Syllabus

Robotic Manipulators

- Applications in assistive robotics: medical robotics, prostheses, companion, monitorization, assistance
- Structure of the robot manipulators
- Drives and sensors
- Spatial location: transformations
- Geometric mode
- Motion control

Visual Servoing

- Position-Based Visual Servoing. 3D scene model, two-view geometry, stereo cameras. Control laws.
- Image-Based Visual Servoing. Definition of targets. Interaction matrix. Image-based visual control loop.
- Stability analysis. Lyapunov.
- Hybrid Visual Servoing.

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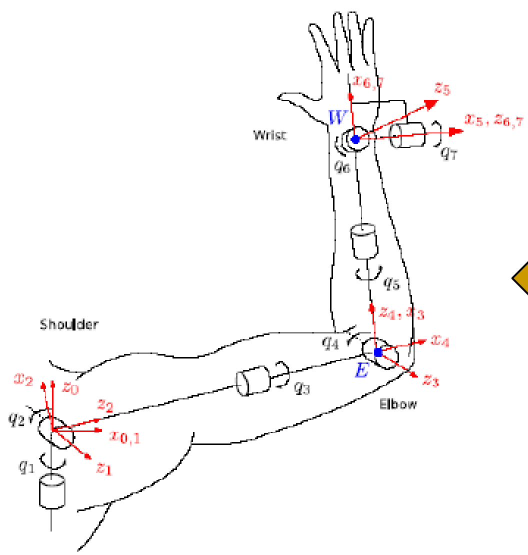
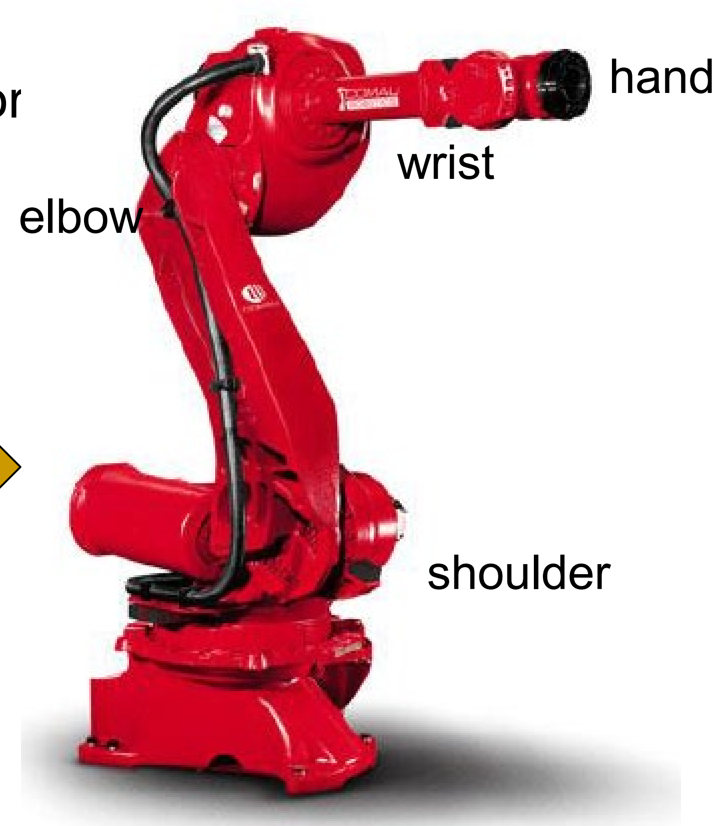
- What is an industrial robot?
  - Robot Institute of America, 1980: A multifunctional reprogrammable manipulator designed to move materials, parts, tools or special artifacts by programmed variable movements for the execution of potentially very diverse tasks.

- Robot, robotic arm, robotic manipulator

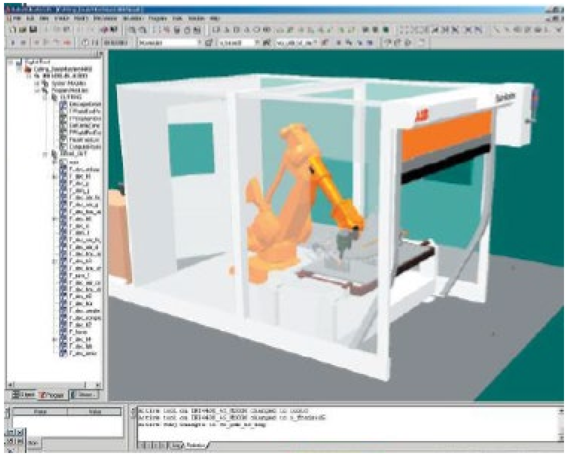




- Components of the robotic system:

Mechanical structure,
actuators and sensors

Control cabinet:
Control unit
Power electronics
Control
Supervision



Programming environment
ABB Robot Studio

Teach pendant:
Programming interface

Industrial Robot ⇒ Kinematic chain composed of links (rigid solids) and kinematic links (joints)

Goal: To position objects in the 3D world
- 3 parameters for position
- 3 parameters for the orientation

Links:

- Each of the rigid solids that compose the robot
- Link division:
  - Arm (first ones) ⇒ Position and initial orientation
  - Wrist (last ones) ⇒ Final orientation

Joints:

- They link together pairs of links
- Types of Joints:
  - Rotational joint (R)
  - Linear (prismatic) joint (P)
- Usually, a single independent parameter

- Examples of robots:

Big size
(maximum load higher than100 Kg.)

KUKA KR 1000
(1000 Kg max.)

ABB IRB 7600
(630 Kg max.)

Small size
(maximum load less than 6 Kg.)

KUKA
KR 6

ABB
IRB 140

Medium size
(maximum load around 100 Kg.)

KUKA
KR 140

ABB
IRB 4400

Structural features

Degrees of freedom (DoF)

- Number of independent parameters that determine the location of the end effector
- Maximum 6 DoF, normally 4 – 6 DoF

Degrees of movement (DoM)

- Number of independent parameters that determine the movements of the industrial robot
- DoM = number of joints = number of motors = number of sensors
- When DoM > DoF for all robot configurations, then the robot is *redundant*
- When DoM < DoF for a particular configuration => a *singular configuration*

Common mechanical structures:

- Concatenation of links and joints
- Classification (arm only):
  - Basic structures
    (Open Kinematic Chain)
    - Cartesian/Gantry (PPP)
    - Cylindrical (RPP)
    - Polar (RRP)
    - Angular (RRR)
    - SCARA (RRP)
    - Hyper-redundant (Elephant trunk)
  - Parallel robots
    (Closed Kinematic Chain)
- Wrist (R, RR or RRR), may depend on the attached end effector

Cartesian/gantry robot

Structure: PPP

https://www.youtube.com/watch?v=7QDpqPtu0iU

https://www.wittmann-group.com/en/w9-and-wx-series

www.tecnowey.com, CC BY 3.0 <https://creativecommons.org/licenses/by/3.0>, via Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Robot_Portico_tecno-840.jpg

Cylindrical robot

RPP Applications: Horizontal load/download (pick and place) in a work cell

https://www.youtube.com/watch?v=Hj7PxjeH5y0

Spherical / polar robot

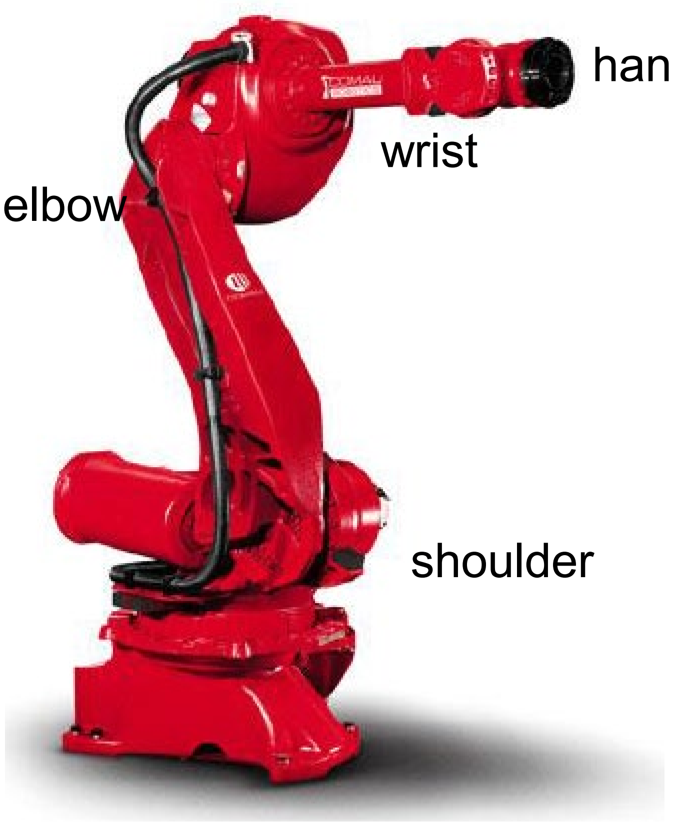
RRP https://www.youtube.com/watch?v=VdolSBpyCaU

Unimate pouring coffee for a woman at Biltmore Hotel, 1967

Frank Q. Brown, Los Angeles Times - https://digital.library.ucla.edu/catalog/ark:/21198/zz0002vfhd https://commons.wikimedia.org/wiki/File:Unimate_pouring_coffee_for_a_woman_at_Biltmore_Hotel,_1967.jpg

Angular robot

RRR (polar: P→R : angular)

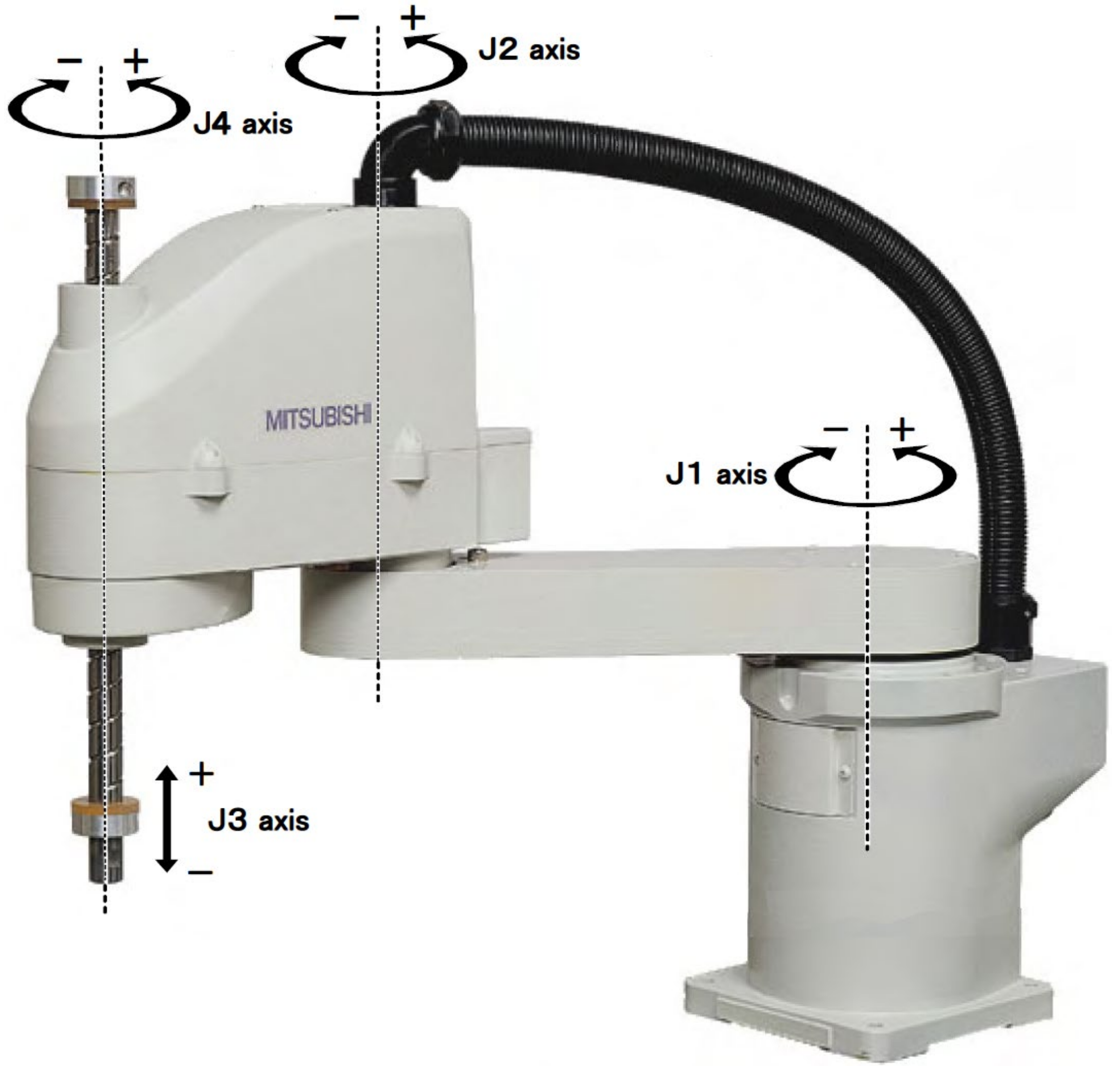


https://youtu.be/CAFFa9hZojQ?t=78

Several commercial examples (ABB, Fanuc, Kuka, Motoman, Universal Robots…)

SCARA robot

RRP



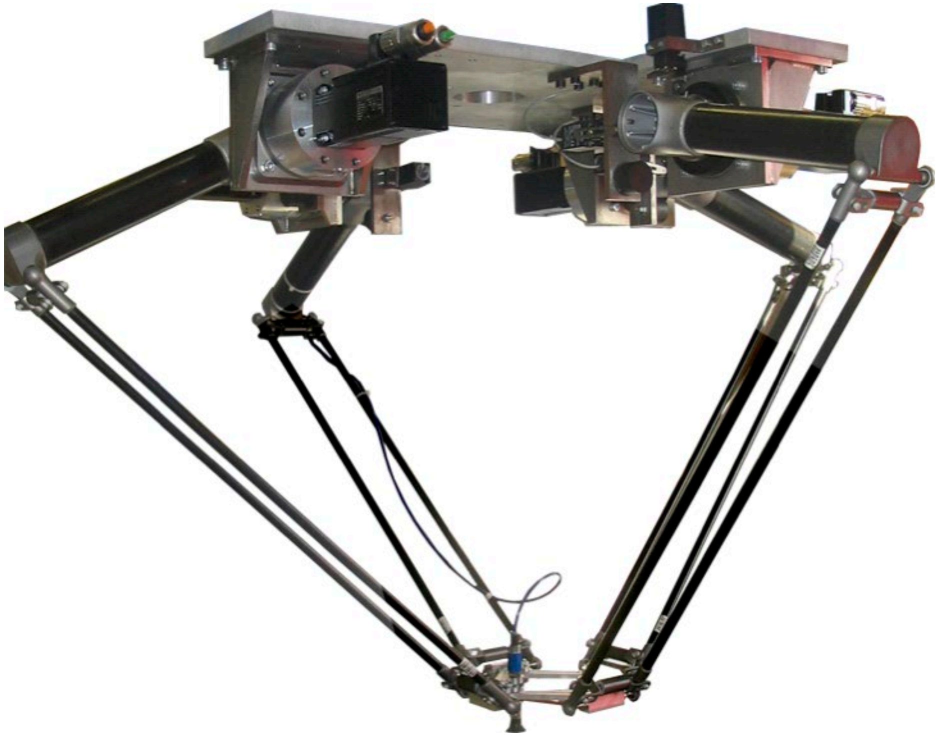
http://www.youtube.com/watch?v=vKD20BTkXhk

Several commercial examples (ABB IRB 910sc, Staübli, Kuka ..)

Mitsubishi Electric Automation, Inc. 500 Corporate Woods Pkwy - Vernon Hills, IL - 60061 - https://commons.wikimedia.org/wiki/File:SCARA_robot_2R.png

Parallel robots

- Mobile platform connected to the base by, at least, 2 kinematic chains in parallel (legs)
- They compose a closed kinematic chain, with active and passive joints
- Common structures:
  - 3 legs in parallel+ wrist with 2 or 3 DoF
  - 6 legs in parallel, robots with 6 DoF



FrancoisPierrot34, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Prototype_robot_parall%C3%A8le_PAR4.jpg

http://www.youtube.com/watch?v=0-Kpv-ZOcKY

Hyper-redundant robots

- Large or infinite number of degrees of motion
- Analogous to snakes or tentacles
- Useful for operation in highly constrained environments

Orientation of the end effector

- Orientation of the end effector
  - Robot arm ⇒ Position and initial orientation
  - Robot wrist ⇒ Final orientation
- Usually, wrists with (1,2) 3 DoF:
  - 3 axis that intersect in a common point
    - Pros: kinematic wrist-partition
    - Cons: singularities
  - Axis not intersecting
    - Cons: without wrist-partition
    - Pros: without singularities

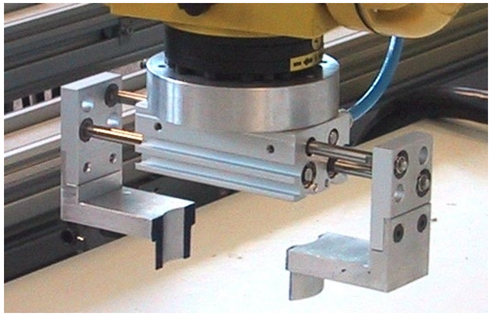
- End effectors (tools) are connected to wrists

End effectors and tools

- Application
  - Manipulation / transformation of objects $\Rightarrow$ Tools
  - It depends on the type of task
    - Spot welding
    - Arc welding
    - Painting
    - Pick and place …
  - Usually, it includes sensors (range, vision, force/torque)
  - Examples
    - https://www.youtube.com/watch?v=fH4VwTgfyrQ
    - http://www.youtube.com/watch?v=aPTd8XDZOEk
  - In medical robots
    - Drill, camera, scalpel, …

https://www.youtube.com/watch?v=XhvHU99ib0o

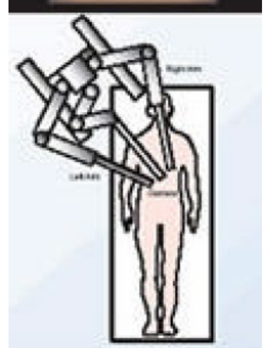
https://www.kuka.com/en-de/industries/healthcare/kuka-medical-robotics

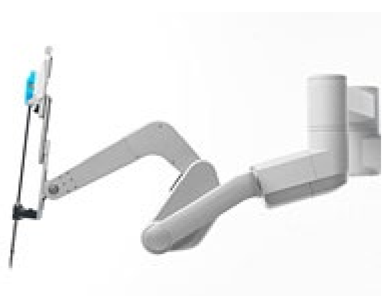


Medical robots

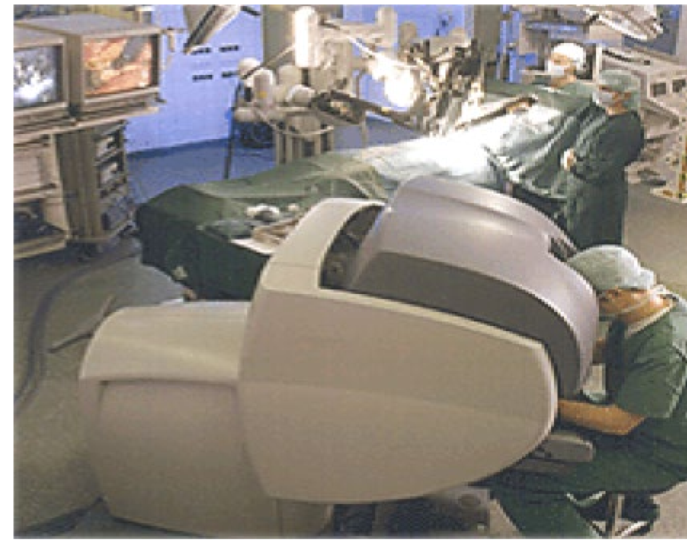
Da Vinci robot

https://www.youtube.com/watch?v=QksAVT0YMEo





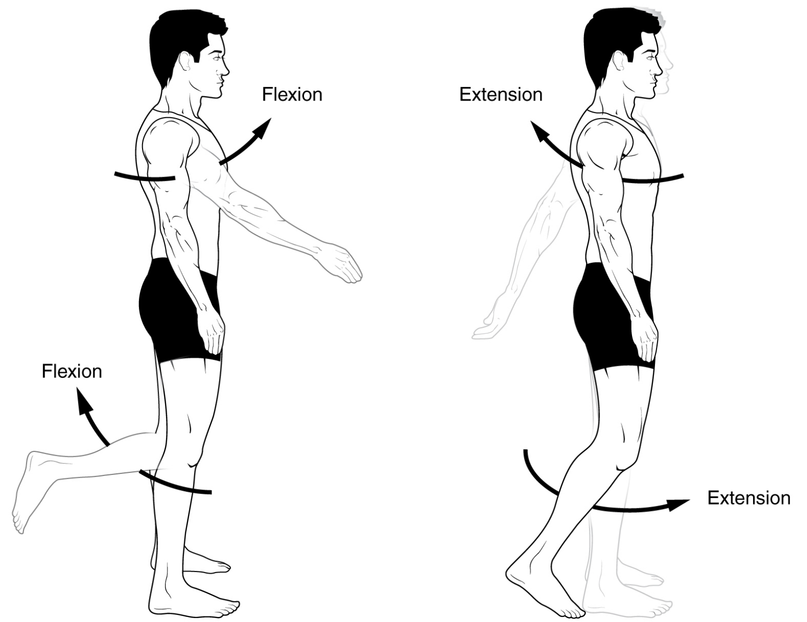
laparoscopic surgery



- great accuracy
- minimally invasive surgery: 1-2 cm
- micro movements
- stereo camera: 3D vision
- additional tools
- tele operated, haptics, voice, console

Robotic Exoskeletons

- Shoulder:
  - Flexion-Extension
  - Abduction-Adduction
  - Rotation (circumduction)
- Elbow:
  - Flexion-Extension
  - Pronation-Supination
- Wrist:
  - Flexion-Extension
  - Abduction-Adduction
- D-H model of the arm:
  - 3 DoF shoulder
  - 2 DoF elbow
  - 2 DoF wrist



(a) and (b) Angular movements: flexion and extension at the shoulder and knees

Robotic Exoskeletons

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  - Abduction-Adduction
  - Rotation (circumduction)
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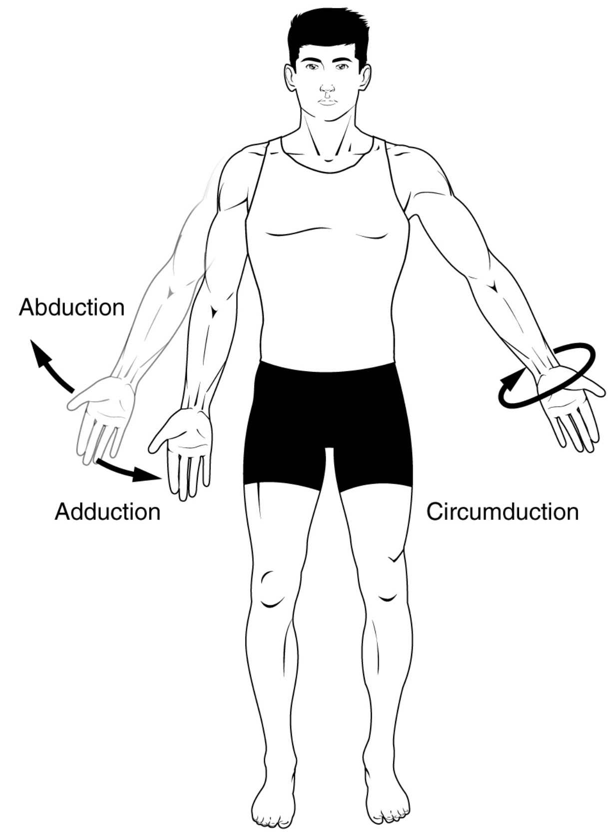

(e) Angular movements: abduction, adduction, and circumduction of the upper limb at the shoulder

Robotic Exoskeletons

https://commons.wikimedia.org/wiki/File:Biomimetics-09-00520-g001.png CC-BY Figure from academic publication showing examples of different types of exoskeletons:
Paper: Kuber, P.M.; Rashedi, E. Training and Familiarization with Industrial Exoskeletons: A Review of Considerations, Protocols, and Approaches for Effective Implementation. Biomimetics 2024, 9, 520. https://doi.org/10.3390/biomimetics9090520

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Actuators (motors and drives)

- **Electrical actuator (the most common)**(+80%)
  - Stepper, DC, AC, Brushless

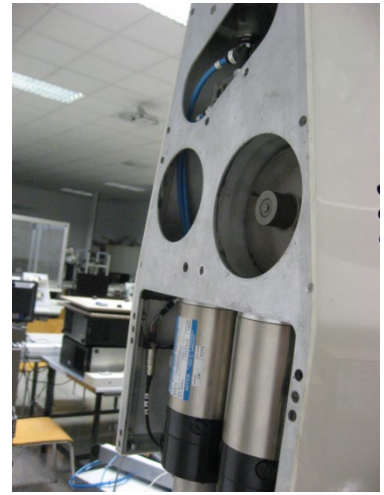
    Improved position control

    DC Motors

    Good controllability / brush issues

    AC Motors + electronic commutation

    Increasing interest



- **Hydraulic / pneumatic**

F. Daerden, D. Lefeber, B. Verrelst and R. Van Ham, "Pleated pneumatic artificial muscles: compliant robotic actuators," IROS 2001

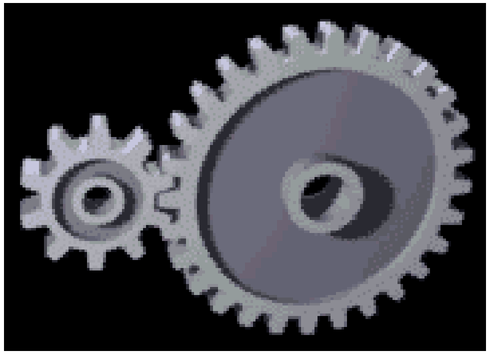
Actuators (Transmission and reduction gears)

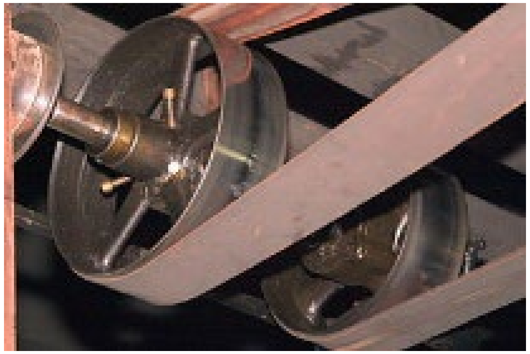
- Actuators $\Rightarrow$ To move the mechanical structure
- Each actuator moves one joint
- Location of actuators in the mechanical structure
  - Distributed (actuators close to the axes)
    - Increase in the inertia of the structure
    - Max. Accelerations are reduced
  - Centralized (actuators near the robot base)
    - Lower inertia
    - It requires using reduction gears and transmission
      - Size and weight
      - Backlash (lash or play)
      - Performance degradation
  - Combination
    - Tradeoff: Inertia – Transmission efficiency

Actuators (Transmission and reduction gears)

- Rotation - Rotation
  - Gears (High torques / backlash issues)
  - Belts and timing/toothed belts (longer distance / noise issues)
  - Parallelogram (limited rotation issue)

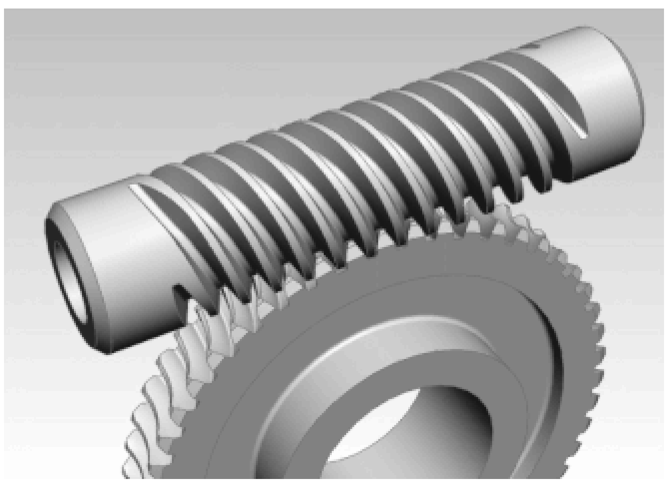
Source: Wikipedia:



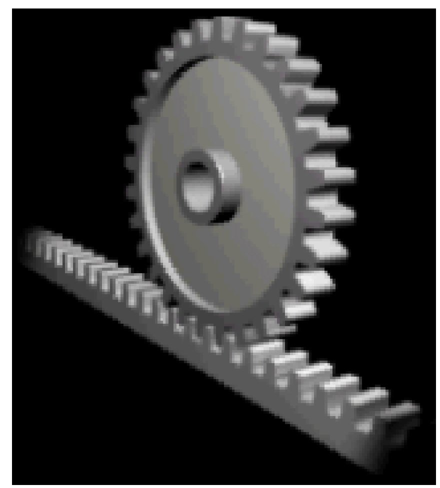


Actuators (Transmission and reduction gears)

- Rotation - Translation
  - Worm gear or "endless screw" (Lower backlash / friction and heat problem)
  - Rack and pinion (Long distance / noise, friction problem)



Source: Wikipedia



Source: Wikipedia

Sensors in Robotics:

- *Proprioceptive* sensors (internal)
  - Inside the robot
  - Measure the robot state
  - To measure variables required for the robot control
    - **Position**, speed

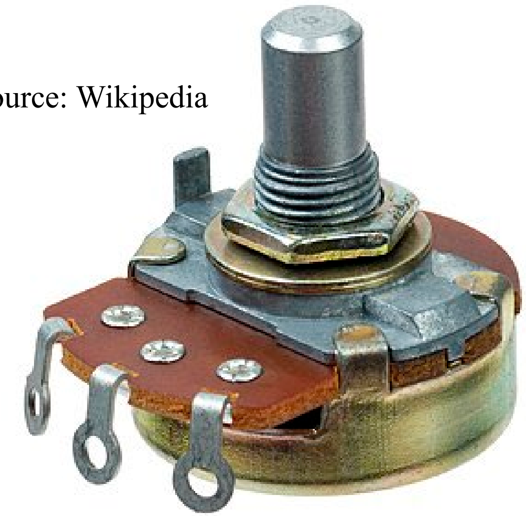
- *Exteroceptive s*ensors (external)
  - Information of the environment / scene
    - Basic: presence or absence detection
    - Advanced: Force/torque, distance (laser, ultrasound, infrared), inertial/accelerometer, vision*, ...*

- Position sensors
  - Proprioceptive
  - Inductive, capacitive, resistive, optical phenomena

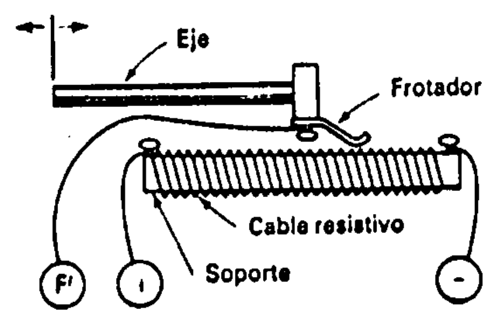
- Examples:
  - Synchro-Resolver
  - Inductosyn
  - LVDT
  - Potentiometers
  - Encoder (absolute, incremental)

Position sensors

Source: Wikipedia



- Potentiometer
  - Linear or angular
  - Features:
    - Cheap
    - Low accuracy
    - Friction, degradation, sensitive to vibrations
  - Common in educational robots, for axis not critical



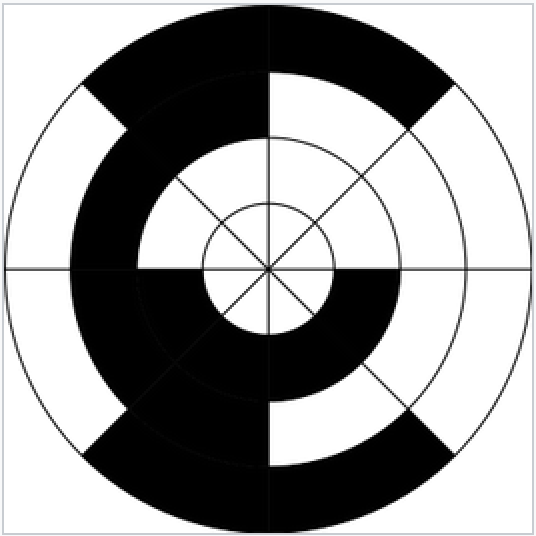
Position sensors

- Optical encoder
  - Metal or glass disk, with slits
  - Light emitter + photodiode (reflective alternatives)
  - Incremental
    - Pulse counter + zero detection
    - Two detectors (and rows) -> detect changes in the orientation
  - Absolute
    - Binary code
    - “Gray” coding
  - Features:
    - Digital output
    - Resolution (2^8 – 2^{19}=0.5M)
    - Sensitive to dust, pollution, vibration.. It requires a high mechanical accuracy in its manufacturing

Position sensors

- Absolute encoder example (Gray encoding)

Source: Wikipedia



Rotary encoder for angle-measuring devices marked in 3-bit binary-reflected Gray code (BRGC). The inner ring corresponds to Contact 1 in the table. Black sectors are "on". Zero degrees is on the right-hand side, with angle increasing counter-clockwise.

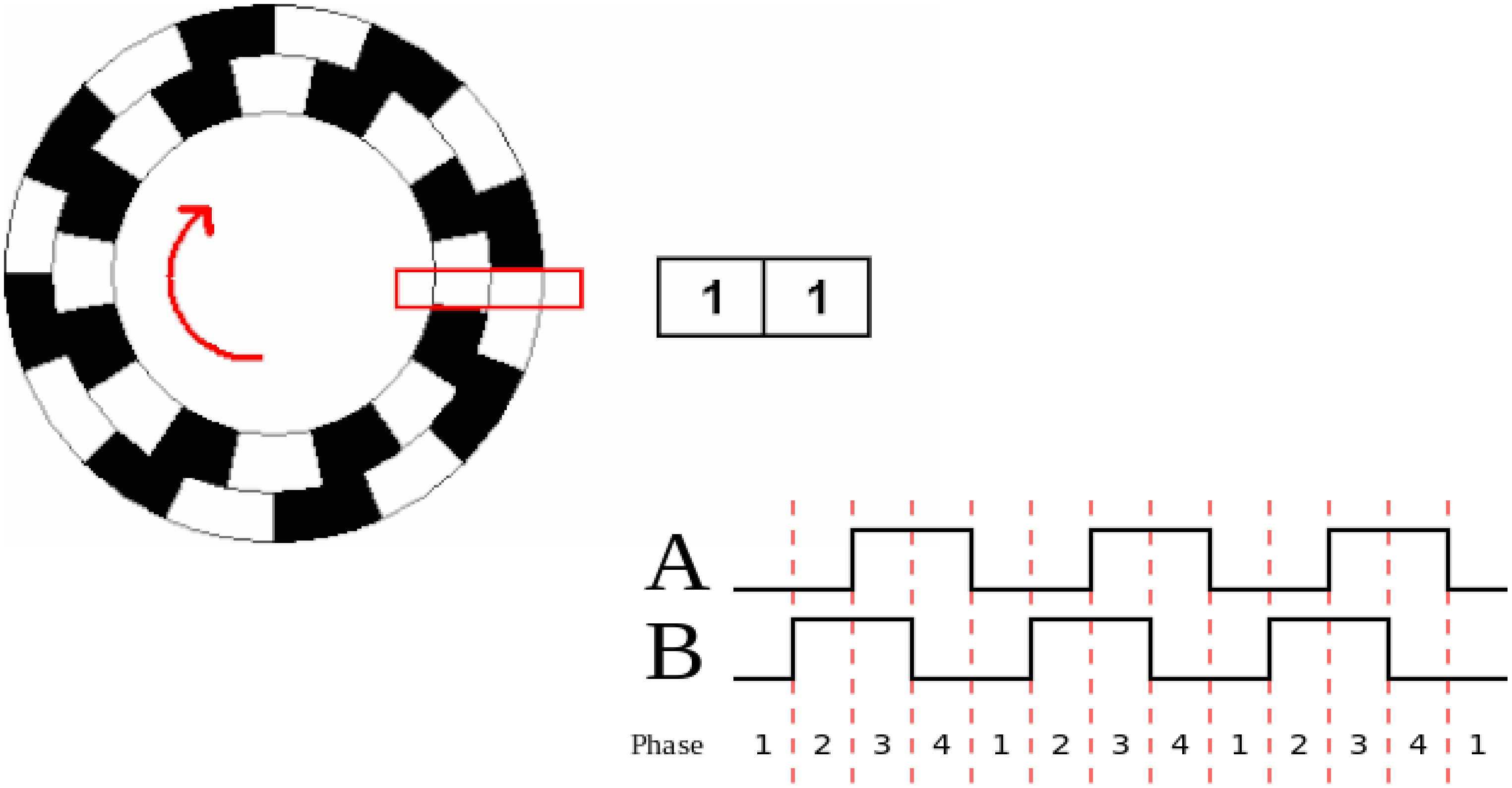
Gray Coding

Sector	Contact 1	Contact 2	Contact 3	Angle
0	off	off	off	0° to 45°
1	off	off	ON	45° to 90°
2	off	ON	ON	90° to 135°
3	off	ON	off	135° to 180°
4	ON	ON	off	180° to 225°
5	ON	ON	ON	225° to 270°
6	ON	off	ON	270° to 315°
7	ON	off	off	315° to 360°

Position sensors

- Incremental encoder example

Source: Wikipedia



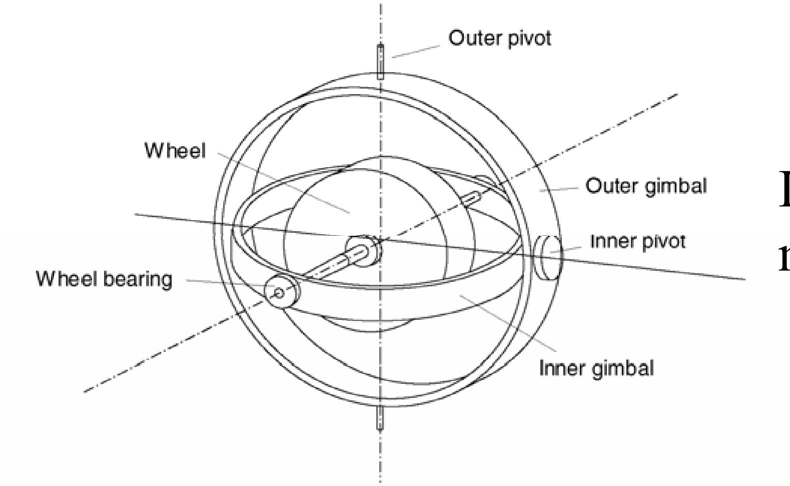
Advanced sensors
Inertial sensors

- gyroscopes (mechanical, piezoelectric, optical)
  Used to measure *relative orientation*
  (angular speed)
  Orientation: by integrating the angular speed

Accuracy error:
- mechanical: 0.1 degrees after 6 hours
- piezoelectric: medium accuracy
- optical: high accuracy (0.0001 degrees/hour), increased robustness and lifetime, more expensive, without mobile components

Advanced sensors

Mechanical gyroscope



Principle of conservation of momentum

$$\boxed{\tau = I\omega\,\Omega}$$

I, inertia; ω axis speed
measuring τ yields Ω (normal axis)

Error: 0.1° in 6 hours

Piezoelectric gyroscope

- Variable electrical resistance depending on the acceleration force (Coriolis)
- Medium accuracy

Optical gyroscope

- It detects rotation due to the interference between light beams in opposite directions
- The phase difference -> used to compute the rotation
- High accuracy: 0.0001 degrees/hour

Inertial sensors

- accelerometers

Measure of the acceleration in 3 orthogonal axis

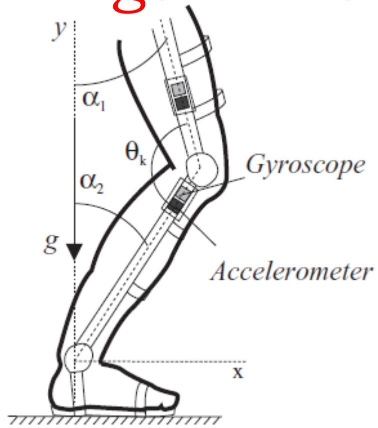
Integrating acceleration ➡ speed ➡ position

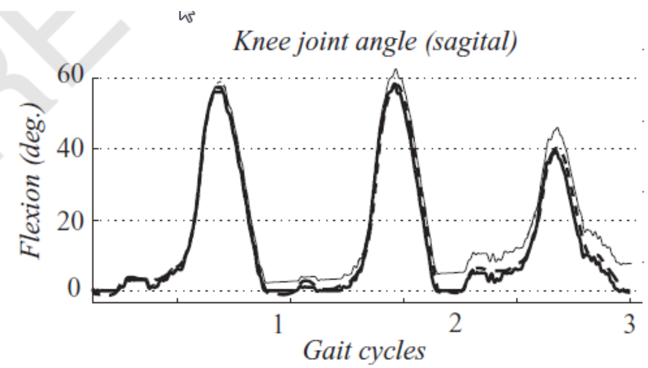
Problems:

- Noisy data
- Limited speed and acceleration
- *drift*: speed: 1-8 cm/s. (high)

Accelerometers are combined with gyroscopes to increase the angular accuracy

Exoskeleton





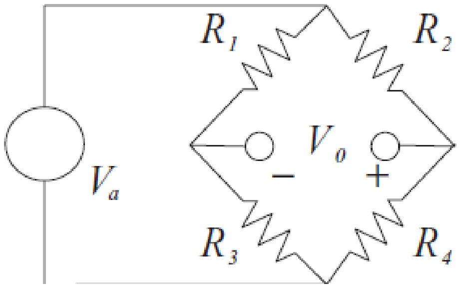
Force / pressure sensors:
(tactile / interaction human - exoskeleton)

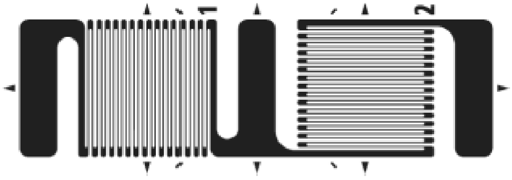
- Piezoelectric: force → deformation → voltage

- Capacitive: force→ capacitance change→ voltage

- Strain gauge

Wheastone bridge





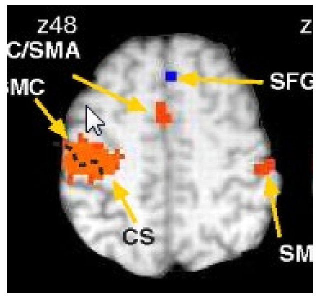
Advanced sensors

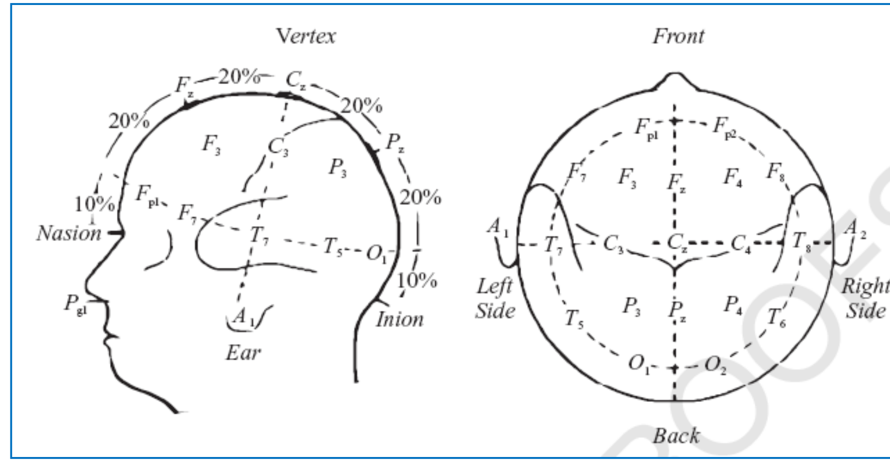
Bio-actuators:
FES (Functional electrical stimulation)

→ (Robot-assisted) rehabilitation

Biosensors

EEG (electroencephalography)





EMG (electromyography)