Robotics 1

Robot components:
Actuators

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Robot as a system

Robot

commands

actions

working environment

program of tasks

Robot

mechanical units

sensor units

actuation units

supervision units
Functional units of a robot

- mechanical units (robot arms)
  - rigid links connected through *rotational* or *prismatic* joints (each 1 dof)
  - mechanical subdivisions:
    - *supporting structure* (mobility), *wrist* (dexterity), *end-effector* (task execution, e.g., manipulation)

- sensor units
  - proprioceptive (internal robot state: position and velocity of the joints)
  - exteroceptive (external world: force and proximity, vision, ...)

- actuation units
  - motors (*electrical, hydraulic, pneumatic*)
  - motion control algorithms

- supervision units
  - task planning and control
  - artificial intelligence and reasoning
Actuation systems

**Power** supply

**Power** amplifier

- **Electrical** power: $P_e$
- **Hydraulic** power: $P_h$
- **Pneumatic** power: $P_p$

**Servomotor**

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

**Transmission** (mechanical gears)

- **Mechanical** power: $P_m$

$P = \text{types of powers in play}$

**Power** = force $\cdot$ speed = torque $\cdot$ angular speed [Nm/s, W]

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

FlexSpline (B) (two contact points)

input from motor

output to load

Robotics 1
Operation of an harmonic drive

commercial video by Harmonic Drives AG
Optimal choice of reduction ratio

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

\( n = \text{reduction ratio} \ (>1) \)

\( \dot{\theta}_m = n \dot{\theta}_u \quad \rightarrow \quad T_u = n T_m \)

for minimizing \( T_m \), we set:

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

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

“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)
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: 10W 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
Electrical servomotors for robots

Direct current (DC) motor

- Stator (permanent magnets)
- Collector
- Brushes
- Rotor (main motor inertia)
- Armature circuit

With electronic switches (brushless)

- Switching circuit
- Stator
- \( V_1 \), \( V_2 \), \( V_n \)
- \( V_a \)
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

DC supply $V_a$

permanent magnets N-S

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

single coil (armature)

$\vec{F} = L(\vec{i} \times \vec{B})$

$T = r|\vec{F}|$

1 pole pair ...

... + commutator

multiple pole pairs

less torque ripple!
Characteristic curves of a DC motor

at steady-state, for constant applied tension $V_a$

conversion SI ⇔ US unit systems (!!)
$1 \text{ Nm} = 141.61 \text{ oz-in}$
$100 \text{ oz-in} = 0.70 \text{ Nm}$

medium size motor 160W

small size motor 5.5W
DC electrical motor
mathematical model for command and control

**Electrical balance**

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

\[ V_{\text{emf}} = k_v \Omega \text{ (back emf)} \]

**Mechanical balance**

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

\[ T_m = k_t I_a \]

\[ k_v = k_t \text{ (energy balance, in SI units!)} \]

\[ \text{current loop} \]

\[ k_i C_i(s) \]

\[ \frac{G_v}{1 + sT_v} \]

\[ k_i = 0 \rightarrow \text{velocity generator*} \]

\[ k_i C_i(0) G_v \gg R_a \rightarrow \text{torque generator*} \]

* = the motor is seen here as a steady state "generator"; to actually regulate velocity or torque in an efficient way against \( T_{\text{load}} \), further control loops are needed!
Data sheet electrical motors

- DC drives

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<th>RHS-17</th>
<th>RHS-20/RFS-20</th>
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nominal/peak torques and speeds
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
Exploded view of a joint in the DLR-III robot

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

Joint torque \( \tau_j \), stiffness \( K \), joint angle \( \theta \), joint displacement \( q \)