UNIVERSITÀ
DI TRENTO
Department of
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Fundamentals of Robotics

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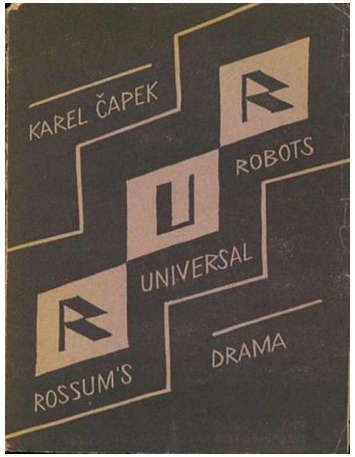
Software Development for Collaborative Robotics

Academic Year 2025/26

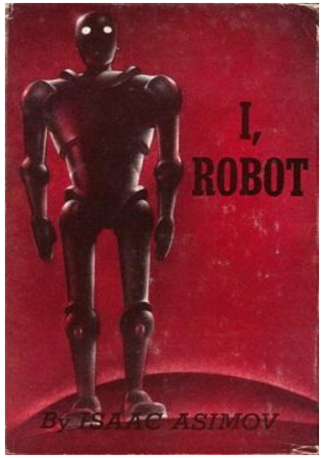
Origin of the name

The word **robot** appears to have first been used in Karel Chapek's 1920's play "Rossum's Universal Robots" to denote a human-like machine. It originates from the Czechoslovakian word "robota" which means **work** and.

Before populating the real world, robots prospered in fictional science novels. For example, Asimov introduced in the novel "Runaround" in 1942 the **Three Laws of Robotics**, the fundamental rules followed by robots in his novels.



Cover of the first edition of the play, 1920.

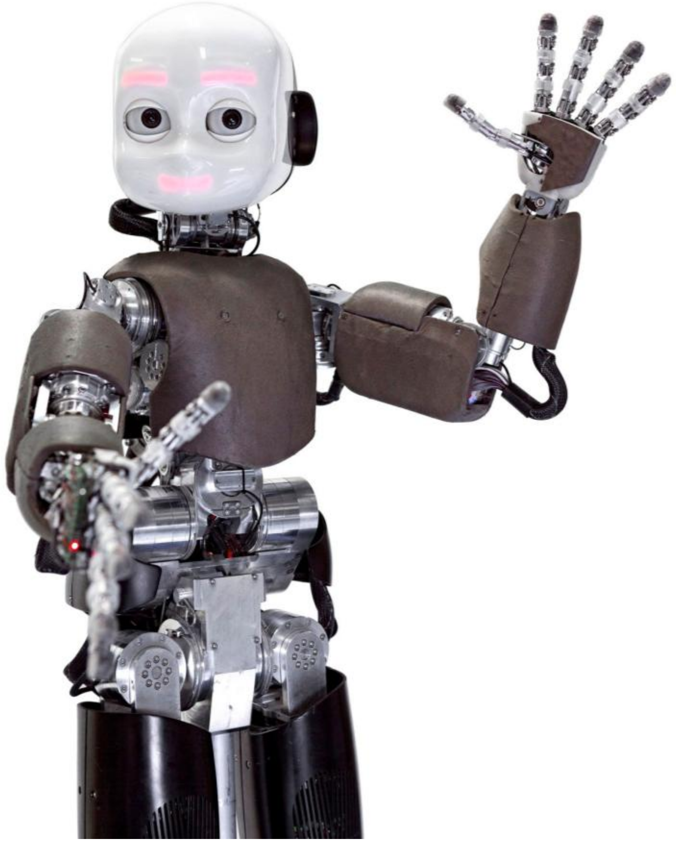


Cover of the first edition of the collection I, robot 1950.

Is this a robot?

Roomba, 2020.

Is this a robot?



iCub, 2009.

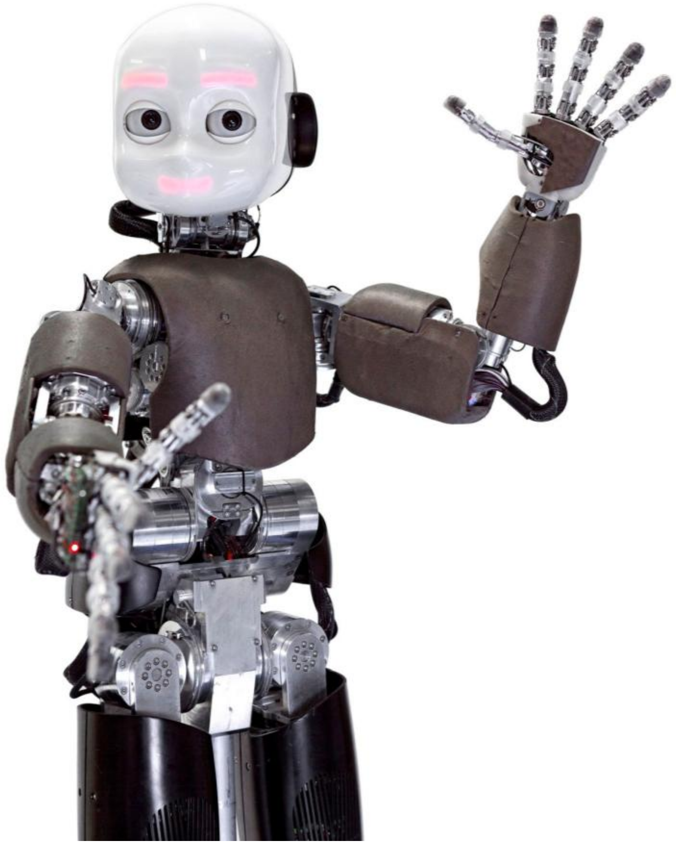
Is this a robot?

Bimby, 2023.

What is a robot?

- A **robot** is a programmable machine capable of carrying out a complex series of actions automatically.

- The word robot refers to agents with physical embodiment; virtual agents are usually referred to as bots.



iCub, 2009.

Sense-Plan-Act Paradigm

Robots can:

- Sense the environment and process data (SENSE);
- Make autonomous decisions (PLAN);
- Operate in the environment (ACT).

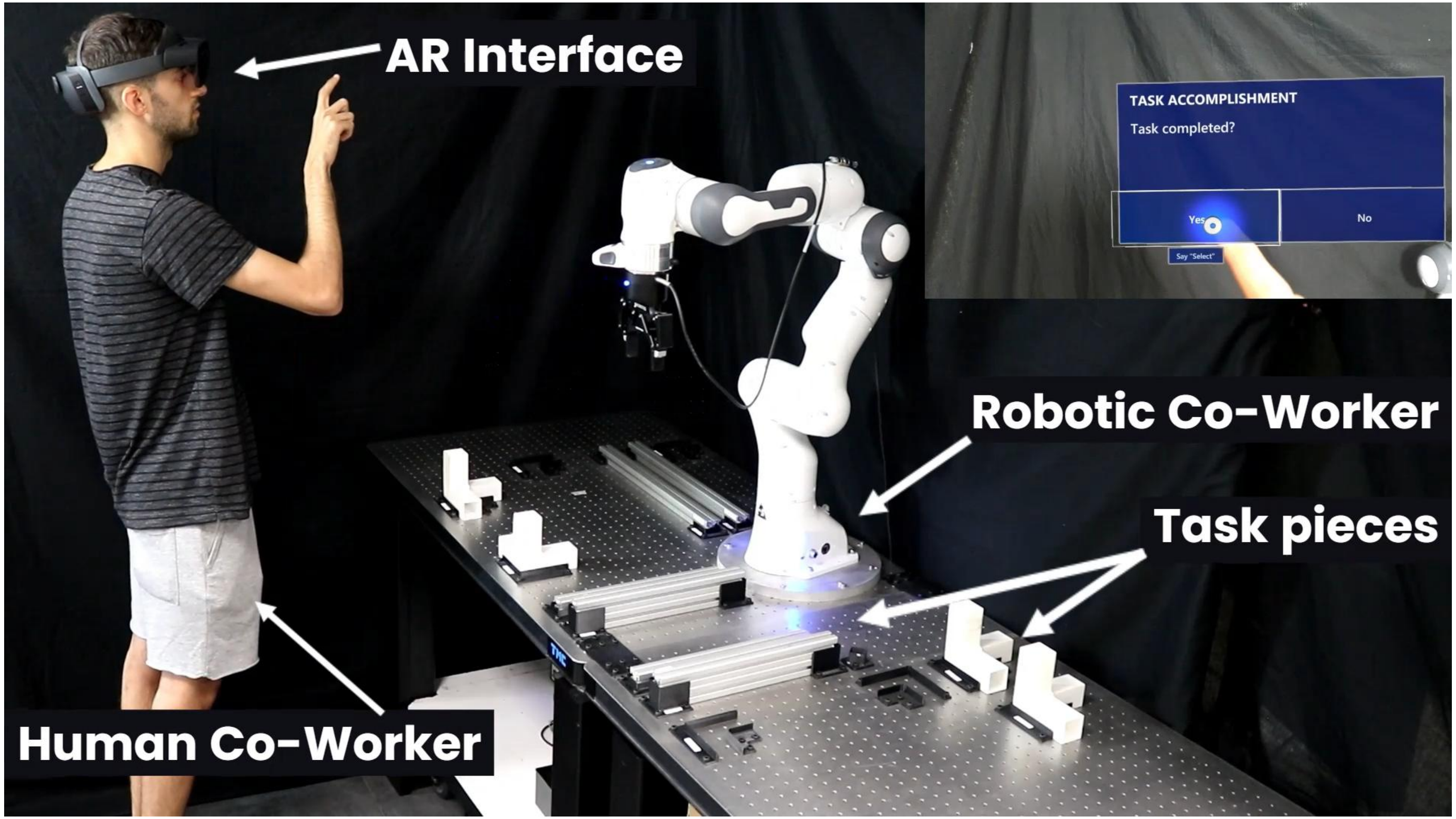
BUT... they need to be programmed!!

```
task main()
{
  bMotorReflected[port2]=1;
  while(true)
  {
    if(SensorValue(bumper)==0)
    {
      motor[port3]=127;
      motor[port2]=127;
    }

    else
    {
      motor[port3]=127;
      motor[port2]=-127;
      wait1Msec(1500);
    }
  }
}
```

Sense-Plan-Act example.

What do you think it is programmed here?



What do you program of a robot?

- Perception (SENSE):
  - Encoders;
  - Artificial Vision;
  - Tactile Sensors;
  - Force/Torque sensors;
- Behaviour (PLAN):
  - Task Planning;
  - Human-Robot Interaction;
- Motion (ACTION):
  - Trajectories;
  - Physical Interactions;
  - Control Inputs (position, velocity, torques).

Robot types (just some)

Manipulators

Wheeled

Mobile
Manipulators

Humanoids

Quadcopter

Quadrupeds

Robot types

Robots may be constructed to evoke **human form** (humanoid), but most robots are task-performing machines, designed with an emphasis on functionality, rather than aesthetics.

UR3e.

- **Manipulators**: fixed-base robot.
- **Mobile robots**: mobile-base robot.

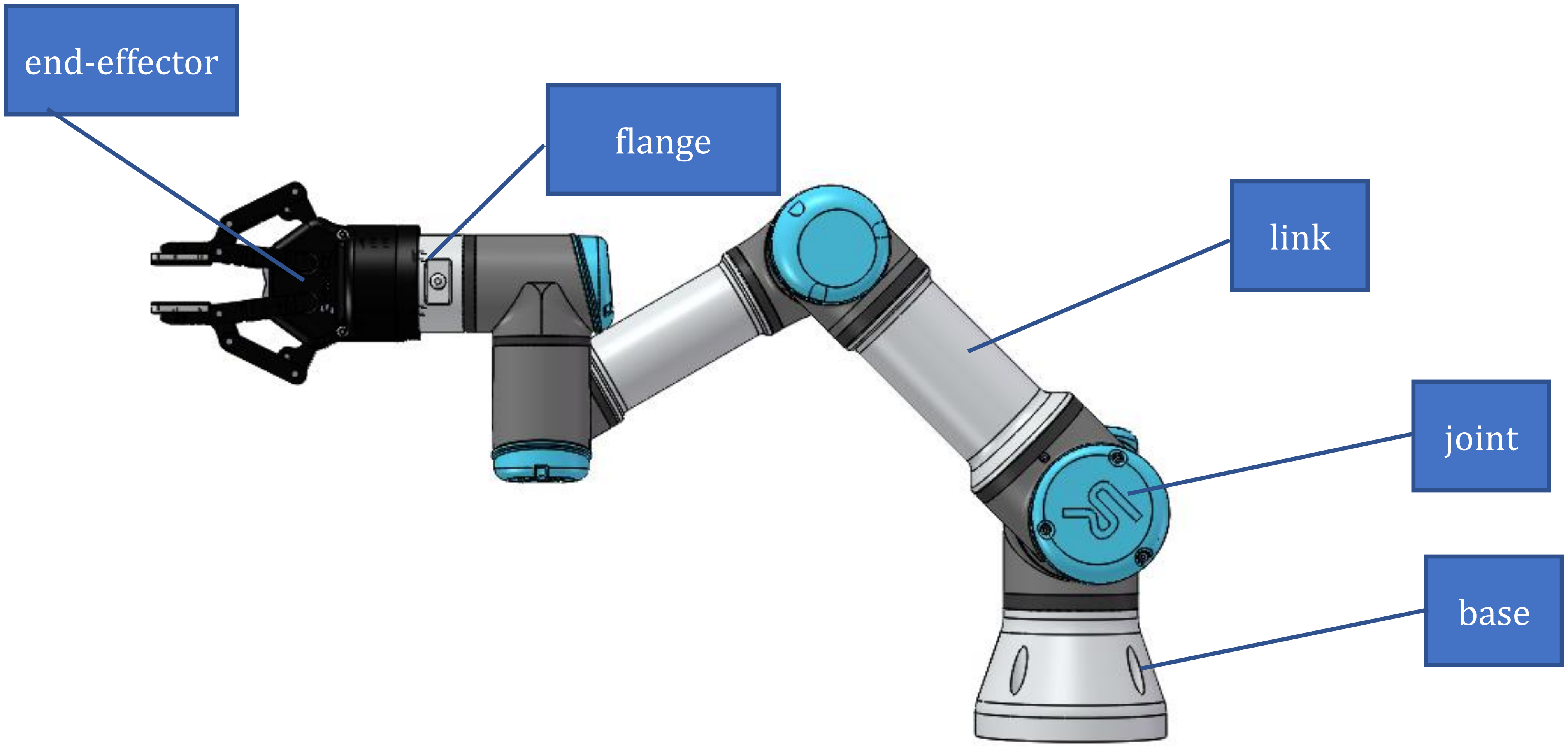
MiR250.

Robotic Manipulators

A robotic **manipulator** is a sequence of bodies (often rigid), called **links**, connected by mechanical articulations called **joints**. The main components are:

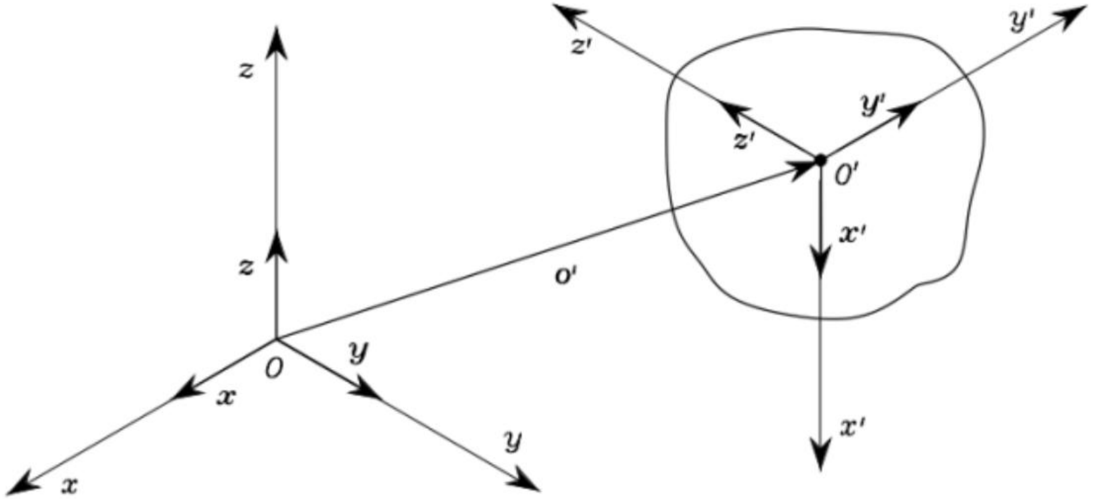
- An **arm** ensuring mobility;
- A **flange** located at the end of the arm where it is possible to mount a tool;
- The tool, when is mounted, is called **end-effector,** which is specific of the robot's tasks.

Manipulator example



Pose of a rigid body

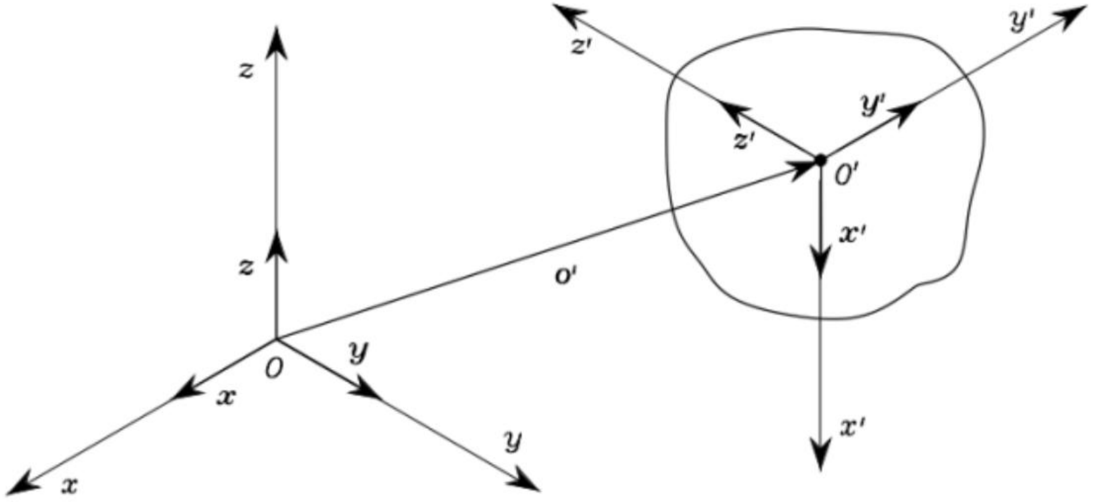
The motion of a body (for example, a link) in space is completely defined by its **position** and **orientation** (**pose**) w.r.t. a reference frame.



Position of a rigid body

The position of a point O' on the rigid body with respect to the coordinate frame O–xyz with unit vectors $\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$, is expressed by the 3D vector:

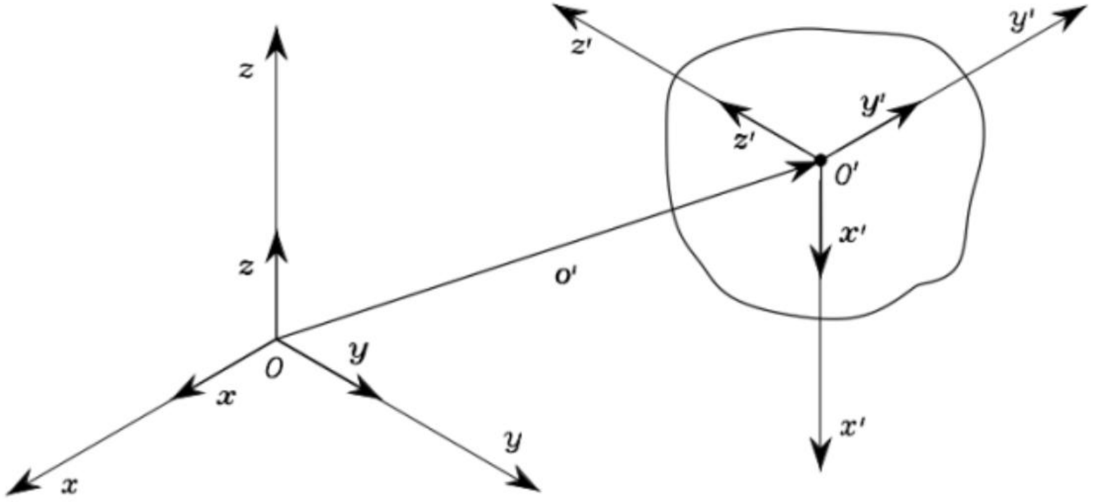
$$\boldsymbol{o}' = \begin{bmatrix} o'_x \\ o'_y \\ o'_z \end{bmatrix}$$



Orientation of a rigid body: Rotation matrix

Consider an orthonormal frame *O'–x'y'z'* attached to the body *O'* with unit vectors ***x', y', z'***. By expressing it w.r.t. to the coordinate frame *O–xyz:*

$$
\begin{aligned}
\boldsymbol{x}' &= x'_x\boldsymbol{x} + x'_y\boldsymbol{y} + x'_z\boldsymbol{z} \\
\boldsymbol{y}' &= y'_x\boldsymbol{x} + y'_y\boldsymbol{y} + y'_z\boldsymbol{z} \\
\boldsymbol{z}' &= z'_x\boldsymbol{x} + z'_y\boldsymbol{y} + z'_z\boldsymbol{z}
\end{aligned}
$$



The orientation of the rigid body *O'* can be expressed with a 3x3 **rotation matrix R**:

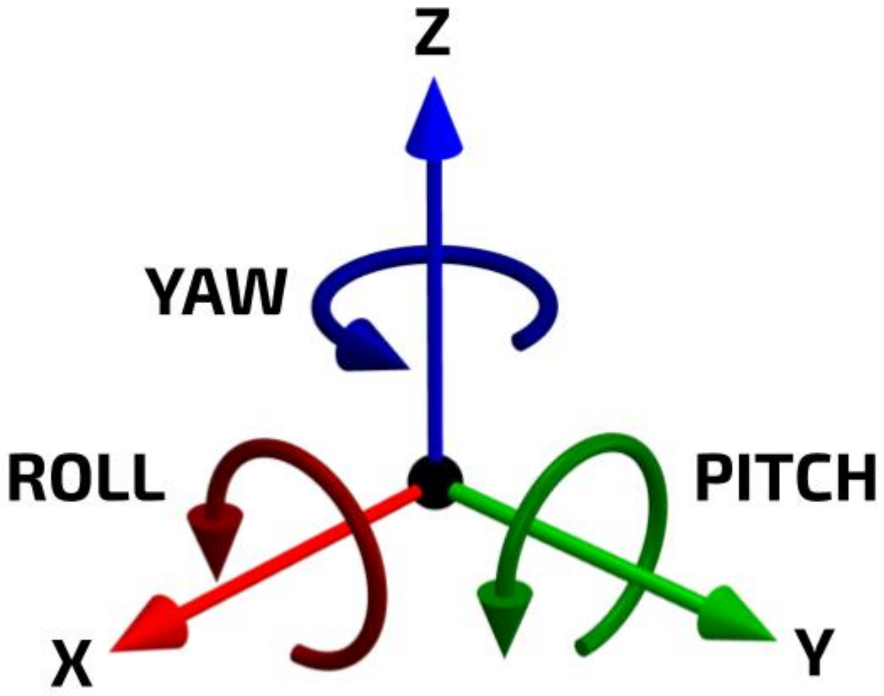
$$
\mathbf{R} = [\boldsymbol{x}' \quad \boldsymbol{y}' \quad \boldsymbol{z}'] = \begin{bmatrix} x'_x & x'_y & x'_z \\ y'_x & y'_y & y'_z \\ z'_x & z'_y & z'_z \end{bmatrix}
$$

R is an *orthogonal* matrix: $\boldsymbol{R}^T\boldsymbol{R} = \boldsymbol{I}_3$

Orientation of a rigid body: Euler angles

- Rotation matrices give a redundant description of frame orientation.
- For a minimal representation of orientation of a rigid body, only 3 parameters are needed, the three angles $\boldsymbol{\phi}$ =(ψ, θ, φ,), called **Euler angles**. Each angle represent the rotation about one of the coordinate axes.
- The most famous set of Euler angles are the XYZ angles, called **Roll–Pitch–Yaw angles**. The related rotation matrix can be composed as sequence of elementary rotations:

$$\boldsymbol{R}(\boldsymbol{\phi}) = \boldsymbol{R}_z(\varphi)\,\boldsymbol{R}_y(\theta)\,\boldsymbol{R}_x(\psi)$$



Orientation of a rigid body: Axis and angle

Axis and angle $\boldsymbol{r}, \theta$:

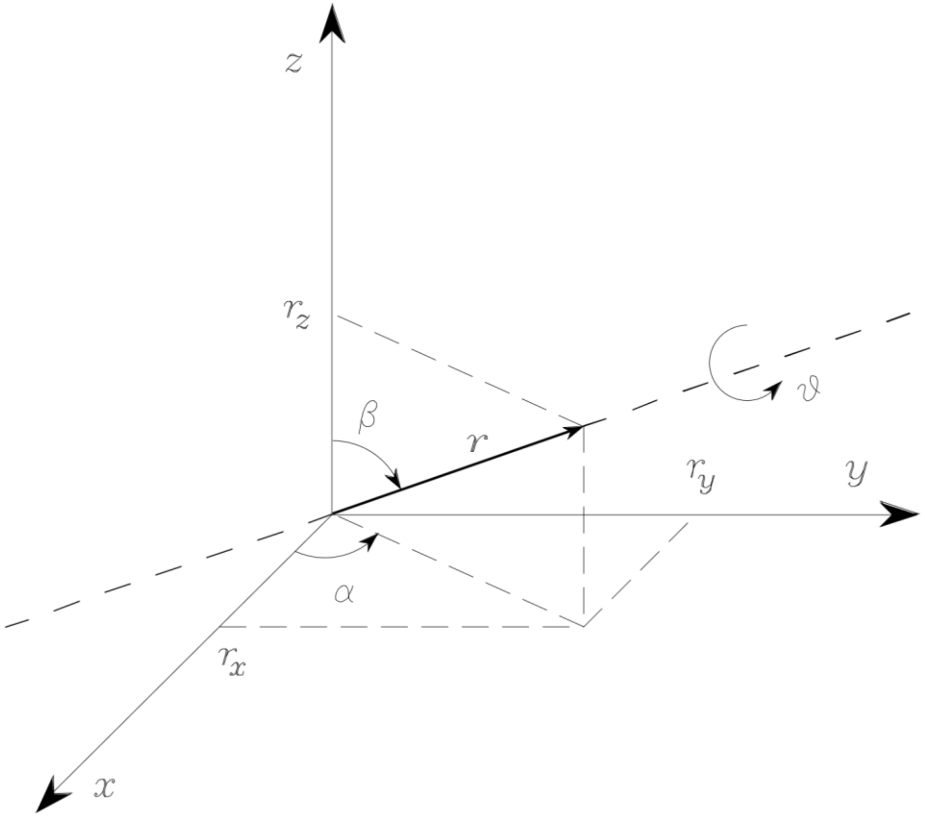
- Unit vector

$\boldsymbol{r} = [r_x \quad r_y \quad r_z]^T;$

- Angle θ about axis r.

Non minimal representation (4 parameters), and mapping is not unique:

$$\mathbf{R}(-\boldsymbol{r}, -\theta) = \mathbf{R}(\boldsymbol{r}, \theta)$$



Orientation of a rigid body: Quaternions

Unit quaternions $Q = \{\eta, \boldsymbol{\epsilon}\}$:

- Scalar part $\eta = \cos\frac{\theta}{2}$;
- Vector part $\boldsymbol{\epsilon} = \sin\frac{\theta}{2}$.

No singularity → One to one map between quaternions and rotation matrices, but quaternions have their own algebra:

Operation	Rotation matrices	Quaternions
Inversion	$R^{-1} = R^T$	$q = (\eta, \epsilon) \rightarrow q^{-1} \leftrightarrow (\eta, -\epsilon)$
Composition	$R_1, R_2 \rightarrow R = R_1 R_2$	$q_1 = (\eta_1, \epsilon_1), q_2 = (\eta_2, \epsilon_2) \rightarrow$ $q = q_1 \cdot q_2 \leftrightarrow \left(\eta_1\eta_2 - {\epsilon_1}^T\epsilon_2, \eta_1\epsilon_2 + \eta_2\epsilon_1 + \epsilon_1 \times \epsilon_2\right).$

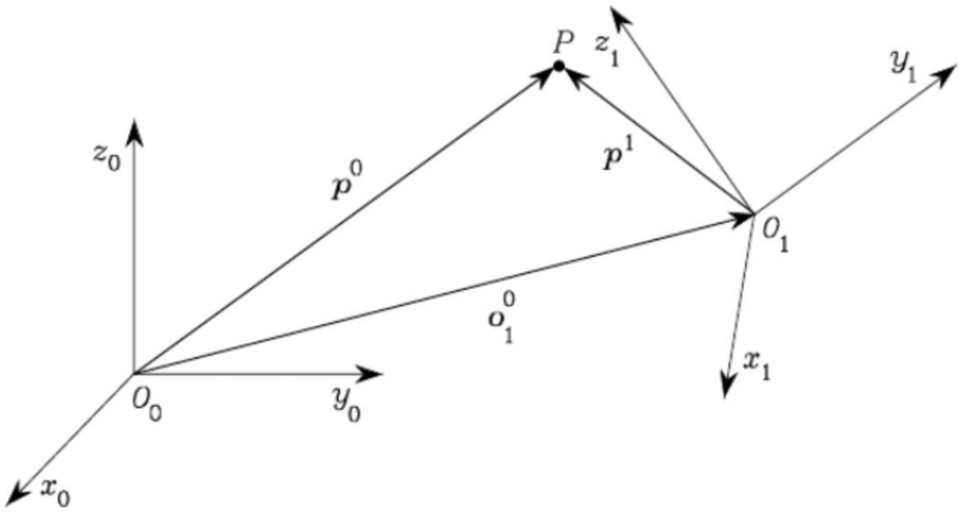
Homogeneous Transformations

Point P can be described with respect to the reference Frame 0:

$$\boldsymbol{p}^0 = \boldsymbol{o}_1^0 + \boldsymbol{R}_1^0 \boldsymbol{p}^1$$

and with respect to the reference Frame 1:

$$\boldsymbol{p}^1 = {\boldsymbol{R}_0^1}^T \boldsymbol{o}_1^0 + {\boldsymbol{R}_0^1}^T \boldsymbol{p}^0$$



To simplify we can use the homogeneous coordinates:

$$\widetilde{\boldsymbol{p}} = \begin{bmatrix} \boldsymbol{p} \\ \boldsymbol{1} \end{bmatrix}, \boldsymbol{A}_0^1 = \begin{bmatrix} \boldsymbol{R}_0^1 & \boldsymbol{o}_1^0 \\ \boldsymbol{0}^T & 1 \end{bmatrix}$$

to express the transformations as

$$\widetilde{\boldsymbol{p}}^0 = \boldsymbol{A}_0^1 \widetilde{\boldsymbol{p}}^1 \text{ and } \widetilde{\boldsymbol{p}}^1 = (\boldsymbol{A}_0^1)^{-1} \widetilde{\boldsymbol{p}}^0$$

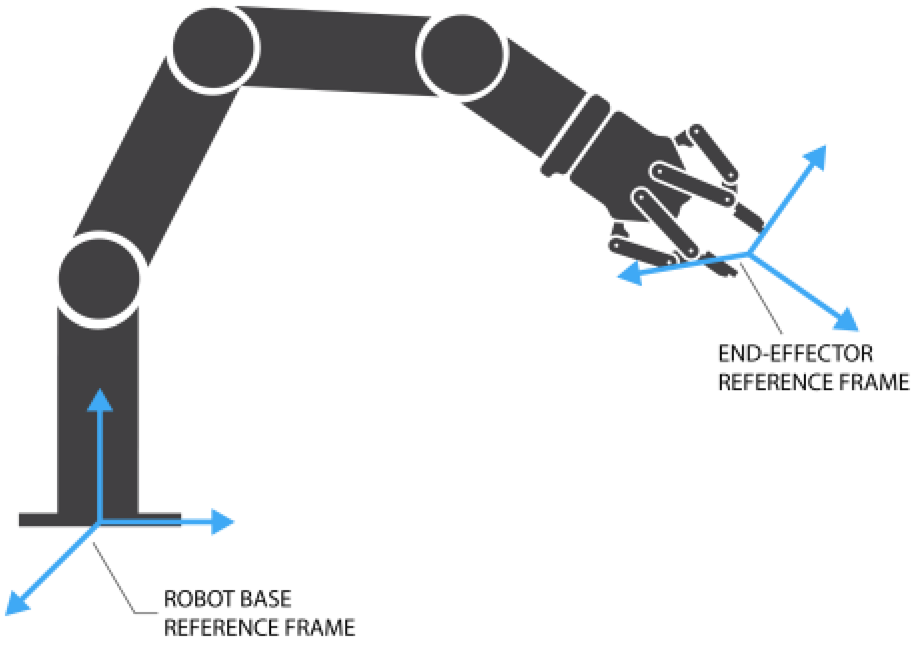
Body motion

- To describe the motion of each manipulator link, it is possible to attach a moving frame to each link and describe it w.r.t. a fixed reference frame;

- The most important frames are:
  - ➢the **base frame**, which is fixed in space for fixed-base robots;
  - ➢the **end-effector frame,** which is a moving reference frame.

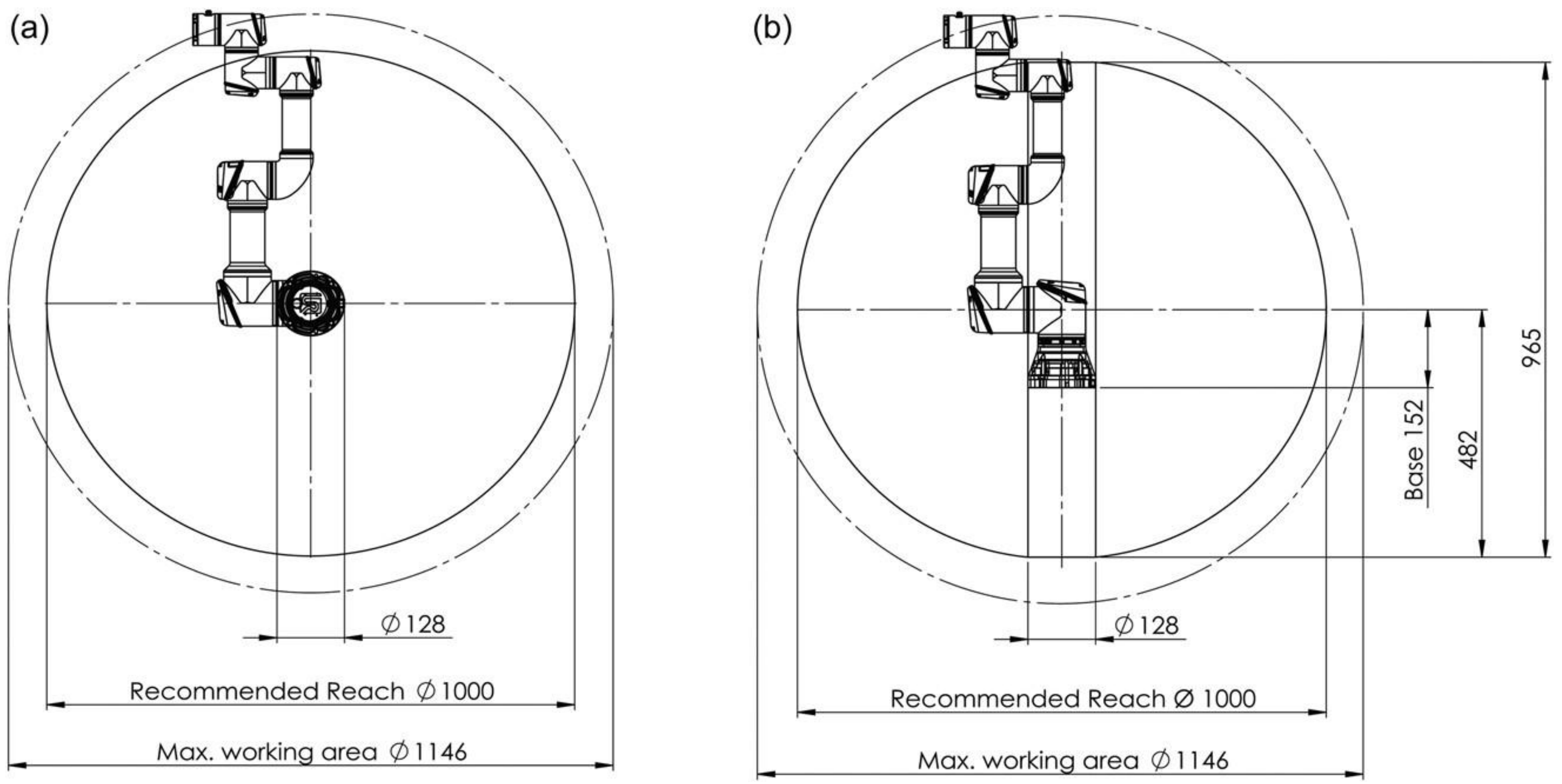
- The motion of the end-effector is described w.r.t. the base frame:

  $\boldsymbol{T}_e^b(\boldsymbol{q})$ **DIRECT KINEMATICS**



Workspace

- The **workspace** of a manipulator is defined as is the area in Cartesian space that the end effector can reach;
- Its structure very much depends on the number and on the type of the joints.



Joints

- A **joint** q is a connection between two or more links, which allows some motion, between the connected links.

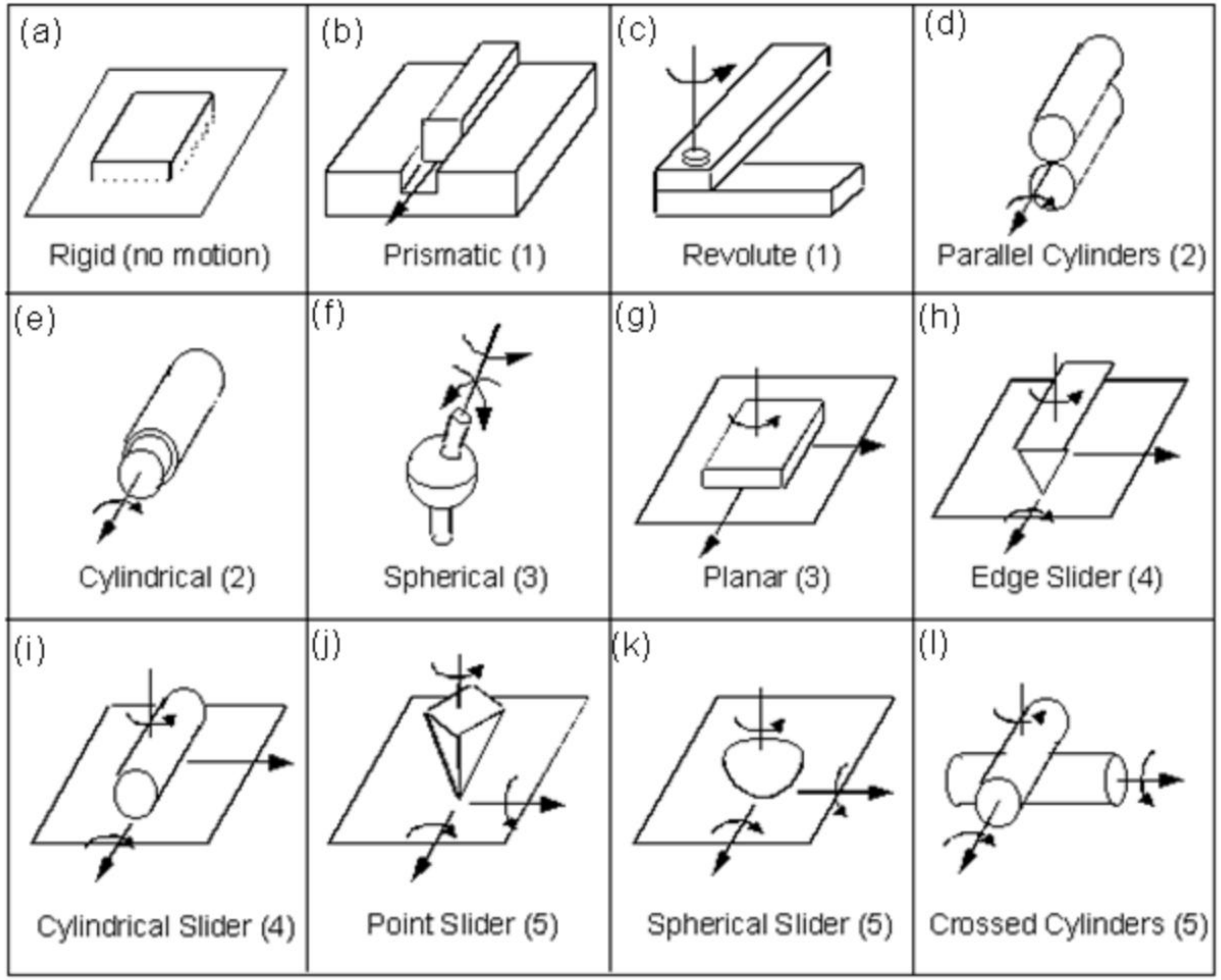
- Each joint constrain one link to move only in certain directions with respect to the other link. Each possible direction is a **Degree of Freedom** (**DoF**).

- Typically, each joint is endowed with an **actuator** (e.g., a brushless, or a linear motor) and provides the structure with 1 DoF.

Joint Types

Common joint types are:

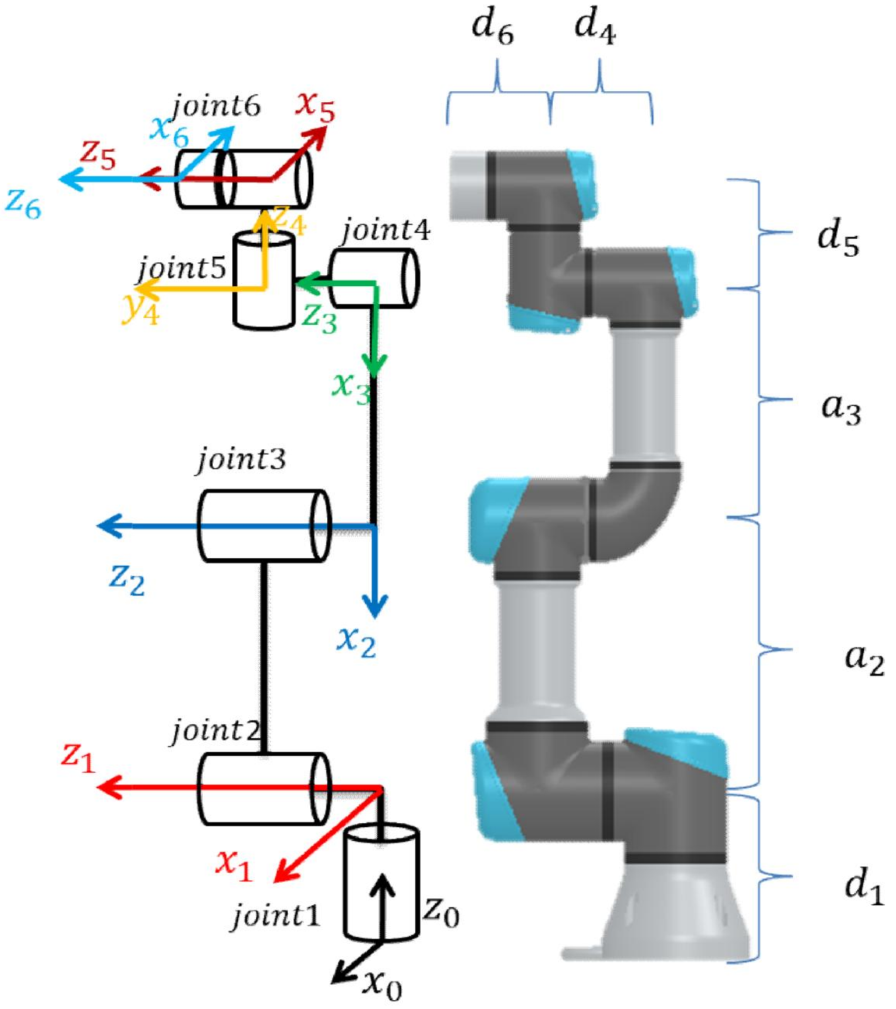
- **Prismatic**: enable a relative **translational** motion between the links (1 DoF);
- **Revolute**: enable a relative **rotational** motion between the links (1 DoF).



Manipulator example

The vector of n joint values **q** is called configuration.

In the example n=6.

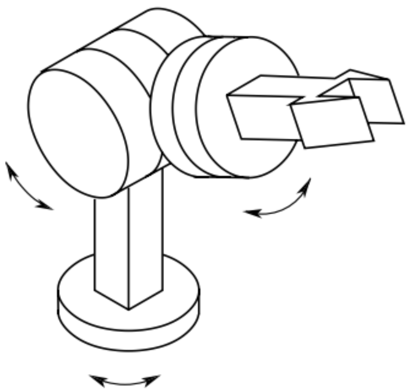


Wrist

- All different manipulators have an end-effector/tool attached to the wrist;

- The end-effector is usually a **gripper** but can be a different thing according to the task (e.g., a welding gun, a spray gun, a screwdriver etc.)

- The configuration of the wrist that maximises dexterity is spherical (3 revolute joints-> 3 DoFs).

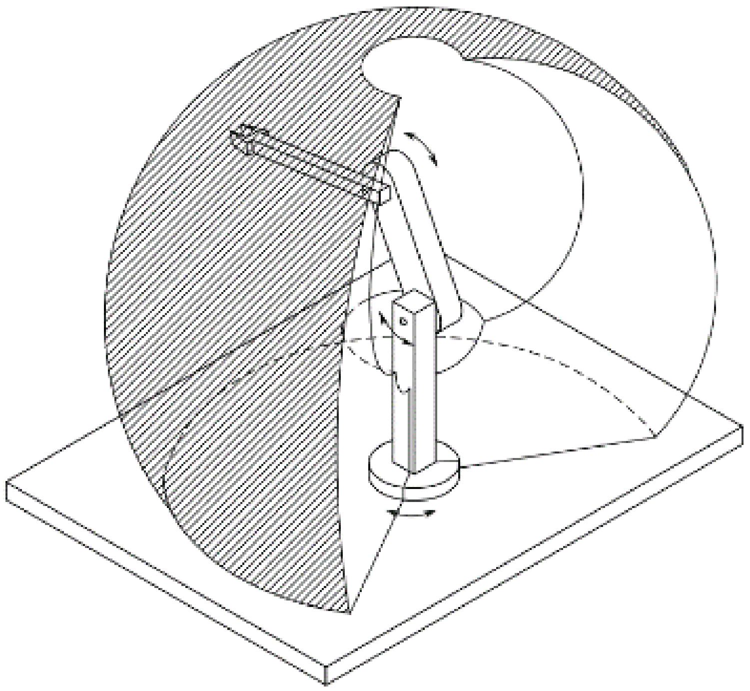


Anthropomorphic arm

- Robotic manipulators which have at least 3 revolute joints, where the axis of second and of the third are parallel and orthogonal to the axis of the first, is called **anthropomorphic** arm.

- The second joint is called **shoulder** and the third **elbow.**

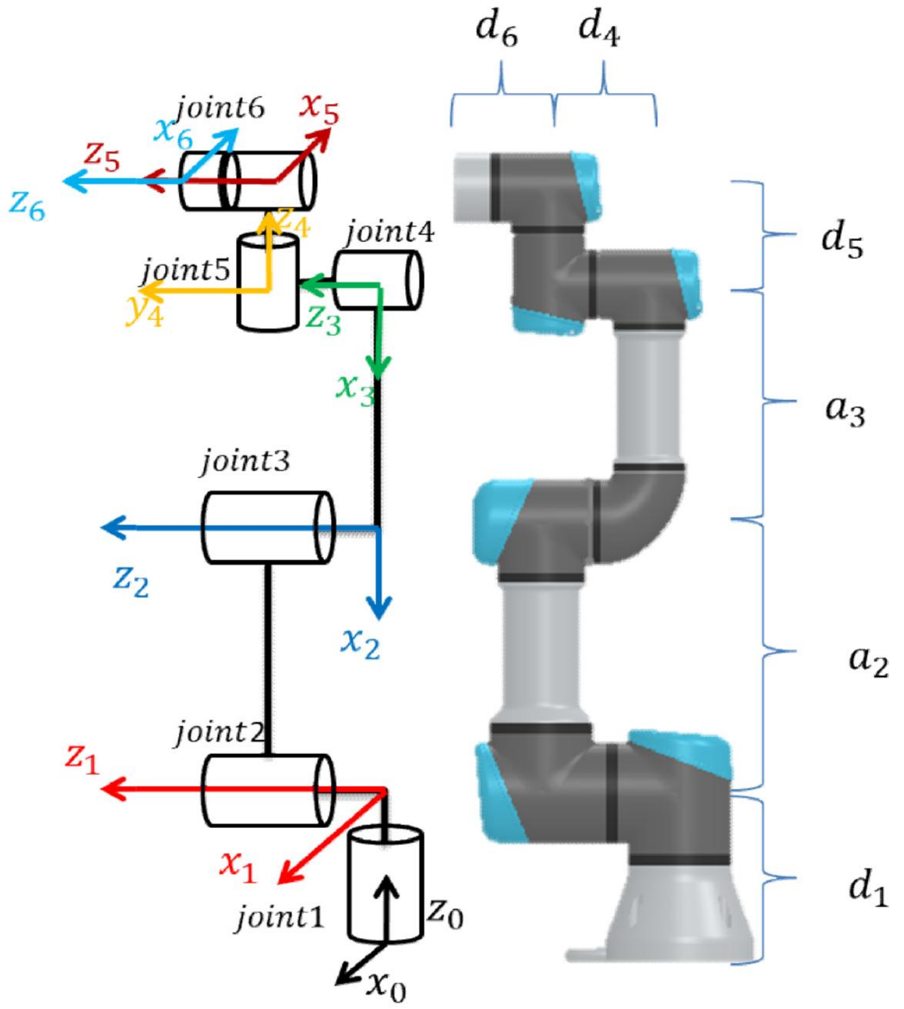
- This robot is by far the most widespread in industry (59% of the installations).



Manipulator example

6 (revolute) joints -> 6 DoFs:

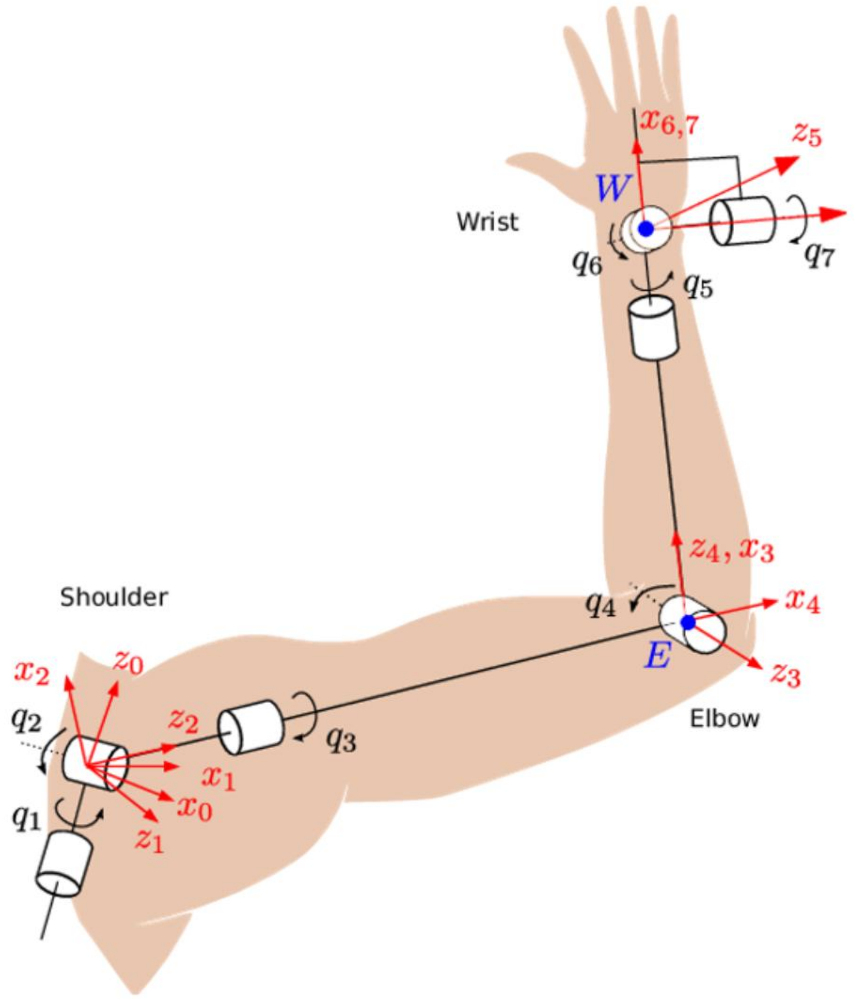
- 2 for the shoulder;
- 1 for the elbow;
- 3 for the wrist.



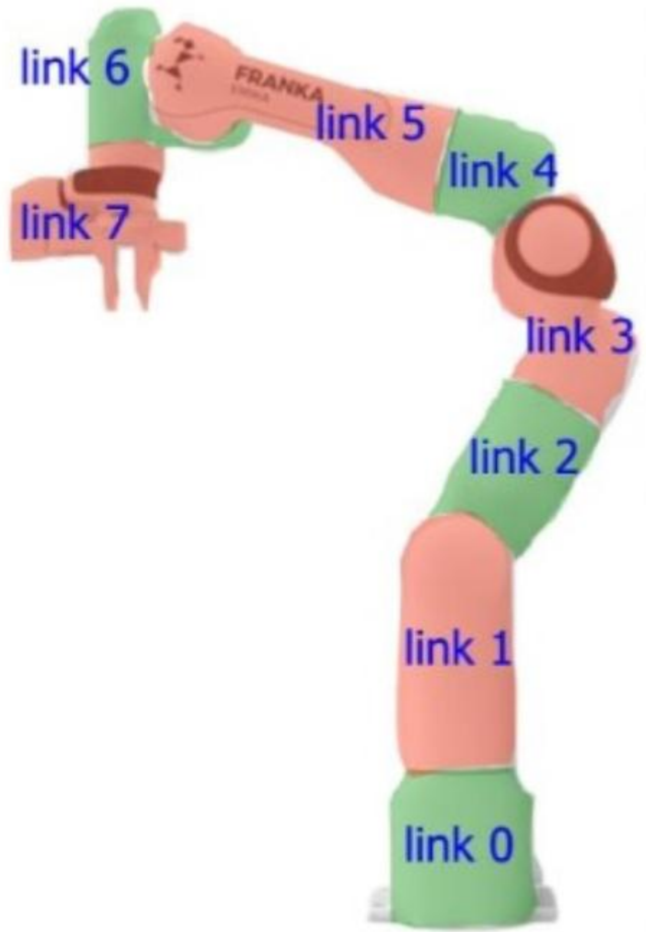
Redundant manipulator

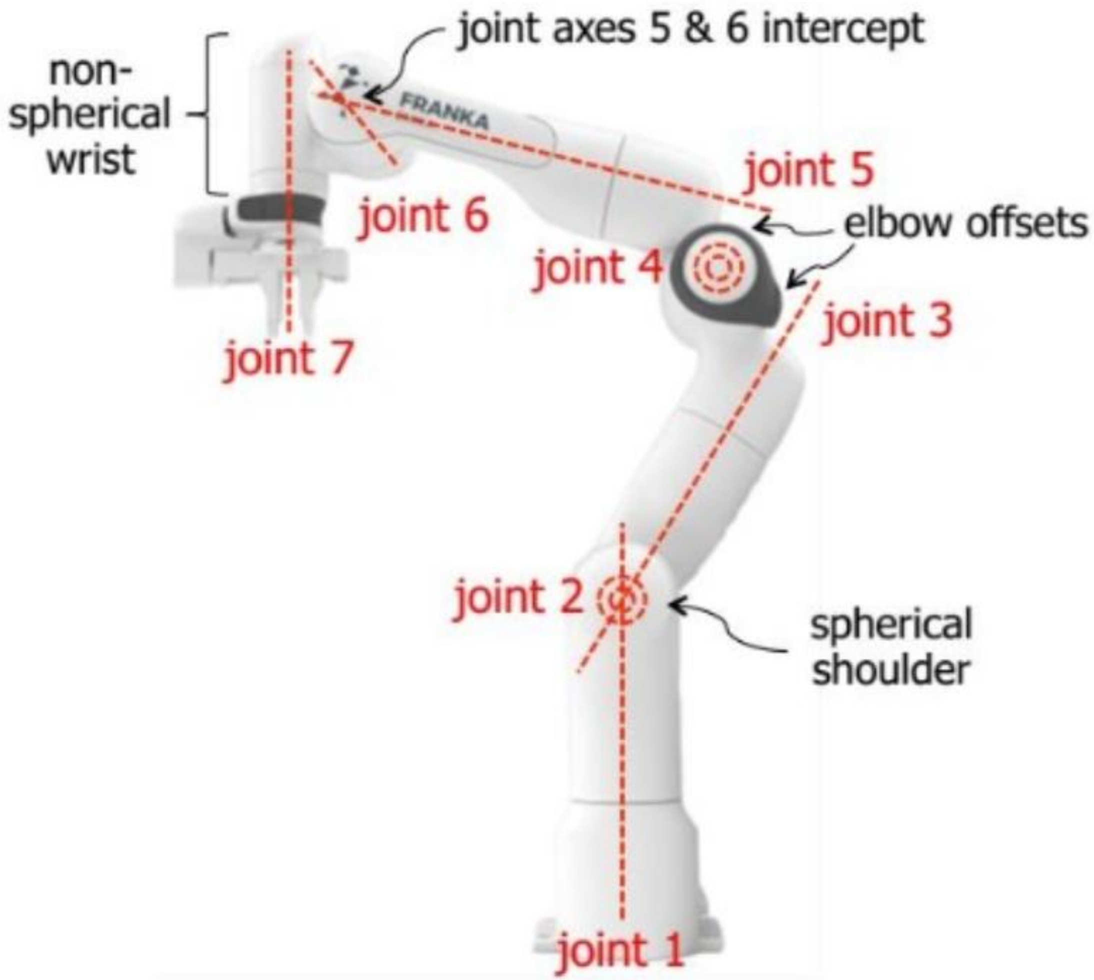
- An anthropomorphic arm with 7 DoFs, has 1 redundant DoF (not necessary to generate motion in Cartesian space). Thus, it is called also **redundant** manipulator.

- It can be used to generate motion at the joint space which does not have effect on the end-effector motion (e.g., to avoid obstacles or maximise manipulability).



Redundant manipulator





Kinematics of a Manipulator

Kinematics is the general problem of describing the motion of a robotic structure with respect to a generic frame.

- **Forward Kinematics**: find the end-effector pose $\boldsymbol{x_e}$ as a function of the joint configuration $\boldsymbol{q}$:

$$\boldsymbol{x_e} = \boldsymbol{k}(\boldsymbol{q})$$

- **Inverse Kinematics**: find the joint configuration $\boldsymbol{q}$ as a function of the “desired” end-effector pose $\boldsymbol{x_e}$.

- **Differential Kinematics**: instead of configurations and poses, it links the joint velocity $\dot{\boldsymbol{q}}$ and position $\boldsymbol{q}$ with the velocity of the end effector:

$$\dot{\boldsymbol{x}}_{\boldsymbol{e}} = \boldsymbol{J}(\boldsymbol{q})\dot{\boldsymbol{q}}$$

Dynamics of a Manipulator

Dynamics is the general problem of describing the motion of a robotic structure as a function of the forces and moments acting on it.

- The **direct (or forward) dynamics**: determining the joint accelerations $\ddot{\boldsymbol{q}}$ resulting from the given joint torques $\boldsymbol{\tau}$ and the possible end-effector forces $\boldsymbol{F_e}$ (used by physics simulators).

- The **inverse dynamics**: determining the joint torques $\boldsymbol{\tau}$ which are needed to generate the motion, once the possible end-effector forces $\boldsymbol{F_e}$ are known (used by motion controllers).

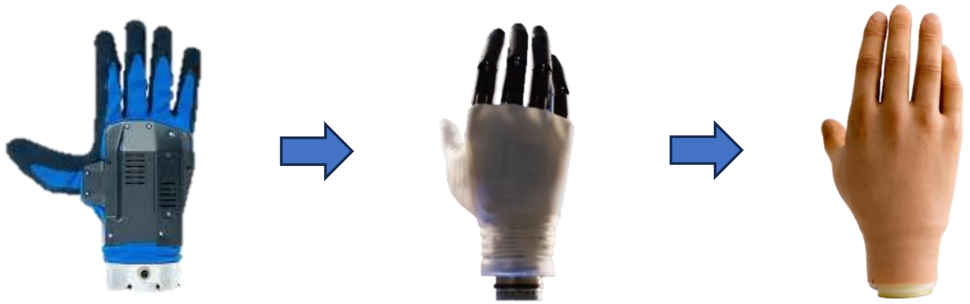
Mobile manipulators

- We can mount an anthropomorphic manipulator on a mobile base (usually 3 DoFs) in order to improve its motion capabilities.

- In theory, the workspace of a **mobile manipulator** is infinite.

Anthropomorphic end-effectors

- A very active research area has been on the development of sophisticated **anthropomorphic hands**.
- Such hands can be used for:
  - rehabilitation and assistive purposes (e.g., as a replacement for a severed human hand);
  - Creation of sophisticated anthropomorphic robots.



SoftHand. Hannes.

Humanoid robots

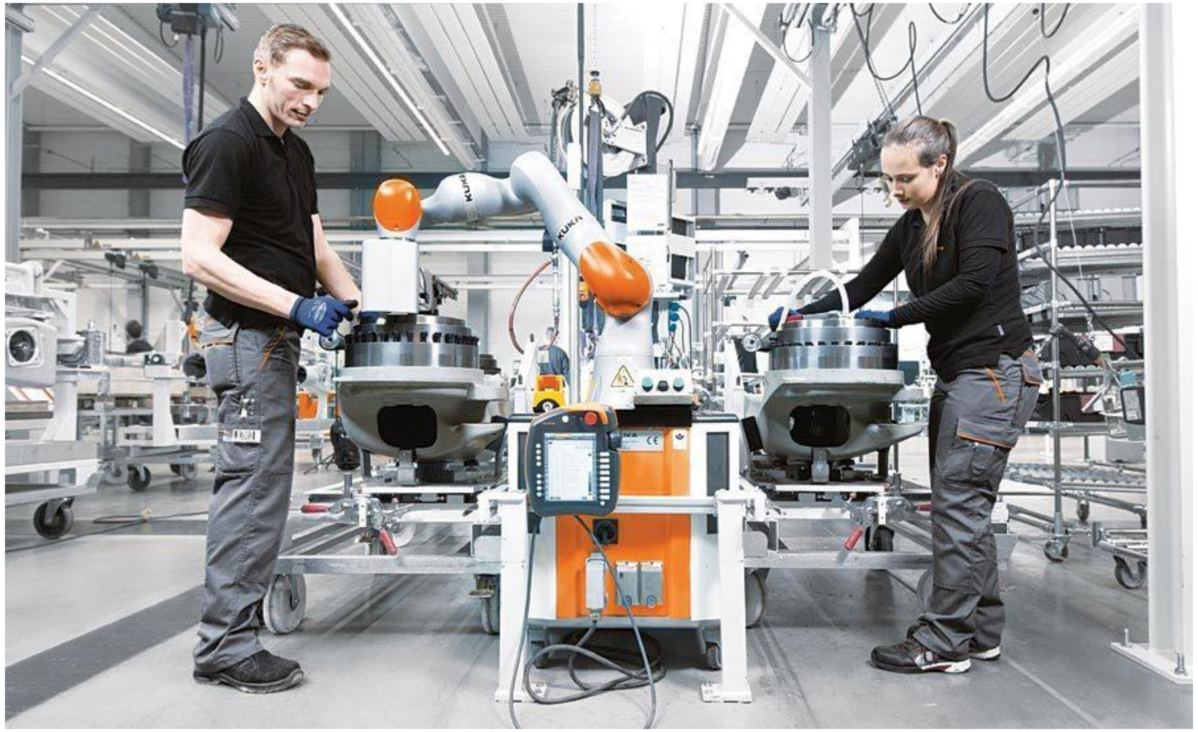
- Manipulators might be seen as the simplest articulated robotic system.

- Putting together several types of robots (manipulators, hands, etc.) we can create **humanoid** robots.

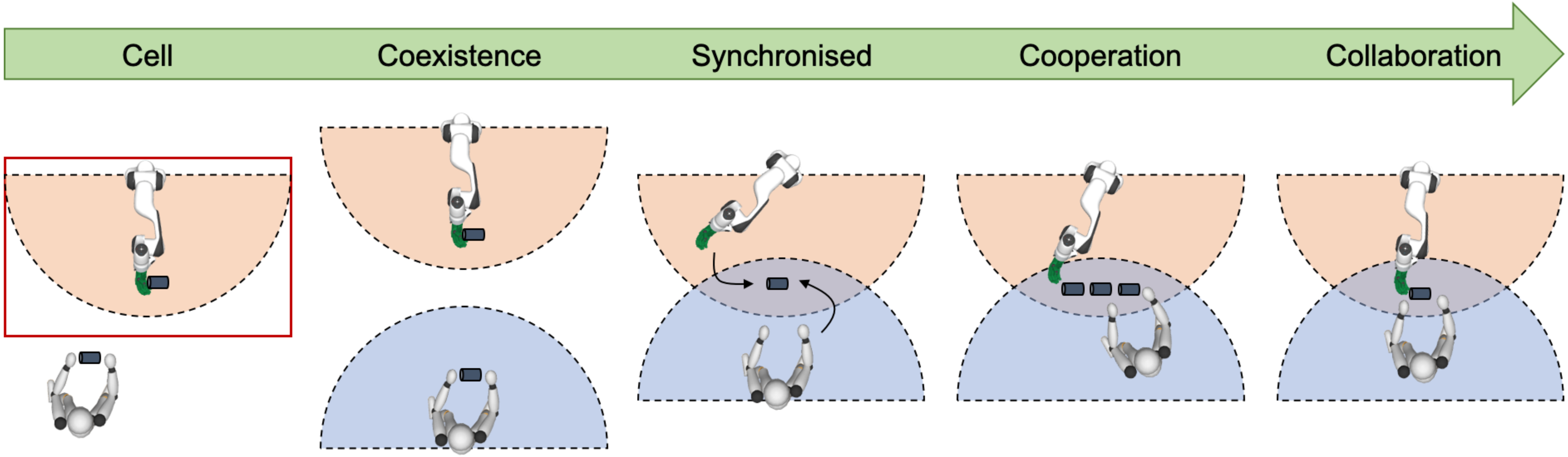
Atlas.

Toro.

Industrial vs Collaborative Robotics



Why Collaborative applications?



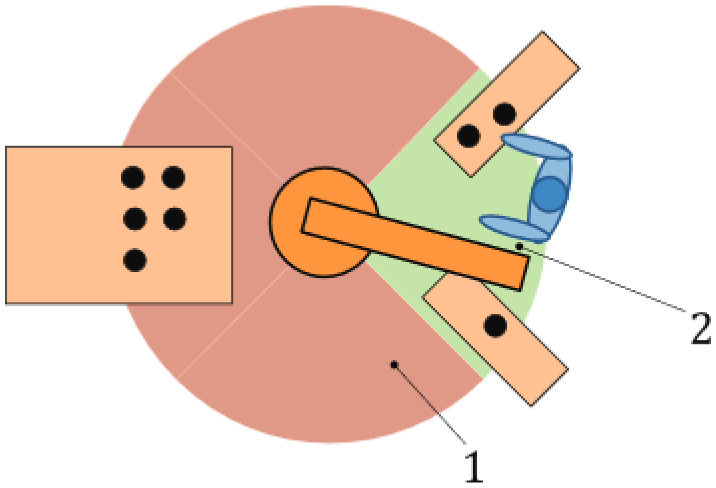
- Safety
- Flexibility
- Ease of programming

Safety

ISO/TS 15066 Collaborative robots

ISO/TS 15066 Collaborative robots

- Design of collaborative workspace
- Design of collaborative operation:
  - Minimum separation distance S / maximum robot speed K_S
  - Static (worst case) or dynamic (continuously computed) limit values
  - Safety-rated sensing capabilities
  - Ergonomics
- Methods of collaborative working:
  - Safety-rated monitored stop
  - Hand-guiding
  - Speed and separation monitoring
  - Power and force limiting (biomechanical criteria!)
- Changing between:
  - Collaborative / non-collaborative
  - Different methods of collaboration



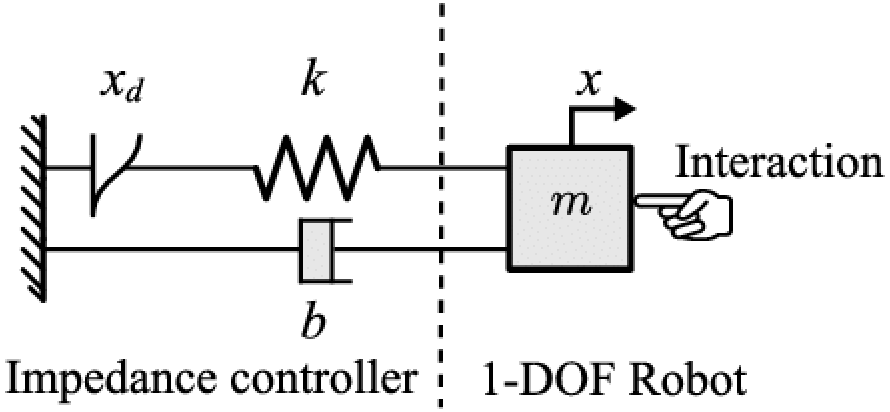
Key

1	operating space
2	collaborative workspace

The Technical Specification is available at this link.

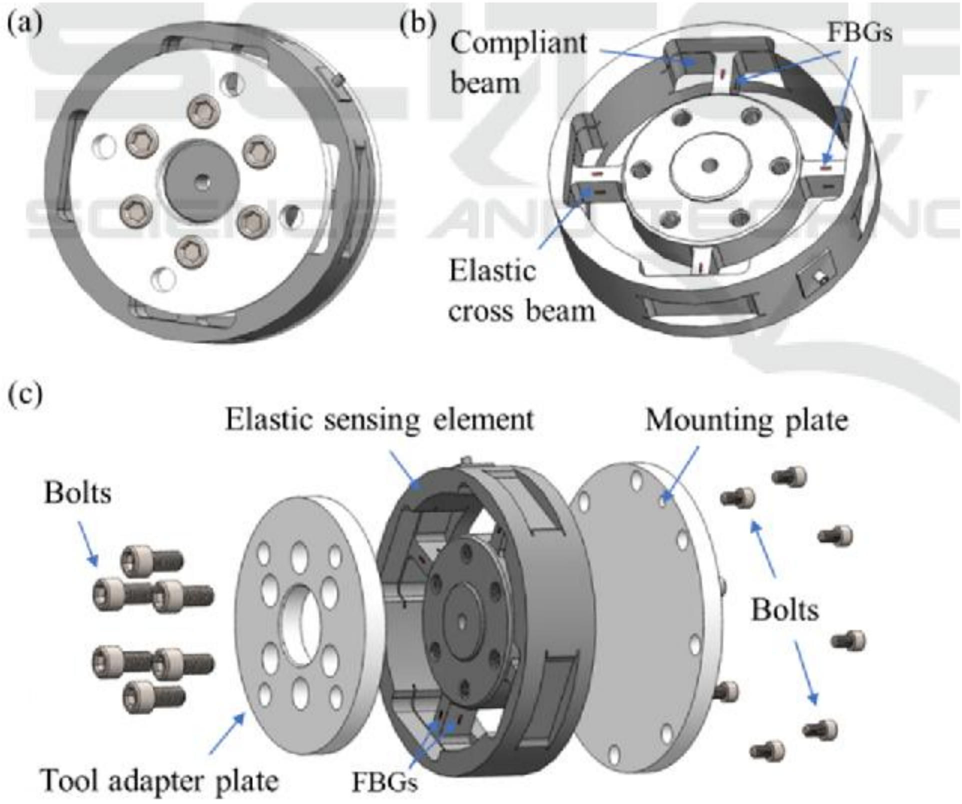
Compliant Controllers

Impedance/Admittance Strategies



6 Axis Force/Torque (F/T) Sensor

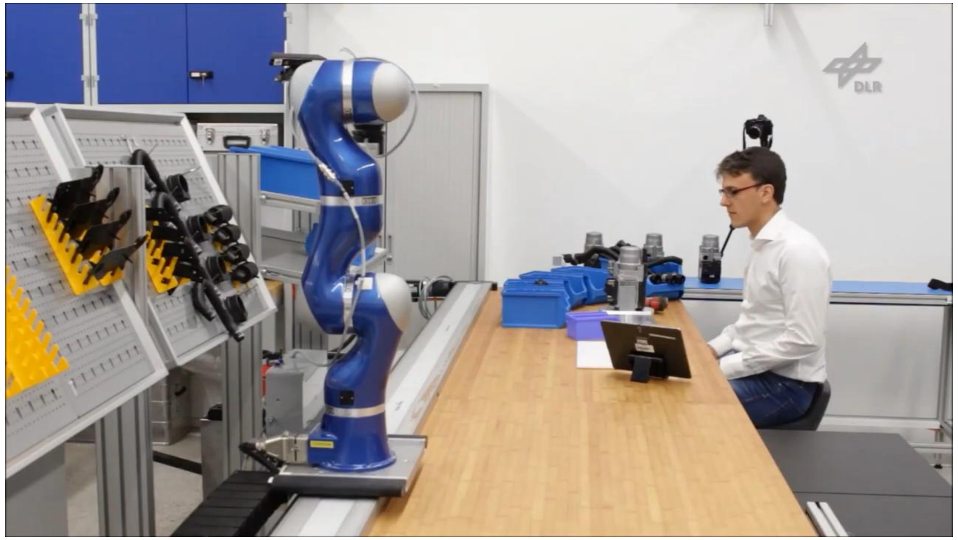
Load cells are transducers that convert **force** into an **electrical signal**. Strain gauge load cells are the most common type used in industrial and research applications. They operate on the principle that a material's electrical resistance changes in response to strain and are highly accurate.



Flexibility

Logistics - Palletizing

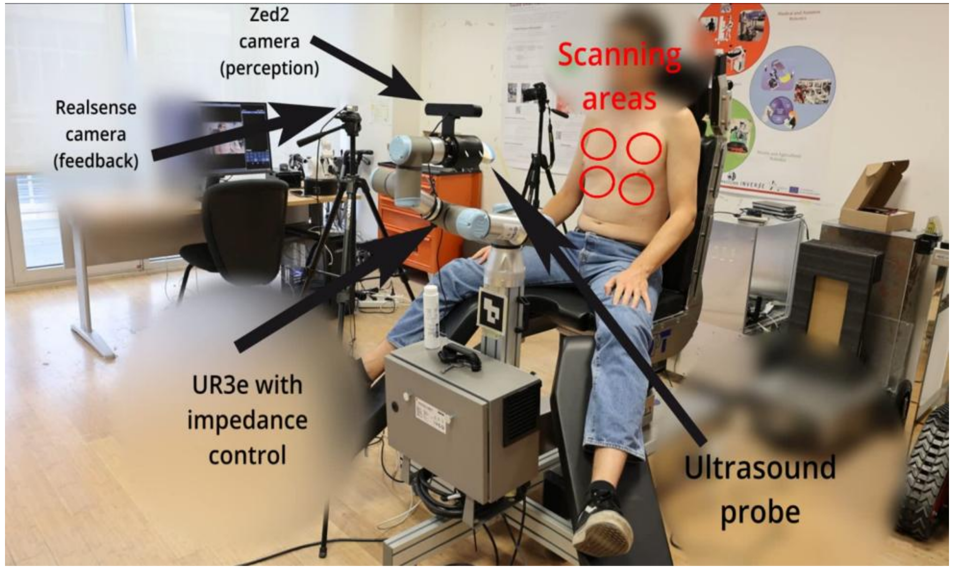
Manufacturing - Assembly

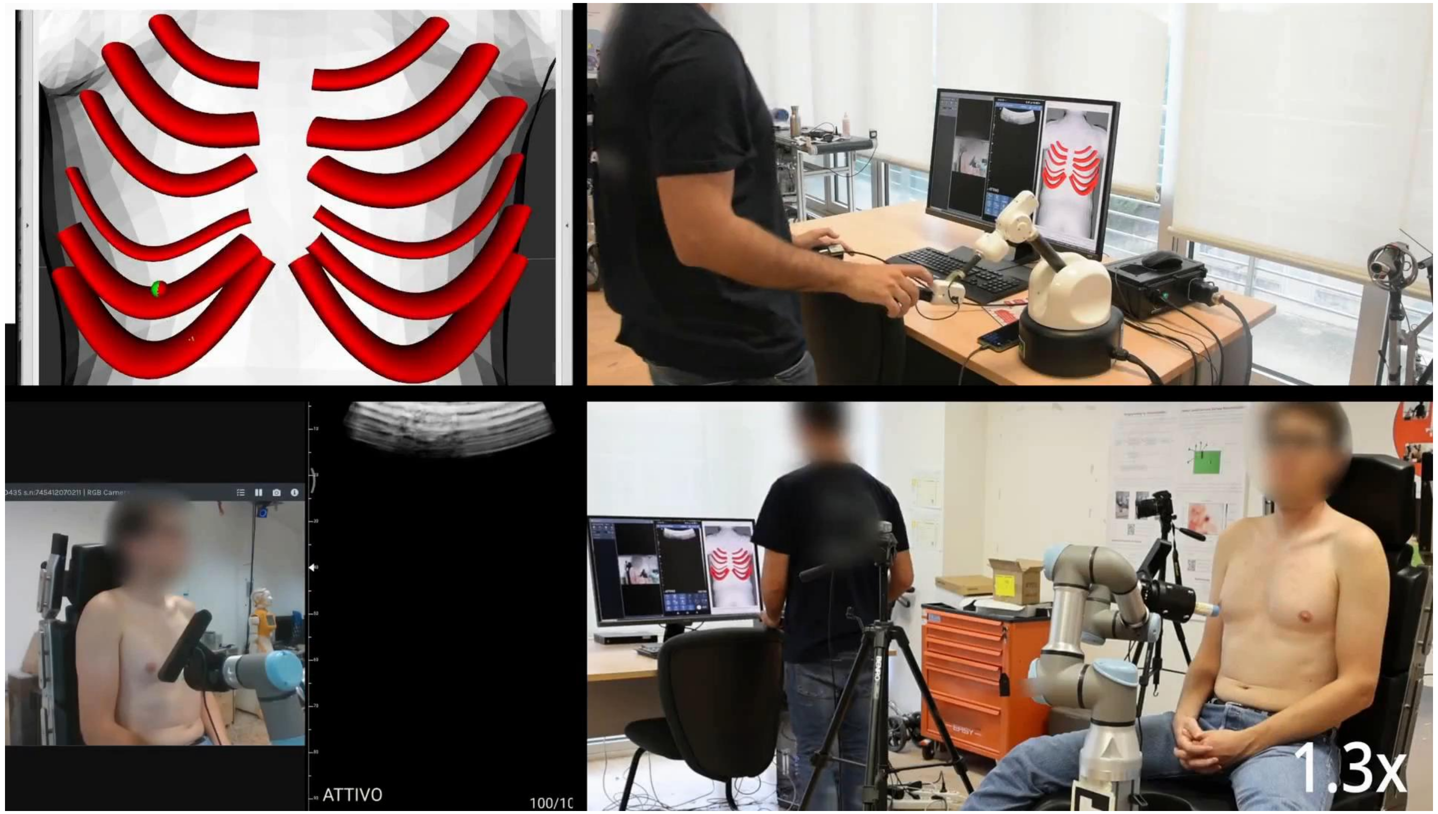


Inspection and quality control

Flexibility

Healthcare – Teleoperated Ultrasound





Ease of programming