Robotics 1

Lecture # 1 - 29.09.22

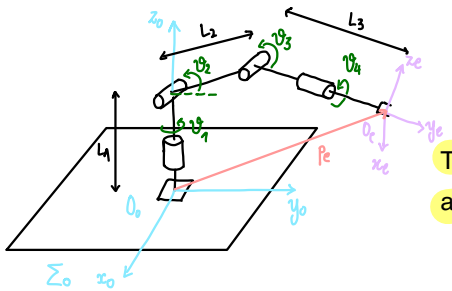
Stiffness vs compliance

stiffness: $F = K \Delta p$ large stiffness → larger force needs to be applied

compliance: $\frac{1}{K} = C \Rightarrow F = \frac{1}{K} \Delta p$ I can program ≠ ones for each direction / orientation!

↳ cedevolezza → se voglio accompagnare il movimento e non oppormi

4R robots → 4 joints



(x_0, y_0, z_0) : fixed frame

(x_e, y_e, z_e) : frame on the end-effector

positive angle : counterclockwise

To understand where the end effector is, I need 4 angles, and distances.

punto fisico che tocca oggetti

Direct Kinematics

I want to know the position of the end effector $p_e \in \mathbb{R}^3$, $p_e = f(\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4) = f(\vartheta)$

ϑ: joint variables

I want to describe how Σ_e is oriented respect to Σ_0

→ I need geometry & trigonometry :

$\sin\vartheta_1 \cos\vartheta_2 + \cos\vartheta_1 \sin\vartheta_2 = \sin(\vartheta_1 + \vartheta_2) = s_{12}$

$c_{12} = \cos\vartheta_1 \cos\vartheta_2 - \sin\vartheta_1 \sin\vartheta_2$

$\tan\vartheta = \frac{\sin\vartheta}{\cos\vartheta} = \frac{a}{b} = K$ for a given ϑ

$\vartheta = \operatorname{arctg} K \in \left(-\frac{\pi}{2}, +\frac{\pi}{2}\right)$

$\Sigma_0 \xrightarrow{\phi(\vartheta)} \Sigma_e$

Σ_0 ↓ terna fissa

Σ_e ↓ terna mobile

$\phi(\vartheta)$ ↓ Esprime rotazione risultante

12.10.22 **Industrial Robotics** < video >

automotive industry

Robot < DEFINITIONS >

→ <RIA> reprogrammable multi-functional manipulator → moves things around

↳ variety of tasks (physical change at the end-effector - different tools)

→ " " " without changes in the structure

acquires info from environment (through sensors) and moves intelligently in response.

<ISO>

→ automatically controlled, reprogrammable multi-purpose manipulator programmable in 3 or more axes, which may be either fixed in place or mobile, for use in industrial automation applications.

↳ revolute, translation, any combination

"visionary"

→ intelligent connection between perception & action

↳ accurate, fast, controlled way

Waseda WABOT-1 (1984) → played piano by seeing notes w camera

Spirit Rover (2002) → Mars. New also has a manipulator (can take rocks and analyze them locally)

"Robota" = work in slavic

Laws of Robotics – Asimov

1950 – CNC (computer numerically controlled) machine (accurate, fast, repeatability)

– mechanical telemanipulators (not autonomous, controlled remotely by humans)

↳ now: force feedback ...

1970 → industrial robots (G. Devol, J. Engelberger → 1st industrial robot, 1961) Unimate 6 dof

first SCARA (1978) → 4 dof (slide 8)

↓ RIASSUNTO

🔷 Definizioni di Robot

Negli appunti ci sono tre definizioni diverse, usate da vari enti:

1. RIA (Robotics Industries Association)

👉 Un robot è un manipolatore multifunzionale riprogrammabile:

- Può eseguire una varietà di compiti.
- Il cambiamento del lavoro si ottiene cambiando l'end-effector (lo strumento in punta, ad esempio pinza, saldatrice, trapano).
- Non serve cambiare la struttura del robot, solo il tool.

📌 Significa che lo stesso robot può fare compiti diversi: basta cambiare il tool.

---

2. ISO (International Organization for Standardization)

👉 Un robot è:

- Automaticamente controllato,
- Riprogrammabile,
- Multi-purpose (cioè non nasce per un solo compito),
- Ha almeno 3 assi o più (rotazionali, traslazionali o misti).
- Può essere sia fisso che mobile.
- Viene usato soprattutto in automazione industriale.

3. Visionaria

👉 Il robot è visto come:
"Un'intelligente connessione tra percezione e azione" → cioè percepisce l'ambiente (tramite sensori) e agisce di conseguenza in modo:

- Accurato
- Rapido
- Controllato

🔷 Storia e curiosità

- Waseda WABOT-1 (1964): primo robot umanoide giapponese → riusciva a suonare il piano guardando le note con una telecamera!
- Spirit Rover (2002): robot esploratore della NASA su Marte. Ora con manipolatori in grado di analizzare rocce.

🔷 Origine della parola "Robot"

- "Robot" viene dallo slavo → significa lavoro forzato.
- Isaac Asimov → formulò le famose Leggi della Robotica.

🔷 Evoluzione della robotica

- 1950:
- Nascono le macchine CNC (Computer Numerically Controlled) → alta precisione, velocità, ripetibilità.
- I primi manipolatori erano telecomandati dall'uomo (non autonomi), con concetto di force feedback (l'operatore sentiva le forze).
- 1960–1970:
- Primi veri robot industriali → creati da George Devol e Joseph Engelberger.
- Unimate (1961): primo robot industriale, con 6 gradi di libertà (DOF).
- 1978:
- Nasce SCARA (Selective Compliance Assembly Robot Arm) → robot con 4 DOF, molto usato in assemblaggio elettronico.

Slide 20 (Industrial & service robots)
22

Coman slide 23 → closed kinematic chain extra dof outside robot
↳ same cabin
(eg: turning table)

We will consider open kinematic chains, ignoring the closed chain part and checking later if my analysis is compatible w the geometry.

limit case: parallel kinematics → closed form for inverse kinematics;
↳ holding medical tools direct kinematics → closed OR numerical method
(Stewart platform)

↓

OPPOSITE from serial manipulator

slide 46 → vertically stiff
horizontally compliant (SCARA)

14.10.22

cannot be mounted on rotating bases

Fanuc R-2000i/165F → 6 joints
(slide 54)

1st: base 360°
2nd: shoulder, doesn't intersect w 1st 135°
3rd: elbow (3 motors, move the 3 joints at the wrist)
horizontal, // 2nd 361,8°
last 3: spherical wrist (intersection of 3 axes)
singularity: 2 axes aligned
└ j4 : 720° → 2 rotations
j5 : 250°
j6 : 720°
useful f.e. for screwing

distant joints can typically move faster: they move less weight

mapping of velocity depends on configuration. $V = J(q)\dot{q}$
↑ config.

Workspace → primary: reachable workspace
→ dexterous workspace: subset where I can achieve any orientation
└ difficult to represent

(we have 2 offsets/displacements → 31 cm and 197 - (67 + 107))

⚠ All the joints can't move completely, also to avoid self-collision
⚠ never use numbers in the code, use symbols

If the trajectory is planned in the joint space the error is in the joint space too
In the cartesian space I could encounter singularities. It's more difficult but more interesting.

Robot end-effector sensors and tools

Force/Torque sensor: 3 forces and 3 momentums, frame attached to it

Pneumatic tool changer > automatic tool change

3 fingers grip : 2 of them have 2 d.o.f., one has 3 (2 phalanxes but can also rotate)

Camera : eye of the robot, moving together with the hand

Every robot has a max payload so I can't mount infinite things to it

Calibration of the robot kinematics : task that has to be done at least once. (small errors can accumulate and lead to an error in the position).

Man-machine interface : teach box as robot programming interface / cabinet for supervision

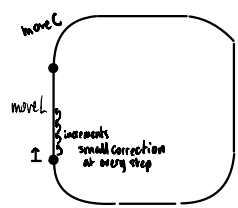
Programming and controlling environment

SCADA : human machine interface by which i have supervisionary control and data analysis.
VME bus - protocol
CAN protocol (controlled area network), by which i communicate w a number of external devices, from which I can take commands and send info.
The programming teachbox is also a peripheral.
Fieldbus : another more generic protocol.

From the robot's motor a signal returns to the controller (resolver signals, no longer used, I have new types of sensors for feedback)

Motion programming and scaling

ABB RAPID programming language : sequence of coordinated Cartesian commands (linear motion MoveL - linear, point-to-point; or circular motion MoveC - center and radius, and in which plane the circle is placed - frame definition, by an arc. I cannot do a full circle.).
I program and then test it at slow speed. Increments of time in the joint space.
I separate the geometric path from the timing law (I can change speed as I like).



What's next in industrial robots?

Growing shift from high volume to low mix (personalised objects).
Less skilled workers on the market.
Quicker return-of-investment ROI wanted, rising wages —> discouraging labour arbitrage (producing in places where labour costs less).
Increased focus on safety in the workplace.
Securing supply chains (f.e. 0km production), increasing resilience and sustainability.

Simplification (easy to install; standardisation), **Digitalisation** (linking the real-life factory w a digital/virtual twins, useful for predicting malfunctions; vision and sensing devices - more acquisition of data) **Collaboration** (collaborative robotics, increases productivity).

Connection - coordinated team work to gain experience from the physical world (same task done by multiple robots who share experience with each other).

Franka Erika robot - compliant and sensitive robot. list of components reduced to the minimal (simplification), so that this robot is able to build itself. Panda robot.

Detecting collision without sensors : by current, if the robot is trying to do something but encounters an obstacle, there will be a spike in the current.

Programmazione e ambiente di controllo

- Man-machine interface: interfaccia uomo-macchina.
- Teach box: telecomando con cui si programma direttamente il robot.
- Cabinet: armadio di controllo per supervisione.
- SCADA (Supervisory Control and Data Acquisition)

Sistema che permette all'operatore di avere controllo e supervisione, con analisi dati.

- Bus di comunicazione
- VME bus: protocollo di comunicazione.
- CAN protocol: rete di controllo molto usata anche nell'automotive, per collegare dispositivi esterni (sensori, attuatori).
- Fieldbus: protocollo generico per scambio dati tra dispositivi industriali.
- Il teachbox è visto come una periferica del sistema.

📌 In sintesi: il robot comunica con sensori, attuatori e l'operatore tramite vari protocolli (SCADA, CAN, Fieldbus), e si programma spesso col teach pendant.

🔷 Programmazione del moto e scaling

- ABB RAPID language (linguaggio di programmazione dei robot ABB).
- Si programmano movimenti cartesiani:
- MoveL → movimento lineare punto-punto.
- MoveC → movimento circolare (definito da centro e raggio).
- Si possono descrivere archi, ma non cerchi completi in un solo comando.
- Tecniche pratiche:
- Si programma e si testa a bassa velocità.
- Si aumenta la velocità gradualmente.
- Si separa il percorso geometrico dalla legge temporale → posso cambiare la velocità indipendentemente dal percorso.

👉 Nel disegno in basso: il robot fa un percorso quadrato con comandi MoveL e MoveC, facendo piccole correzioni incrementali.

🔷 Tendenze future nella robotica industriale

- Shift produttivo: da grandi volumi standardizzati → a piccoli lotti personalizzati.
- Problema manodopera: meno lavoratori specializzati disponibili.
- ROI più rapido richiesto: con aumento dei salari, non conviene più spostare la produzione dove la manodopera costa meno.
- Più attenzione alla sicurezza nei luoghi di lavoro.
- Supply chain: garantire continuità (es. produzione a km 0), maggiore resilienza e sostenibilità.

🔷 Parole chiave per il futuro

- Semplificazione → robot facili da installare e standardizzati.
- Digitalizzazione → collegamento fabbrica reale con il suo gemello digitale (digital twin), più visione e sensori per raccogliere dati.
- Collaborazione → robot collaborativi (cobot) che lavorano con gli umani e migliorano la produttività.
- Connessione → robot che imparano gli uni dagli altri, condividendo esperienza.

🔷 Esempi di robot moderni

- Franka Emika Panda (nei tuoi appunti scritto come “Franka Erika” o “Panda robot”):
- Robot collaborativo, sensibile e sicuro.
- Progettato con componenti ridotti al minimo → semplice da installare.
- Compliant → può adattarsi a contatto con persone/oggetti.
- Collision detection senza sensori:

Anche se non ha sensori esterni, un robot può capire se ha urtato un ostacolo:

- Se prova a muoversi e incontra resistenza, si registra un picco di corrente nei motori → segnale di collisione.

✅ Riassunto semplice della pagina

1. I robot comunicano con operatori e sensori tramite protocolli (SCADA, CAN, Fieldbus).
2. Si programmano con linguaggi come ABB RAPID, separando percorso e velocità.
3. Futuro: personalizzazione, sicurezza, resilienza della supply chain.
4. Concetti chiave: semplificazione, digitalizzazione, collaborazione, connessione.
5. Esempio → Panda robot: robot collaborativo, sensibile, semplice da usare.
6. Rilevamento collisioni anche senza sensori → tramite variazioni di corrente nei m

Ex 1 - January 11, 2018

7R Panda robot (spherical shoulder, offsets at elbow, non-spherical wrist)

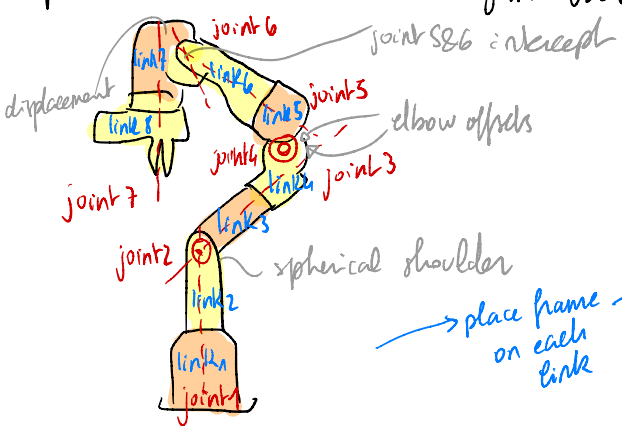
<u>Assign frames</u> to each link to find position of end-effector.

→ find homogeneous transformation matrices (used to obtain end-effector pose)

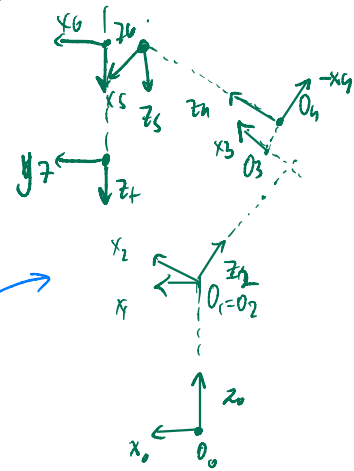
→ # of elementary operations (trig, ×, +) for evaluating end-effector position.

7 dof → 8 frames (0 → 7)
7 joints 8 links

4 parameters + 3 constraints + ϑ joint variable



→ place frame on each link →



+ joint variables

https://plex.it/referrals/I2XVVYCO

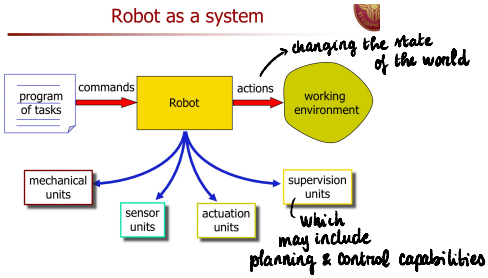
https://plex.it/referrals/I2XVVYCO

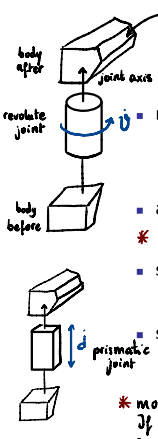
19-21.10.2022 (recorded lessons)

Robot components

Actuators

Robot as a system





Will rotate thanks to motion of the joint w. respect to the before body
→ 1 elementary motion: rotation around joint axis by quantity specified by $\dot{\theta}$ (velocity)

Functional units of a robot

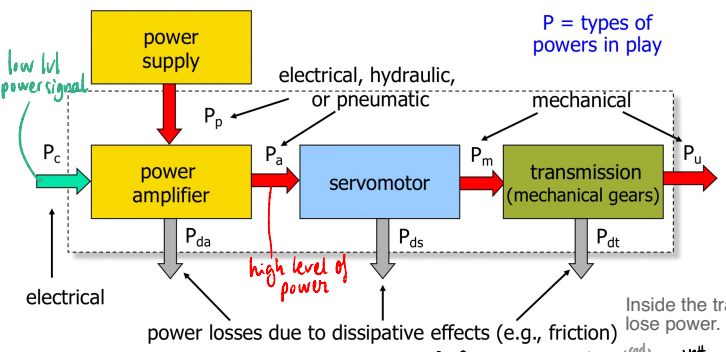
- mechanical units (robot arms)
  - serial manipulators: rigid links connected via rotational or prismatic joints (each giving 1 degree of freedom = DOF)
  - supporting structure (mobility), wrist (dexterity), end-effector (for task execution, e.g., manipulation)
- actuation units • main joint axis
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

↳ contact forces typically measured on device mounted on the wrist.

* cognitive intelligence

* motors: brute components.
If we close some feedback loops around them in order to achieve some desired performance → SERVODRIVE: controlled motor: delivers torque or velocity according to desired profiles in time.
<SERVOMOTORS>

Actuation systems:



P = types of powers in play

low level power signal amplified by power amplifier and transmitted to the servomotor. The power amplifier is typically located within the cabinet of the industrial robot, except from some advanced research robots where the power components are inside the robot itself.

Inside the transmission I may have friction, and I lose power. I want to lubrificate the transmission.

[N] [m/s] [Nm] [rad/s] ($\frac{rad}{s}$) watt

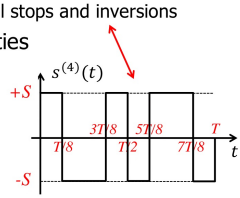
power = voltage · current = pressure · flow rate = force · speed = torque · angular speed [W, Nm/s]

$W = V i = F \cdot v = M \cdot \omega$

efficiency = power out/power in [%] energy ~ work = power · time [kWh, Nm, J]
↳ would be 100% w./ dissipation

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



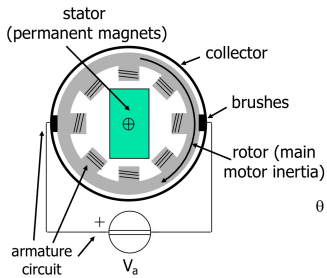
SERVOMOTORS

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

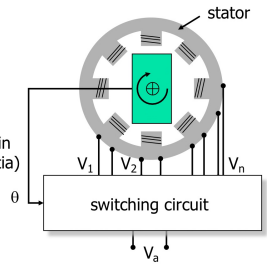
- hydraulic: hydraulic energy (accumulation tank) → pumps/valves → mechanical energy
  - advantages: no static overheating, self-lubricated, inherently safe (no sparks), excellent power-to-weight ratio, large torques at low velocity (w/o reduction)
  - disadvantages: needs hydraulic supply, large size, 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



direct current (DC) motor



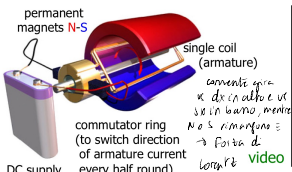
with electronic switches (brushless)

Advantages of brushless motors:

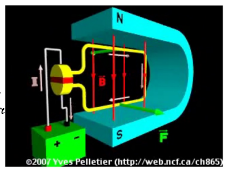
- reduced losses, both electrical (due to tension drops at the collector-brushes contacts) and mechanical (friction)
- reduced maintenance (no substitution of brushes)
- easier heat dissipation
- more compact rotor (less inertia and smaller dimensions)

but higher cost!

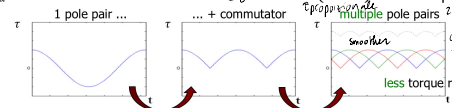
Principle of operation of a DC motor



video



$\vec{F} = L(\vec{i} \times \vec{B}) \rightarrow \tau = d|\vec{F}|$



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)

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

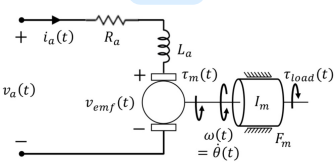
$$\tau_m(t) = k_t i_a(t)$$

(motor torque)

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

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

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



using Laplace transform, differential equations become algebraic relations!

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

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)

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

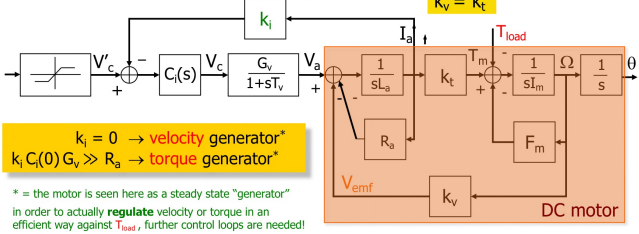
mechanical balance

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

$$T_m = k_t\, I_a$$

$$k_v = k_t$$

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!

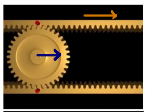
Motion transmission gears: (rules)

- optimize the transfer of mechanical torque from actuating motors to driven links (to move the links we rotate the joints, the joints don't have mass, the links have mass / inertia).
- quantitative transformation (from low torque/high velocity → "reduction" elements: essential to bring up the torque capability of a motor. to high torque/low velocity) → I can accelerate larger masses w. the same motor w. high torque. <conservation of power> (w/dissipation)
  On the datasheet of the motor I may have very low output torque, but it's because the reduction element, which will be mounted on it, is missing.
- 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)
  through transmissions, we can remotely drive links w. motors that are placed on the base. → we gain high efficiency.

* 99% of the time, in robotics, electrical motors are rotational machines

examples of transmissions:

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



for example: revolute motion transferred into linear motion of the upper rack (lower rack fixed)
↳ application on robots: wheel axis fixed, two racks move linearly $\overleftrightarrow{2}$
scaling factor depending on nr. of teeth of the wheel.

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

2 wheels w. ≠ ratio → ≠ nr. of teeth.
Scaling of angular velocity → reduced → ↑ torque (by the same factor)

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

depending of which part I block I can have ≠ behaviours.
⇒ reduction ratio of the elementary gear
triangular structure keeps balance.

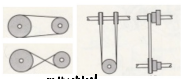
// axes

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

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

← vite s.fine

- 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)



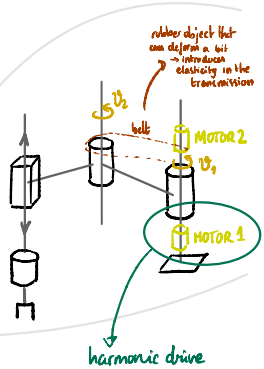
← w/backlash

- harmonic drives: compact, in-line, power efficient, with high reduction ratio (up to 150-200:1) ↳ small motors ⇒ high torque
  - problems: elasticity
    like belts. BUT IT'S INTENTIONAL ⇔ COMPLIANCE OF STRUCTURE → adjusts to small position errors in insertion ops.
- transmission shafts: long, inside the links, with flexible couplings for alignment

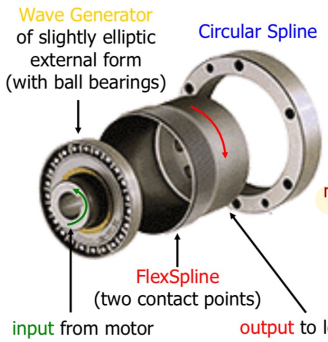
* no ≠ axes

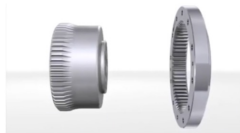
→ SCARA TYPE ROBOTS

advantage: motors spin but their cdm stays fixed → they don't have to be moved around → their mass does not count at all.



Harmonic drives

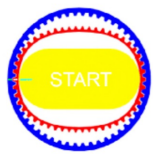




inner #teeth CS = outer #teeth FS + 2

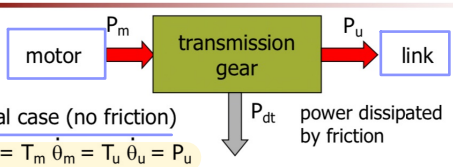
reduction ratio

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



$$\tau = \frac{\text{FS teeth}}{\text{CS teeth} - \text{FS teeth}} = \text{FS teeth}/2$$

Optimal choice of reduction ratio



ideal case (no friction)

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

torque × angular speed

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

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

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

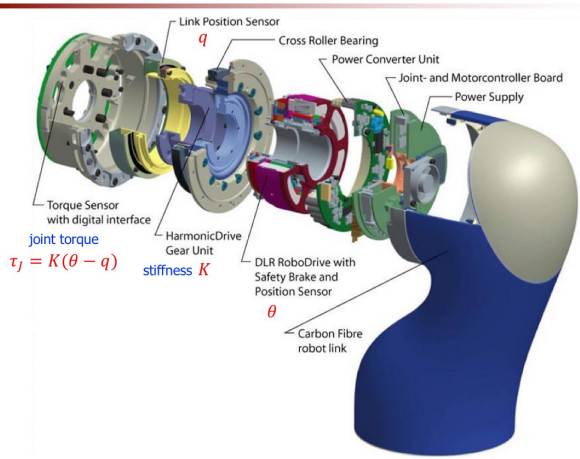
inertia × angular acceleration

for minimizing T_m, we set: $\dfrac{\partial T_m}{\partial n} = (J_m - J_u/n^2)\,a = 0$ → ↔ stationary point. How do I check if it's a minimum or a max? → 2nd derivative > 0

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

OPTIMAL REDUCTION RATIO (minimum torque for the same acceleration of the load)

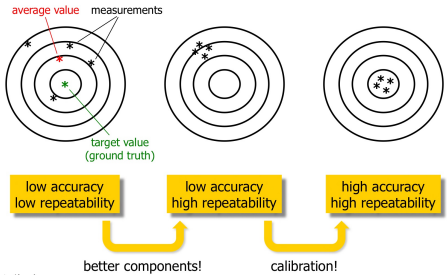
Exploded view of a joint
in the DLR-III robot



Robot components – proprioceptive sensors (internal robot state: position & velocity of joints)

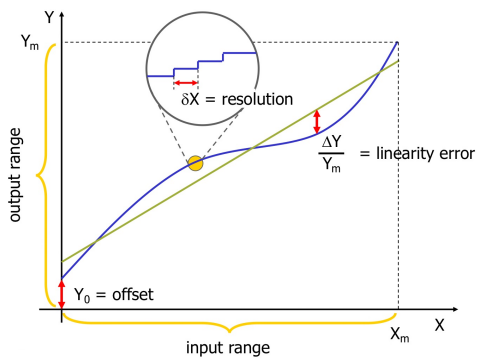
Properties of measurement systems:

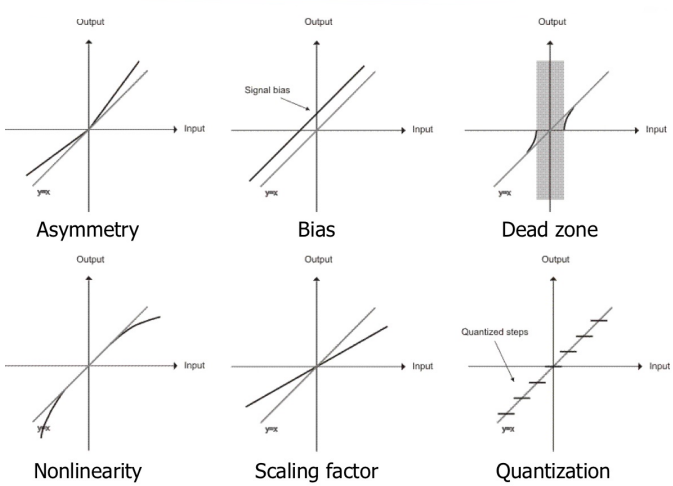
- accuracy
  agreement of measured values with a given reference standard (e.g., ideal characteristics)
- repeatability
  capability of reproducing as output similar measured values over consecutive measurements of the same constant input quantity
- stability
  capability of keeping the same measuring characteristics over time/temperature (similar to accuracy, but in the long run)



- accuracy 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
- 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"

- 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



Sensor measurements

some non-idealities