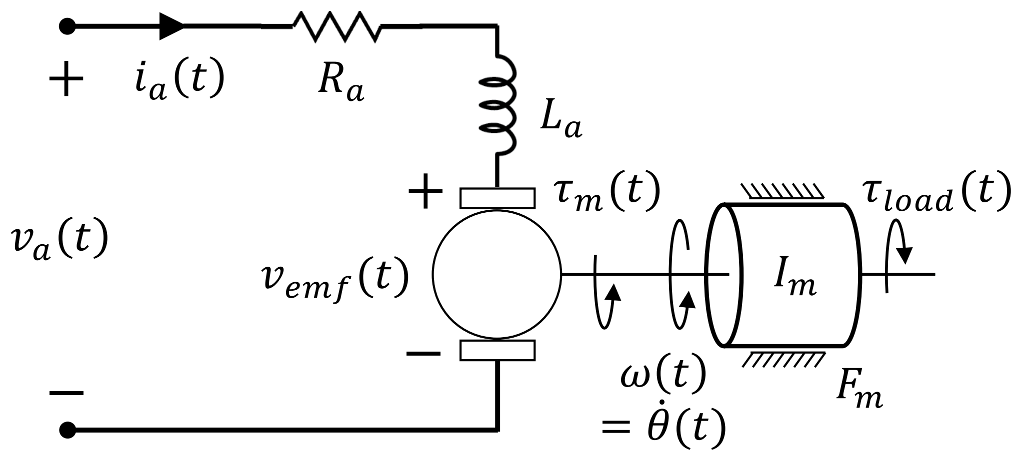
$$\tau_m(t) = k_t i_a(t)$$

(motor torque)

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

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

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



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)

time constants

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

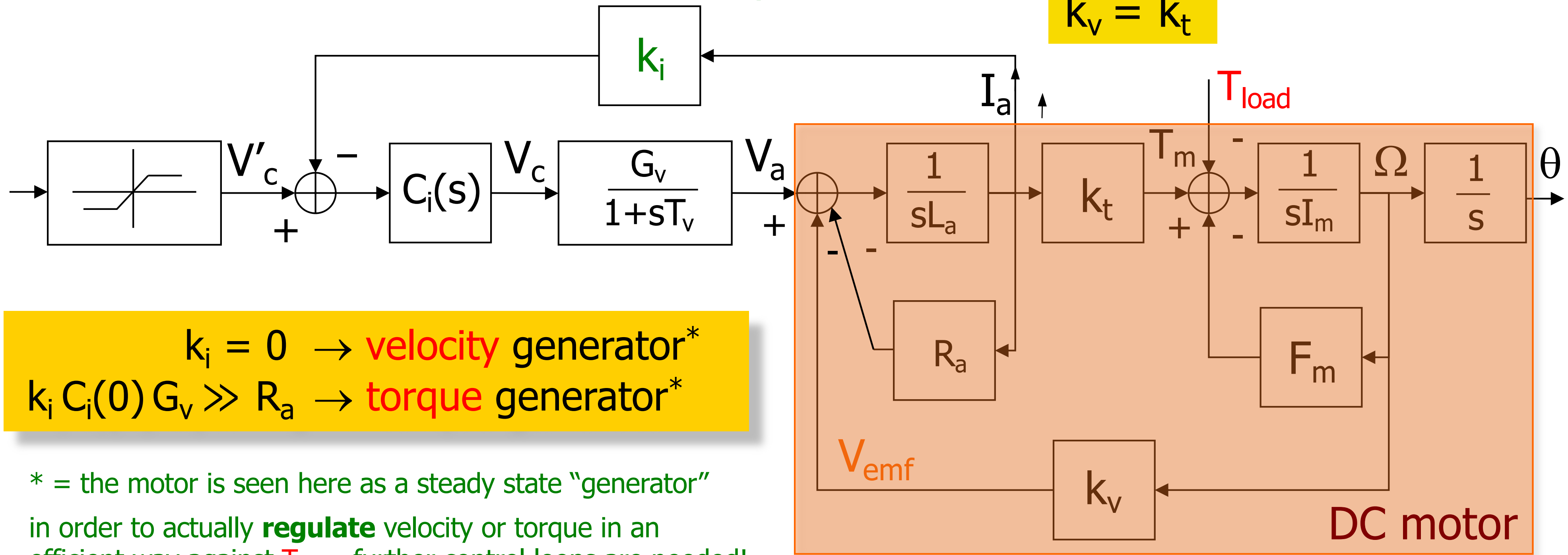
mechanical balance

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

$T_m = k_t\, I_a$

$k_v = k_t$

current loop



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

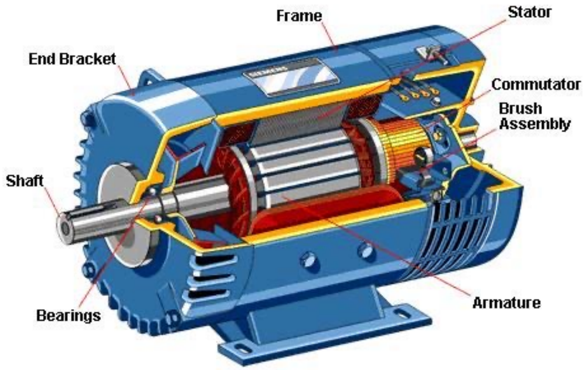
$k_i\, C_i(0)\, G_v \gg R_a \;\rightarrow$ torque generator*

* = 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!

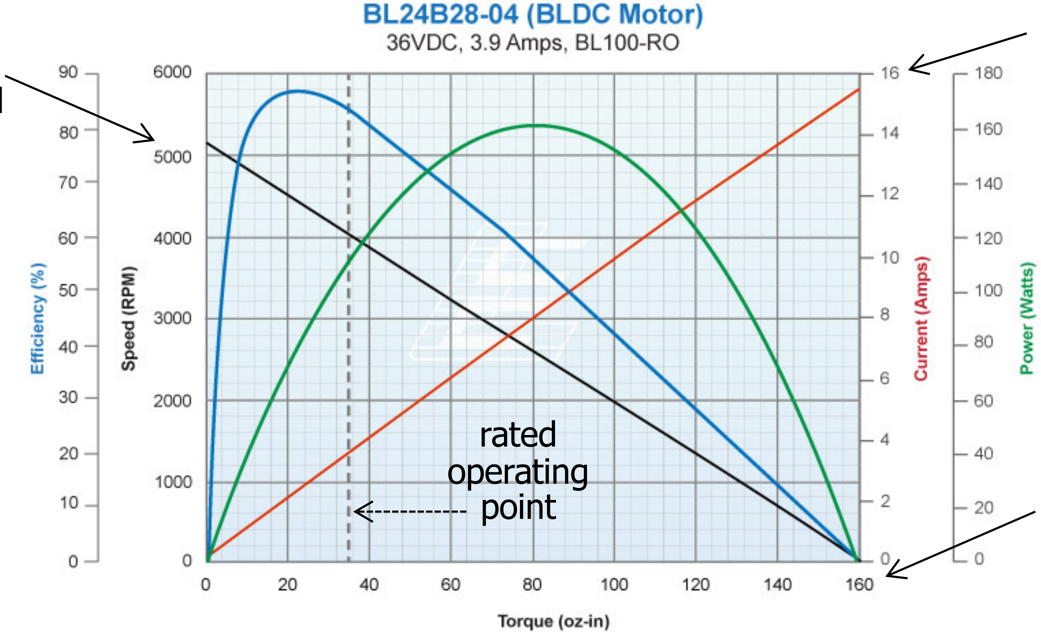
Characteristic curves of a DC motor

at steady-state, for constant applied tension v_a



no-load
max speed

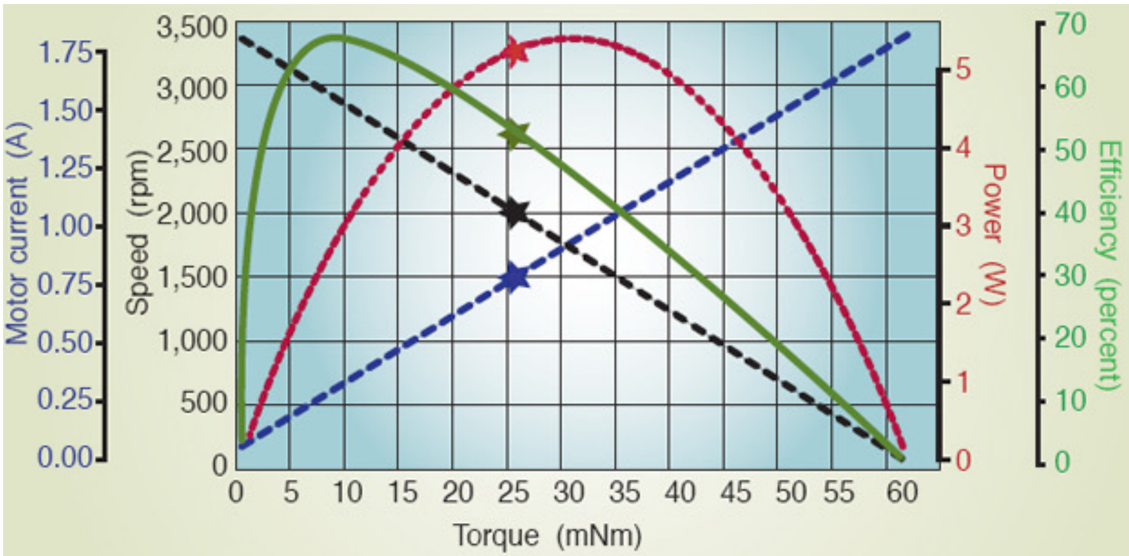
stall current



medium
size
motor
160 W

stall
load torque

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

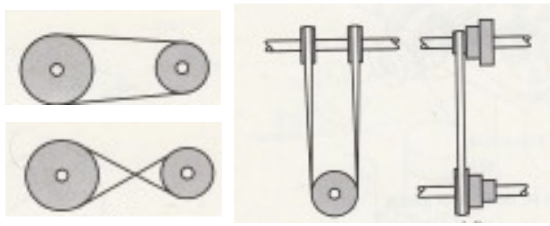
- optimize the transfer of mechanical torque from actuating motors to driven links
- quantitative transformation (from low torque/high velocity to high torque/low velocity)
- qualitative transformation (e.g., from rotational motion of an electrical motor to a linear motion of a link along the axis of 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/bevel gears: modify direction and/or translate axis of 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)

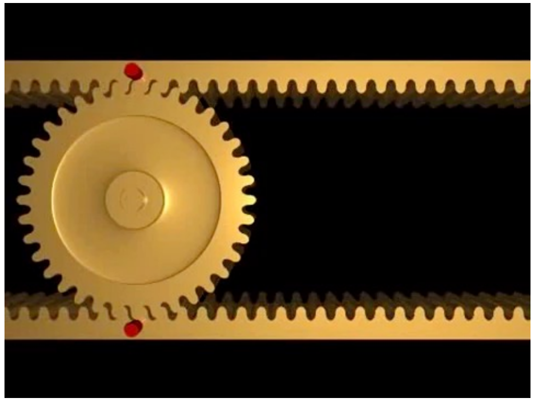


- harmonic drives: compact, in-line, power efficient, with high reduction ratio (up to 150-200:1)
  - problems: elasticity

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

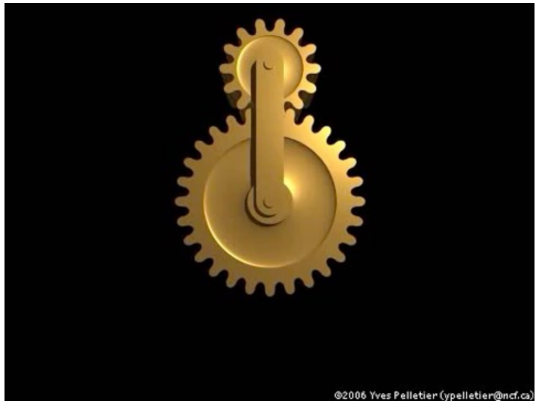
Transmission gears in motion

- 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

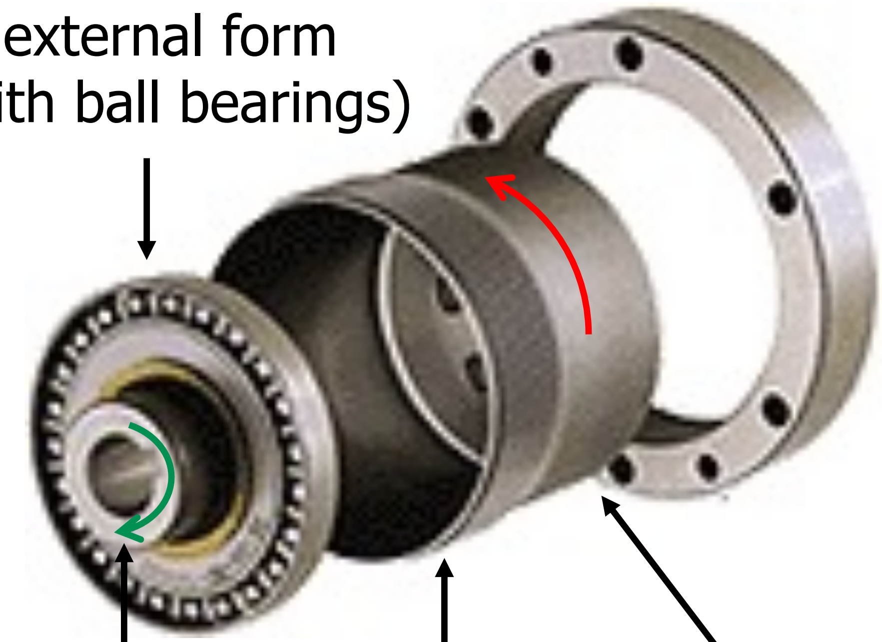
video

Harmonic drives

video

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

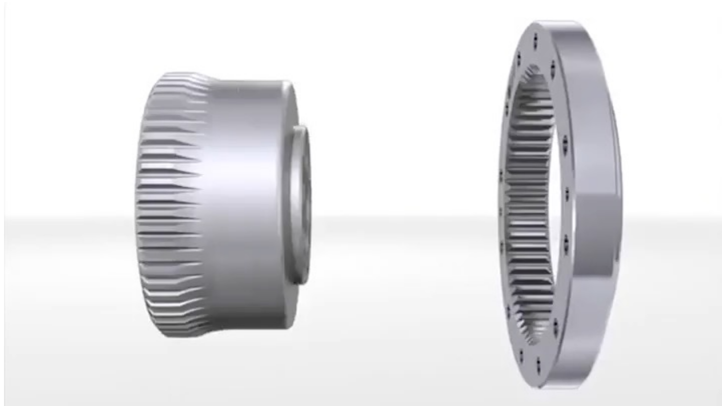
Circular Spline



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

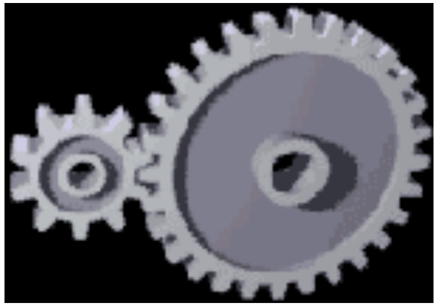
Operation of a harmonic drive

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

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

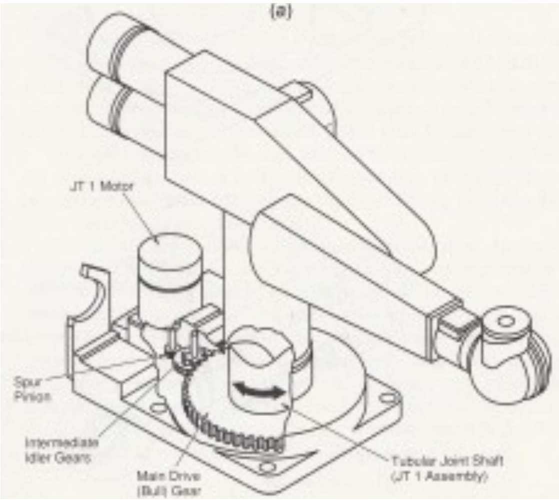
$$T_m = \underbrace{J_m\, \ddot{\theta}_m}_{\text{inertia} \times \text{angular acceleration}} + 1/n\, (J_u\, \ddot{\theta}_u) = (J_m\, n + J_u/n)\, a$$

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

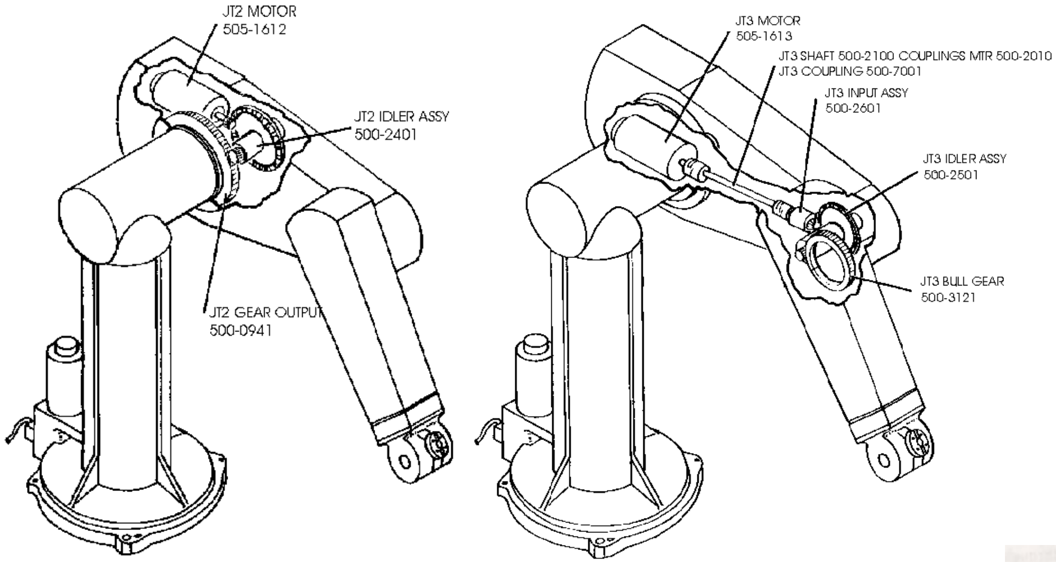
$\Rightarrow$ $\boxed{n = (J_u / J_m)^{1/2}}$ "matching" condition between inertias

Transmissions in industrial robots

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

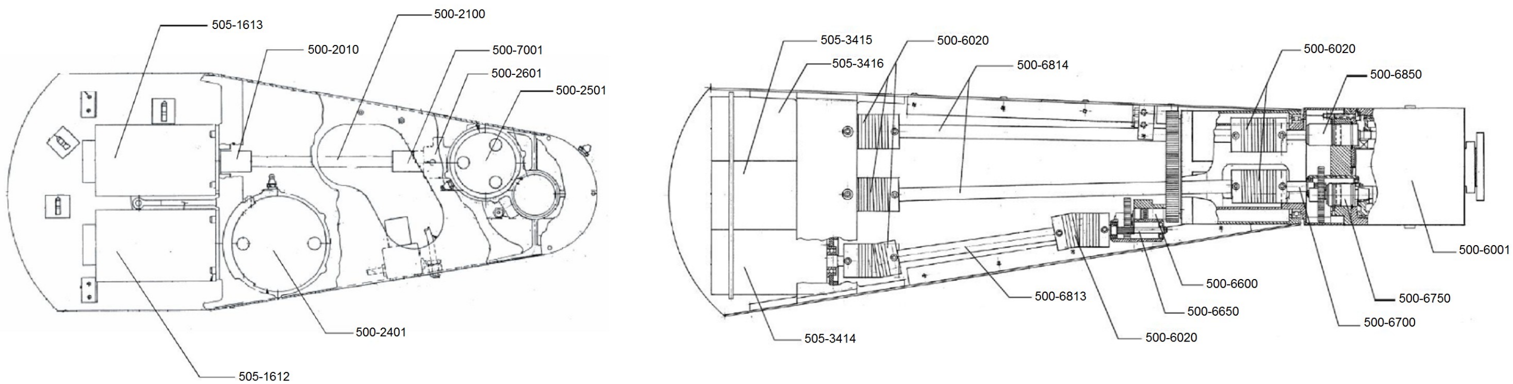


PUMA 260: 1st axis

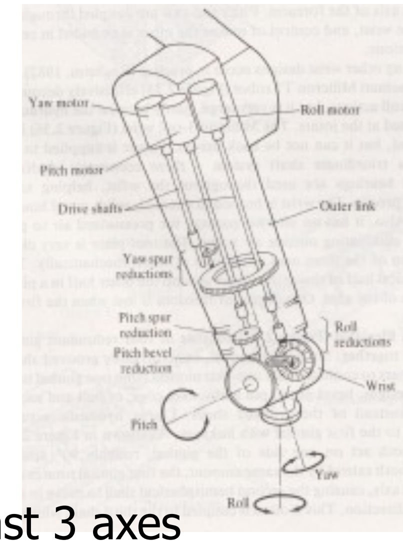


PUMA 560: 2nd and 3rd axes

PUMA 560



PUMA 560: inner and outer links



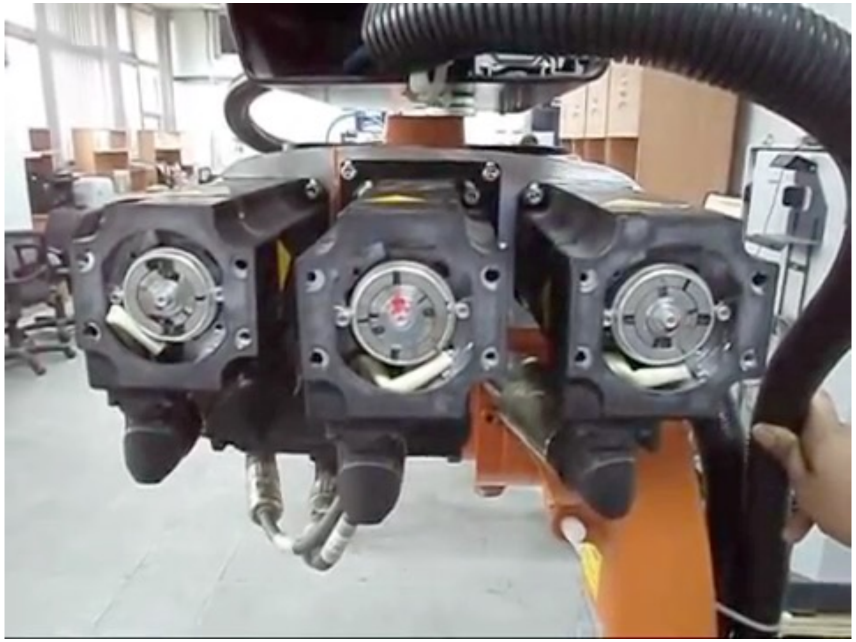
PUMA 560: last 3 axes

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)

https://youtu.be/iRKDfknqtbc

video



video

Differential drive at wrist

two motors + transmissions for moving joints 5 & 6

video

both motors are rotating in the same direction (same speed)

⇓

only joint 5 moves

video

the motors are rotating in opposite directions (same speed)

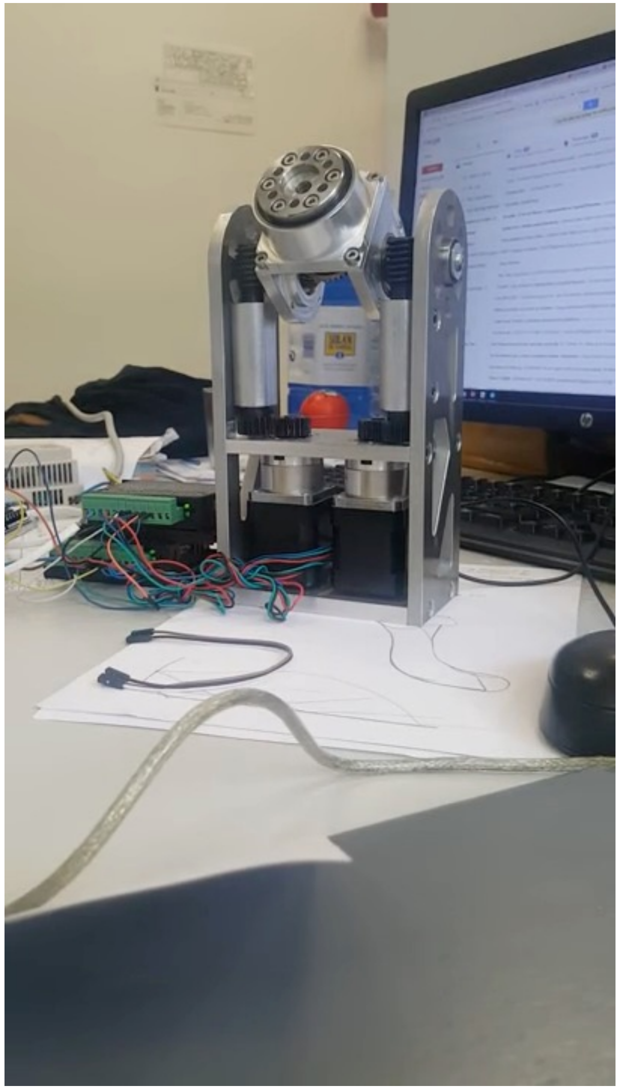
⇓

only joint 6 moves

any other combination of motor velocities

⇓

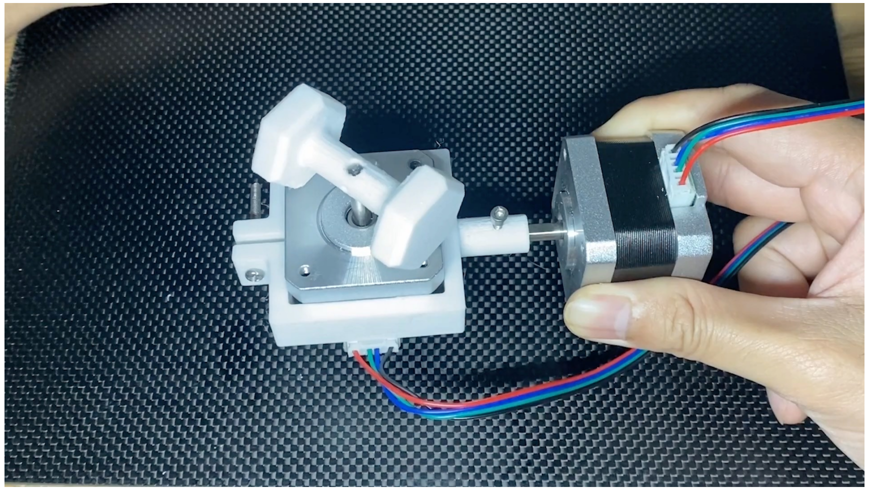
both joints move simultaneously

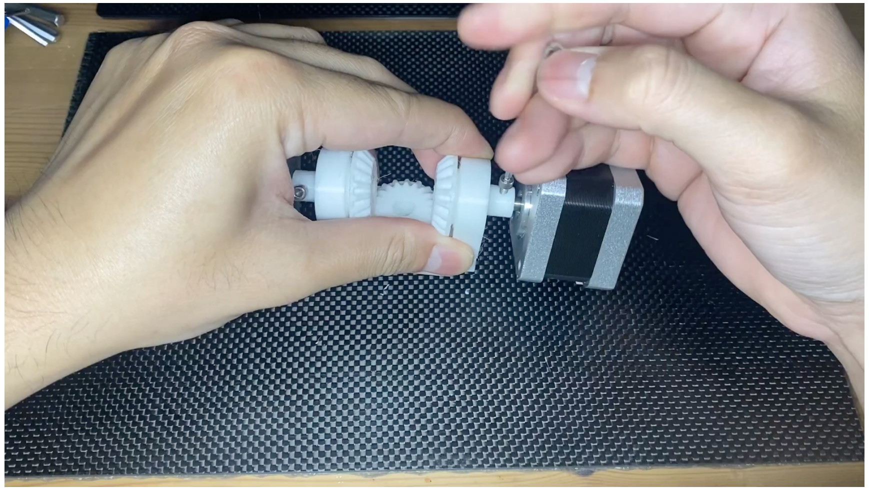


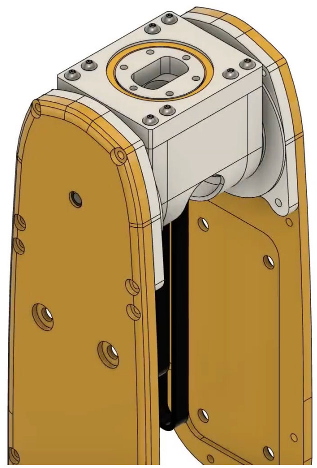
https://www.youtube.com/@MRBEngineering

Trivia on differential drive at wrist
to achieve pitch and roll motion

4 clips from 1 video https://youtu.be/lr-Zh8kpTuo



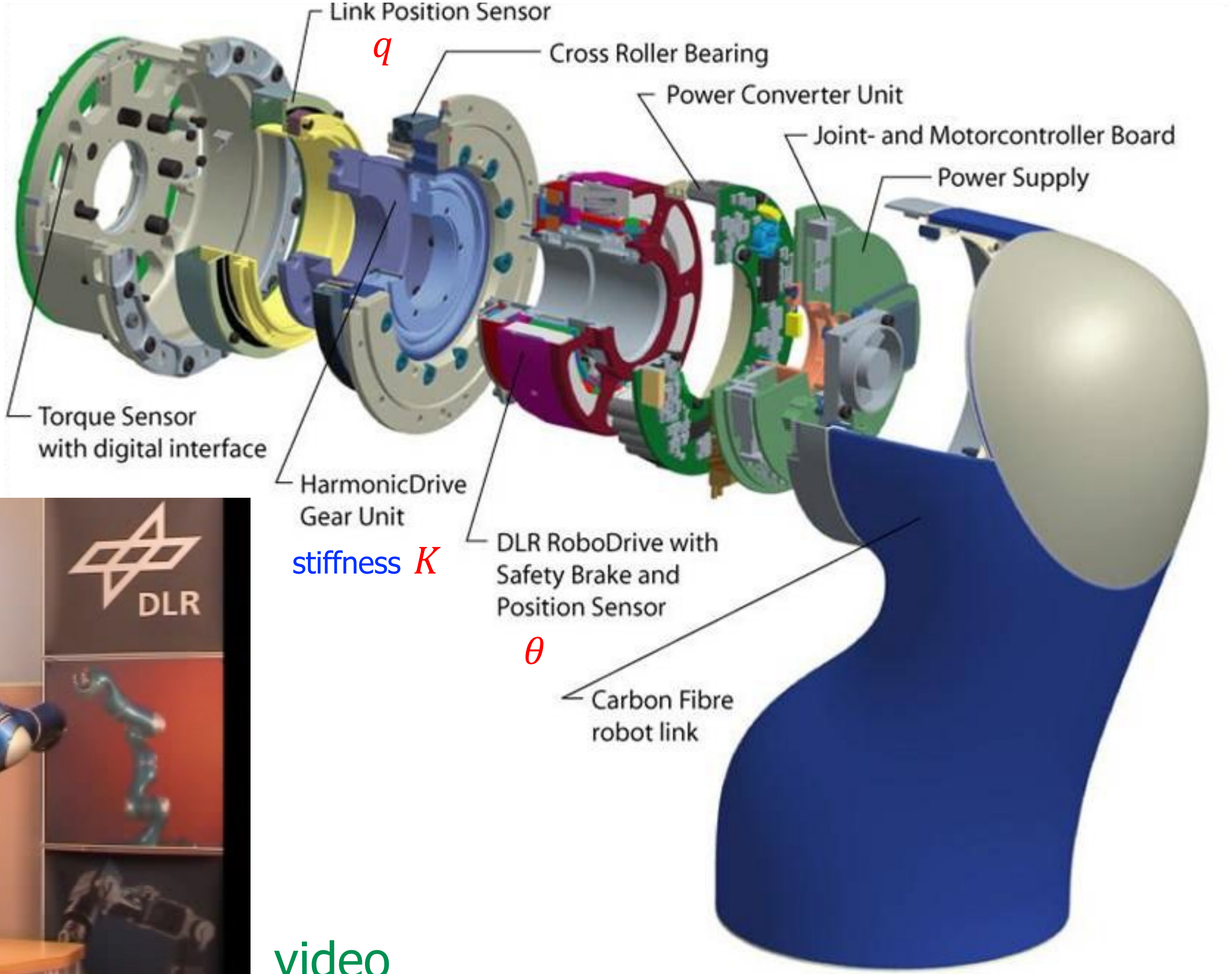




Exploded view of a joint
in the DLR-III robot

joint torque

$\tau_J = K(\theta - q)$



video