Universität Hamburg
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MIN Faculty
Department of Informatics

Introduction to Robotics

Lecture 1

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University of Hamburg
Faculty of Mathematics, Informatics and Natural Sciences
Department of Informatics
Technical Aspects of Multimodal Systems

April 24, 2020

General Information

Lecture:	Friday 10:15 c. t. - 11:45 c. t.
Room:	F-334
Web:	`http://tams.inf...burg.de/lectures/`
Exercises /RPC:	Friday 09:00 c. t. - 11:00 c. t. / Friday 09:00 c. t. - 13:00 c. t. (alternating) see website for dates
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- See website for more information

TAMS course website:
http://tams.informatik.uni-hamburg.de/lectures/2020ss/vorlesung/itr

This course is organized with Moodle:
https://lernen.min.uni-hamburg.de/

Related Courses

Lecture

- Intelligent Robotics (winter, Bestmann)
- RoboCup - Playing football with humanoid robots (Summer, Bestmann)
- Lecture Computer Vision I (winter, Frintrop)
- Lecture Computer Vision II (summer, Frintrop)
- Neural Networks (summer, Wermter)

Projects

- Masterproject intelligent robotics (winter, TAMS)
- RoboCup - Playing football with humanoid robots (winter, Bestmann)
- Human-Computer Interaction (winter, Heinecke)

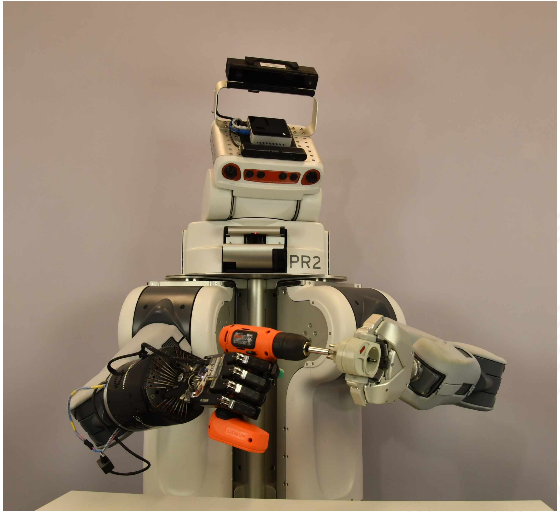
Previous Knowledge

- Linear algebra
  - Essence of linear algebra by 3Blue1Brown
- Basics in physics
  - force, torque, work...
- Related computer skills
  - Linux (RPC)
  - Python (RPC and Excercises)
  - Matlab (Excercises)
  - git (RPC)
  - access to `mafiasi.de` and pool computers

Own Hardware

If you use your own laptop, you require a `Ubuntu 18.06` (Live or Virtual Machine) and fully installed `ros-melodic-desktop-full`

PR2 robot



Content

- Mathematic concepts
  - spatial description
  - kinematics
  - dynamics
- Control concepts
  - movement execution
- Programming aspects
  - ROS, URDF, Kinematics Simulator
- Task-oriented movement and planning

Slides & Dates

24.04.	#01	[EX] Introduction, Coordinate Systems
01.05.	#02	[NO] Kinematics, Robot Description
08.05.	#03	[RPC] Robot Description, Inverse Kinematics
15.05.	#04	[EX] Differential Motion
	#05	[EX] Jacobian
22.05.	#06	[RPC] Trajectory Planning
29.05.	#07	[EX] Trajectory Generation
05.06.	No lecture	(Holiday)
12.06.	#08	[RPC] Dynamics
19.06.	#09	[EX] Robot Control
26.06.	#10	[RPC] Task-oriented Trajectory Generation and Object Representation
03.07.	#11	[EX] Path Planning
10.07.	#12	[RPC] Architectures of Sensor-Based Intelligent Systems
	#LC	[RPC] Summary, Conclusion, Outlook

Outline

Outline (cont.)

Background of some terms

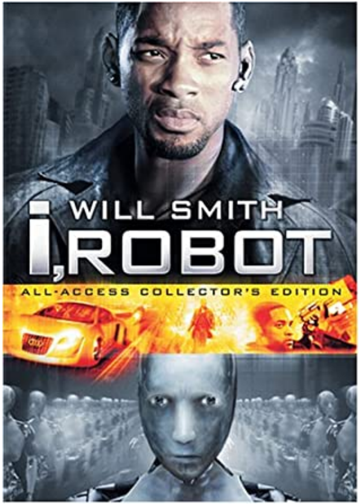
Robot became popular through a stage play by Karel Čapek in 1920, being a capable servant.

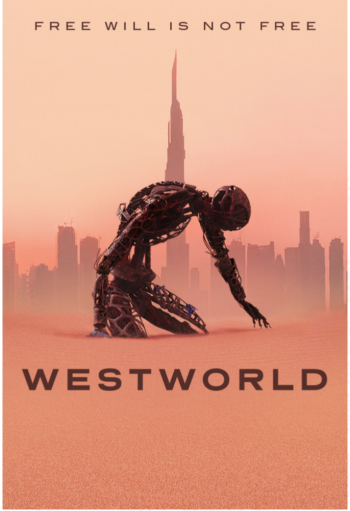
Robotics was first used by Isaac Asimov in 1942.

Three Laws of Robotics

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.

Obey or not

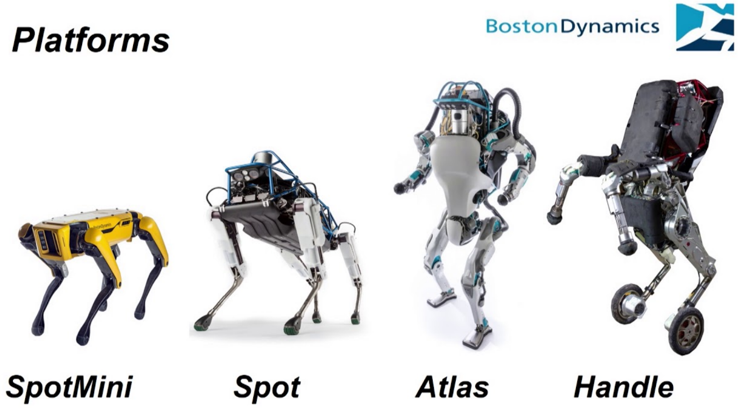




1 2

[1] https://irobot.fandom.com/wiki/I,_Robot_(film)
[2] https://www.rottentomatoes.com/tv/westworld/s03

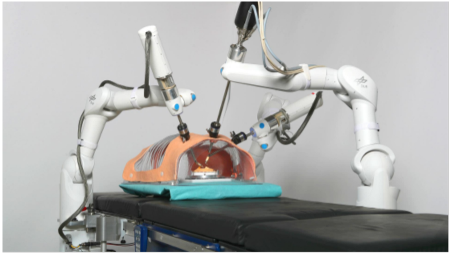
Legged-robots in Boston Dynamics



[3]

[3] https://www.youtube.com/watch?v=iZD6hkRwZKM

Medical Robot



[4] [5] [6]

[4] https://www.dlr.de/content/en/articles/news/2019/02/20190507_dih-hero-a-medical-robotics-network.html

[5] https://newatlas.com/hyundai-robotic-exoskeleton/43331/

[6] https://www.youtube.com/watch?v=wOzw71j4b78&t=4s

Industrial Robot

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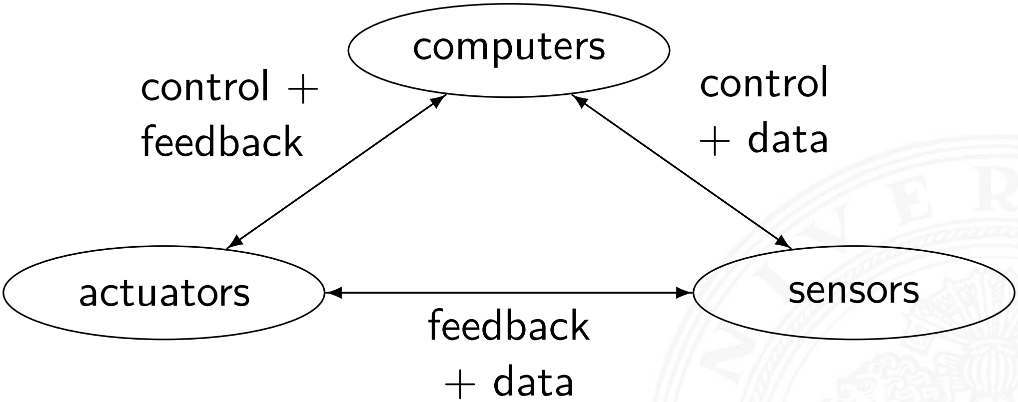
[7] https://www.robotics.org/blog-article.cfm/Industrial-Robot-Sales-Broke-Records-in-2018/136

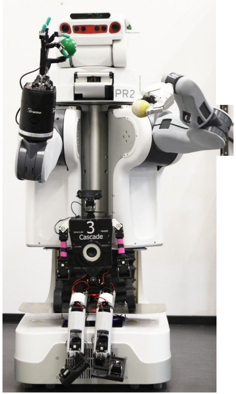
Components of a robot

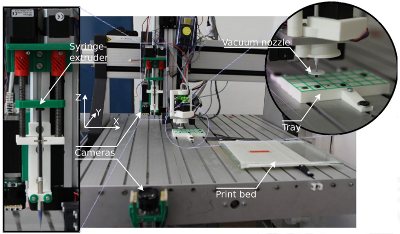


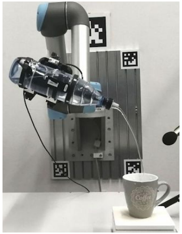
Robotics

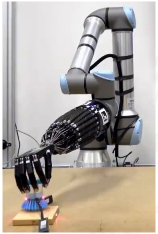
Intelligent combination of computers, sensors and actuators.

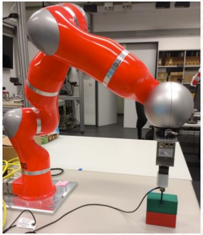
Hardwares in TAMS

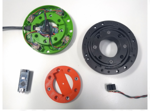










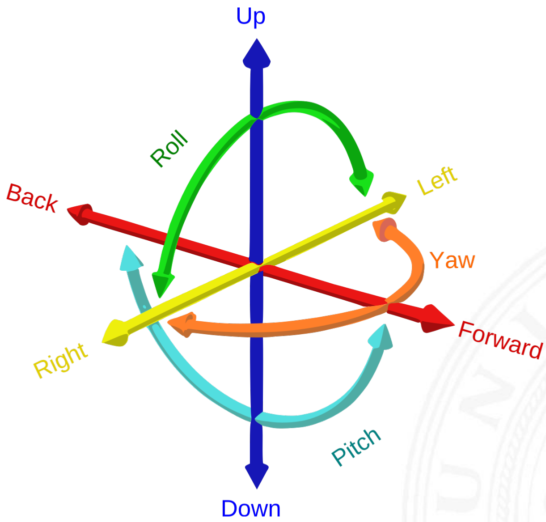


Degree of Freedom (DOF)

The number of variables to determine position of a control system in space.

- Point on a line
- Point on a plane
- Point in space
- Rigid body
  - in space
  - on a plane
- Non-rigid body
- Manipulator
  - number of independently controllable joints

DOF of rigid body



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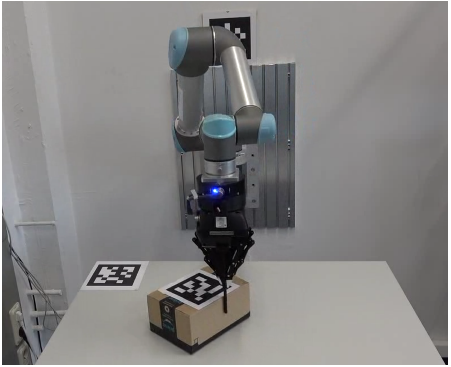
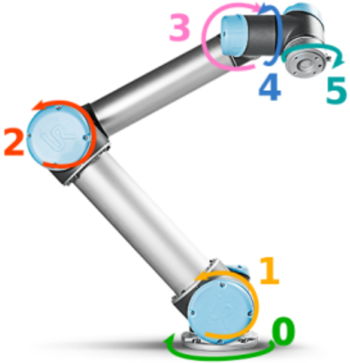
[8] https://commons.wikimedia.org/wiki/File:6DOF.svg

DOF examples

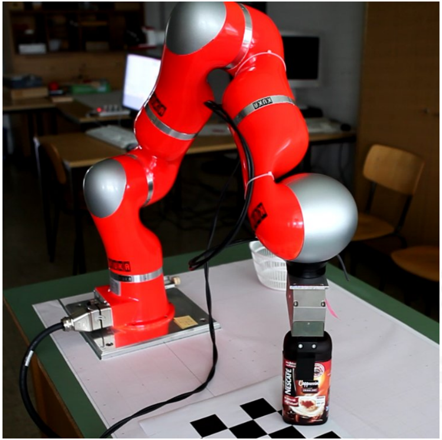




UR5 robot with Robotiq 3-finger gripper

$\underbrace{6\text{-DOF} + 3\text{-DOF gripper}}_{9}$

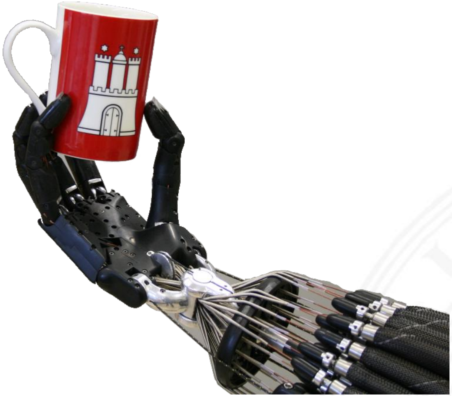
DOF examples (cont.)



KUKA LWR 4+ arm with Schunk gripper

7-DOF + 1-DOF gripper

DOF examples (cont.)



Shadow C5 Air Muscle hand

20-DOF + 4 unactuated joints

DOF examples (cont.)

PR2 service robot with Shadow C6 electrical hand

19-DOF + 20-DOF hand

DOF examples (cont.)

Boston Dynamics Atlas (2020)

28-DOF
10

[9] https://studywolf.wordpress.com/2016/08/

[10] https://medium.com/its42/the-reality-of-the-state-of-affairs-in-robotics-fyi-apart-from-the-hyperbole-it-is-sad-2c24a7f560ba

Robot classification by input power source

by input power source

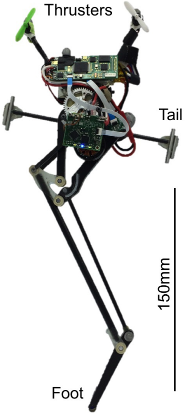
- electrical
- hydraulic
- pneumatic

Robot classification by fileld of work

by field of work

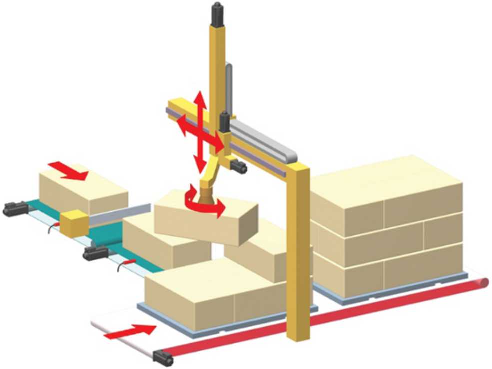
- stationary
  - arms with n DOF
  - multi-finger hand
- mobile
  - portal robot
  - mobile platform
  - running machines and flying robots
  - anthropomorphic robots (humanoids)

Salto Robot [2]



Robot classification by mechanical structure

by mechanical structure



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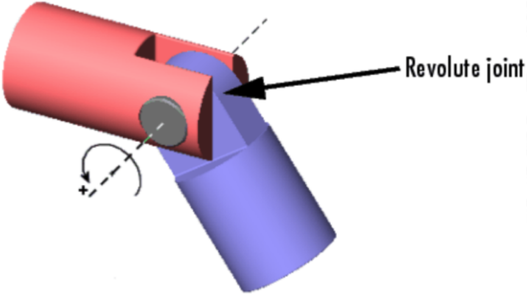
[11] https://www.machinedesign.com/mechanical-motion-systems/article/21831692/the-difference-between-cartesian-sixaxis-and-scara-robots

Type of a joint

- rotatory
  - revolute
- translatory
  - prismatic
- combinations
  - spherical
  - cylindrical
  - planar

Type of a joint

revolute joint



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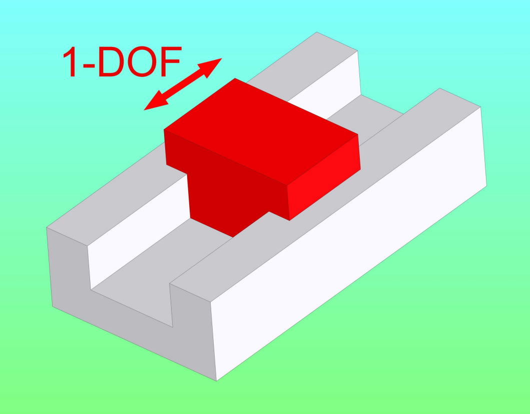
[12]https://www.youtube.com/playlist?list=PLrIVgT56nVQ4pm5QFeQ8Z288_VwopKmfW

Type of a joint

prismatic joint



13

[13] https://www.youtube.com/playlist?list=PLrIVgT56nVQ4pm5QFeQ8Z288_VwopKmfW

Type of a joint

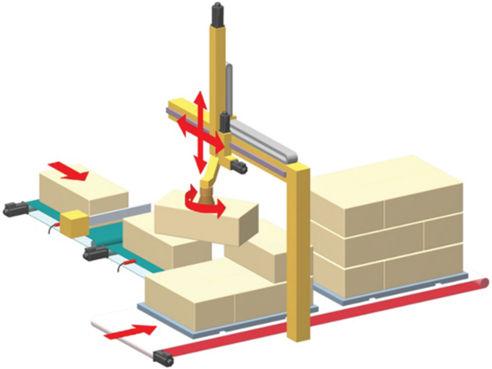
joints with more than one degree of freedom

[14]

[14] https://www.youtube.com/playlist?list=PLrIVgT56nVQ4pm5QFeQ8Z288_VwopKmfW

Robot classification by mechanical structure

by mechanical structure



Robot classification by mechanical structure

by mechanical structure

- cartesian
- cylindrical
- spherical / polar
- Articulated Robot
- SCARA (Selective Compliance Assembly Robot Arm)

Robot classification by mechanical structure

Selective Compliance Assembly Robot Arm

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Task

Please find SCARA robots in the Fanuc industrial robot part.

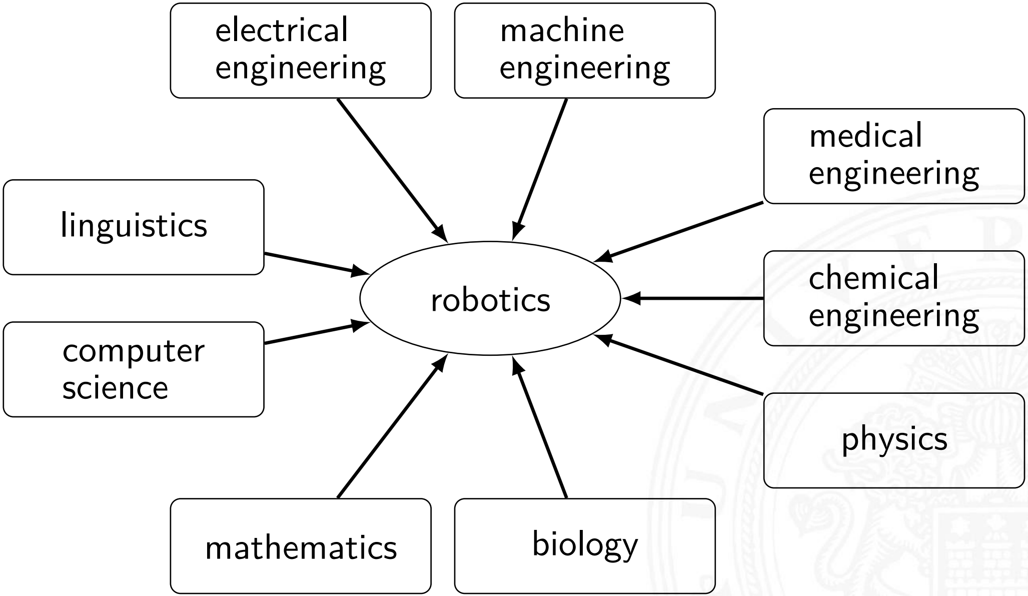
[15] https://www.youtube.com/watch?v=97KX-j8Onu0&t=30s

Robot classification by usage

by usage

- object manipulation
- object processing
- transport
- assembly
- quality testing
- deployment in non-accessible areas
- agriculture and forestry
- underwater
- building industry
- service robot in medicine, housework, ...

An interdisciplinary field

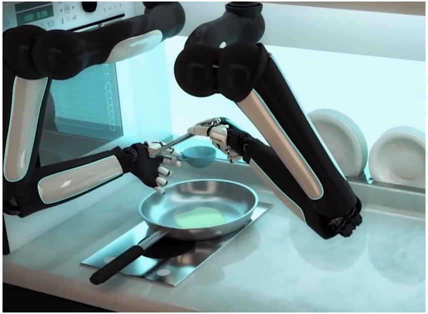


Robotics is Fun!

- A dream of mankind:

  Computers are the most ingenious product of human laziness to date.

computers ⇒ robots



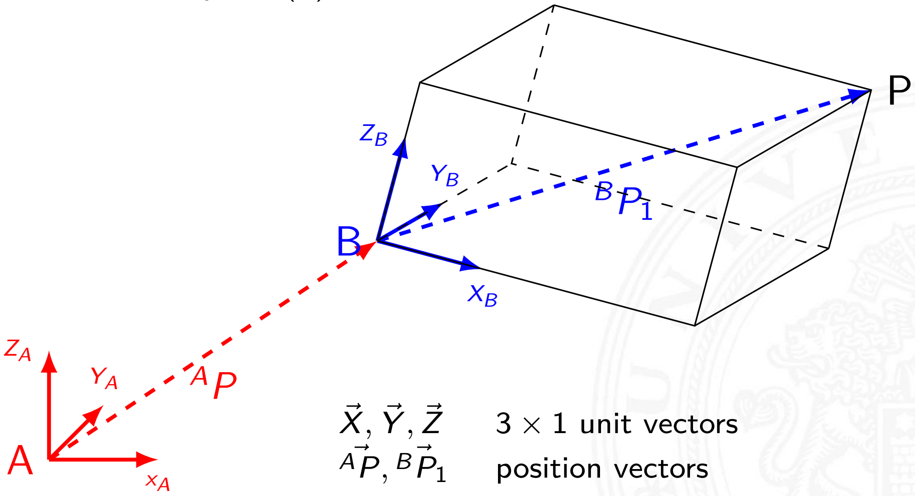
[16]

[16] https://www.youtube.com/watch?v=P1Irm1HlwnQ

Outline

Outline (cont.)

The **pose** of objects, in other words their **position** and **orientation** in Euclidian space can be described through specification of a cartesian coordinate system (B) in relation to a base coordinate system (A).



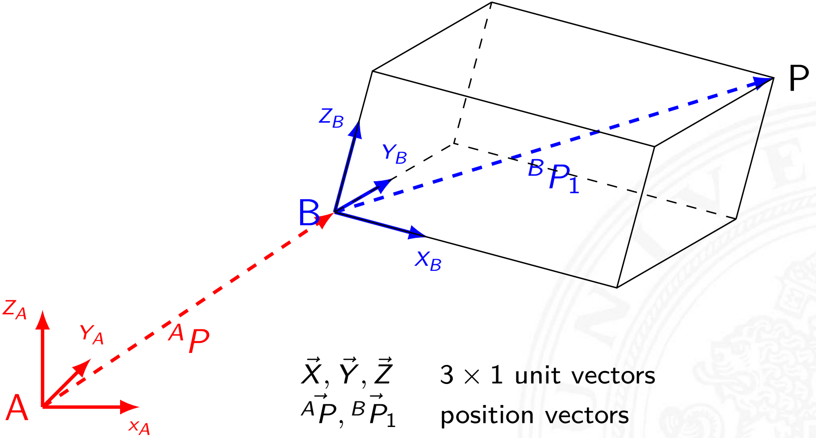
$\vec{X}, \vec{Y}, \vec{Z}$ — 3×1 unit vectors

$^A\vec{P}, {}^B\vec{P}_1$ — position vectors

Specification of position and orientation

Position:

- translation along the axes of the base coordinate system (A)



$\vec{X}, \vec{Y}, \vec{Z}$	3×1 unit vectors
${}^{A}\vec{P}, {}^{B}\vec{P}_1$	position vectors

- given by position vector $\vec{^{A}\mathbf{P}} = [{}^{A}p_x, {}^{A}p_y, {}^{A}p_z]^T \in \mathcal{R}^3$

Specification of position and orientation

`Orientation` (in space):

- given by Rotation matrix $R_B = [\vec{X}_B \ \vec{Y}_B \ \vec{Z}_B] \in \mathcal{R}^{3\times 3}$
- given by Rotation matrix ${}^A R_B = [{}^A\vec{X}_B \ {}^A\vec{Y}_B \ {}^A\vec{Z}_B] \in \mathcal{R}^{3\times 3}$

- ${}^A R_B$: the orientation of B with respect to A.
  (Latex: `$^{A}R_{B}$`)
- ${}^A\vec{X}_B, {}^A\vec{Y}_B, {}^A\vec{Z}_B$ are projection of $\vec{X}_B$, $\vec{Y}_B$, $\vec{Z}_B$ in A.

Dot product

In terms of the geometric definition, the dot product of two unit vectors $\vec{a}$ and $\vec{b}$ means the projection of the $\vec{a}$ in $\vec{b}$.
$\vec{a} \cdot \vec{b} = \|a\| \|b\| \cos(\theta)$

$$ {}^A\vec{X}_B = \begin{bmatrix} \vec{X}_B \cdot \vec{X}_A \\ \vec{X}_B \cdot \vec{Y}_A \\ \vec{X}_B \cdot \vec{Z}_A \end{bmatrix} \quad \text{and} \quad {}^A R_B = \begin{bmatrix} {}^A\vec{X}_B & {}^A\vec{Y}_B & {}^A\vec{Z}_B \end{bmatrix} $$

$$ {}^A R_B = \begin{bmatrix} \vec{X}_B \cdot \vec{X}_A & \vec{Y}_B \cdot \vec{X}_A & \vec{Z}_B \cdot \vec{X}_A \\ \vec{X}_B \cdot \vec{Y}_A & \vec{Y}_B \cdot \vec{Y}_A & \vec{Z}_B \cdot \vec{Y}_A \\ \vec{X}_B \cdot \vec{Z}_A & \vec{Y}_B \cdot \vec{Z}_A & \vec{Z}_B \cdot \vec{Z}_A \end{bmatrix} $$

Inverse of rotation matrix

$$ {}^{A}R_{B} = \begin{bmatrix} \vec{X}_B \cdot \vec{X}_A & \vec{Y}_B \cdot \vec{X}_A & \vec{Z}_B \cdot \vec{X}_A \\ \vec{X}_B \cdot \vec{Y}_A & \vec{Y}_B \cdot \vec{Y}_A & \vec{Z}_B \cdot \vec{Y}_A \\ \vec{X}_B \cdot \vec{Z}_A & \vec{Y}_B \cdot \vec{Z}_A & \vec{Z}_B \cdot \vec{Z}_A \end{bmatrix} $$

${}^{B}X_{A}^{T}$

the projection of $\vec{X}_A$ in B

$$ {}^{A}R_{B} = \begin{bmatrix} {}^{A}\vec{X}_B & {}^{A}\vec{Y}_B & {}^{A}\vec{Z}_B \end{bmatrix} = \begin{bmatrix} {}^{B}\vec{X}_A^{T} \\ {}^{B}\vec{Y}_A^{T} \\ {}^{B}\vec{Z}_A^{T} \end{bmatrix} = \begin{bmatrix} {}^{B}\vec{X}_A & {}^{B}\vec{Y}_A & {}^{B}\vec{Z}_A \end{bmatrix}^{T} = {}^{B}R_{A}^{T} $$

$$
{}^{A}R_{B} = \begin{bmatrix} {}^{A}\vec{X}_{B} & {}^{A}\vec{Y}_{B} & {}^{A}\vec{Z}_{B} \end{bmatrix} = \begin{bmatrix} {}^{B}\vec{X}_{A}^{T} \\ {}^{B}\vec{Y}_{A}^{T} \\ {}^{B}\vec{Z}_{A}^{T} \end{bmatrix} = \begin{bmatrix} {}^{B}\vec{X}_{A} & {}^{B}\vec{Y}_{A} & {}^{B}\vec{Z}_{A} \end{bmatrix}^{T} = {}^{B}R_{A}^{T}
$$

The inverse of a rotation matrix is simply its transpose:

$$
{}^{A}R_{B}^{-1} = {}^{B}R_{A} = {}^{B}R_{A}^{T} \quad \text{and} \quad {}^{A}R_{B}{}^{B}R_{A} = I
$$

whereas I is the identity matrix.

Specification of position and orientation

- Position:
  - given through ${}^{A}\vec{P} \in \mathcal{R}^3$
- Orientation:
  - given through the projection of $\vec{X}_B, \vec{Y}_B, \vec{Z}_B \in \mathcal{R}^3$ of B to the origin system A
  - summarized to rotation matrix ${}^{A}R_B = [{}^{A}\vec{X}_B \; {}^{A}\vec{Y}_B \; {}^{A}\vec{Z}_B] \in \mathcal{R}^{3\times 3}$

$$
{}^{A}R_B = \begin{bmatrix} r_{11} & r_{21} & r_{31} \\ r_{12} & r_{22} & r_{32} \\ r_{13} & r_{23} & r_{33} \end{bmatrix}
$$

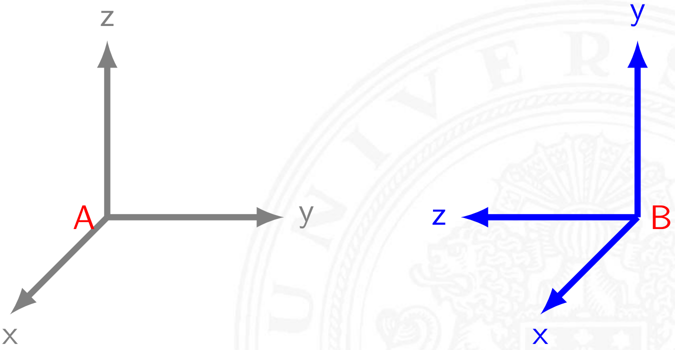
  - redundant, since there are 9 parameters for 3 degrees of freedom

Example of rotation matrix

Write the Rotation matrix of ${}^{A}R_{B}$.

${}^{A}R_{B} = [{}^{A}\vec{X}_{B}\ {}^{A}\vec{Y}_{B}\ {}^{A}\vec{Z}_{B}]$

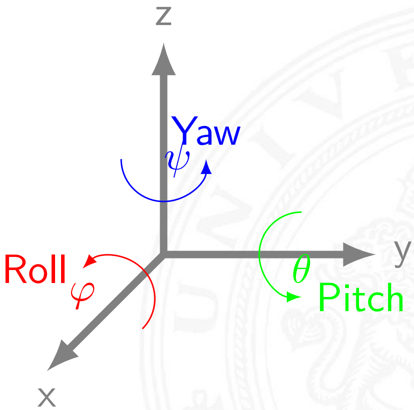
$$
{}^{A}R_{B} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}
$$



Rotation by rotation matrix

Sequential multiplication of the rotation matrices by order of rotation.

1. rotation φ (*phi*) around the x-axis
   $R_{x,\varphi}$ – Roll
2. rotation θ (*theta*) around the y-axis
   $R_{y,\theta}$ – Pitch
3. rotation ψ (*psi*) around the z-axis
   $R_{z,\psi}$ – Yaw



Rotatory transformation

(shortened representation: S : sin, C : cos)
The rotation matrix corresponding to a rotation around the x-axis with angle φ (*phi*):

$$R_{x,\varphi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\varphi & -S\varphi \\ 0 & S\varphi & C\varphi \end{bmatrix}$$

Rotatory transformation (cont.)

The rotation matrix corresponding to a rotation around the y-axis with angle θ (*theta*):

$$R_{y,\theta} = \begin{bmatrix} C\theta & 0 & S\theta \\ 0 & 1 & 0 \\ -S\theta & 0 & C\theta \end{bmatrix}$$

Rotatory transformation (cont.)

The rotation matrix corresponding to a rotation around the *z*-axis with angle ψ (*psi*):

$$R_{z,\psi} = \begin{bmatrix} C\psi & -S\psi & 0 \\ S\psi & C\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Concatenation of rotation matrices

$$R_{\psi,\theta,\varphi} = R_{z,\psi} R_{y,\theta} R_{x,\varphi}$$

$$= \begin{bmatrix} C\psi & -S\psi & 0 \\ S\psi & C\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\theta & 0 & S\theta \\ 0 & 1 & 0 \\ -S\theta & 0 & C\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\varphi & -S\varphi \\ 0 & S\varphi & C\varphi \end{bmatrix}$$

$$= \begin{bmatrix} C\psi C\theta & C\psi S\theta S\varphi - S\psi C\varphi & C\psi S\theta C\varphi + S\psi S\varphi \\ S\psi C\theta & S\psi S\theta S\varphi + C\psi C\varphi & S\psi S\theta C\varphi - C\psi S\varphi \\ -S\theta & C\theta S\varphi & C\theta C\varphi \end{bmatrix}$$

Remark: Matrix multiplication is not commutative:

$$AB \neq BA$$

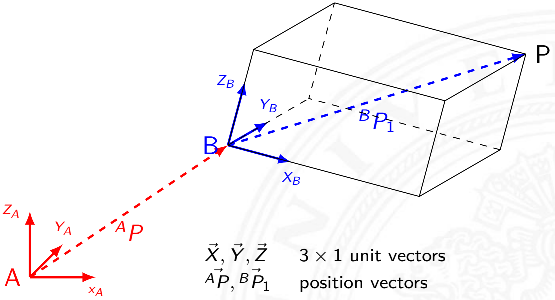
Concatenation of rotation matrices

- `Several rotations` can be multiplied. The following applies:
  - If the rotations are performed in relation to the current, newly defined (or changed) coordinate system, the newly added transformation matrices need to be multiplicatively appended on the right-hand side.
  - If all of them are performed in relation to the fixed reference coordinate system, the transformation matrices need to be multiplicatively appended on the left-hand side.

Mapping by rotation matrix

Mapping: changing descriptions from frame to frame.
For example, change the reference frame of ${}^B\vec{P}_1$?

$$
\begin{aligned}
{}^A\vec{P}_1 &= \begin{bmatrix} {}^B\vec{X}_A \cdot {}^B\vec{P}_1 \\ {}^B\vec{Y}_A \cdot {}^B\vec{P}_1 \\ {}^B\vec{Z}_A \cdot {}^B\vec{P}_1 \end{bmatrix} \\
&= \begin{bmatrix} {}^B\vec{X}_A^T \\ {}^B\vec{Y}_A^T \\ {}^B\vec{Z}_A^T \end{bmatrix} \cdot {}^B\vec{P}_1 \\
&= {}^A R_B {}^B\vec{P}_1
\end{aligned}
$$



$\vec{X}, \vec{Y}, \vec{Z}$	3 × 1 unit vectors
${}^A\vec{P}, {}^B\vec{P}_1$	position vectors

Summary: three common uses of a rotation matrix

Three common uses of a rotation matrix:

- represent an orientation
- rotate a vector or frame
- change the frame of reference of a vector or frame

Homogenous transformation

- `Homogeneous transformation matrix:`

$$T = \begin{bmatrix} R & \vec{p} \\ P & S \end{bmatrix}$$

  where P depicts the perspective transformation and S the scaling.
- In robotics, $P = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}$ and $S = 1$. Other values are used for computer graphics.

Homogenous transformation (cont.)

- Combination of $\vec{p}$ and R to $T = \begin{bmatrix} R & \vec{p} \\ \vec{0} & 1 \end{bmatrix} \in \mathcal{R}^{4\times 4}$
- Concatenation of several T through matrix multiplication
  - ${}^{A}T_{B}\,{}^{B}T_{C} = {}^{A}T_{C}$
- not commutative, in other words ${}^{B}T_{C}\,{}^{A}T_{B} \neq {}^{A}T_{B}\,{}^{B}T_{C}$

Homogenous transformation (cont.)

They are represented as four vectors using the elements of homogeneous transformation.

$$T = \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{r}_3 & \mathbf{p} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{21} & r_{31} & p_x \\ r_{12} & r_{22} & r_{32} & p_y \\ r_{13} & r_{23} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Inverse transformation

The inverse of a rotation matrix is simply its transpose:

$$R^{-1} = R^T \text{ and } RR^T = I$$

whereas I is the identity matrix.

The inverse of (1) is:

$$T^{-1} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & -\mathbf{p}^\mathbf{T} \cdot \mathbf{r}_1 \\ r_{21} & r_{22} & r_{23} & -\mathbf{p}^\mathbf{T} \cdot \mathbf{r}_2 \\ r_{31} & r_{32} & r_{33} & -\mathbf{p}^\mathbf{T} \cdot \mathbf{r}_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

whereas $\mathbf{r}_1$, $\mathbf{r}_2$, $\mathbf{r}_3$ and $\mathbf{p}$ are the four column vectors of (1) and $\cdot$ represents the dot product of vectors.

Translatory transformation

A translation with a vector $[p_x, p_y, p_z]^T$ is expressed through a transformation:

$$T_{(p_x, p_y, p_z)} = \begin{bmatrix} 1 & 0 & 0 & p_x \\ 0 & 1 & 0 & p_y \\ 0 & 0 & 1 & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotatory transformation

The transformation corresponding to a rotation around the x-axis with angle φ (*phi*):

$$T_{x,\varphi} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C\varphi & -S\varphi & 0 \\ 0 & S\varphi & C\varphi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotatory transformation (cont.)

The transformation corresponding to a rotation around the y-axis with angle θ (*theta*):

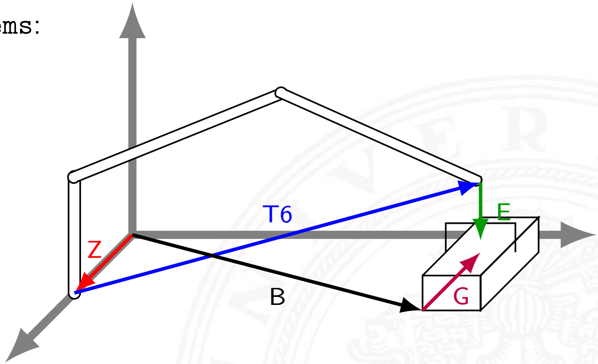
$$T_{y,\theta} = \begin{bmatrix} C\theta & 0 & S\theta & 0 \\ 0 & 1 & 0 & 0 \\ -S\theta & 0 & C\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotatory transformation (cont.)

The transformation corresponding to a rotation around the z-axis with angle ψ (*psi*):

$$T_{z,\psi} = \begin{bmatrix} C\psi & -S\psi & 0 & 0 \\ S\psi & C\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

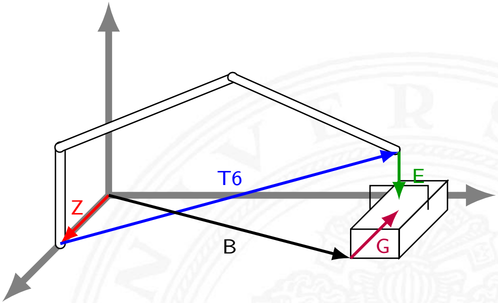
- `Transform of Coordinate systems:`
  frame: a reference S
  typical frames:
  - robot base
  - end effector
  - table (world)
  -
  - object
  - camera
  - ...



Relative transformations

One has the following transformations:

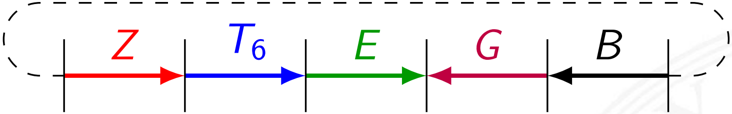
- Z :
  World $\rightarrow$ Manipulator base
- T_6 :
  Manipulator base $\rightarrow$ Manipulator end
- E :
  Manipulator end $\rightarrow$ End effector
- B :
  World $\rightarrow$ Object
- G :
  Object $\rightarrow$ End effector



Transformation equation

There are two descriptions for the desired end effector position, one in relation to the object and the other in relation to the manipulator. Both descriptions should equal to each other for grasping:

$$Z T_6 E = B G$$



In order to find the manipulator transformation:

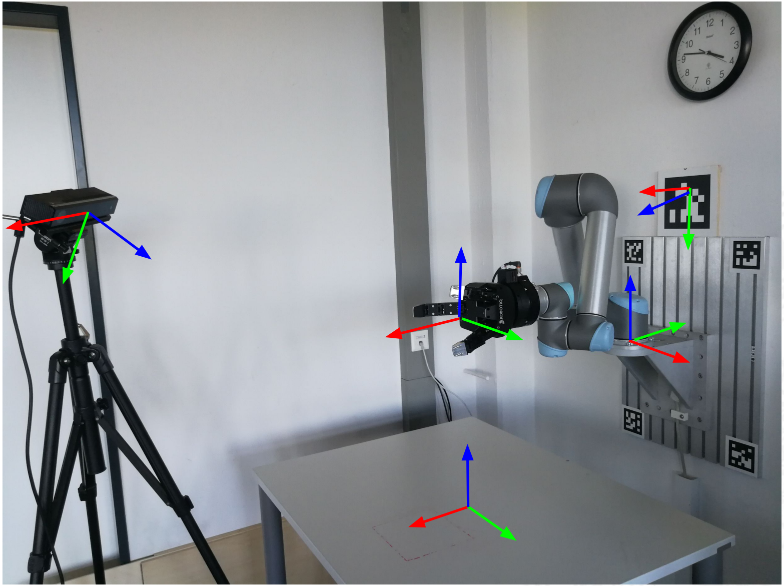
$$T_6 = Z^{-1} B G E^{-1}$$

In order to determine the position of the object:

$$B = Z T_6 E G^{-1}$$

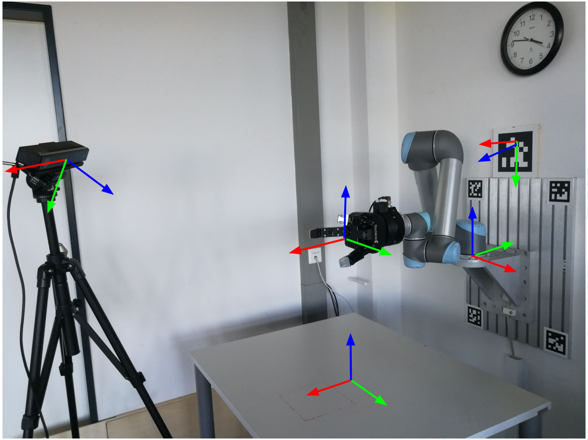
This is also called kinematic chain.

Example: coordinate transformation



Example: coordinate transformation

Given $T_{Base-Apriltag}$, $T_{Camera-Apritag}$, $T_{Camera-Object}$, calculate $T_{Base-Object}$.



$$T_{Base-Object} = T_{Base-Apriltag} \, T^{-1}_{Camera-Apritag} \, T_{Camera-Object}$$

Summary of homogeneous transformations

- `A homogeneous transformation` depicts the position and orientation of a coordinate frame in space.
- `If the coordinate frame` is defined in relation to a solid object, the position and orientation of the solid object is unambiguously specified.
- Three common uses of a transformation matrix: to represent a rigid-body configuration; to change the frame of reference of a vector or a frame; to displace a vector or a frame.

Summary of homogeneous transformations (cont.)

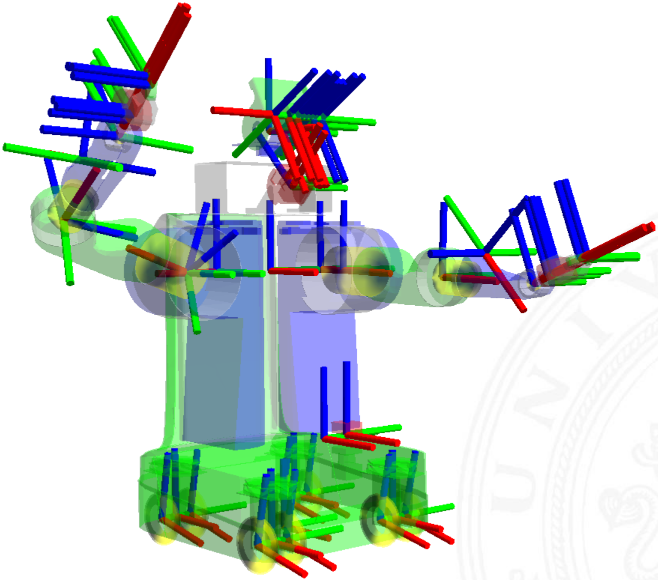
- Several translations and rotations can be multiplied.
  - right-hand multiplication → in relation to thecurrent, newly defined (or changed) coordinate system, .
  - left-hand multiplication → in relation to the fixed reference coordinate system.

Coordinates of a manipulator

- **Joint coordinates:**
  A vector $\mathbf{q}(t) = (q_1(t), q_2(t), ..., q_n(t))^T$
  (a robot configuration)
- **End effector coordinates**
  (Object coordinates):
  - A vector $\mathbf{p} = [p_x, p_y, p_z]^T$
  - Rotation matrix:

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

Outlook



Outlook (cont.)

- Can we use less of 9 parameters to represent the orientation?
- How to construct the transformation matrix of the manipulator's end-effector relative to the base of the manipulator?

Suggestions

- Read (available on google & library):
  - J. F. Engelberger, *Robotics in service*. MIT Press, 1989
  - K. Fu, R. González, and C. Lee, *Robotics: Control, Sensing, Vision, and Intelligence*. McGraw-Hill series in CAD/CAM robotics and computer vision, McGraw-Hill, 1987
  - R. Paul, *Robot Manipulators: Mathematics, Programming, and Control: the Computer Control of Robot Manipulators*. Artificial Intelligence Series, MIT Press, 1981
  - J. Craig, *Introduction to Robotics: Pearson New International Edition: Mechanics and Control*. Always learning, Pearson Education, Limited, 2013
- Repeat your linear algebra knowledge, especially regarding elementary algebra of matrices.

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