Robotics 1

Robot components:
Actuators

Prof. Alessandro De Luca
Robot as a system

- **Robot**
  - Program of tasks
  - Commands
  - Robot
  - Actions
  - Working environment

- **Units**
  - Mechanical units
  - Sensor units
  - Actuation units
  - Supervision units
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

UNIVERSAL ROBOTS

COMAU

YASHKAWA
Actuation systems

![Diagram of actuation system]

- **Power supply**
- **Power amplifier**
- **Servomotor**
- **Transmission** (mechanical gears)

**Power**
- Electrical, hydraulic, or pneumatic

**Power losses due to dissipative effects** (e.g., friction)

**Types of powers in play**

**Power** = voltage \cdot current = pressure \cdot flow rate = force \cdot speed = torque \cdot angular speed [W, Nm/s]

**Efficiency** = power out/power in [%]

**Energy** ~ **Work** = power \cdot 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) → 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

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**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 $v_a$

Mathematical expressions:

\[ \vec{F} = L(\vec{i} \times \vec{B}) \]
\[ \tau = d|\vec{F}| \]

Graphs showing:
- 1 pole pair ...
- \( \tau \) vs. \( t \)
- \( \tau \) vs. \( t \)
- Multiple pole pairs
- Less torque ripple!
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)

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

\[ \tau_m(t) = k_t i_a(t) \]

(motor torque)

In absence of losses, conservation of power holds in energy transformation.

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

\[ \Rightarrow k_v = k_t \] (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**

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### Electrical Balance

\[ V_a = (R_a + sL_a) I_a + V_{emf} \]

### Mechanical Balance

\[ T_m = (sI_m + F_m) \Omega + T_{load} \]

### Current Loop

\[ V_{emf} = k_v \Omega \]

\[ T_m = k_t I_a \]

\[ k_v = k_t \]

---

### Laplace Domain (Transfer Functions)

- \[ V_c = \frac{G_v}{1 + sT_v} V_a \]
- \[ I_a = k_i \]
- \[ V' = V_c \]

---

**Laplace Domain**

**Mechanical Balance**

**Electrical Balance**

**Current Loop**

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**k_i = 0 → velocity generator**

**k_i C_i(0) G_v \gg R_a → torque generator**

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* = 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 $v_a$

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

medium size motor 160 W

small size motor 5.5 W

Robotics 1
## Data sheet electrical motors

- DC drives

### Nominal/Peak Torques and Speeds

<table>
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<tr>
<th>Model of actuator</th>
<th>RHS-14 6003</th>
<th>RHS-17 6006</th>
<th>RHS-20/RFS-20 6007</th>
<th>RHS-25/RFS-25 6012</th>
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Data sheet electrical motors

- AC drives

- 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

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<th>HKM-20-30</th>
<th>HKM-25-60</th>
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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)

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

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

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

Circular Spline (A)

inner \#teeth CS = outer \#teeth FS + 2

reduction ratio

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

input from motor

output to load

START
Operation of an harmonic drive

Harmonic Drive Gearing

PRINCIPLE of OPERATION

commercial video by Harmonic Drives AG
Optimal choice of reduction ratio

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

\[ n = \text{reduction ratio (} \gg 1) \]

\[ \dot{\theta}_m = n \dot{\theta}_u \quad \Rightarrow \quad T_u = n T_m \]

\[ T_m = J_m \ddot{\theta}_m + \frac{1}{n} (J_u \ddot{\theta}_u) = (J_m n + J_u / n) a \]

\[ \frac{\partial T_m}{\partial n} = (J_m - J_u / n^2) a = 0 \]

\[ n = (J_u / J_m)^{1/2} \]

“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:** 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)
Exploded view of a joint in the DLR-III robot

\[ \tau_j = K(\theta - q) \]

Stiffness \( K \)

Joint torque \( \tau_j \)

\( q \)

\( \theta \)