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.

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

- **Mechanical structure**:
  - n bodies or rigid links L1,...Ln (open kinematic loop)
  - n joints: rotational / prismatic joints J1,..,Jn

GOAL: To place the last link (position and orientation) in space

- **Description of geometry**:
  - Joint coordinates: $\mathbf{q} = (q_1, \cdots, q_n)$
    - Unique representation
  - Task / operational / Cartesian coordinates $\mathbf{X} = (x_1, \cdots, x_m)^t$
    - location (position + orientation) of end effector (relative to base frame)

Homogeneous transformation matrices

- Euclidean transformation:

Translation and Rotation in space $\mathbf{R}^3$

$$\mathbf{T} = \begin{pmatrix} \mathbf{R}_{3x3} & \mathbf{p}_{3x1} \\ \mathbf{0}_{1x3} & 1 \end{pmatrix}$$

where **R** is orthonormal: $\mathbf{R}^{-1} = \mathbf{R}^t$; $|\mathbf{R}|=1$

- Rotation matrices
  - Around a single **x, y, z** axis of the reference frame

$$\mathrm{Rot}(\mathbf{x},\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\mathrm{sen}\,\theta & 0 \\ 0 & \mathrm{sen}\,\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \mathrm{Rot}(\mathbf{y},\theta) = \begin{pmatrix} \cos\theta & 0 & \mathrm{sen}\,\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\mathrm{sen}\,\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \mathrm{Rot}(\mathbf{z},\theta) = \begin{pmatrix} \cos\theta & -\mathrm{sen}\,\theta & 0 & 0 \\ \mathrm{sen}\,\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Homogeneous transformation matrices

- Transformation matrix (Rotation and translation)

$$\mathbf{T} = \begin{pmatrix} \mathbf{R} & \mathbf{p} \\ \mathbf{0} & 1 \end{pmatrix} = \mathrm{Trasl}(\mathbf{p})\,\mathrm{Rot}(\mathbf{R});$$

Rotation followed by translation (relative to initial ref. frame)

- Composition of transformations (movements)
  - Product of homogeneous transformation matrices

$$\mathbf{T}_1\,\mathbf{T}_2 = \begin{pmatrix} \mathbf{R}_1 & \mathbf{p}_1 \\ \mathbf{0} & 1 \end{pmatrix} \begin{pmatrix} \mathbf{R}_2 & \mathbf{p}_2 \\ \mathbf{0} & 1 \end{pmatrix} = \begin{pmatrix} \mathbf{R}_1\mathbf{R}_2 & \mathbf{p}_1 + \mathbf{R}_1\mathbf{p}_2 \\ \mathbf{0} & 1 \end{pmatrix}$$

  - Inversion of homogeneous matrices

  - Neutral element: identity matrix $\mathbf{I_4}$

Rotations and translations relative to the initial (base) reference frame (*absolute*) -> **Pre-multiplication**

Rotations and translations relative to reference frame of the body, that changes with every transformation (*relative*) -> **Post-multiplication**

Reference frames (coordinate systems) and transforms

- If we transform (move) the origin and the axis directions of reference frame A according to: ${}^{A}\mathbf{T}_{\mathbf{H}}$

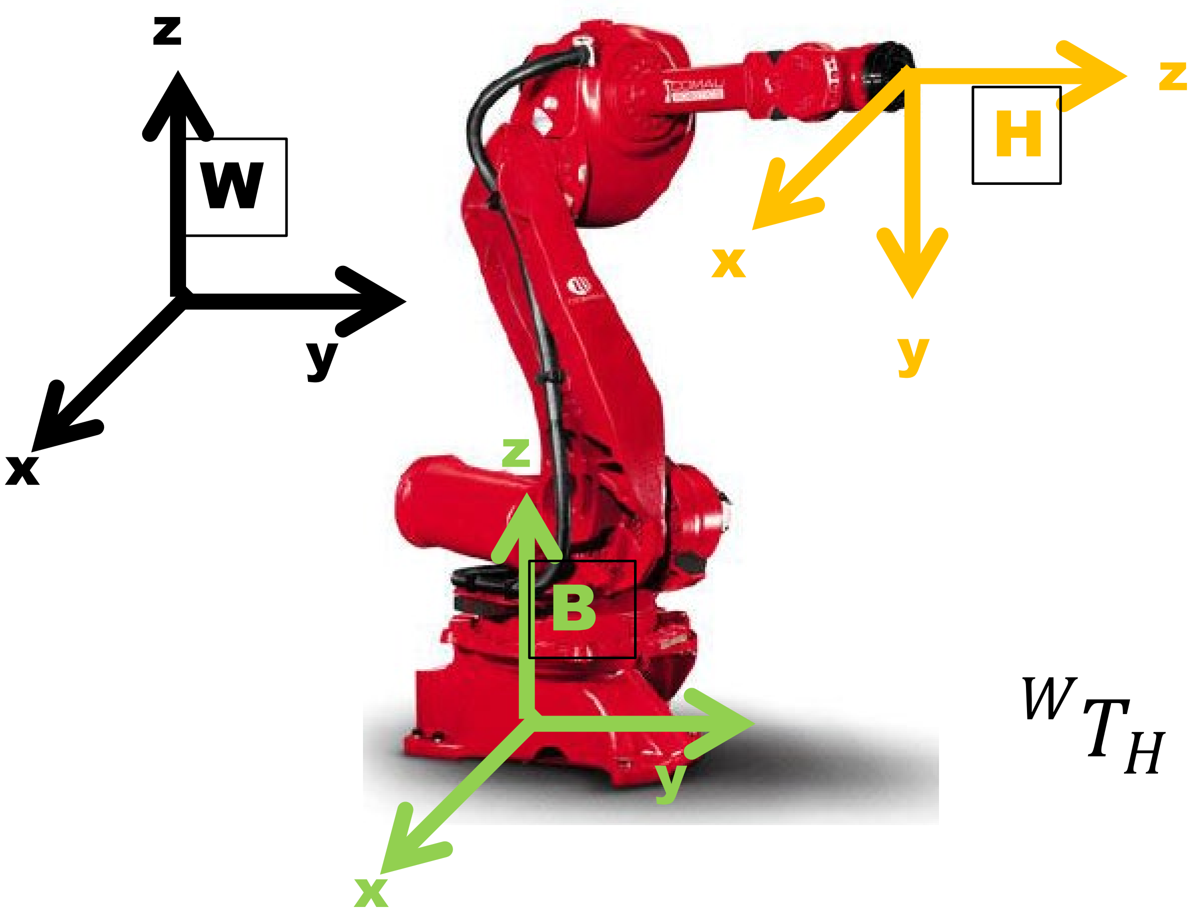
  we obtain:

$$
{}^{A}\mathbf{T}_{\mathbf{H}} = \begin{pmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} \mathbf{n} & \mathbf{o} & \mathbf{a} & \mathbf{p} \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} \mathbf{R} & \mathbf{p} \\ \mathbf{0} & 1 \end{pmatrix}
$$

$$
{}^{A}\mathbf{T}_{\mathbf{H}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} p_x \\ p_y \\ p_z \\ 1 \end{pmatrix} = \text{origin } \mathbf{H} \qquad {}^{A}\mathbf{T}_{\mathbf{H}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} n_x \\ n_y \\ n_z \\ 0 \end{pmatrix} = \text{direction } \mathbf{X}_{\mathbf{H}}.
$$

$$
{}^{A}\mathbf{T}_{\mathbf{H}} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} o_x \\ o_y \\ o_z \\ 0 \end{pmatrix} = \text{direction } \mathbf{Y}_{\mathbf{H}}. \qquad {}^{A}\mathbf{T}_{\mathbf{H}} \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} a_x \\ a_y \\ a_z \\ 0 \end{pmatrix} = \text{direction } \mathbf{Z}_{\mathbf{H}}.
$$

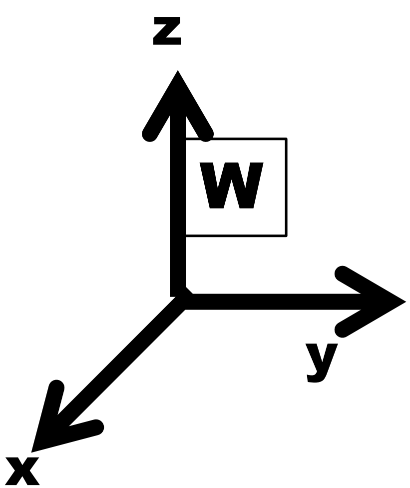
Reference frames: change of coordinate systems



$$^{W}T_{H} = {}^{W}T_{B} * {}^{B}T_{H}$$

Reference frames: 3D rotations

Relative / absolute order



Euler(Z,Y,Z) relative

$$R=Rotz(a)*\ Roty(b)*\ Rotz(c)$$

Roll-Pitch-Yaw(Z,Y,X) absolute

$$R=Rotz(a)*\ Roty(b)*\ Rotx(c)$$

2 solutions
1 singularity

Reference frames: 3D rotations

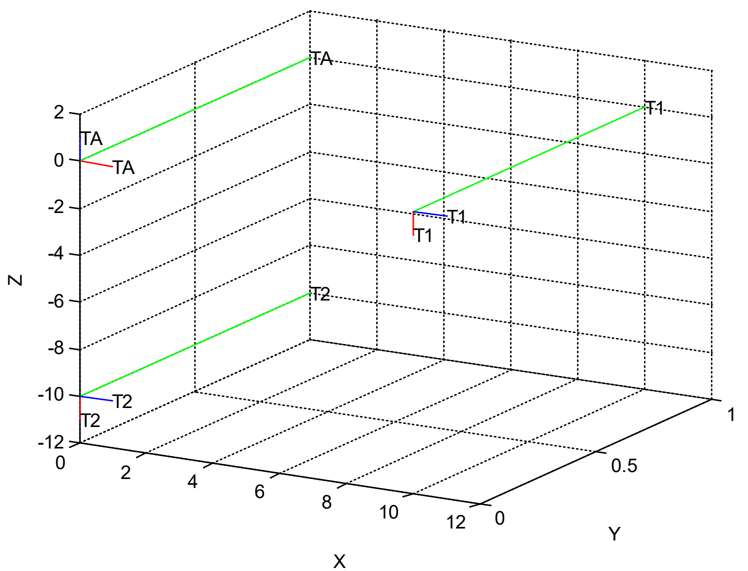
- Transformation between the different representations for the orientation: using the rotation matrix.

- Industrial robots
  - Many use 3 angle representations and operation with **R**,**T**
    - Karel (Fanuc): RPY angles
    - Val II (Unimation): OAT angles
  - Rapid (ABB): quaternion
  - (Often) Operations to change between representations, including homogeneous matrices

$$\mathrm{OAT}(\alpha,\beta,\gamma)=\mathrm{EULER}(\alpha-90,\beta+90,\gamma)$$

Exercises with MATLAB and Robotics Toolbox

- Run **rtbdemo**
- Learn about the representation of translations and rotations using homogeneous matrices
- Learn about the order of application of the rotations
- Learn about displaying 3D plots with relative transformation matrices



Exercises with MATLAB and Robotics Toolbox

- Solve and implement the following examples

Example 1

Obtain the homogeneous matrices that transform a reference system according to the following basic movements (all expressed in the **original reference system**)

- Rotation of 90º about the X axis, followed by a translation of 2 units along the Y axis.

- Translation of 2 units along the Y axis, followed by a 90º rotation about the X axis.

- Compare both transformations. Interpret the differences considering both the translation and the rotation parts

Exercises with MATLAB and Robotics Toolbox

- Solve and implement the following examples

Example 2

Obtain the homogeneous matrices that transform a reference system according to the following basic movements

- Rotation of 90º about the Z axis, followed by a translation of -5 units along the Y axis of the **original** reference system.

- Translation of -5 units along the Y axis, followed by a 90º rotation about the **new** Z axis.

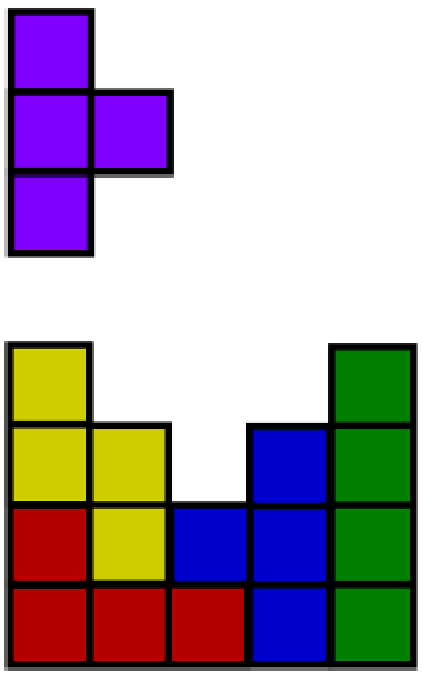
- Compare both transformations

Exercises with MATLAB and Robotics Toolbox

- Solve and implement the following examples

Example 3

Define a set of transformations to fit the T-shape piece into the gap (Each square is of 1x1 units):



-First, two translations and then a rotation.

-First, a rotation and then two translations.

-Which sequence of transformations is better to be implemented if collisions are not desirable?