Computational Robotics

L0: Introduction, Terminology and General Definition

Roberto Marino, PhD

Computational Modeling for Robotics and Human Computer Interaction
University of Messina - FCRLab
roberto.marino@unime.it

March 17, 2026



UniMe
1548

About the Instructor



Roberto Marino, PhD

Research Fellow @ University of Messina - FCRLab

Short Bio

- B.Sc. Computer and Telecommunication Engineering, University of Messina
- M.Sc. Robotics Engineering, Ecole Centrale de Nantes (France)
- Ph.D. Robotics Engineering, University of Genova

Homepage

`https://roberto-marino.github.io`

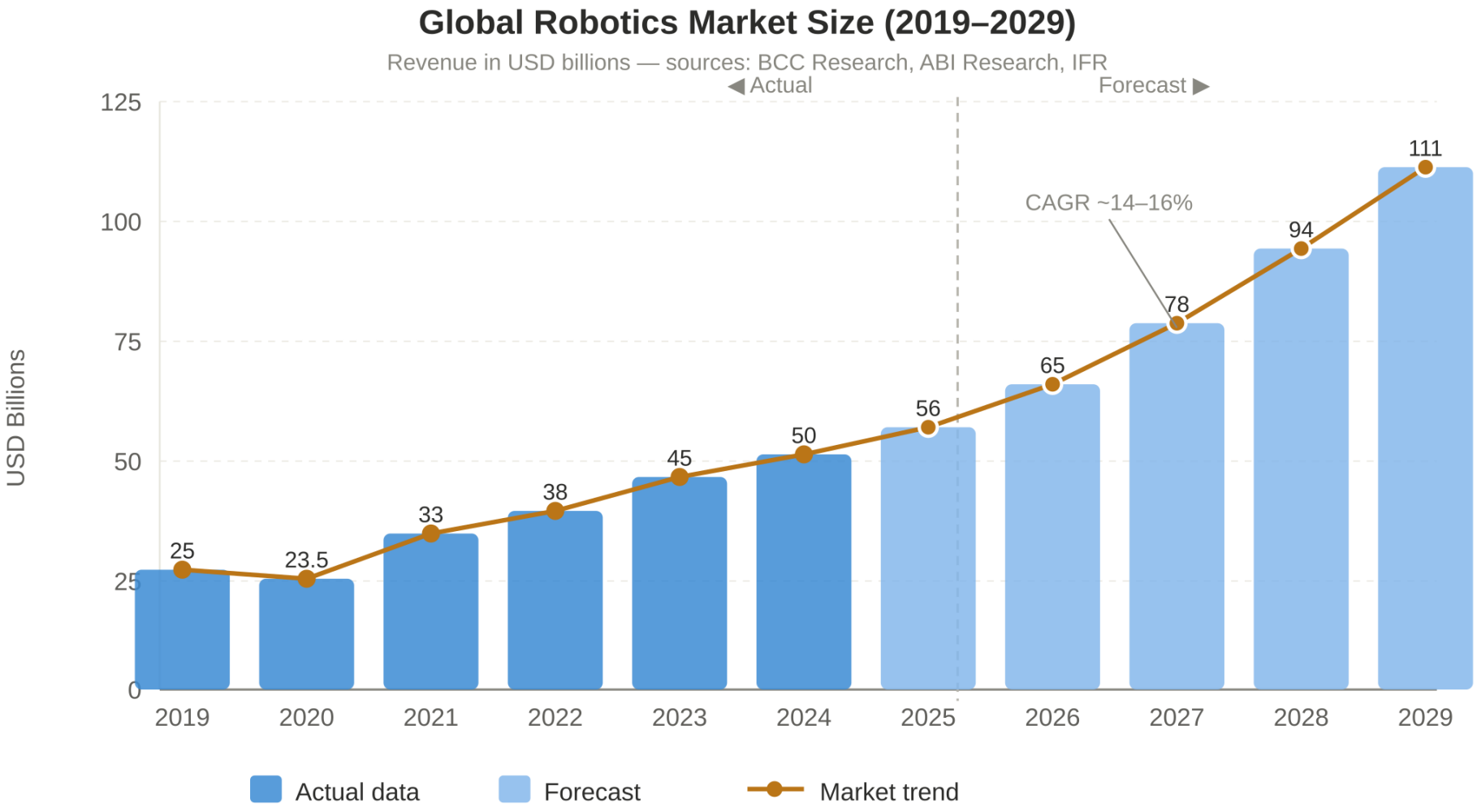
Course Telegram Group

`https://t.me/ComputationalRoboticsUniME`

Thesis Opportunities

Data-driven Modeling and Control, SLAM, Machine-Learning OS Scheduling, Federated Learning, Scientific Machine Learning

Why studying robotics?



Sources: BCC Research (2024), ABI Research (2025), IFR World Robotics Report

Why studying robotics?



Because of PHYSICAL AI

"Artificial Intelligence will not evolve without **physical interaction**". (cit. Yann Le Cun)

What is a Robot?

A robot is a mechanical device containing electrical, electronic and IT components, capable of:

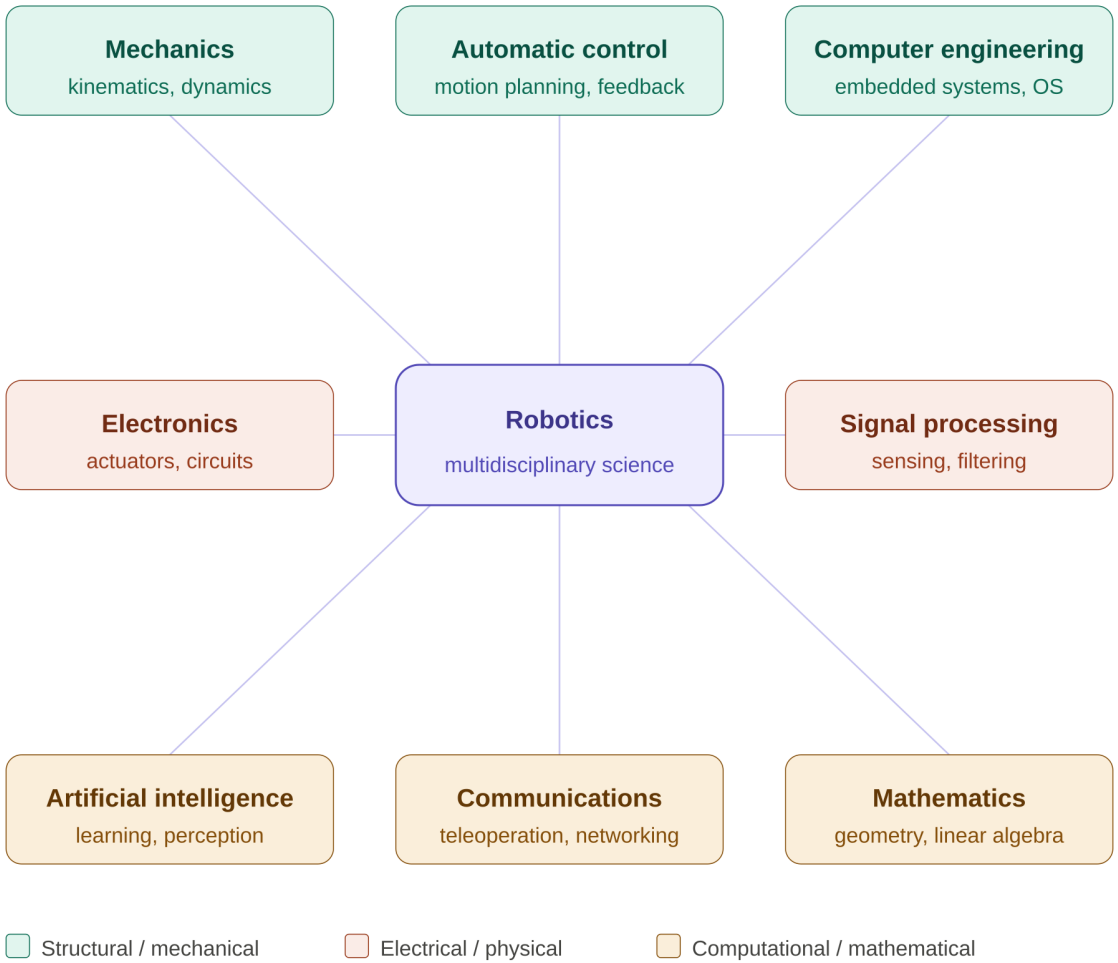
- **Perception** of the environment
- **Action** on objects and the surroundings
- **Decision** and **learning**
- **Communication** and interaction with humans

Key Properties

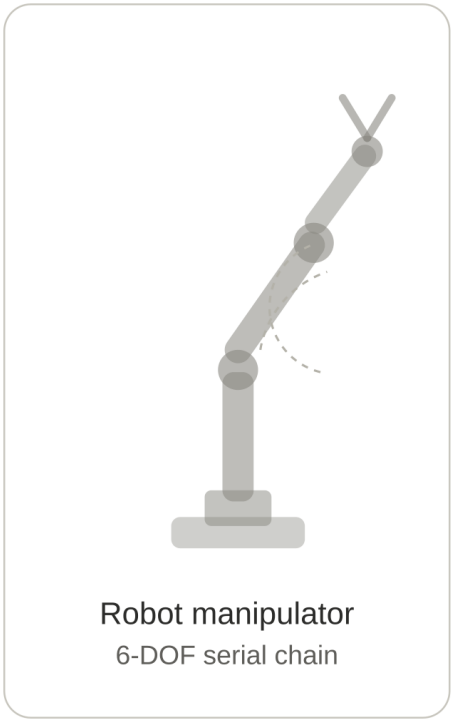
Adaptability Adjusts motion to comply with environmental changes during task execution.

Versatility Carries out a variety of tasks without changing the mechanical structure or control system.

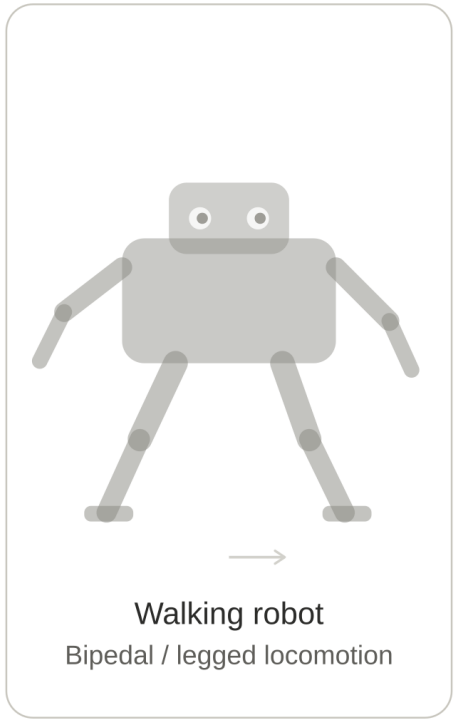
Robotics is strongly multidisciplinar



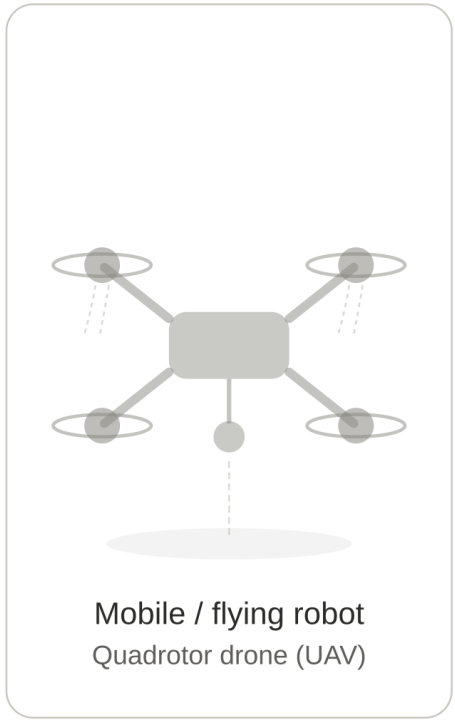
Main Classes of Robots



Robot manipulator
6-DOF serial chain



Walking robot
Bipedal / legged locomotion



Mobile / flying robot
Quadrotor drone (UAV)

Robot Manipulators

Imitate the human arm

Walking Robots

Imitate human, animal or insect locomotion

Mobile / Flying Robots

Cars, drones, underwater vehicles

Main Classes of Robots



Robot Subsystems

A robot is composed of the following subsystems:

- **Mechanism:** articulated mechanical structure with electric, pneumatic or hydraulic actuators and suitable transmission systems.
- **Perception:** internal sensors (joint positions & velocities) and external sensors (contact, distance, vision).
- **Controller:** generates actuator input signals from user instructions and sensor outputs.
- **Communication Interface:** allows the user to program robot tasks.
- **Workcell & Peripherals:** constitute the working environment.

Robotics is a *multidisciplinary* science: mechanics, control, electronics, signal processing, communications, computer engineering.

Mechanical Components

The mechanism of a robot manipulator consists of:

- **End-effector:** any device to manipulate or transform objects (grippers, welding torches, paint guns, etc.). It is the interface between robot and environment.
- **Articulated mechanical structure:** places the end-effector at a given location with desired velocity and acceleration. Composed of a *kinematic chain* of rigid links.

Types of Kinematic Chains

- Serial (simple open chain)
- Tree structured
- Closed chain (including parallel robots)

Kinematic Chains – Serial and Tree Structured

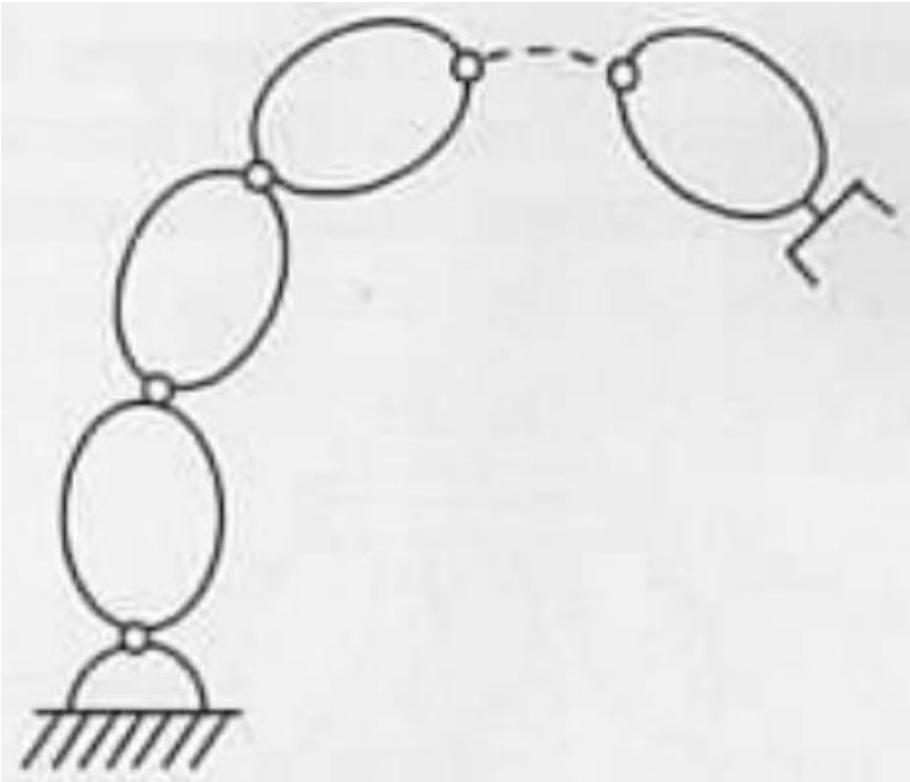


Fig. 1.1 – Simple open (serial) chain

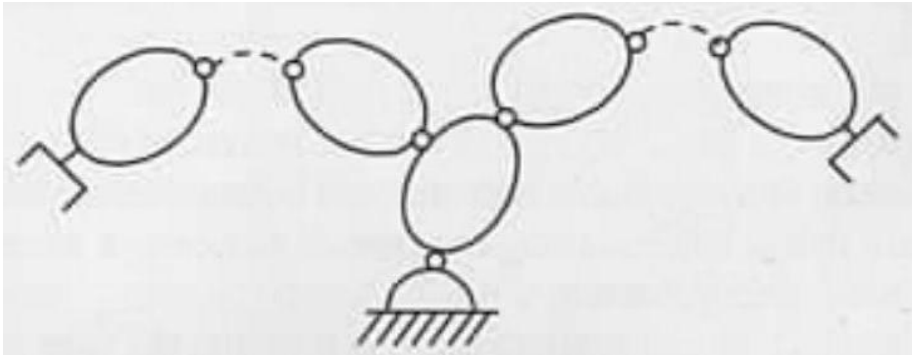


Fig. 1.2 – Tree structured chain

Serial robots with simple open chains are the most commonly used industrial robots.

Kinematic Chains – Closed and Parallel

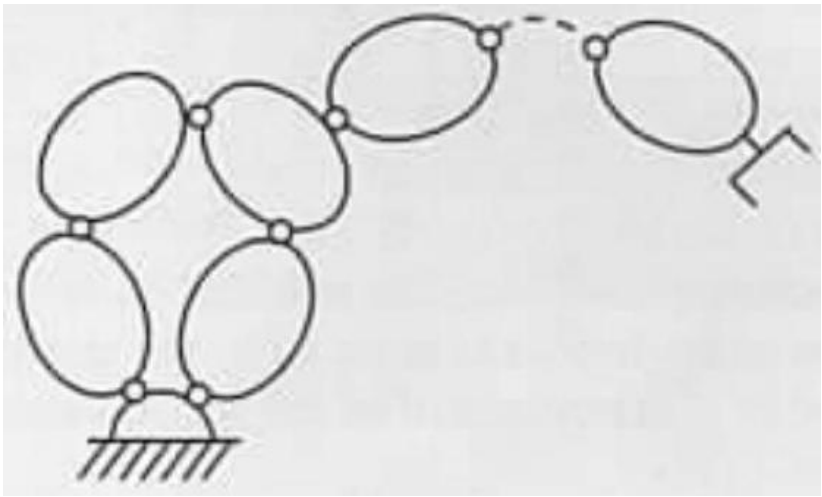


Fig. 1.3 – Closed chain

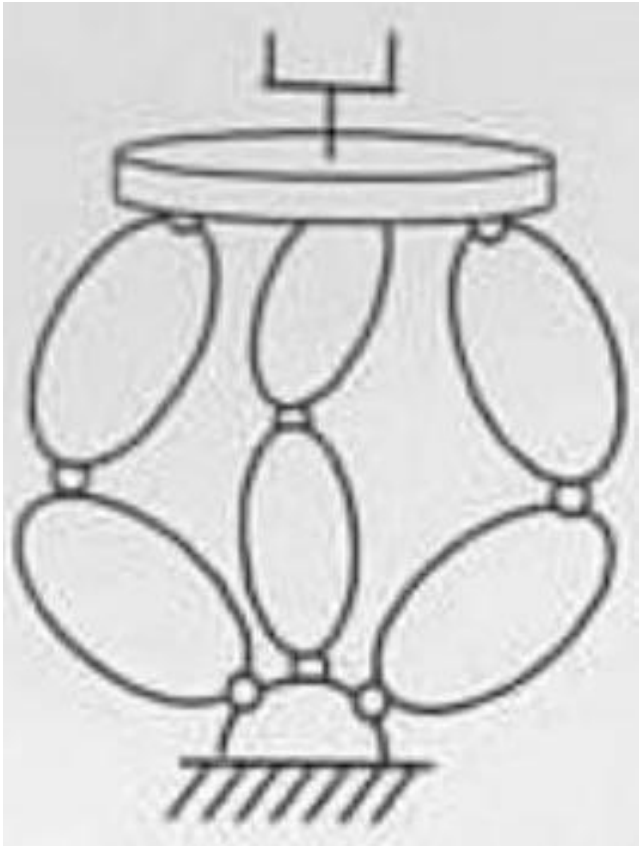


Fig. 1.4 – Parallel robot

Parallel robots connect the end-effector to the base via several parallel chains. They offer a higher payload/mass ratio and are promising for heavy-load manipulation.

Joints

A joint connects two successive links, limiting the degrees of freedom between them. The joint mobility m satisfies $0 \leq m \leq 6$.

Main Joint Types (m = 1)

Revolute (R) Rotation about a common axis; position given by the rotation angle.

Prismatic (P) Translation along a common axis; position given by the distance.

A complex joint ($m > 1$) can be built from equivalent combinations of R and P joints. E.g., a spherical joint $\equiv$ three revolute joints whose axes intersect at a point.

Revolute Joint

- Denoted by **R**
- Limits relative motion to a *rotation* about a common axis
- Location described by the *angle* about the axis

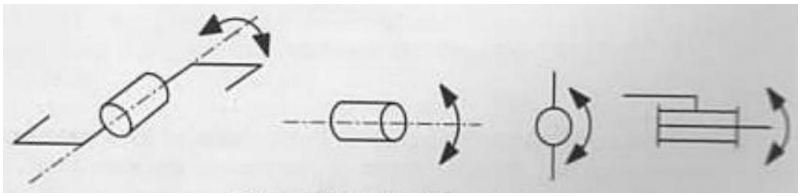


Fig. 1.5 – Revolute joint symbols

Prismatic Joint

- Denoted by **P**
- Limits relative motion to a *translation* along a common axis
- Location described by the *distance* along the axis

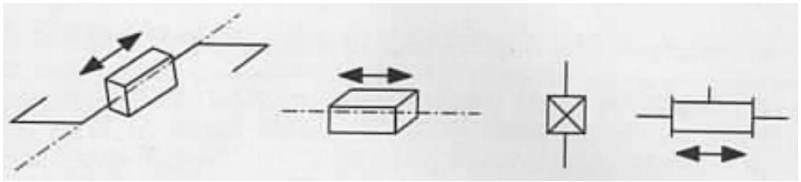


Fig. 1.6 – Prismatic joint symbols

Key Spaces and Definitions

Degree of Mobility Number of independent components of the instantaneous velocity of a body. Equal to 6 for a free body in space, 3 for a body in a plane.

Joint Space Space in which all link locations are represented using joint variables $q \in \mathbb{R}^N$, where N = number of degrees of freedom.

Task Space Space representing the position and orientation of the end-effector. Described by $X \in \mathbb{R}^M$, with $M \leq 6$ and $M \leq N$.

Degree of Mobility

"The mobility of a body is defined as the number of independent components of its instantaneous velocity"

Degree of Freedom

"The dimension N [of the joint space] is equal to the number of independent joints and corresponds to the number of degrees of freedom of the mechanical structure, also known as the mobility of the structure"

Redundancy and Singular Configurations

Redundancy

A robot is *redundant* when the DOF of its joint space exceeds that of its task space ($N > M$). Redundancy increases the reachable workspace and enables secondary objectives.

Singular Configurations

Configurations in which the end-effector DOF becomes less than M. Examples:

- Axes of two prismatic joints become parallel
- Axes of two revolute joints become collinear
- End-effector origin lies on a line intersecting all joint axes

Choosing the Number of Degrees of Freedom

- A **non-redundant** robot needs **6 DOF** to place an arbitrary object anywhere in 3D space.
- **5 DOF** suffice if the object has revolution symmetry (rotation about that axis need not be specified).
- **3 DOF** suffice for planar tasks (2 for positioning + 1 for orientation).

Design Principle

The number of DOF is chosen as a function of the shape of the object to be manipulated and the class of tasks to be performed. A necessary (but not sufficient) condition is: end-effector DOF $\geq$ task DOF.

Possible Architectures

Considering only revolute or prismatic joints with consecutive axes either parallel or perpendicular:

Table 1.1 – Number of possible architectures vs. DOF

DOF	Architectures
2	8
3	36
4	168
5	776
6	3508

For 3 DOF, only **12 mathematically distinct and non-redundant** shoulder architectures are meaningful (shown in Fig. 1.7).

Shoulder Architectures

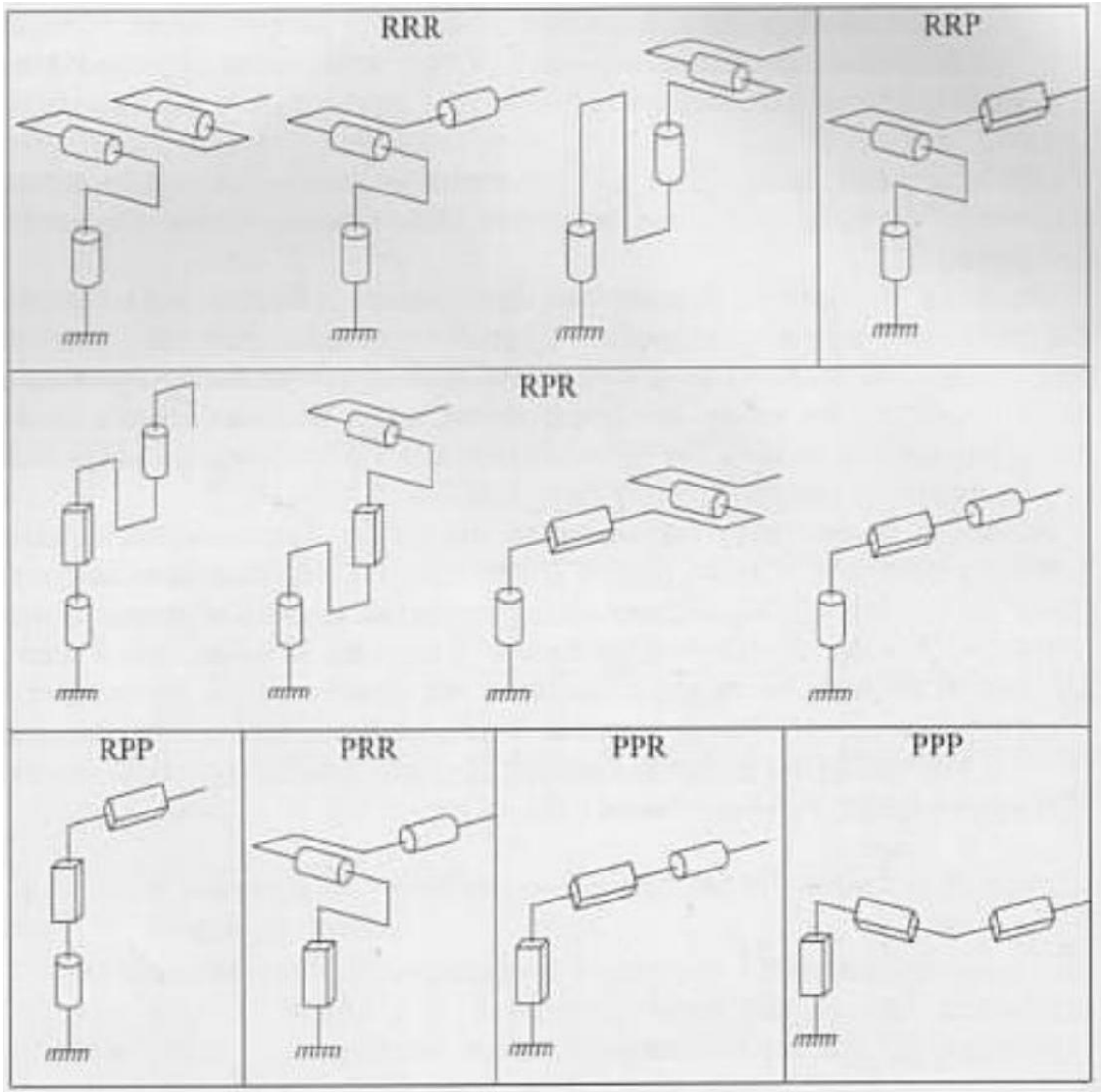


Fig. 1.7 – Shoulder architectures (from Milenkovic 1983)

Industrial Shoulder Structures

Five shoulder structures are commonly manufactured:

- **RRR (Anthropomorphic):** PUMA, ABB IRBx400, KUKA KR series, Stäubli RX, Fanuc
- **RRP (Spherical):** Stanford manipulator, Unimation Series 1000–4000
- **RPR:** Acma-H80 – basis of the **SCARA**
- **RPP (Cylindrical):** Acma-TH8, AFMA ROV/ROH
- **PPP (Cartesian):** Acma-P80, IBM-7565, AFMA RP/ROP

SCARA Robot

- **S**elective **C**ompliance **A**ssembly **R**obot **A**rm
- Based on the RPR shoulder + 1 revolute wrist joint
- Designed by Sankyo; manufactured by IBM, Bosch, Adept, ...
- Widely used for *planar assembly* applications

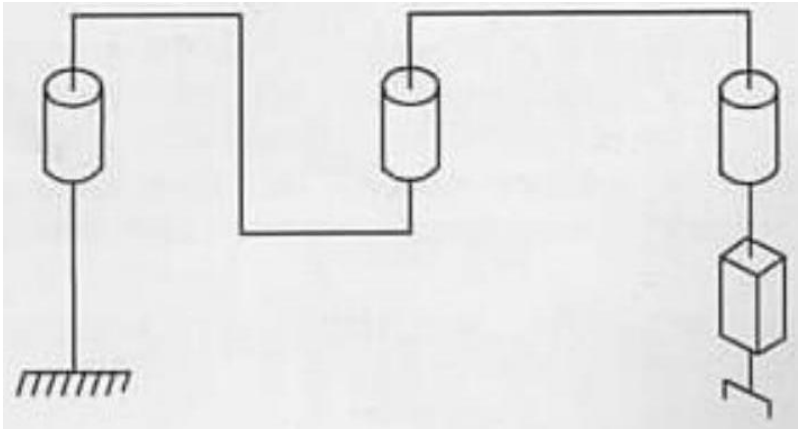


Fig. 1.8 – SCARA robot

Wrist Architectures

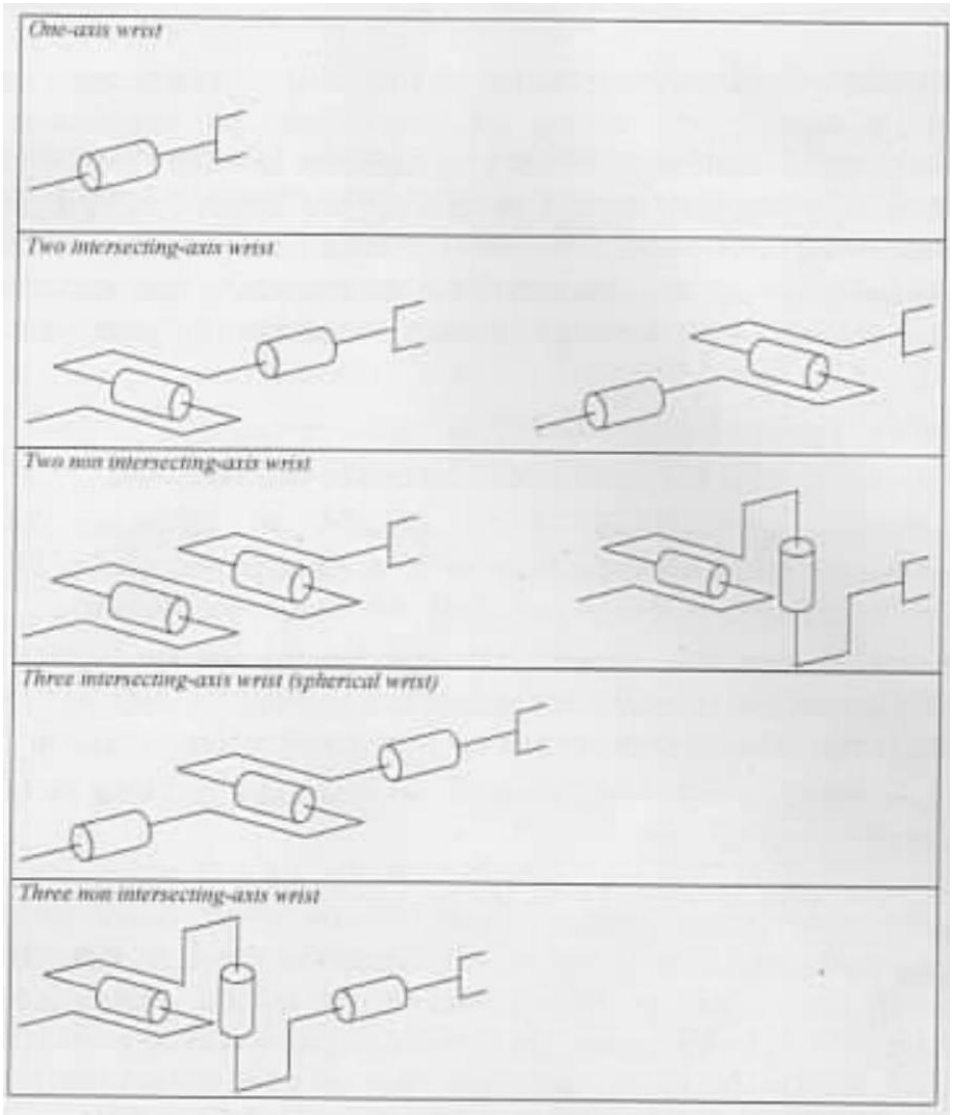


Fig. 1.9 – Wrist architectures (from Delignières 1987)

Classical 6-DOF Structure

- 3-DOF shoulder + **spherical wrist** (3 intersecting revolute axes)
- Position of wrist center depends *only* on joints 1–3
- Enables **analytical** solution of the inverse geometric model (Chapter 4)
- 59.5% of industrial robots have 6 or more DOF

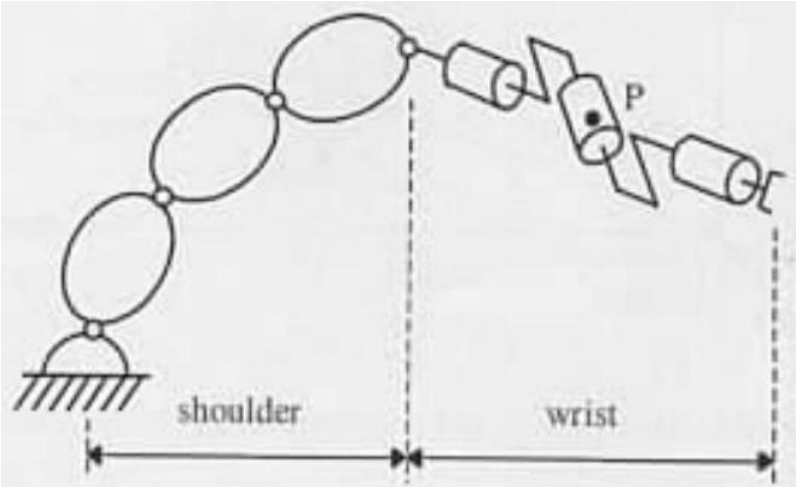


Fig. 1.10 – Classical 6-DOF robot

Robot Characteristics (ISO 9946)

- **Workspace:** space reachable by the end-effector (depends on DOF, joint limits, link lengths).
- **Payload:** maximum load the robot can carry.
- **Maximum velocity & acceleration:** determine cycle time.
- **Position accuracy:** difference between commanded position and mean of attained positions.
- **Position repeatability:** distance between mean attained position and furthermost attained position.
- **Resolution:** smallest achievable movement increment of joint or end-effector.

Other criteria: energy consumption, control architecture, programming environment, price, maintenance.

Position Accuracy and Repeatability

Position Accuracy

Difference between the **commanded position** and the **mean of the attained** (i.e. actually reached) **positions**:

$$\text{accuracy} = \|\mathrm{p}_{\text{cmd}} - \bar{\mathrm{p}}\|$$

Position Repeatability

Distance between the **mean of the attained positions** and the **furthermost attained position**:

$$\text{repeatability} = \max_k \|\mathrm{p}_k - \bar{\mathrm{p}}\|$$

where $\bar{\mathrm{p}} = \frac{1}{N}\sum_{k=1}^{N} \mathrm{p}_k$ is the mean of the N attained positions.

Note: accuracy measures systematic error (how far the mean is from the target); repeatability measures dispersion (how scattered the attempts are around their mean). The two indices are *independent*.

Accuracy vs. Repeatability

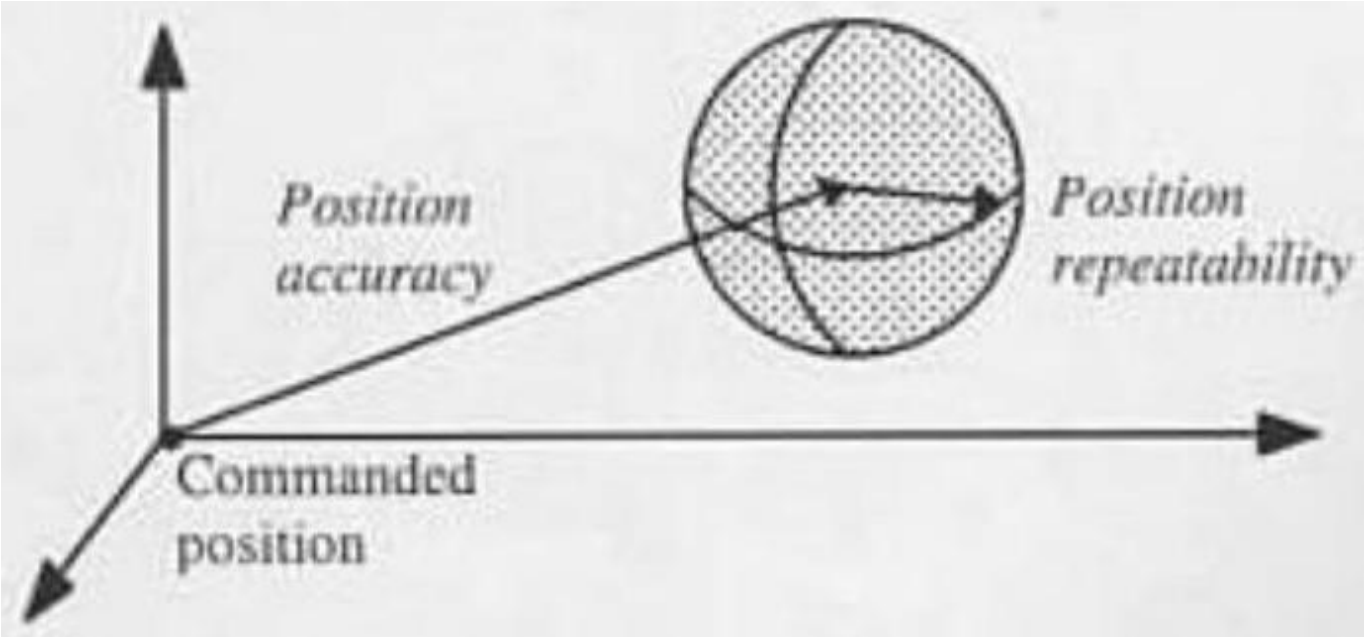


Fig. 1.11 – Position accuracy and repeatability (from Priel 1990)

Conclusion

Summary

- Defined fundamental concepts: joints (R, P), joint space, task space, DOF, redundancy, singular configurations.
- Reviewed kinematic chain types: serial, tree structured, closed, parallel.
- Surveyed industrial shoulder and wrist architectures.
- Discussed key performance characteristics (ISO 9946).