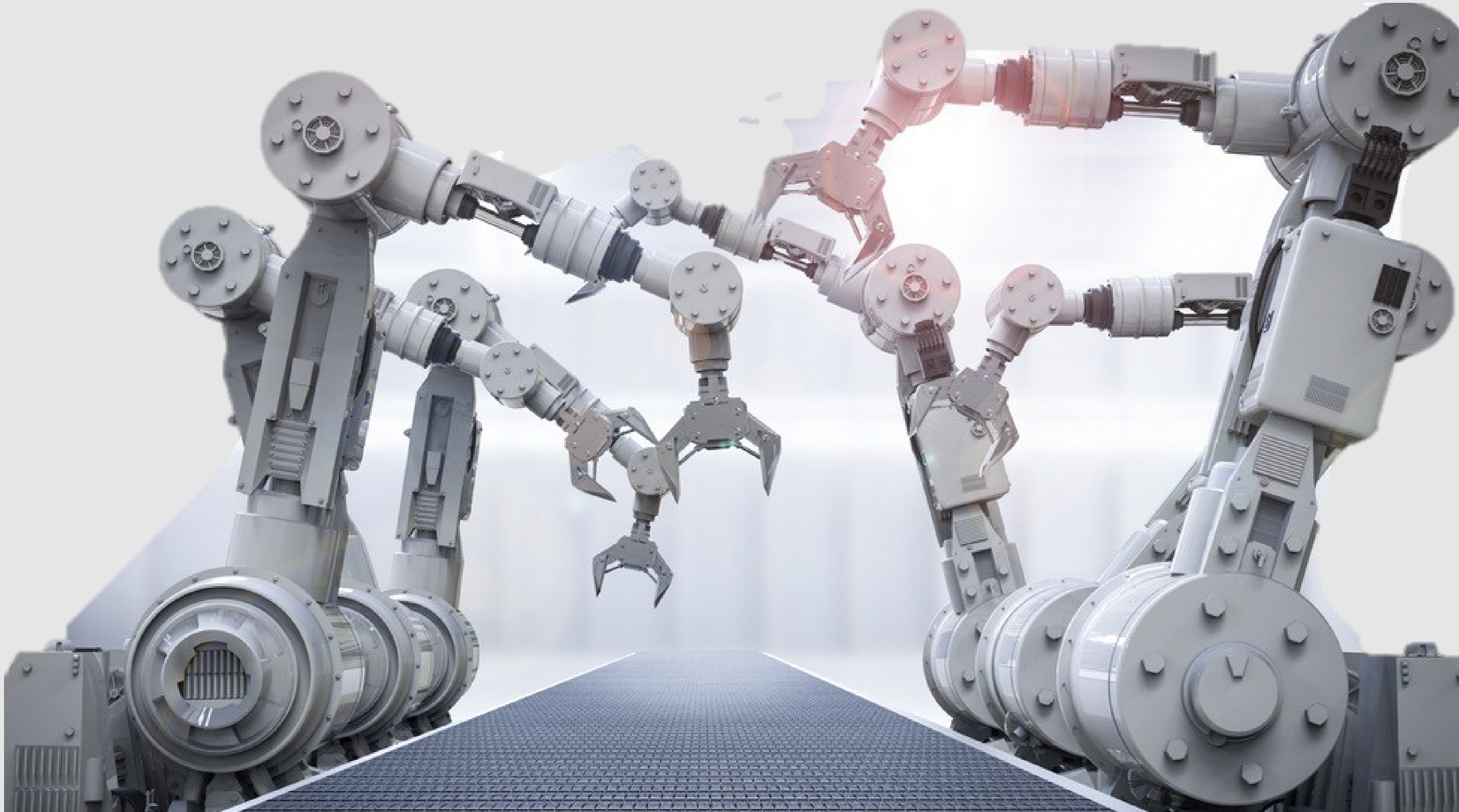
# Introduction to Industrial Robotics

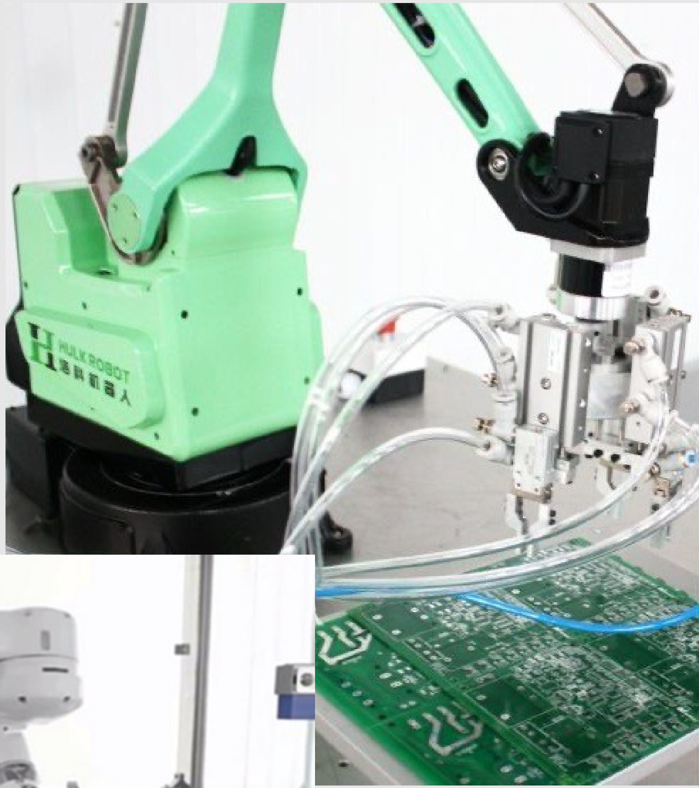
Prof Antonios Gasteratos

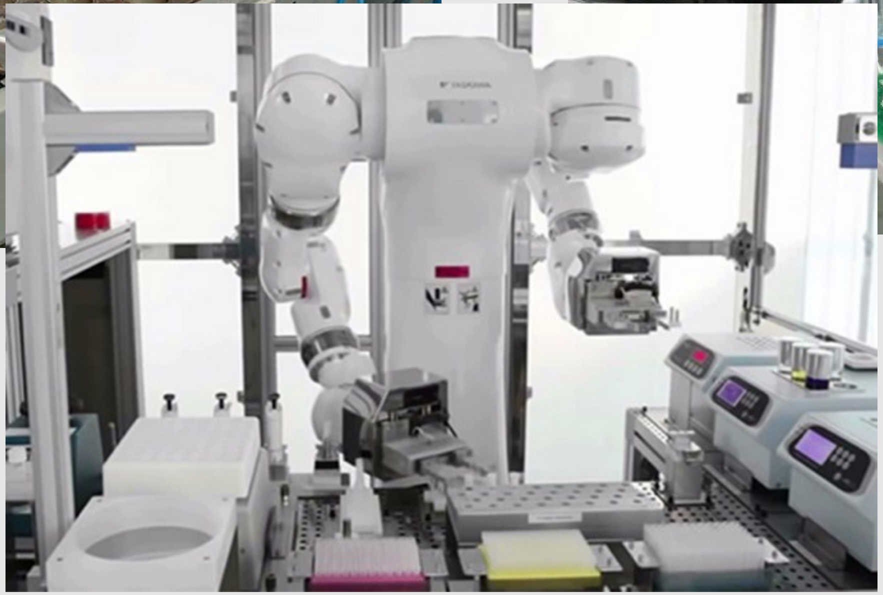


# I4.0 characteristics


- **Vertical Integration** through smart devices interconnetion
- **Horizontal integration** through a global value web
- **Efficient technical solutions** throughout the entire value chain
- **Acceleration** by materializing innovative ideas

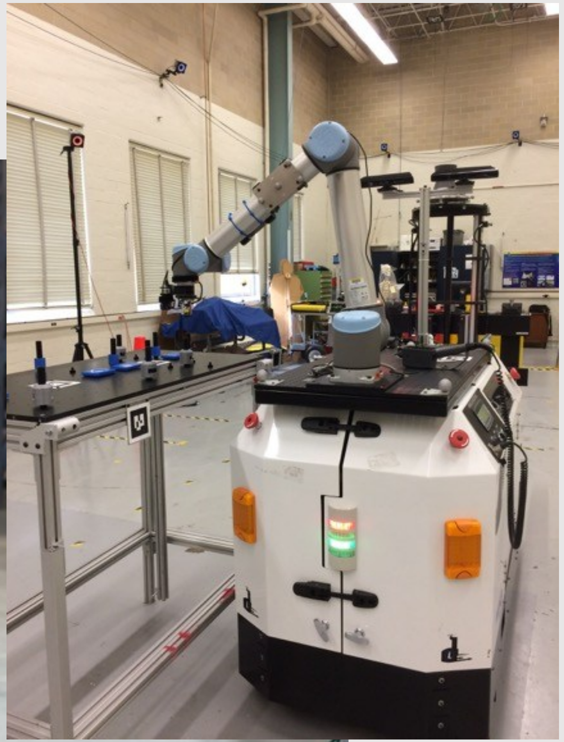
# Industrial robot manipulators

# Industrial AGVs





# Typical applications of industrial robots

## Production

- Materials management
  - Loading/unloading, packaging, palletizing
- Assembly
- Spraying/painting
- Electro-welding
- Cutting
- Polishing/finishing
- Mechanical processing
- Inspection
- Transportation

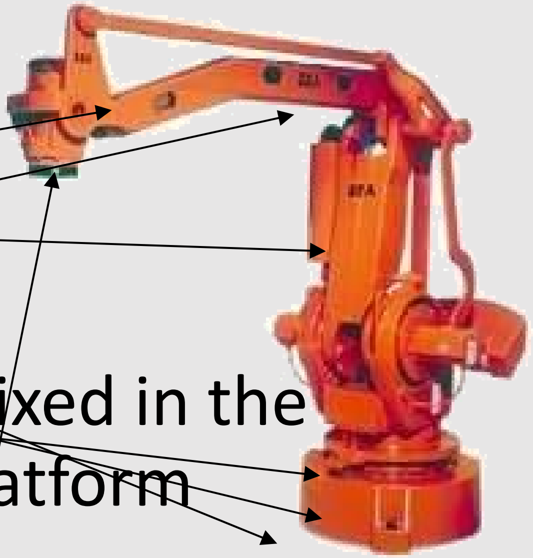
## Warehouse

- Storage and retrieval of goods
  - Loading/unloading, packaging, palletizing
- Transportation
- Picking and placing
- Inspection

# Basic parts of an industrial robot

- The mechanical part, which can be a manipulator or a rover
- The mechanical part comes in different complexities and construction types
- The electronic part, for the programming and control of the robot
- The electronic part can be integrated into the mechanical part or separate from it

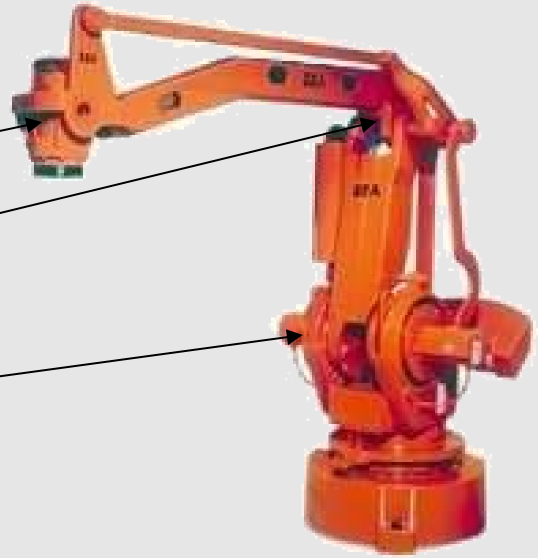
# Manipulator’s mechanical part



- Manipulator
  - A series of solid bodies, the links
  - Mobile connections, the joints
- One end of the manipulator, the base, is either fixed in the working environment or placed on a movable platform
- The other end of the manipulator, the end effector, is equipped with the appropriate tool each time for performing tasks or carries a gripper for handling operations

# Manipulator’s mechanical part

- The end-effector is mounted on a compound joint, namely the wrist
- The rest of the joints of the manipulator are usually called shoulder and elbow



# Manipulator’s electronic part

- The controller of the manipulator is a special device, comprising a multi-CPU computing unit, connected to a local network containing several control and storage media.

- Requirements
  - Complex mechanical part
  - High efficiency
  - Differentiation in several manipulator’s assignments

**teaching pendant**

# Manipulator’s electronic part

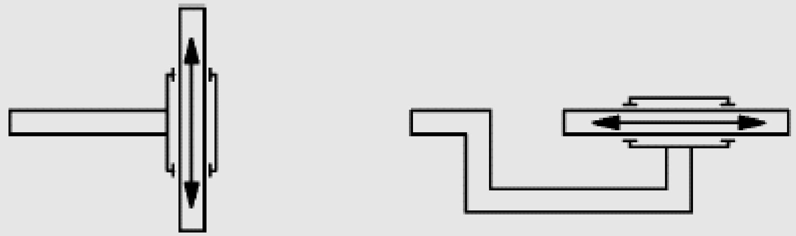
- The basic functions that a robotic controller must perform are:
  - Interaction with the user
  - Data storage
  - Calculation of manipulator motions
  - Real-time control of joint movements
  - Monitoring of robot sensors
  - Integration with other machines
  - Integration with other computational resources

# Mechanical part of an AGV

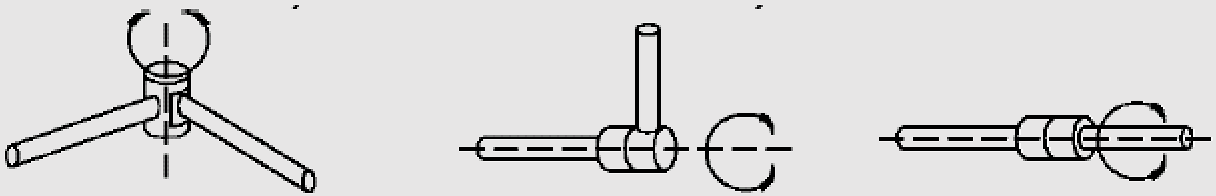
- It consists of:
  - The platform
    - Embedded on it is the electronic component for control
    - It can accommodate one or two arms for manipulation and space for material placement
  - The motion system
    - Typically comprised of wheels, while other motion systems (e.g., tracks) are also possible

# Types of joints

- There are two basic types of joints:
  - Prismatic (P), where movement is linear displacement



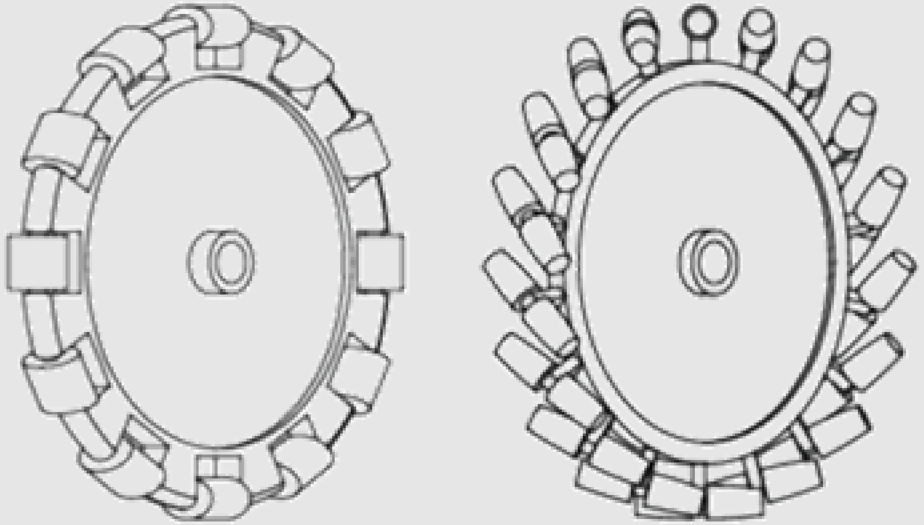
  - Rotary (R), where movement is rotation



- Joints with a different, more complex topology, such as spherical, helical, etc., can be considered as a combination of two or more of the basic joints.

# Types of wheels

- There are three basic types of wheels:
  - Standard wheel: rotation around the wheel's axis and the point of contact; activation (motion) is provided along the wheel's axis.
  - Caster wheel: rotation around the wheel's axis (without activation), as well as around the point of contact and the axis of the arrangement.
  - Mecanum wheel: rotation around the wheel's axis (with activation), around the rollers, and around the point of contact.



# End effector

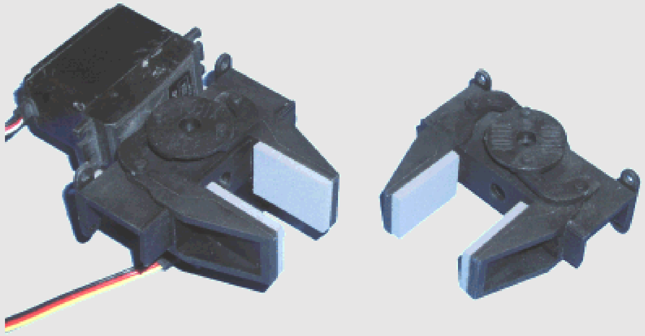
- The end effector is the mechanism through which the operator interacts with the environment.
- Examples of applications include handling objects, welding, painting, and assembly.
- It is one of the points of maximum importance and complexity of a robot, which can limit the robot's dexterity in its workspace.

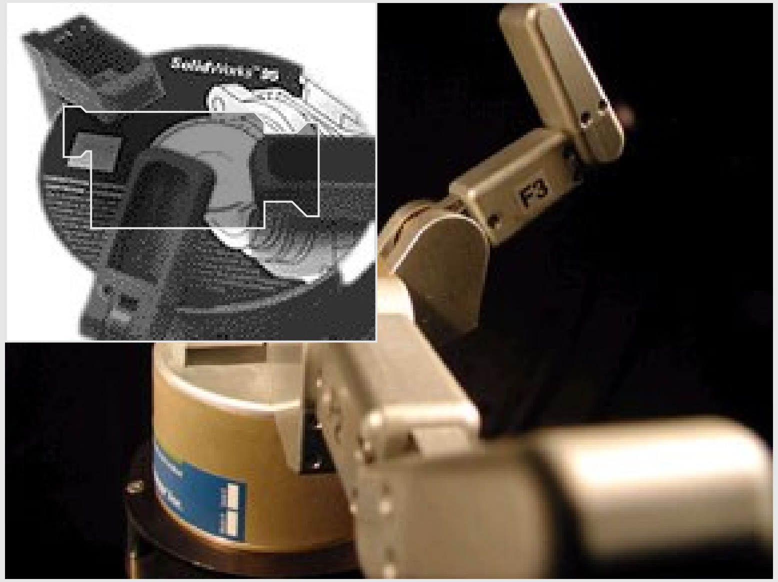
# End effector

- The high dexterity of an operator cannot be compared with that of the end effector, which is generally highly specialized, capable of accomplishing few manipulations, and equipped with a simple sensor arrangement and a basic kinematic setup.
- Since it is a specialized mechanism, it should be able to be changed easily and quickly if the job requires it. In some cases, there is a real repertoire of end effectors that can be connected to the manipulator, resulting in a versatile tool capable of performing different phases of a mission.
- The most well-known end effector is the gripper, a device for grasping objects. Grippers come in a wide variety of designs depending on the material and size of the objects they handle.

# Grippers

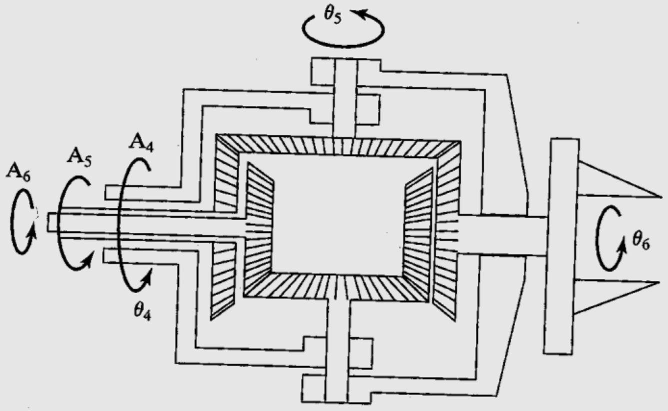
- There are grippers with two or more "fingers" that mechanically grasp objects, utilizing both the inner and outer parts of the fingers.
- These fingers are designed to handle large objects and can be long, narrow, cylindrical, equipped with suction cups, adhesive materials, electromagnets, etc.





# Wrist

- It is the mechanism connected to the end of the manipulator, onto which the end effector is attached, enabling it to assume any orientation in the workspace.
- Typically, it includes three degrees of freedom, implemented through rotary joints.

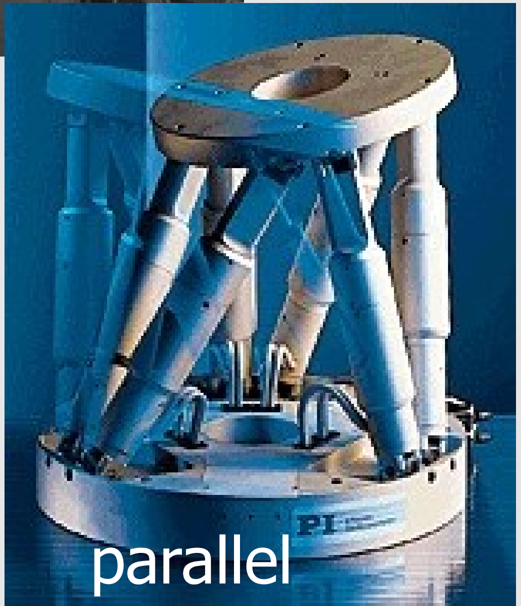



# Types of manipulators

The typologies of robotic manipulators are distinguished based on whether their kinematic chain is open or closed, or in other words, whether one or more joints act directly on the end effector

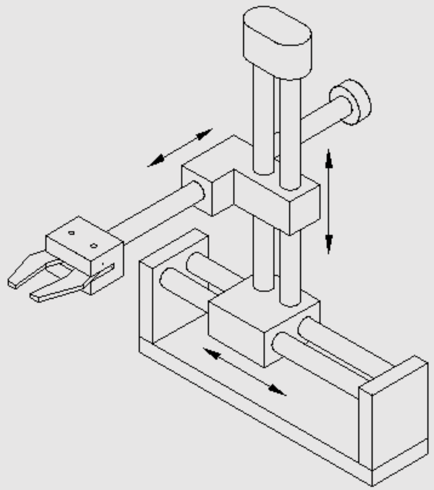
- in series or
- in parallel

respectively.

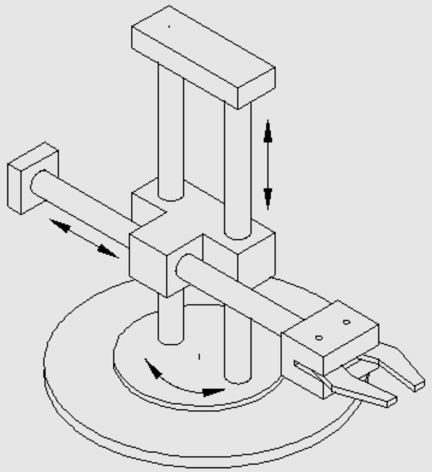



# Serial manipulators

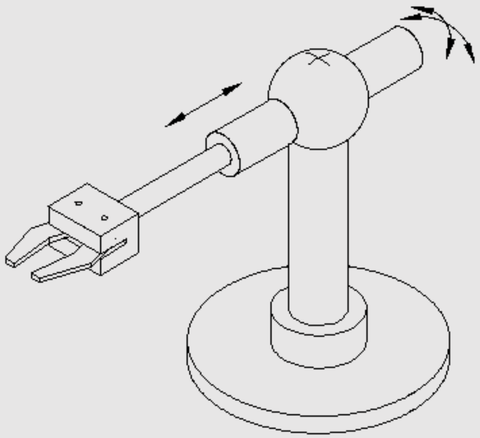
- There are various geometric typologies in manipulator design, primarily based on the sequence of joints, which can be prismatic (P) or rotary (R).



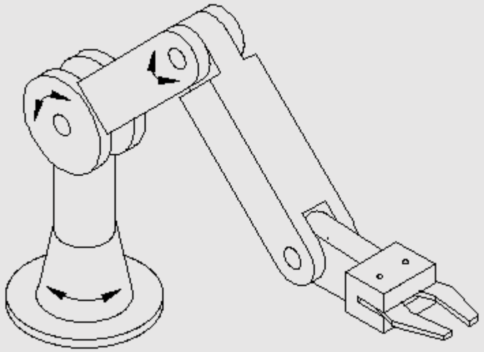
Cartesian: PPP



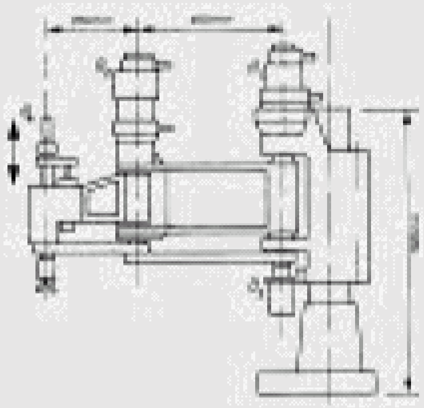
Cylindrical: RPP



Spherical: RRP



Articulated: RRR

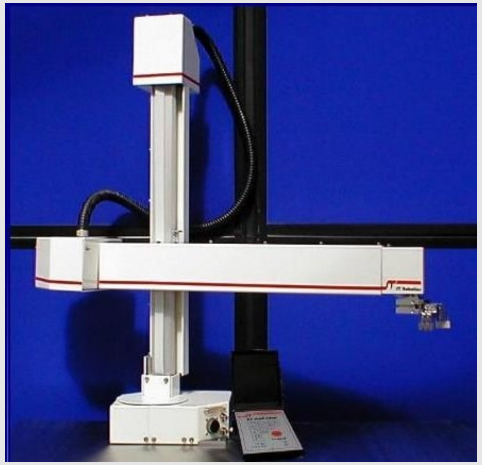


SCARA: RRP

(Selective Compliance Assembly Robot Arm)

# Serial manipulators

Cartesian: PPP



Cylindrical: RPP


Spherical: RRP

Articulated: RRR


SCARA: RRP

(Selective Compliance Assembly Robot Arm)

# Parallel manipulators

☑ Pos

- Speed
- Accuracy
- Mechanical Power

☒ Con

- Smaller workspace
- Bulky
- Costly

# Comparison of manipulators

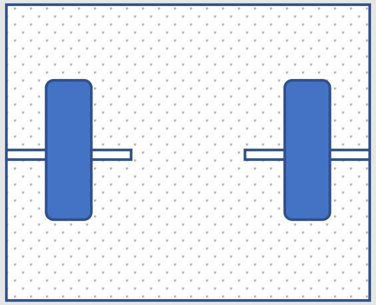
- Advantages and disadvantages of each topology:
  - The Cartesian topology integrates internal robustness, especially in cases where heavy loads need to be transported and good repeatability characteristics are required.
  - The Cylindrical topology is also robust and suitable for transporting heavy loads.
  - The Spherical, as well as the cylindrical, are the most suitable for machine loading and unloading tasks, where the operator can perform the task without interacting mechanically with the environment.
  - The Articulated, like the spherical, are suitable for tasks that may be relatively remote from their base.

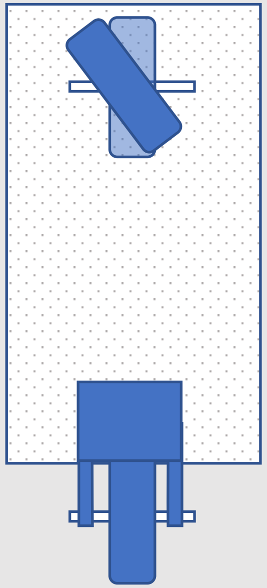
# Comparison of manipulators

| Characteristics / Type | Robustness | Repeatability | Load | Dexterity |
| --- | --- | --- | --- | --- |
| Cartesian | X | X | | |
| Cylindrical | X | | X | X |
| Spherical | | | X | X |
| Articulated | | | X | X |

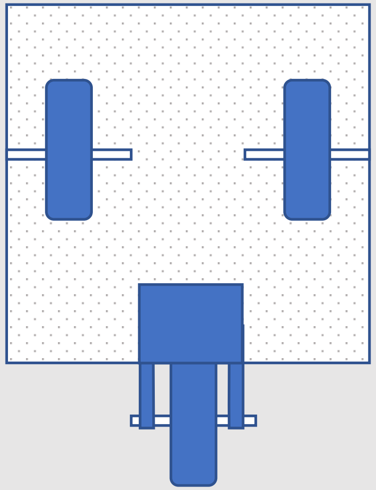
# Wheel configurations

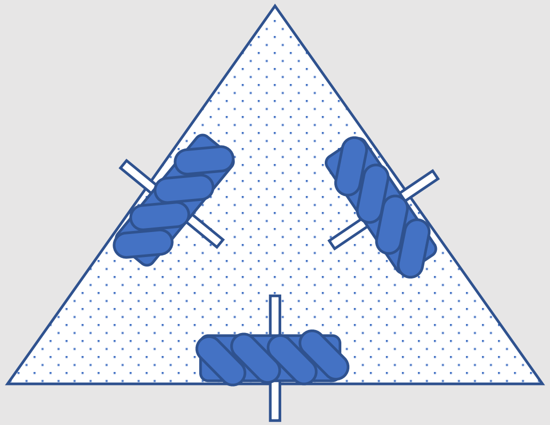
- Two wheels





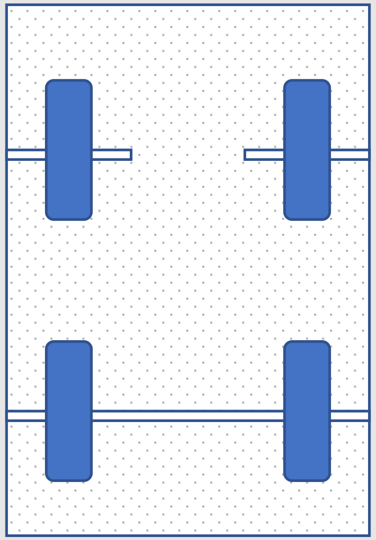
- Three wheels

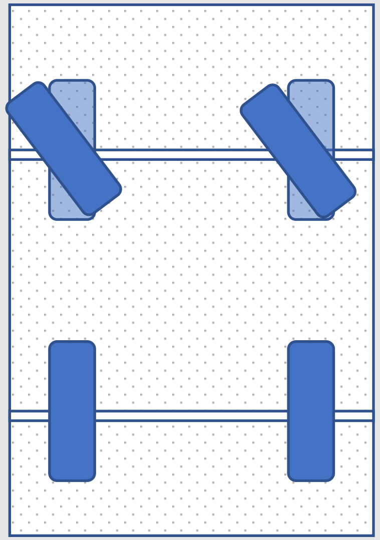


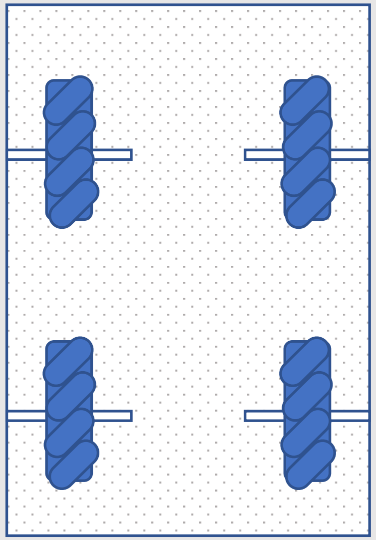


# Wheel configurations

- Four wheels



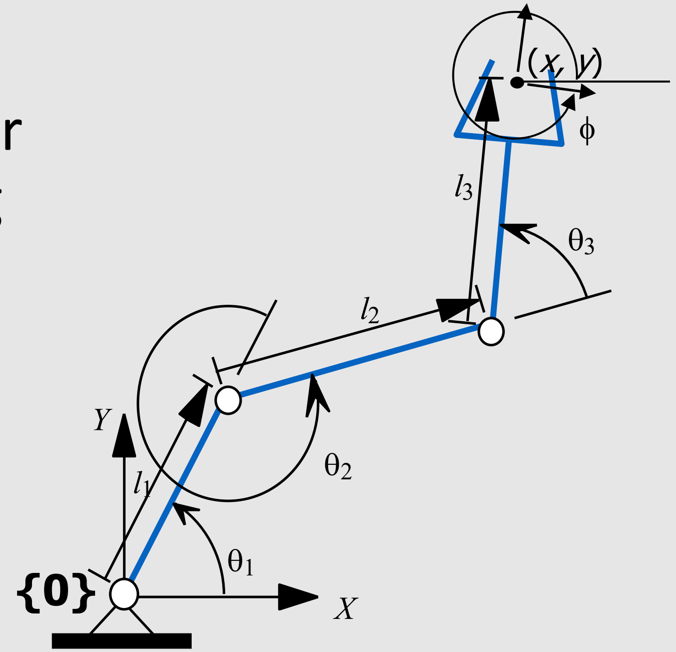




# Manipulator’s configuration

- The vector $\boldsymbol{q} = [q_1, q_2, \ldots q_n]^T$, describing the values of the joints 1, 2, … *n*, is called manipulator’s configuration
- The knowledge of configuration of the manipulator is a necessary and sufficient condition for knowing the pose of the manipulator's end effector.
- Pose includes both position and orientation.

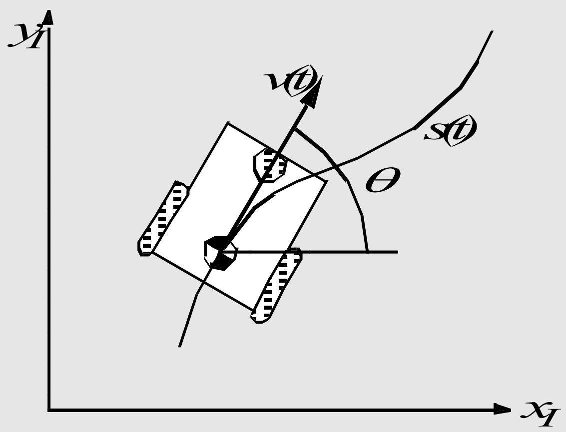
configuration: (x, y, φ)




orientation: $(\theta_1, \theta_2, \theta_3)$

# Configuration of moving platform

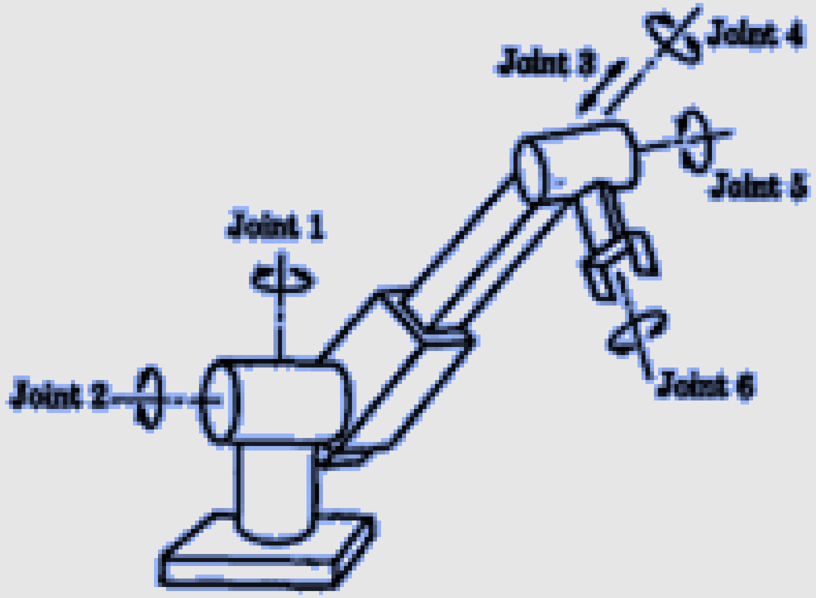
- The configuration of a mobile robot is a vector that includes the wheel velocities, steering angles, steering velocities, and geometric parameters of the robot.
- Based on the robot's configuration, its velocity can be determined, and the calculation of its next position in space can be performed.



# Manipulator’s degrees of freedom

- The degrees of freedom (d.o.f.) of a manipulator are equal to its number of joints. A manipulator with *n* joints has *n* degrees of freedom.

- The degrees of freedom of a space *m* are the minimum number of parameters needed to specify the position and orientation in that space. The number of joints *n* can be any value, while the degrees of freedom of space can be at most *m*=6.



# Manipulator’s degrees of freedom

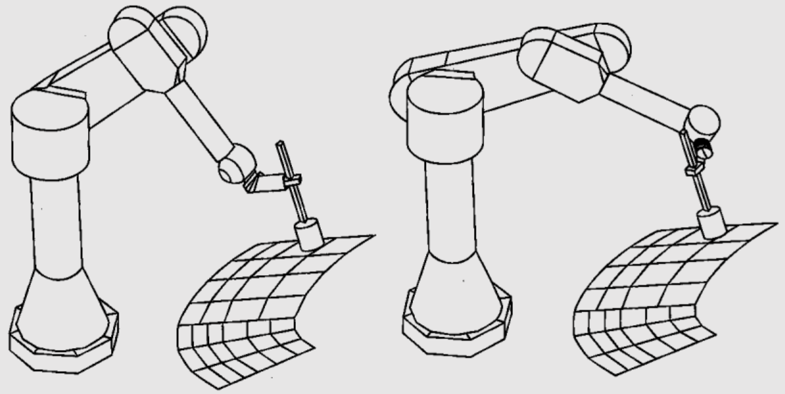
- A very common case is when $m=n$, meaning that the manipulator has as many joints as the degrees of freedom of the space. For industrial manipulators, this typically implies $m=n=6$.

- Underactuated manipulators are those for which $m>n$. For these manipulators, it is not possible to perform all possible manipulations within the workspace, but only within a specific subset of the space.

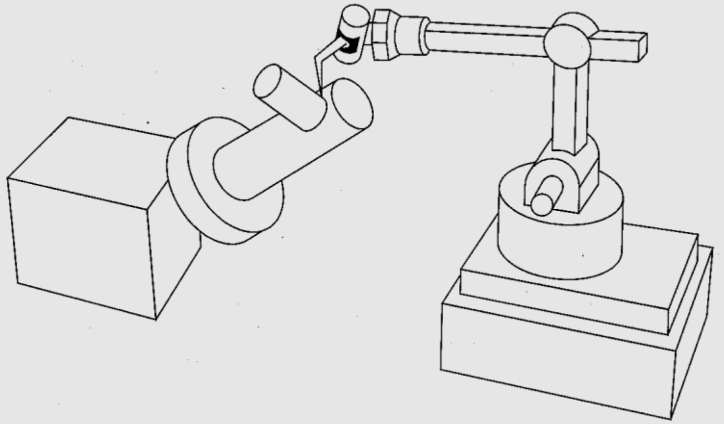
- Overactuated manipulators are those for which $m<n$. For these manipulators, it is possible to perform all possible manipulations within the workspace, with more than one way.

# Manipulator’s degrees of freedom

- When the tool exhibits symmetry with respect to an axis (usually the Z-axis), then the existence of a degree of freedom for the roll angle of the wrist is redundant, so a robot with 5 degrees of freedom is sufficient.



- For other applications, such as placing electronic components on a circuit board, only 4 degrees of freedom are required.

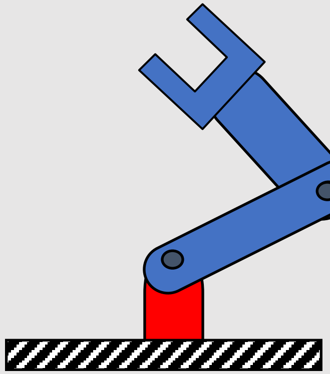


- In cases where the platform itself has its own degrees of freedom, the robot's degrees of freedom can be further restricted.

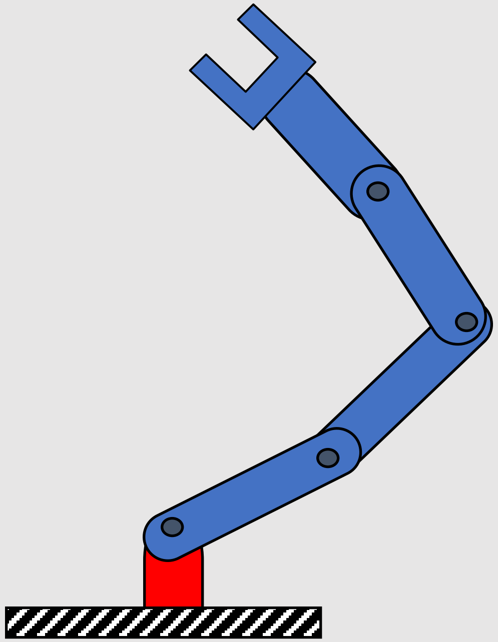
# Manipulator’s degrees of freedom

- Underactuated

(non-holonomic)
  - $m$=3
  - $n$=2



- Overactuated (holonomic)
  - $m$=3
  - $n$=4

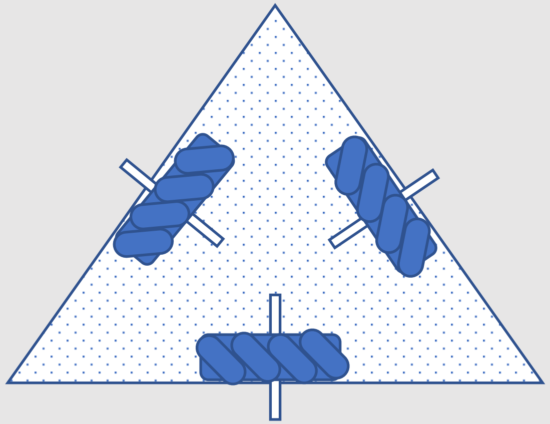


# Mobility capability of a moving platform

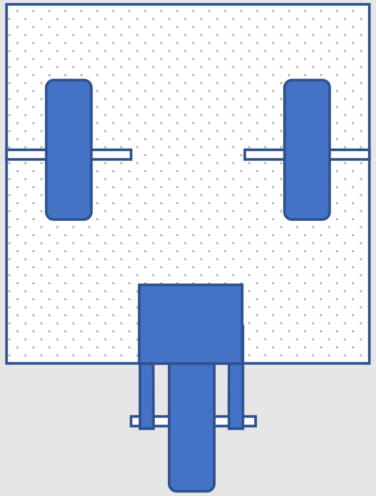
- The mobility capability (flexibility) of a robotic platform is its ability for immediate movement in the environment, which is a result of:
  - the rule that each typical wheel must meet slip and roll constraints (i.e., each wheel imposes zero or more constraints on movement)
    - this determines the degrees of mobility, $\boldsymbol{\delta}_m$, i.e., the degrees of controlled freedom, based on changes in wheel speeds
  - the additional freedom provided by the motion of the driving mechanism
    - this determines the degrees of steerability, $\boldsymbol{\delta}_s$, i.e., the degrees of controlled freedom, based on changes in wheel direction and then movement
- The degree of maneuverability $\boldsymbol{\delta}_M$ is the sum of the above two:
  - $\boldsymbol{\delta}_M = \boldsymbol{\delta}_m + \boldsymbol{\delta}_s$

# Holonomicity of a mobile robot

- The degree of maneuverability quantifies the controllable degrees of freedom of a mobile robot based on the changes applied to the speeds of its wheels.
- A mobile platform is holonomic if the controllable degrees of freedom are equal to or greater than the total degrees of freedom. Otherwise, it is non-holonomic

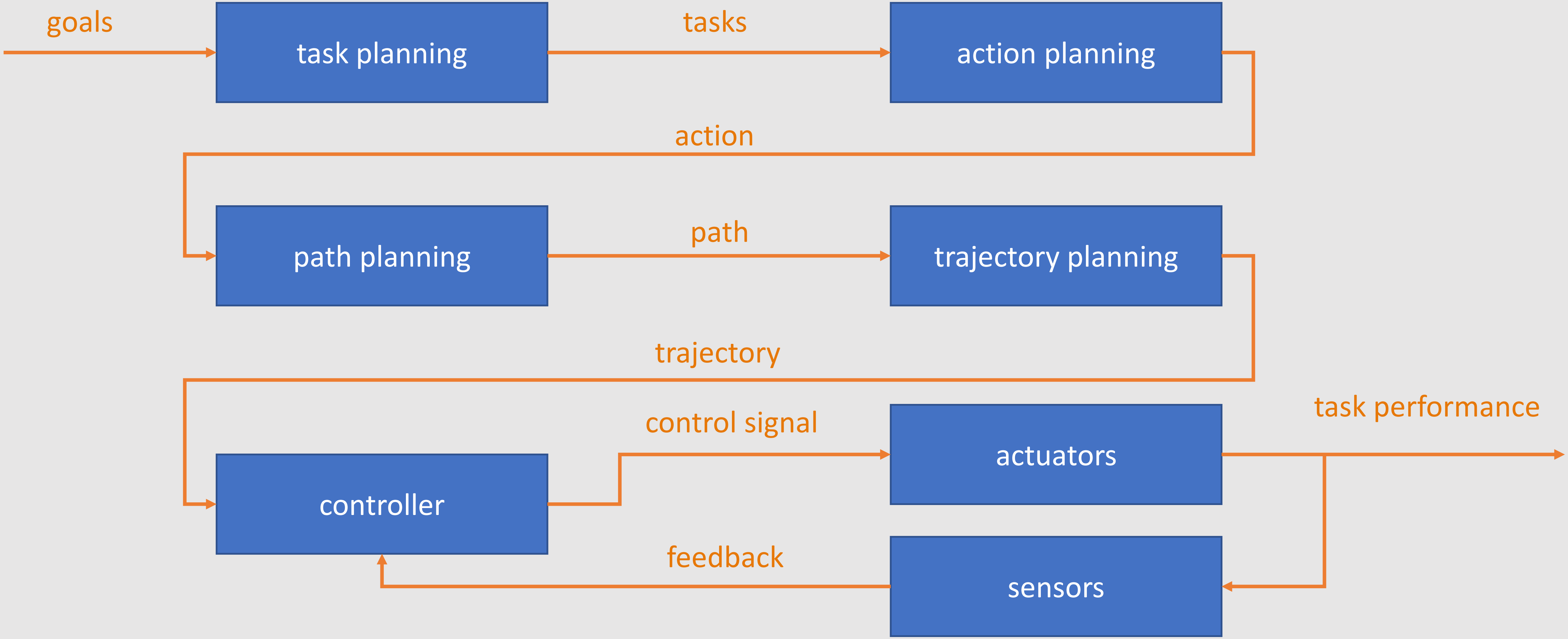


$\delta_M$=3

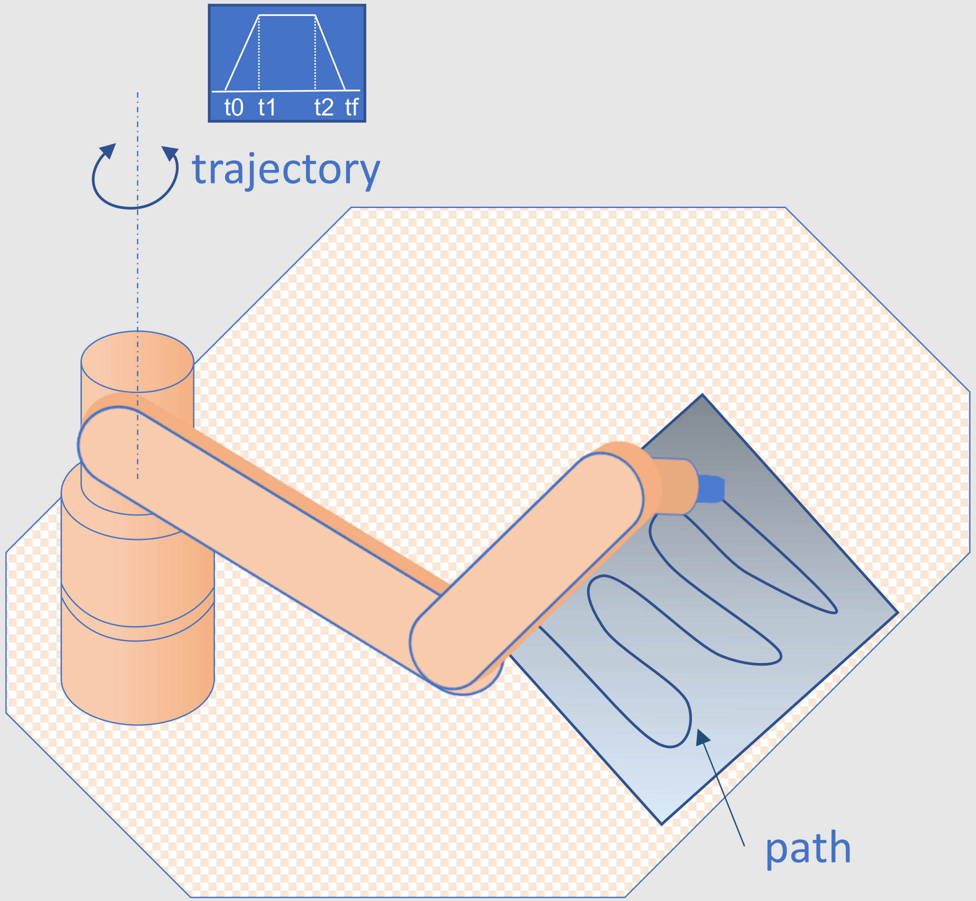


$\delta_M$=2

# Motion planning

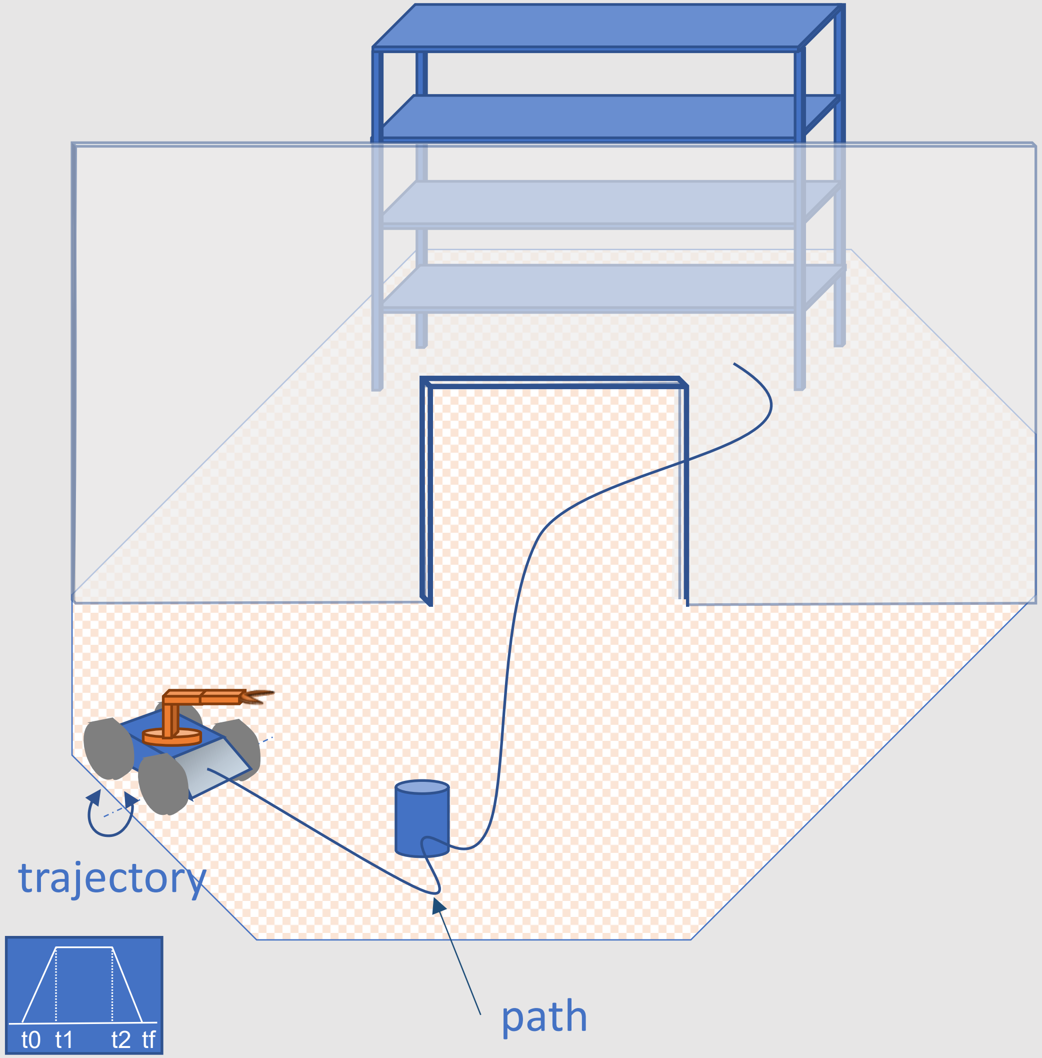


# Motion planning



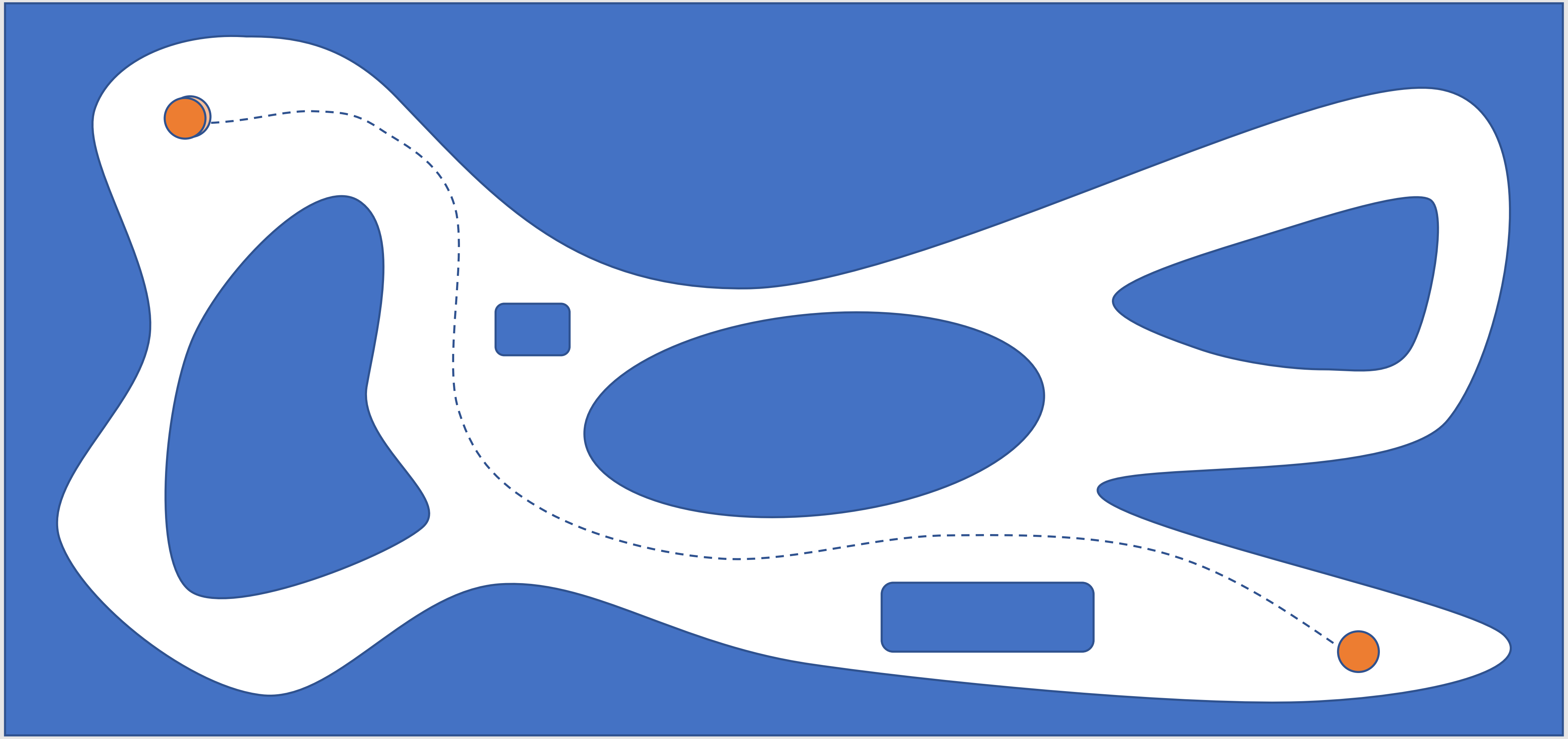

- Goal:
  - Car finishing
- Task:
  - Painting car sheet metal
- Action:
  - Moving the nozzle at a distance of 2cm from the surface of the sheet metal and covering the entire surface of the sheet metal
- Path:
  - The minimum required to cover the entire surface of the sheet metal
- Trajectory:
  - As derived from the analysis of the path, the movement times, and the profile we choose

# Motion planning




- Goal:
  - Product storage
- Task:
  - Transporting the product to the warehouse
- Action:
  - Approaching the object, picking it up, and moving towards the warehouse
- Path:
  - The minimum possible while avoiding obstacles (passing through the door)
- Trajectory:
  - As derived from the analysis of the path, the movement times, and the profile we choose

# Path planning



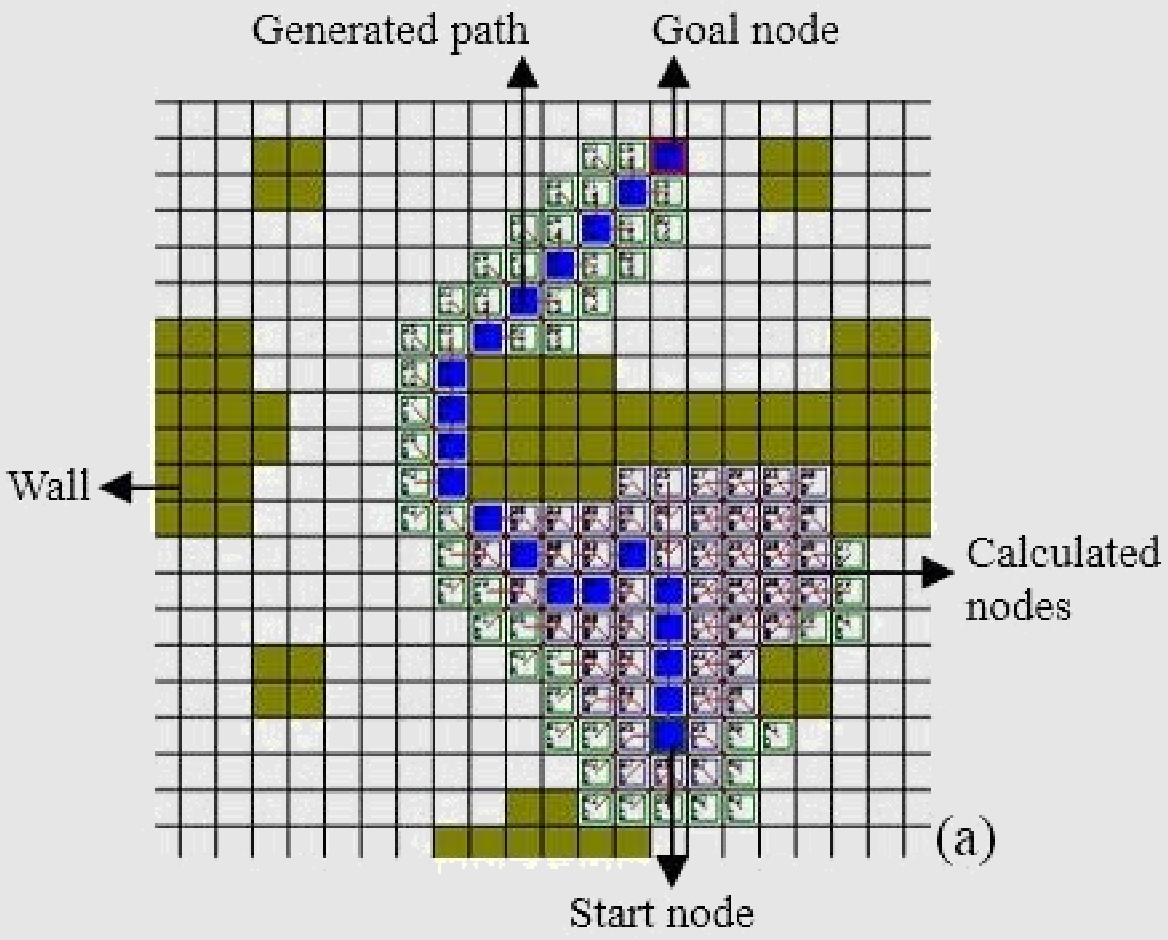
Are the starting point and the destination connected by some path?

# Path planning

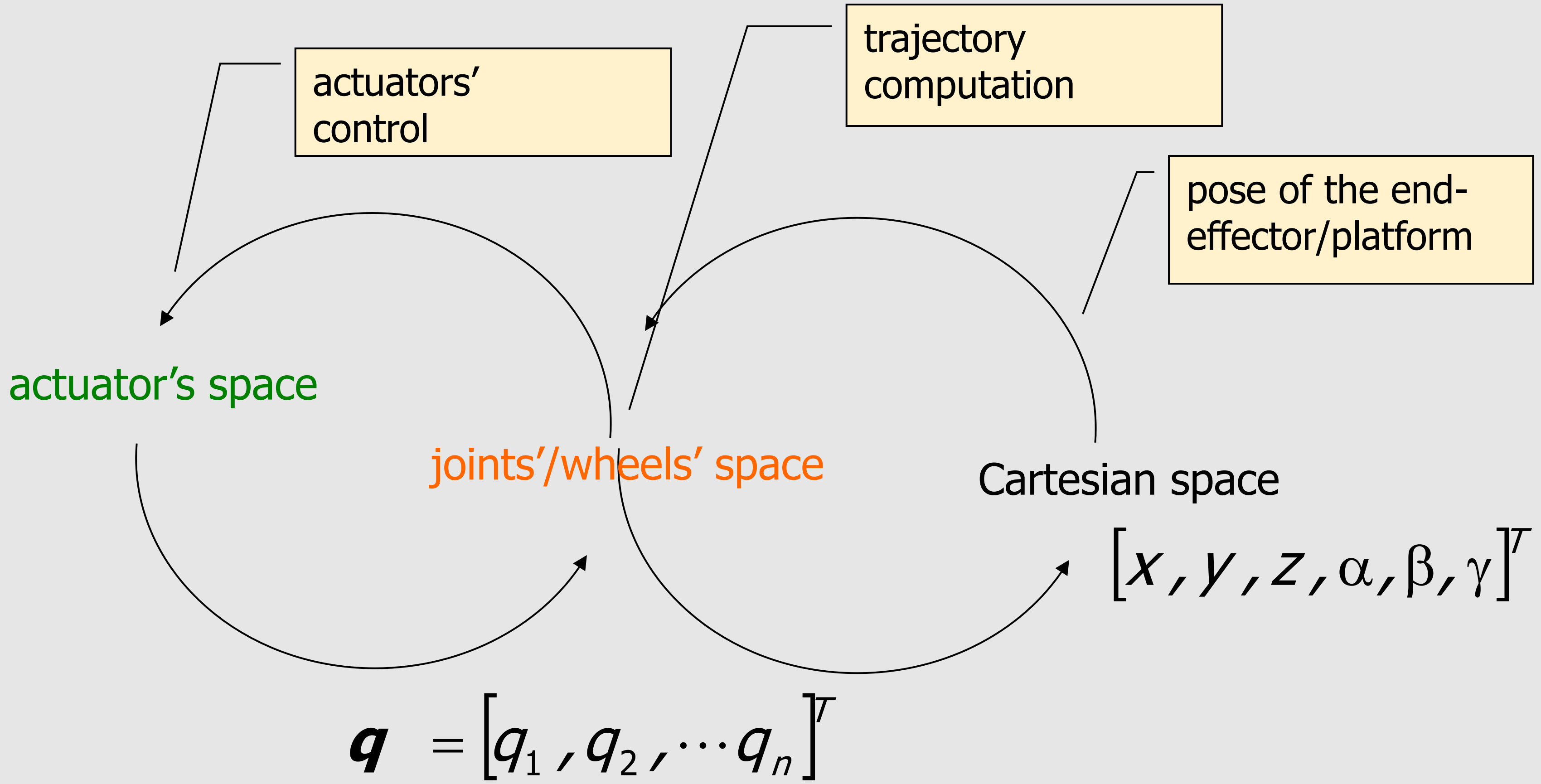
- Calculation of obstacle-free path for a rigid body or an articulated mechanism within an environment with static obstacles.
- Data:
  - Geometry of the moving objects and obstacles.
  - Kinematics of the moving objects (degrees of freedom).
  - Initial and final configuration.
- Result:
  - Continuous obstacle-free path connecting the initial and final configuration of the robot.

# Path planning algorithms

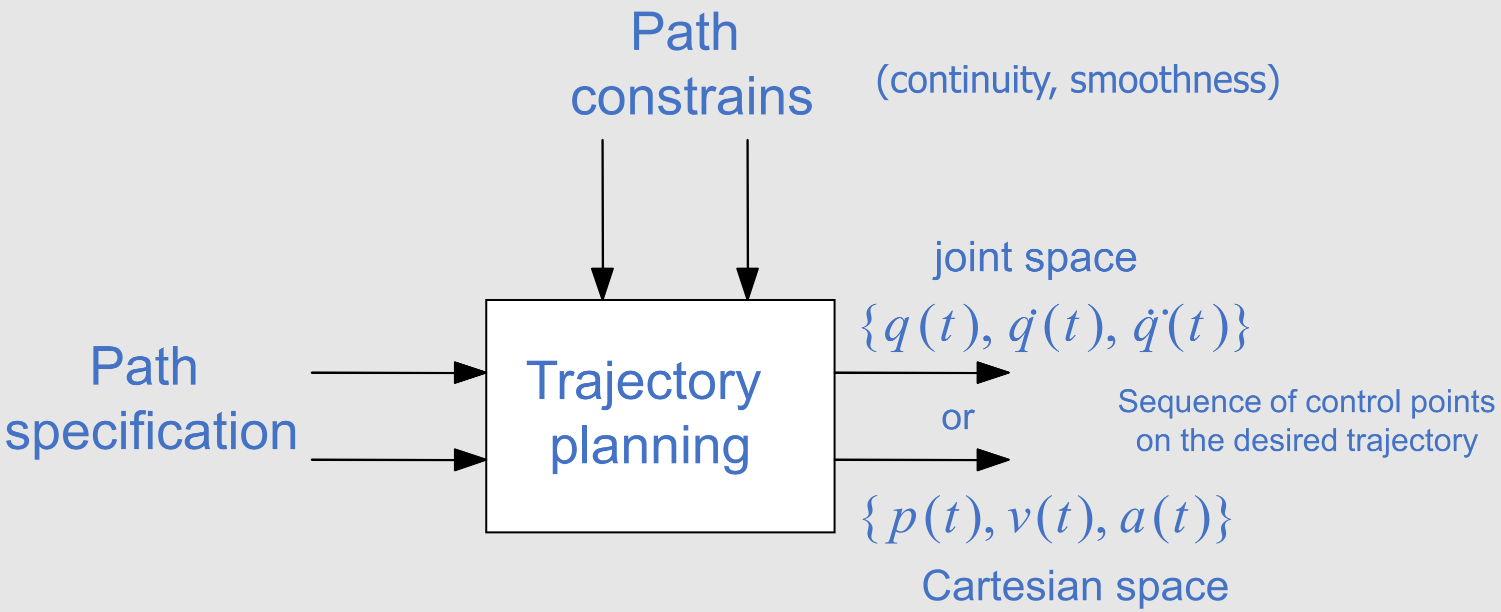
- Visibility graphs
- Minkowski sum
- A*
- D*
- …



# Transformations in robot spaces



# Trajectory planning




- Path planning
  - Geometric path
  - Considerations: obstacle avoidance, minimum path length, optimal path
- Trajectory planning
  - 'Interpolation' or 'approximation' of the desired trajectory with a set of polynomial functions and creating a sequence of control points for controlling the manipulator from its initial position to the destination

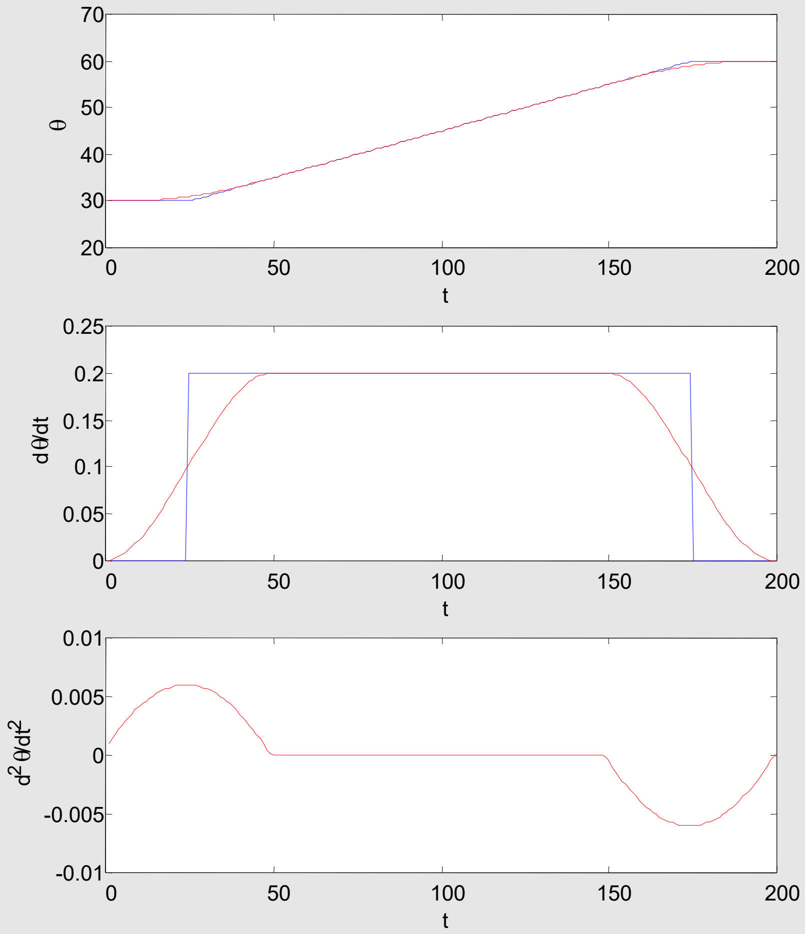
# Path constraints

- Smooth trajectory
  - Path function: continuous
  - First derivative: continuous
  - Second derivative: often desired to be continuous

  - Brutal and abrupt movements tend to wear down the mechanism and create vibrations

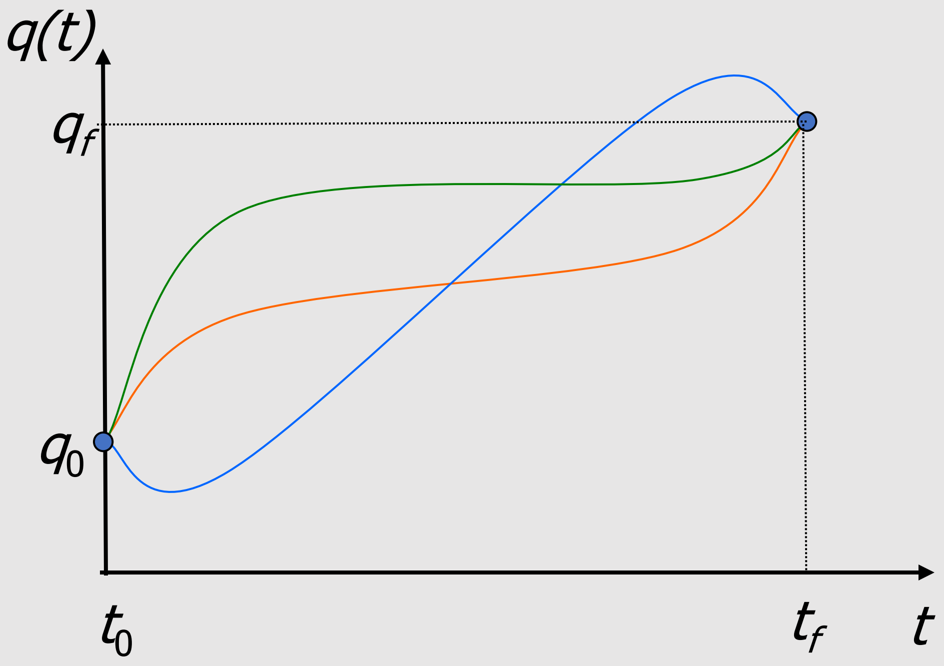
# Trajectory planning

- Trajectory profile
- Velocity profile
- Acceleration profile

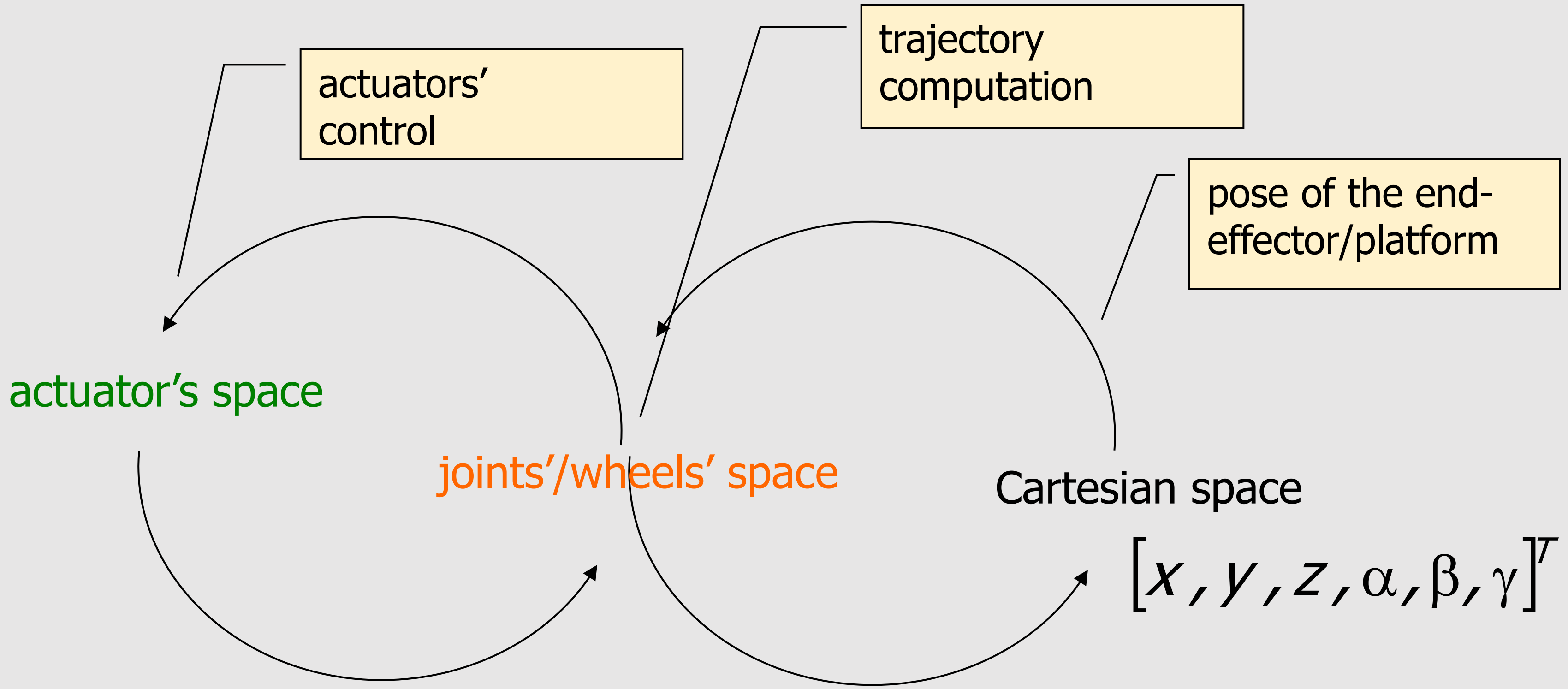


# Smooth trajectory planning functions

- There are many smooth functions that transition from the value $q_0$ to $q_f$ over the time interval $t_f$-$t_0$
  - Cubic polynomials
  - Higher-order polynomials
  - Linear functions with parabolic blends

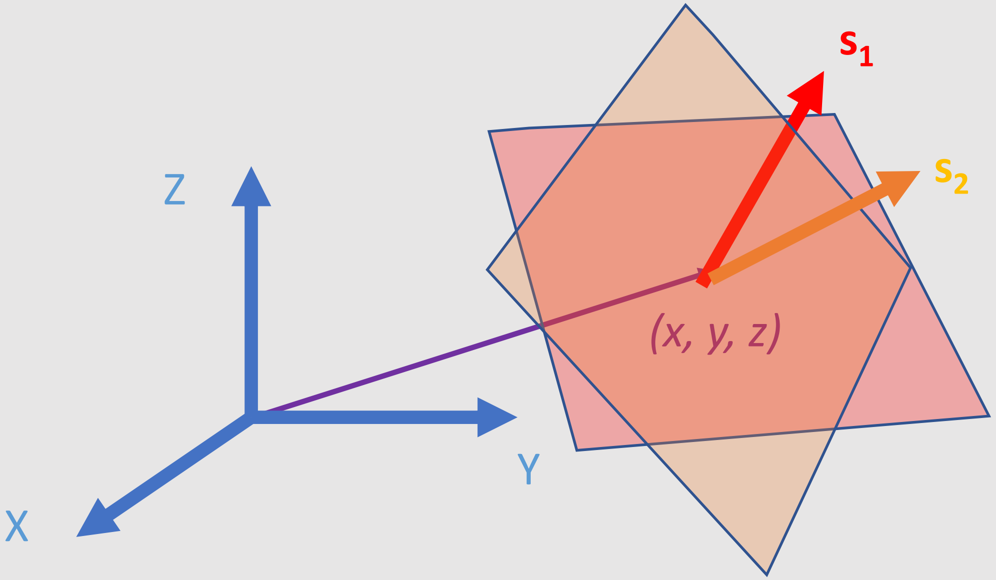


# Transformations in robot spaces



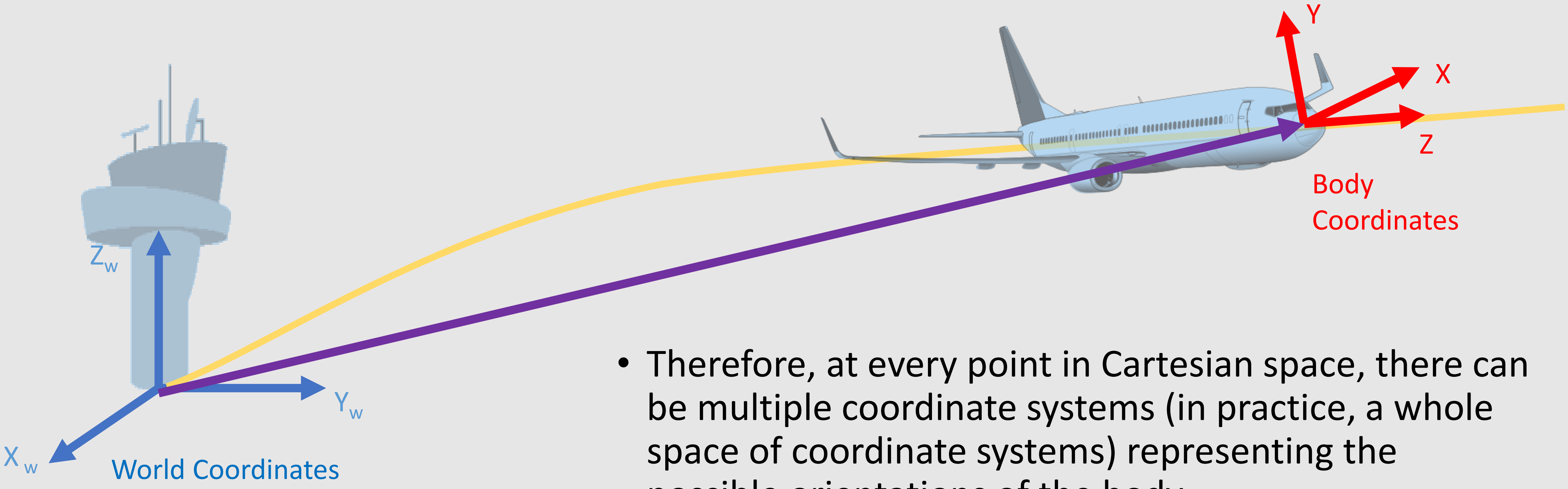

$$\boldsymbol{q} = [q_1, q_2, \cdots q_n]^T$$

# Pose



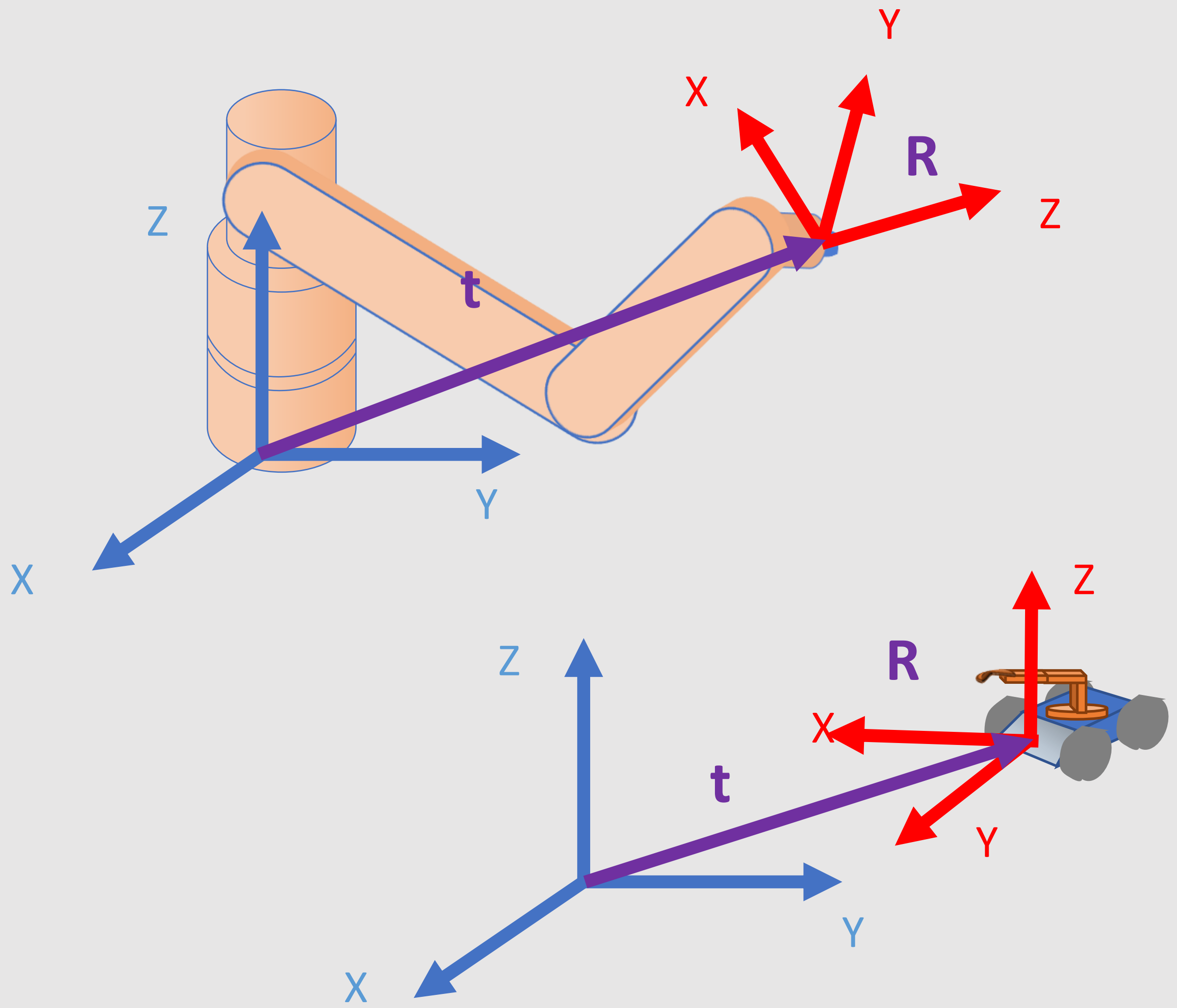

- From any point in Cartesian space, an infinite number of planes with different orientations can pass through
- The orientation of each of these planes is defined by a set of three angles (Euler or fixed)

# Orientation




- Therefore, at every point in Cartesian space, there can be multiple coordinate systems (in practice, a whole space of coordinate systems) representing the possible orientations of the body
- The combination of position and orientation of the body is called pose

# Robot pose

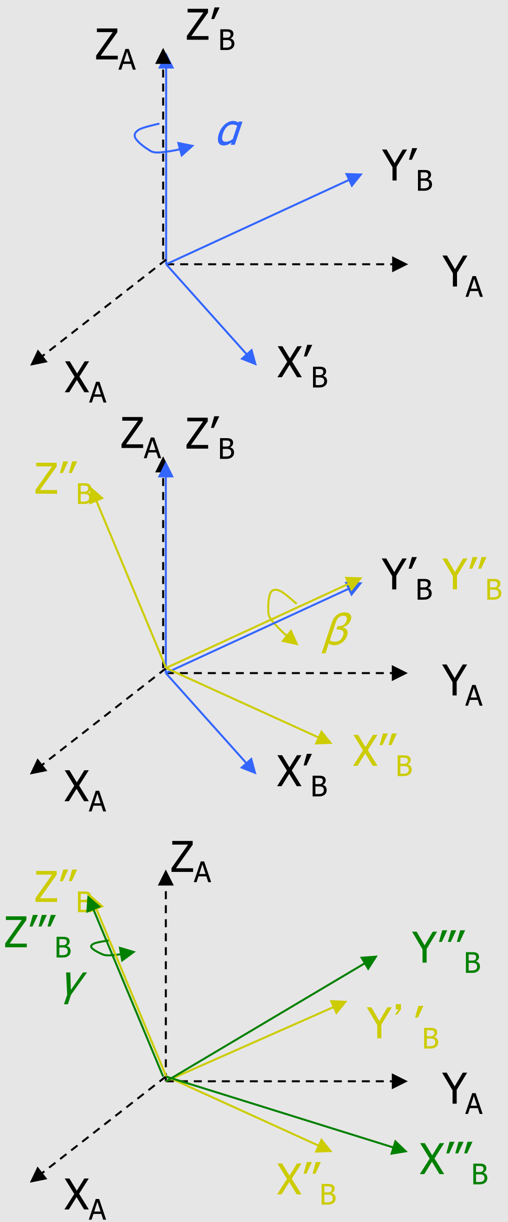



$$[x, y, z, \alpha, \beta, \gamma]^{\mathrm{T}}$$

- For manipulators, pose refers to the coordinate system attached to the end-effector
- For mobile platforms, it refers to the coordinate system attached to the robot's body

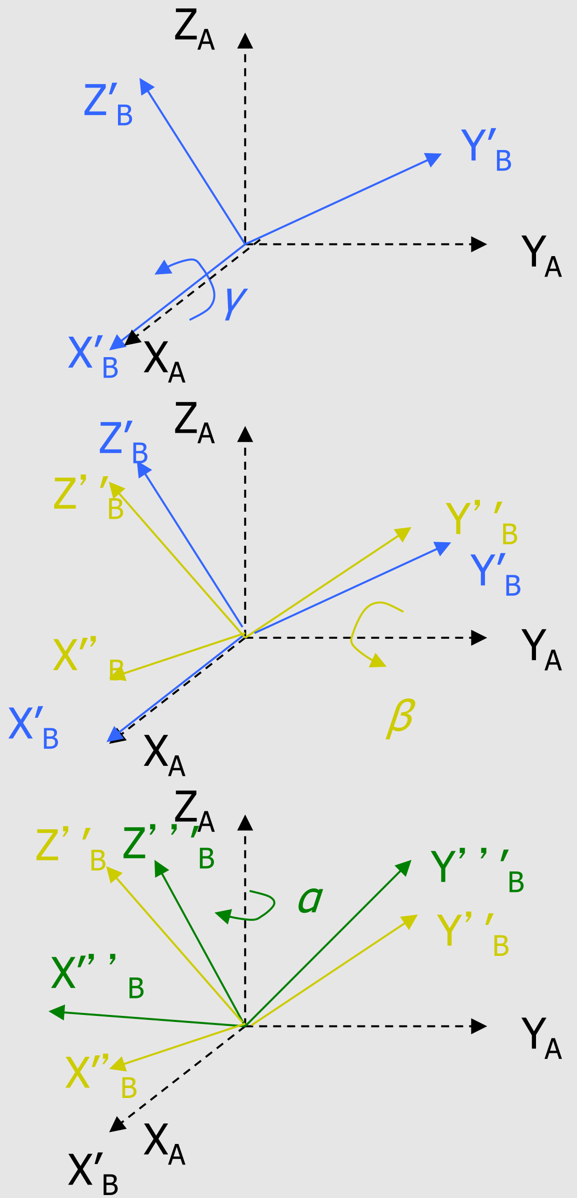
# Euler’s angles

- Assuming the two coordinate systems are aligned
- We first rotate by angle α around the $Z_B$ axis, then by angle β around $Y_B$ axis and finally by γ angle around $Z_B$ axis



# Roll, Pitch, Yaw angles

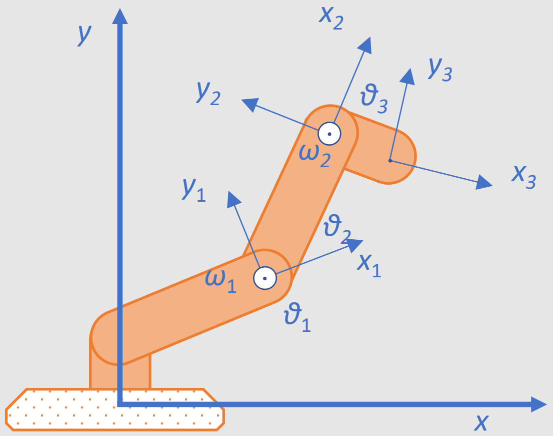
- Assuming the two coordinate systems are aligned
- We first rotate by angle γ around the $X_A$ axis, then by angle β around $Y_A$ axis and finally by α angle around $Z_A$ axis



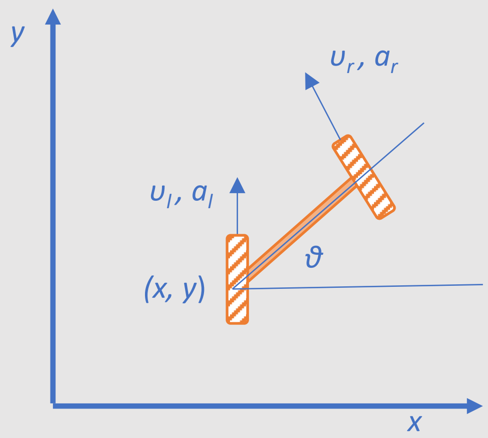
# Kinematics

- If we move an actuator by *x* degrees, how does the end effector of the robot move?
- Kinematics, combined with the robot's geometry, provide the answers

manipulators




moving platforms



# Kinematics vs Dynamics

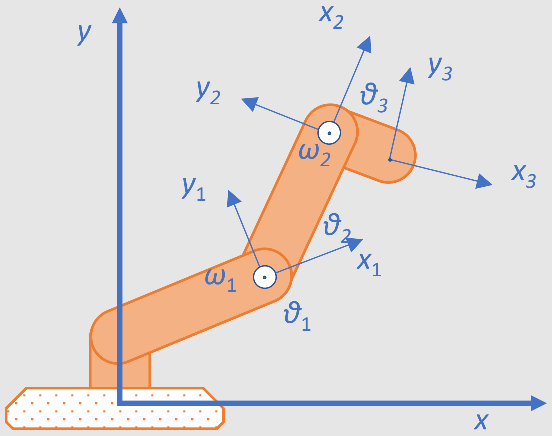
- Kinematics
- The influence of a robot's geometry on its motion
- If the motors are moved, where will the robot go?
- Control relies on the encoders' readings of the actuators

- Dynamics
- The influence of all the forces on robot's movement
- If the motors apply a force, where will the robot go?
- Control relies on the current flowing at the actuators

# Kinematics vs Dynamics

- Kinematics
- The influence of a robot's geometry on its motion
- Easy

$$\mathbf{T} = [\mathbf{R}|\mathbf{t}] \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$




- Dynamics
- The influence of all the forces on robot’s movement
- How easy?

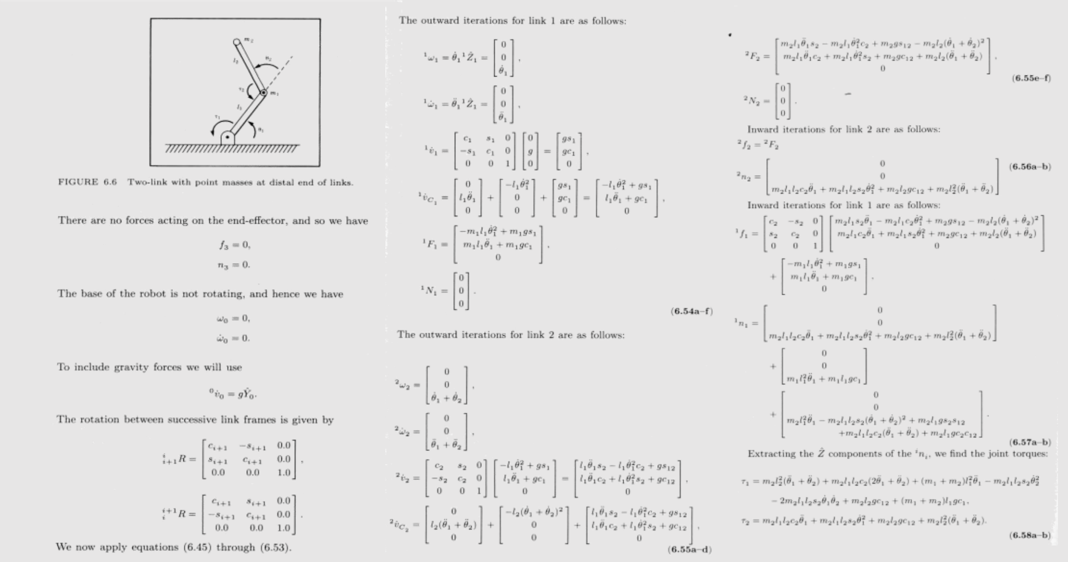


FIGURE 6.6 Two-link with point masses at distal end of links.

There are no forces acting on the end-effector, and so we have

$$f_3 = 0,$$
$$n_3 = 0.$$

The base of the robot is not rotating, and hence we have

$$\omega_0 = 0,$$
$$\dot{\omega}_0 = 0.$$

To include gravity forces we will use

$$^0\dot{v}_0 = g\hat{Y}_0.$$

The rotation between successive link frames is given by

$$^{i}_{i+1}R = \begin{bmatrix} c_{i+1} & -s_{i+1} & 0.0 \\ s_{i+1} & c_{i+1} & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix},$$

$$^{i+1}_{i}R = \begin{bmatrix} c_{i+1} & s_{i+1} & 0.0 \\ -s_{i+1} & c_{i+1} & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix}.$$

We now apply equations (6.45) through (6.53).

The outward iterations for link 1 are as follows:

$$^1\omega_1 = \dot{\theta}_1 {}^1\hat{Z}_1 = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 \end{bmatrix},$$

$$^1\dot{\omega}_1 = \ddot{\theta}_1 {}^1\hat{Z}_1 = \begin{bmatrix} 0 \\ 0 \\ \ddot{\theta}_1 \end{bmatrix},$$

$$^1\dot{v}_1 = \begin{bmatrix} c_1 & s_1 & 0 \\ -s_1 & c_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ g \\ 0 \end{bmatrix} = \begin{bmatrix} gs_1 \\ gc_1 \\ 0 \end{bmatrix},$$

$$^1\dot{v}_{C_1} = \begin{bmatrix} 0 \\ l_1\ddot{\theta}_1 \\ 0 \end{bmatrix} + \begin{bmatrix} -l_1\dot{\theta}_1^2 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} gs_1 \\ gc_1 \\ 0 \end{bmatrix} = \begin{bmatrix} -l_1\dot{\theta}_1^2 + gs_1 \\ l_1\ddot{\theta}_1 + gc_1 \\ 0 \end{bmatrix},$$

$$^1F_1 = \begin{bmatrix} -m_1l_1\dot{\theta}_1^2 + m_1gs_1 \\ m_1l_1\ddot{\theta}_1 + m_1gc_1 \\ 0 \end{bmatrix},$$

$$^1N_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}. \qquad \textbf{(6.54a–f)}$$

The outward iterations for link 2 are as follows:

$$^2\omega_2 = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 + \dot{\theta}_2 \end{bmatrix},$$

$$^2\dot{\omega}_2 = \begin{bmatrix} 0 \\ 0 \\ \ddot{\theta}_1 + \ddot{\theta}_2 \end{bmatrix},$$

$$^2\dot{v}_2 = \begin{bmatrix} c_2 & s_2 & 0 \\ -s_2 & c_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -l_1\dot{\theta}_1^2 + gs_1 \\ l_1\ddot{\theta}_1 + gc_1 \\ 0 \end{bmatrix} = \begin{bmatrix} l_1\ddot{\theta}_1s_2 - l_1\dot{\theta}_1^2c_2 + gs_{12} \\ l_1\ddot{\theta}_1c_2 + l_1\dot{\theta}_1^2s_2 + gc_{12} \\ 0 \end{bmatrix},$$

$$^2\dot{v}_{C_2} = \begin{bmatrix} 0 \\ l_2(\ddot{\theta}_1 + \ddot{\theta}_2) \\ 0 \end{bmatrix} + \begin{bmatrix} -l_2(\dot{\theta}_1 + \dot{\theta}_2)^2 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} l_1\ddot{\theta}_1s_2 - l_1\dot{\theta}_1^2c_2 + gs_{12} \\ l_1\ddot{\theta}_1c_2 + l_1\dot{\theta}_1^2s_2 + gc_{12} \\ 0 \end{bmatrix}, \qquad \textbf{(6.55a–d)}$$

$$^2F_2 = \begin{bmatrix} m_2l_1\ddot{\theta}_1s_2 - m_2l_1\dot{\theta}_1^2c_2 + m_2gs_{12} - m_2l_2(\dot{\theta}_1 + \dot{\theta}_2)^2 \\ m_2l_1\ddot{\theta}_1c_2 + m_2l_1\dot{\theta}_1^2s_2 + m_2gc_{12} + m_2l_2(\ddot{\theta}_1 + \ddot{\theta}_2) \\ 0 \end{bmatrix}, \qquad \textbf{(6.55e–f)}$$

$$^2N_2 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}.$$

Inward iterations for link 2 are as follows:

$$^2f_2 = {}^2F_2$$

$$^2n_2 = \begin{bmatrix} 0 \\ 0 \\ m_2l_1l_2c_2\ddot{\theta}_1 + m_2l_1l_2s_2\dot{\theta}_1^2 + m_2l_2gc_{12} + m_2l_2^2(\ddot{\theta}_1 + \ddot{\theta}_2) \end{bmatrix} \qquad \textbf{(6.56a–b)}$$

Inward iterations for link 1 are as follows:

$$^1f_1 = \begin{bmatrix} c_2 & -s_2 & 0 \\ s_2 & c_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} m_2l_1s_2\ddot{\theta}_1 - m_2l_1c_2\dot{\theta}_1^2 + m_2gs_{12} - m_2l_2(\dot{\theta}_1 + \dot{\theta}_2)^2 \\ m_2l_1c_2\ddot{\theta}_1 + m_2l_1s_2\dot{\theta}_1^2 + m_2gc_{12} + m_2l_2(\ddot{\theta}_1 + \ddot{\theta}_2) \\ 0 \end{bmatrix} + \begin{bmatrix} -m_1l_1\dot{\theta}_1^2 + m_1gs_1 \\ m_1l_1\ddot{\theta}_1 + m_1gc_1 \\ 0 \end{bmatrix},$$

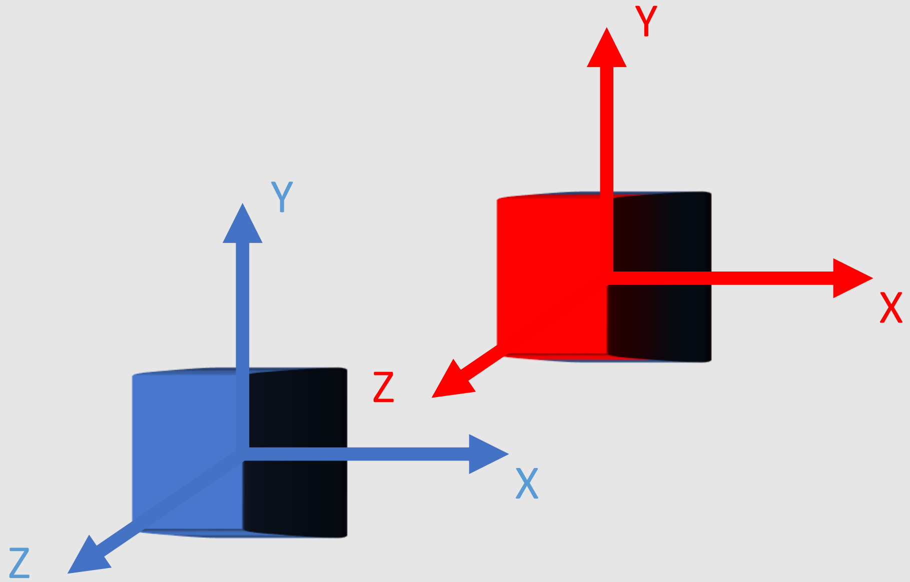
$$^1n_1 = \begin{bmatrix} 0 \\ 0 \\ m_2l_1l_2c_2\ddot{\theta}_1 + m_2l_1l_2s_2\dot{\theta}_1^2 + m_2l_2gc_{12} + m_2l_2^2(\ddot{\theta}_1 + \ddot{\theta}_2) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ m_1l_1^2\ddot{\theta}_1 + m_1l_1gc_1 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ m_2l_1^2\ddot{\theta}_1 - m_2l_1l_2s_2(\dot{\theta}_1 + \dot{\theta}_2)^2 + m_2l_1gs_2s_{12} \\ +m_2l_1l_2c_2(\ddot{\theta}_1 + \ddot{\theta}_2) + m_2l_1gc_2c_{12} \end{bmatrix}. \qquad \textbf{(6.57a–b)}$$

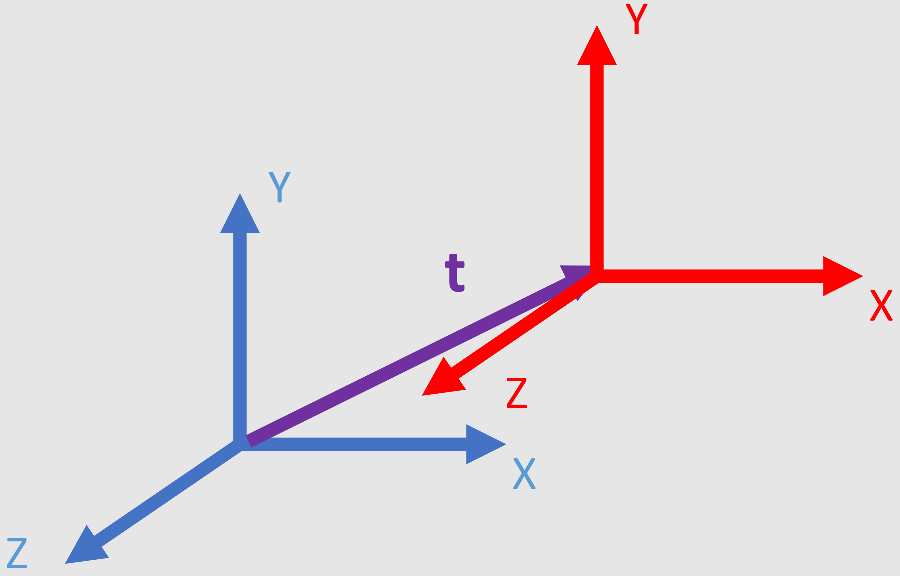
Extracting the $\hat{Z}$ components of the $^in_i$, we find the joint torques:

$$\tau_1 = m_2l_2^2(\ddot{\theta}_1 + \ddot{\theta}_2) + m_2l_1l_2c_2(2\ddot{\theta}_1 + \ddot{\theta}_2) + (m_1 + m_2)l_1^2\ddot{\theta}_1 - m_2l_1l_2s_2\dot{\theta}_2^2 - 2m_2l_1l_2s_2\dot{\theta}_1\dot{\theta}_2 + m_2l_2gc_{12} + (m_1 + m_2)l_1gc_1,$$

$$\tau_2 = m_2l_1l_2c_2\ddot{\theta}_1 + m_2l_1l_2s_2\dot{\theta}_1^2 + m_2l_2gc_{12} + m_2l_2^2(\ddot{\theta}_1 + \ddot{\theta}_2). \qquad \textbf{(6.58a–b)}$$

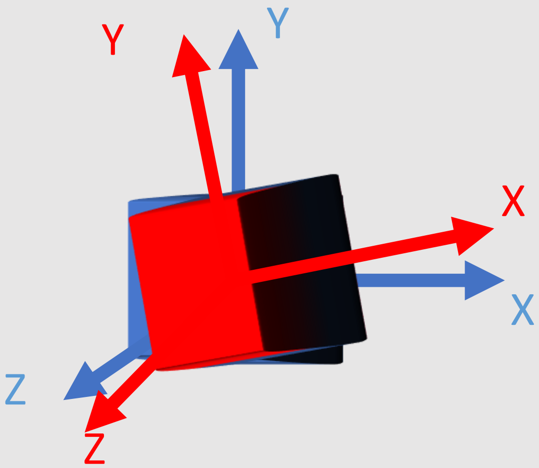
# Translation

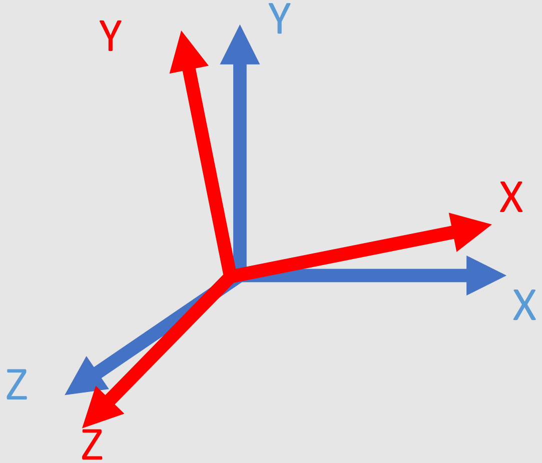



$$\mathbf{t} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}$$

# Rotation

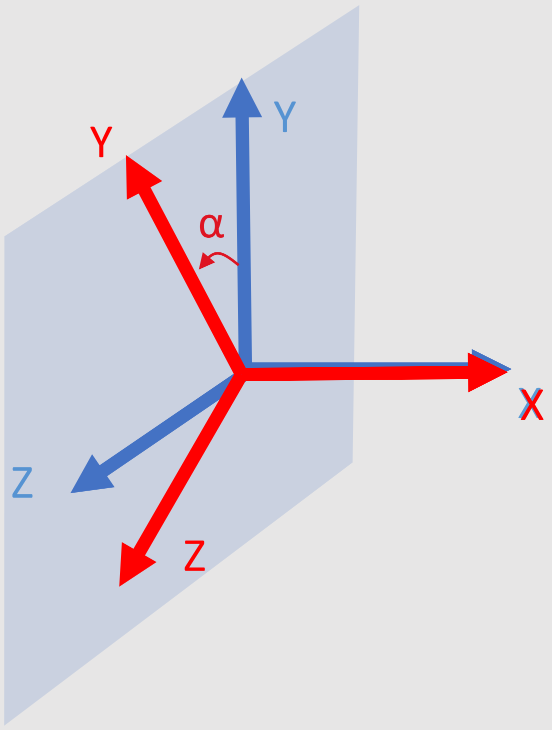



$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

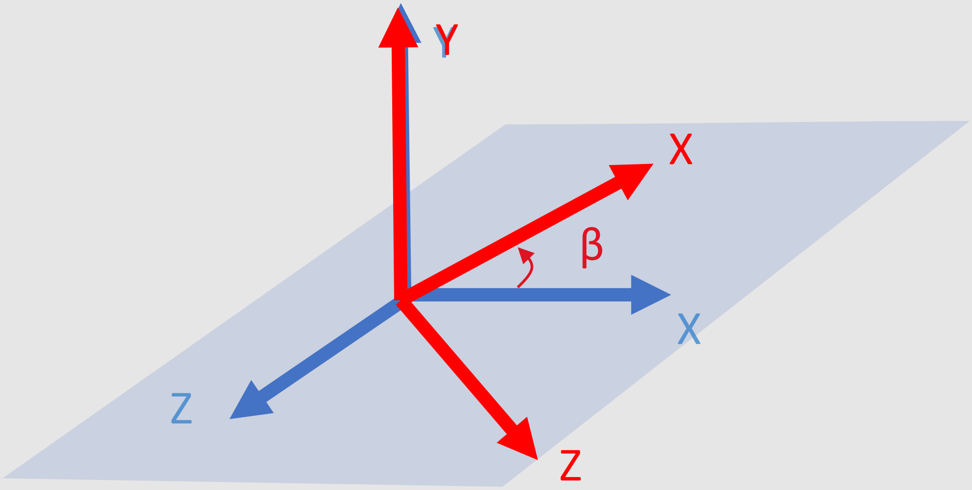
# Rotation matrix

## Rotation around the X-axis



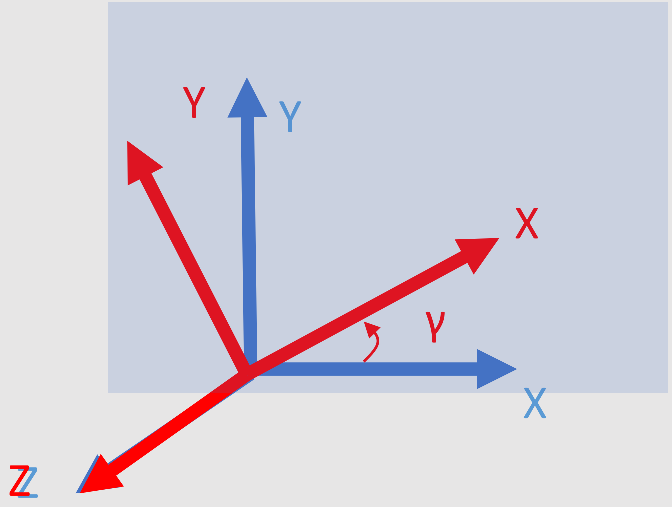

$$\mathbf{R}_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix}$$

# Rotation matrix
# Rotation around the Y-axis



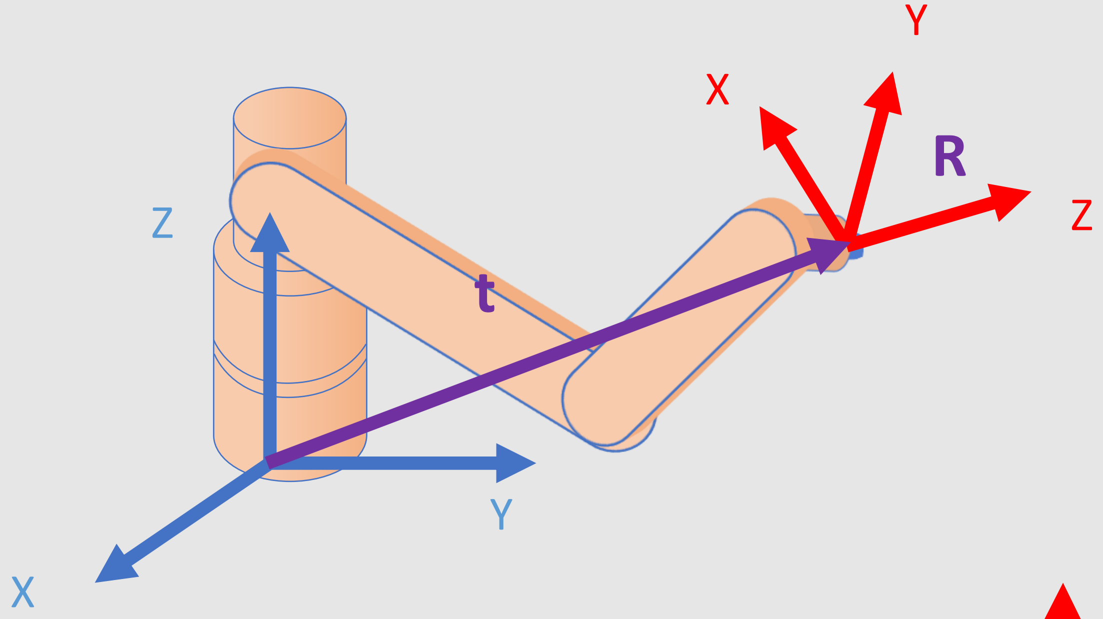

$$\mathbf{R}_y = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}$$

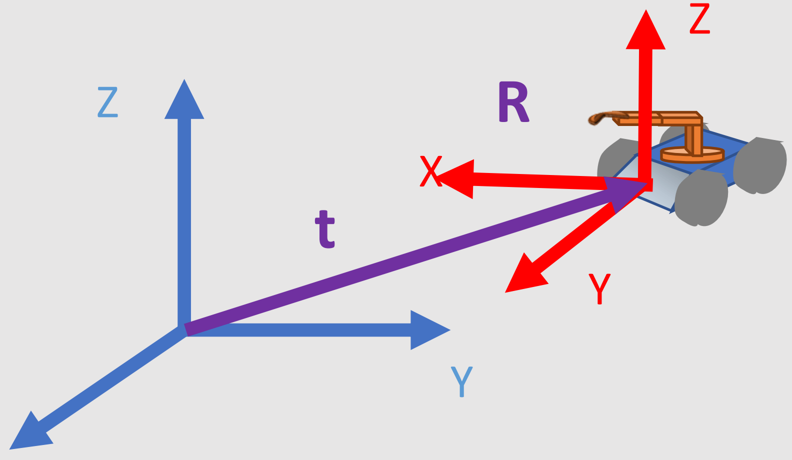
# Rotation matrix
# Rotation around the Z-axis




$$\mathbf{R}_z = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

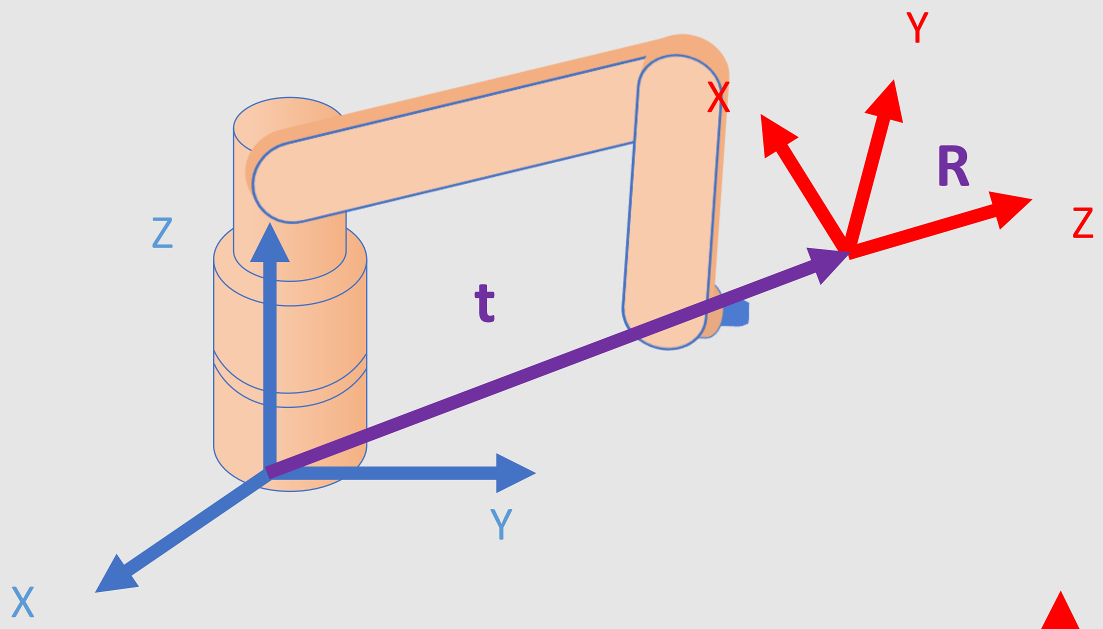
# Homogeneous transformation matrix

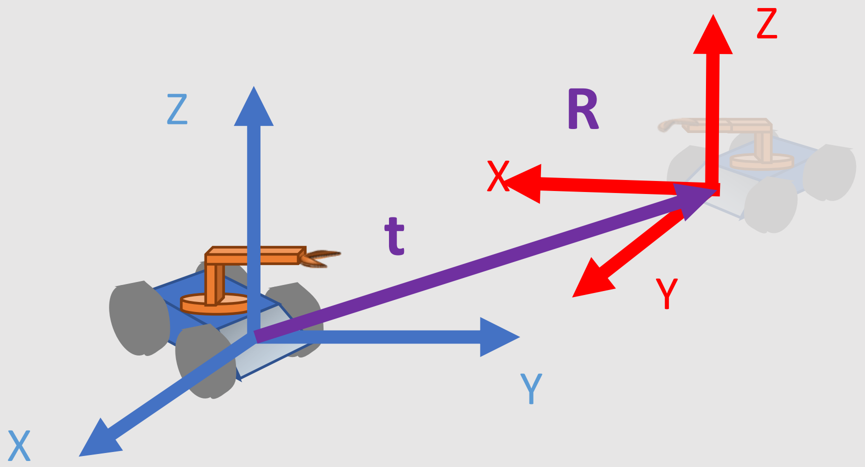



$$\mathbf{T} = [\mathbf{R}|\mathbf{t}] \left[\begin{array}{ccc|c} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

# Inverse kinematics



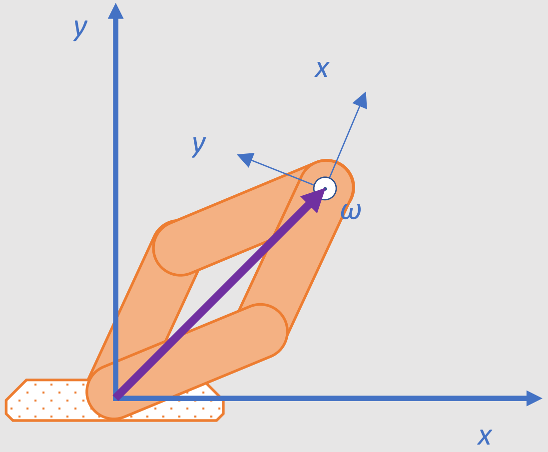




$$\mathbf{R} = [?]$$

$$\mathbf{t} = [?]$$

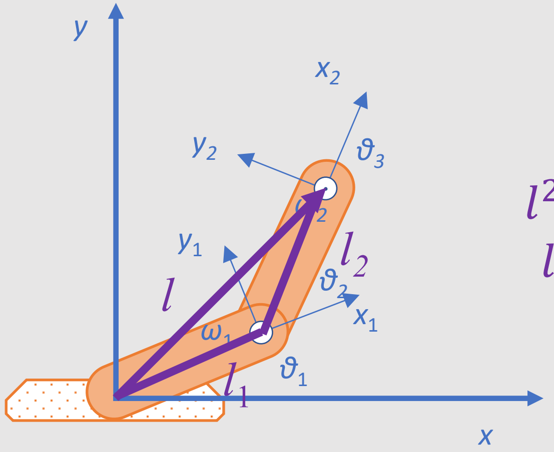
# Inverse kinematics

- Multiple solutions



# Inverse kinematics

- Geometrical solutions




$$l^2 = x^2 + y^2$$
$$l_1^2 + l_2^2 \pm l_1 l_2 \cos(\pi - \theta_2)$$

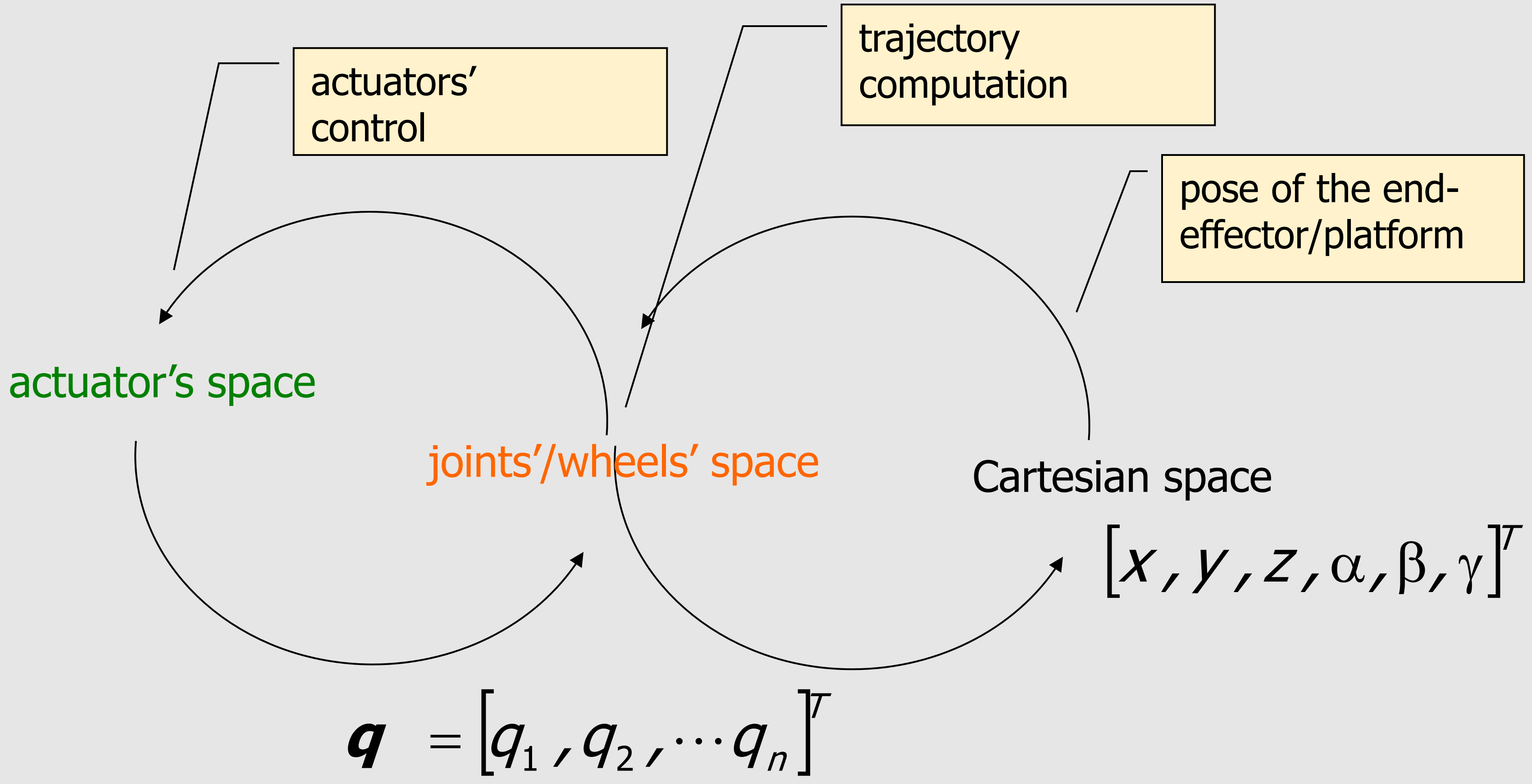
- Algebraic solutions

orientation

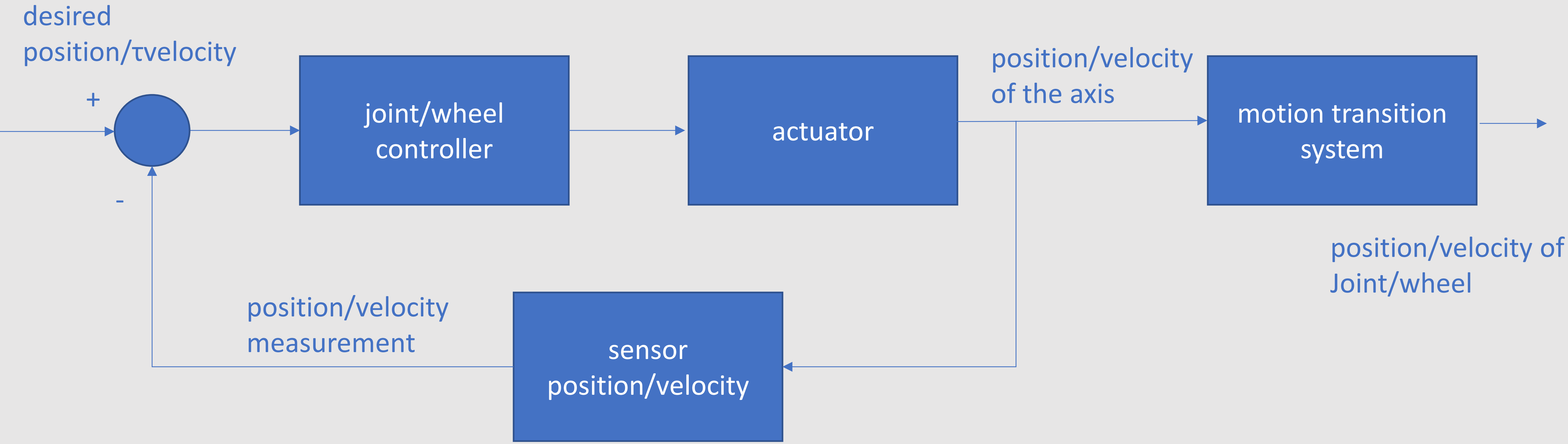
pose

$$\mathbf{T} = [\mathbf{R}|\mathbf{t}] \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

# Transformations in robot spaces



# Position/velocity control

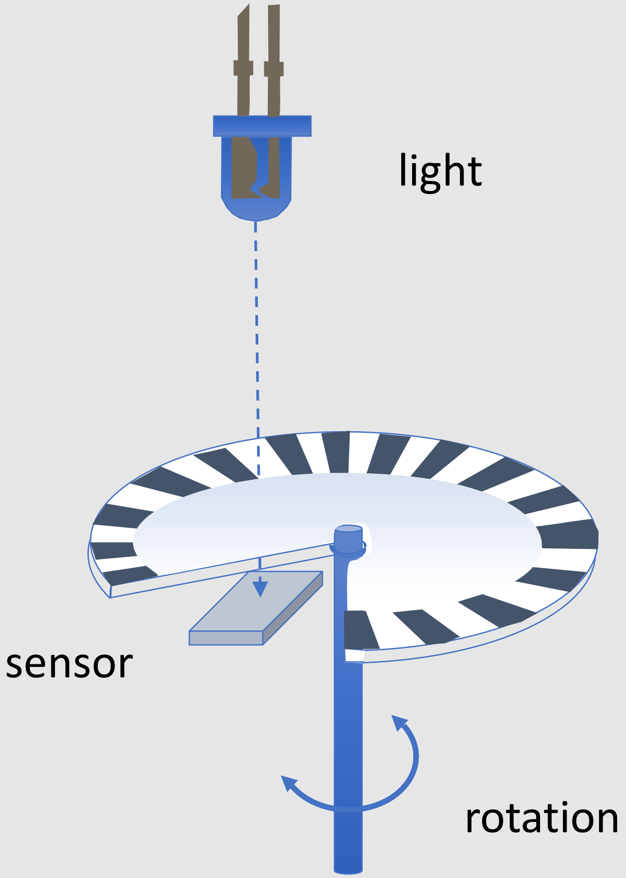


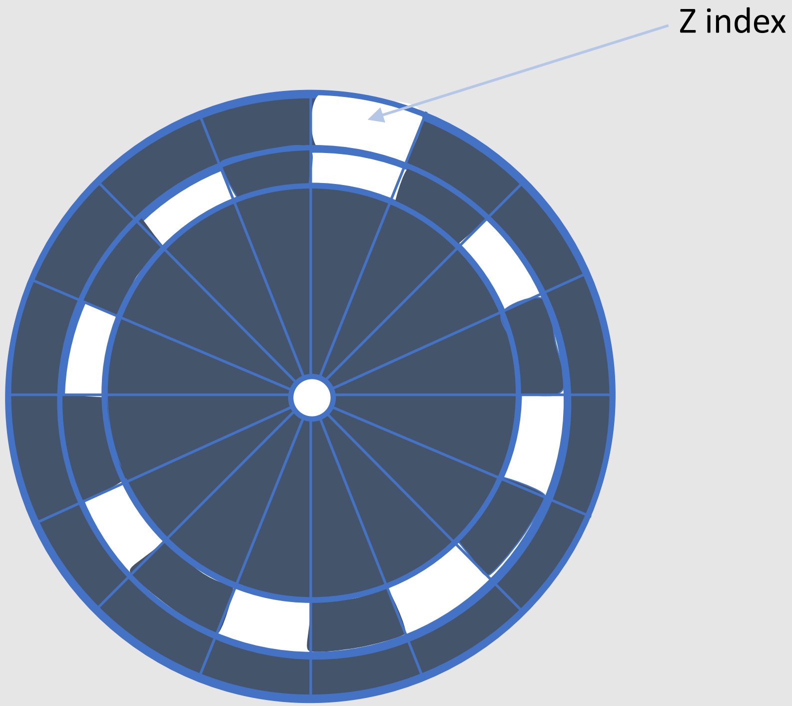
# Sensors

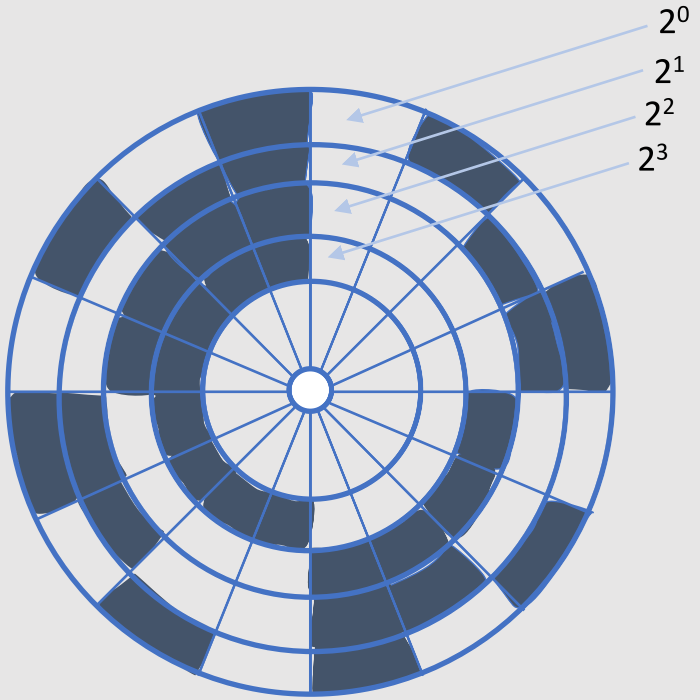
They are the most important and technologically complex parts of a robot. They are mainly distinguished into:

- Proprioceptive sensors: devices capable of accurately measuring robot parameters such as position or velocity of joints, or forces applied to the wrist. Examples include:
  - Potentiometers
  - Resolvers
  - Encoders
  - Tachometers
  - Force sensors in 3 or 6 axes
- Heteroceptive sensors: devices capable of measuring environmental parameters in which a robot operates, in order to ensure its proper functioning. They can be broadly categorized as:
  - Tactile sensors
  - Proximity or distance sensors
  - Vision sensors
  - Others

# Optical encoder



# Actuators

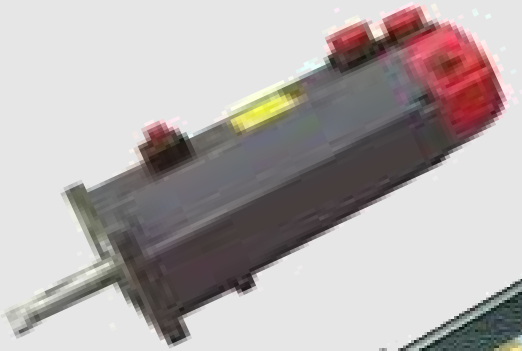
- The actuators used in the implementation of robotic systems can be categorized as follows:
    - Electric (DC motors, stepper motors, brushless motors, etc., comprising ~50% of cases)
    - Hydraulic (~35%)
    - Pneumatic (also used in grippers and end effectors, comprising ~15%)
    - Others

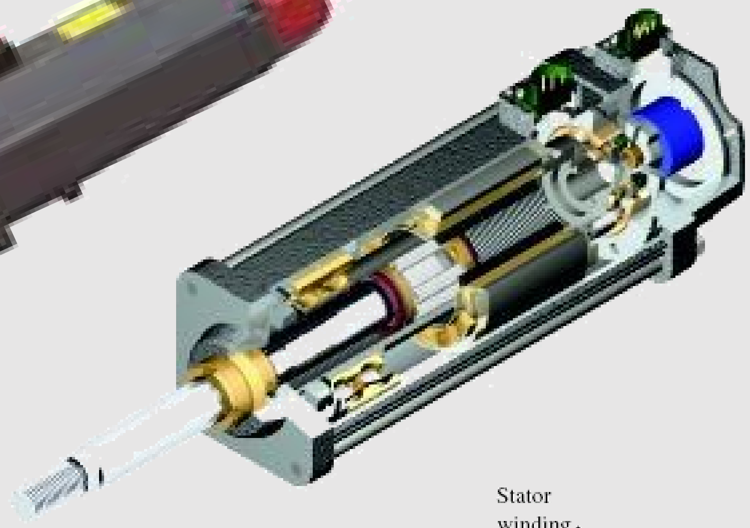
# Electric actuators

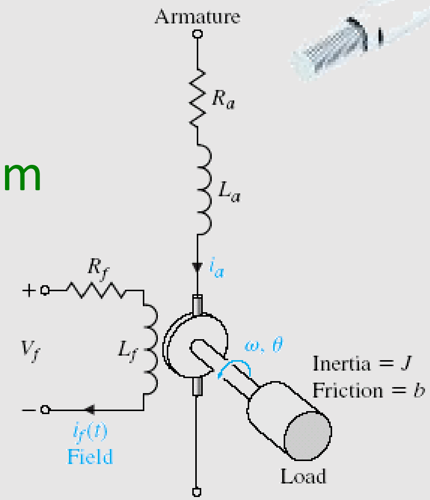
Systems for converting electrical power into mechanical power

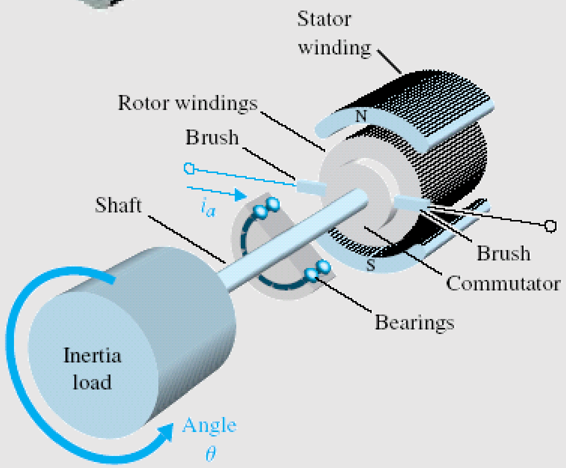
☑ Advantages

- Adequately fast and precise
- Ability to use sophisticated control algorithms
- Ease of availability and cost-effective
- Simple to use
- Reduced dimensions
- Exceptional performance
- Wide range of power provided (from mW to MW)





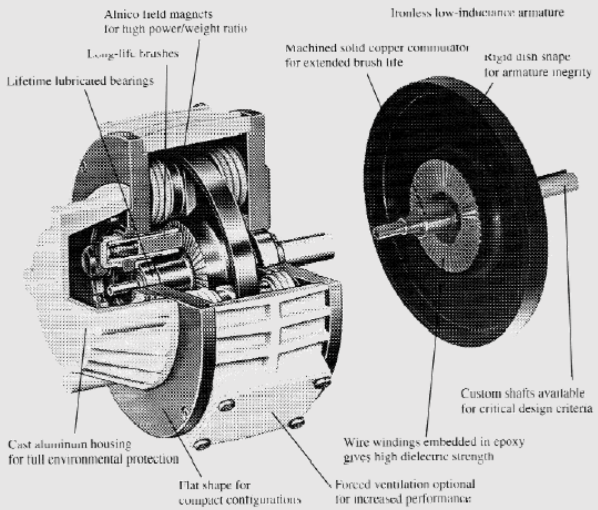


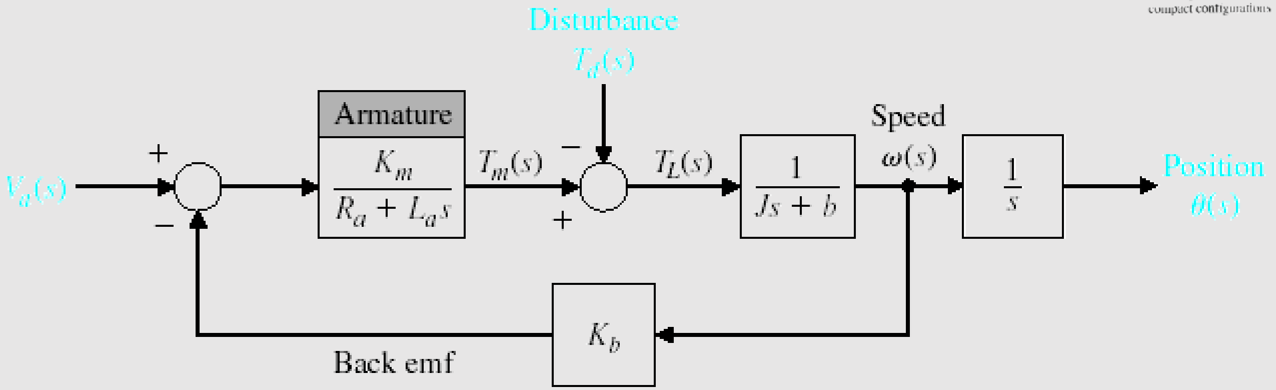



# Electric actuators

☒ Disadvantages

- Need for the placement of a reducer (except for direct drives) resulting in reduced precision and increased cost
- The available power may not be sufficient for some applications



# Hydraulic actuators

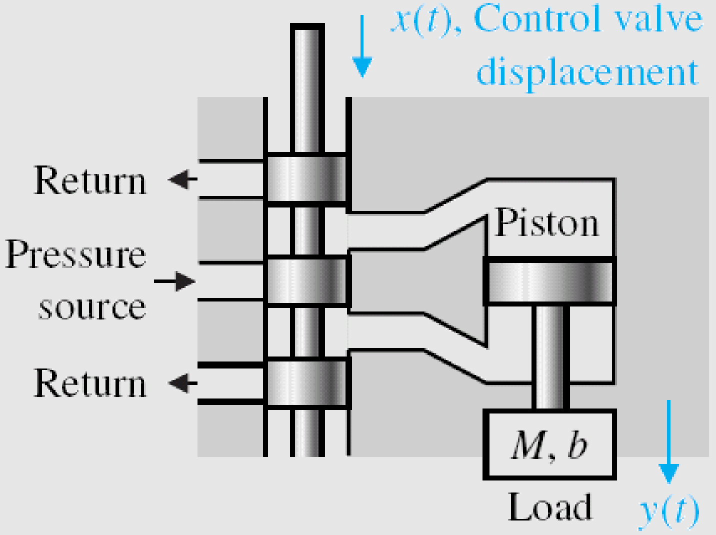
Systems for converting hydraulic power (compressed oil power) into mechanical power

☑ Advantages

- High load capacity
- High speed
- Maintain a position once reached
- Linear displacement
- Ability for precise control

☒ Disadvantages

- Poor performance
- High cost, especially in small dimensions
- Noise issues
- Oil leakage problems
- Occupy a large volume



# Pneumatic actuators

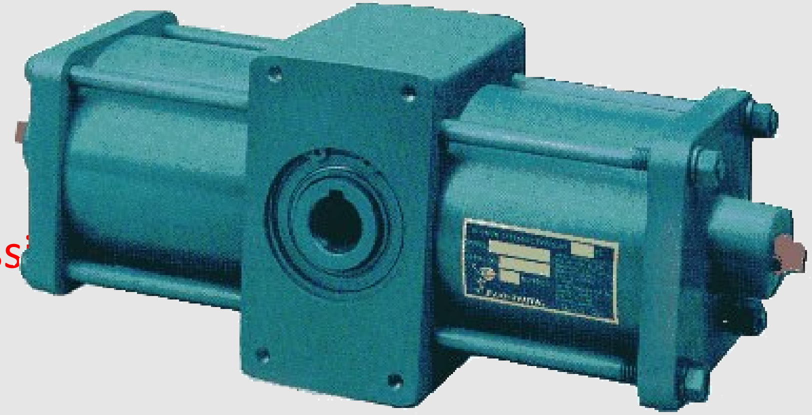
Systems for converting pneumatic power (compressed air power) into mechanical power

☑ Advantages

- Relatively low cost
- High speed

☒ Disadvantages

- Low precision due to high compress
- Noise issues
- Loss problems
- Need for air filters
- Requires maintenance
- Issues due to continuous supply of compressed air (cost, autonomy, etc.)



# Ερωτήσεις