Lecture 1

Robotics and Intelligent Systems

Faculty of Artificial Intelligence

Prepared by

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Robotics and Intelligent Systems

Course Title: **Robotics and Intelligent Systems**

Course Code: **AI401**

Credit Hours: **3**

Level: **4th** Year, Faculty of Artificial Intelligence

Course Description

- This course provides an in-depth exploration of the field of robotics and intelligent systems, focusing on the **design**, **programming**, and **application** of robots in various industries.
- It covers **essential concepts** such as **kinematics**, **dynamics**, **control systems**, and **AI-based decision-making** for robotic systems.
- Students will gain **practical experience** through **lab assignments**, **projects**, and **programming simulations**.

Course Objectives

Upon completing this course, students will be able to:

- **Understand** the fundamental **concepts** of robotics, including **kinematics, dynamics**, and **control**.
- **Design** and **develop intelligent** robotic systems capable of decision-making using artificial intelligence.
- Apply **advanced algorithms** in robotic systems for **navigation**, **obstacle avoidance**, and **manipulation**.
- Integrate **sensors** and **actuators** into robotic systems and develop **real-time** control mechanisms.
- Evaluate the ethical and societal implications of **deploying intelligent** robotic systems.

Marks Distribution

- **Total = 100 points**
  - **Mid Term = 20 %**
  - **Lab Activities and Assignments = 10 %**
  - **Quizzes = 5 %**
  - **12th week Exam or Final Project Presentation = 15%**
  - **Final Exam = 50 %**

References

- Siciliano, B., Sciavicco, L., Villani, L., & Oriolo, G. (2010). Robotics: Modelling, Planning and Control. Springer.
- Craig, J. J. (2004). Introduction to Robotics: Mechanics and Control (3rd Edition). Pearson.
- Russell, S. J., & Norvig, P. (2016). Artificial Intelligence: A Modern Approach (3rd Edition). Pearson.
- Sutton, R. S., & Barto, A. G. (2018). Reinforcement Learning: An Introduction (2nd Edition). MIT Press.

Introduction to Robotics and Intelligent Systems

Robotics: is a **multidisciplinary** field that merges **engineering**, **computer science**, and **artificial intelligence** to create machines capable of **performing** tasks **autonomously** or **semi-autonomously**.

Robotics encompasses a variety of **applications**, from industrial automation to healthcare, and is integral to modern technological advancements.

Key Concepts

- **Robot**: A *programmable machine capable of carrying out a series of actions autonomously.*

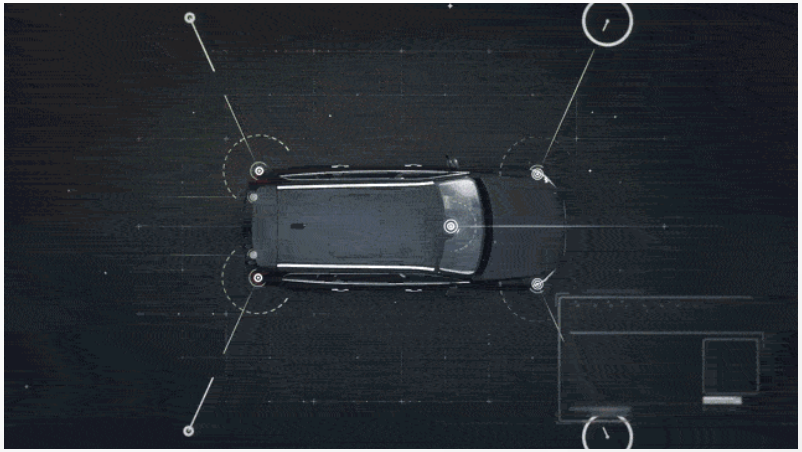
Automation: *The use of technology to perform tasks with minimal human intervention*

Current Trends in Robotics

- **Collaborative Robots (Cobots)**: Designed to work alongside humans, enhancing safety and productivity.

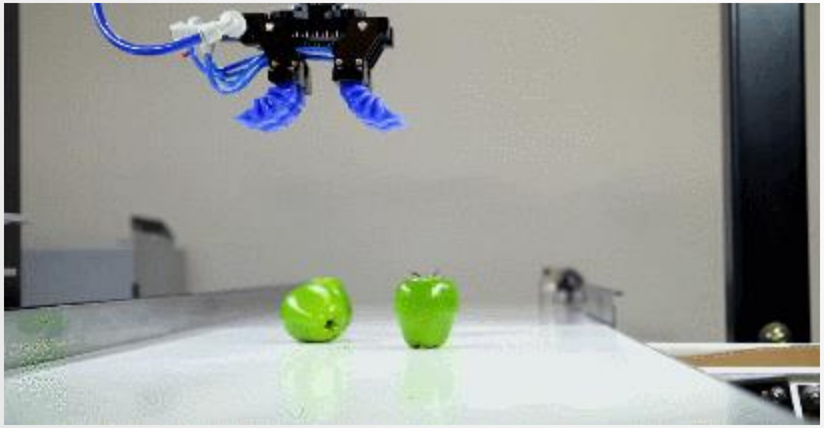
Current Trends in Robotics

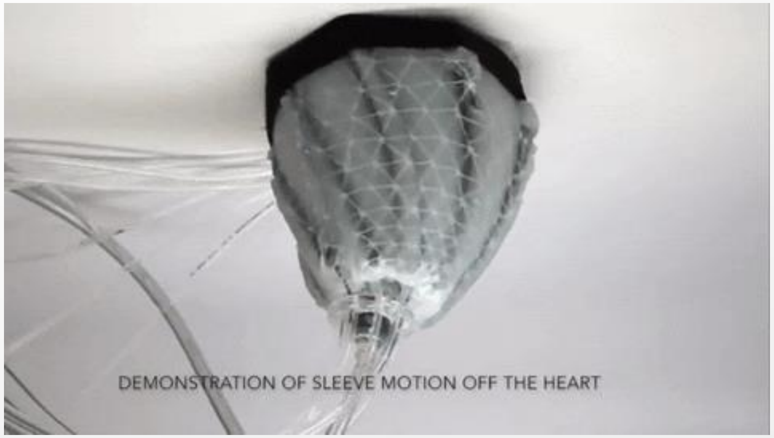
- **Autonomous Vehicles**: Rapid advancements in self-driving technology and drones.



Current Trends in Robotics

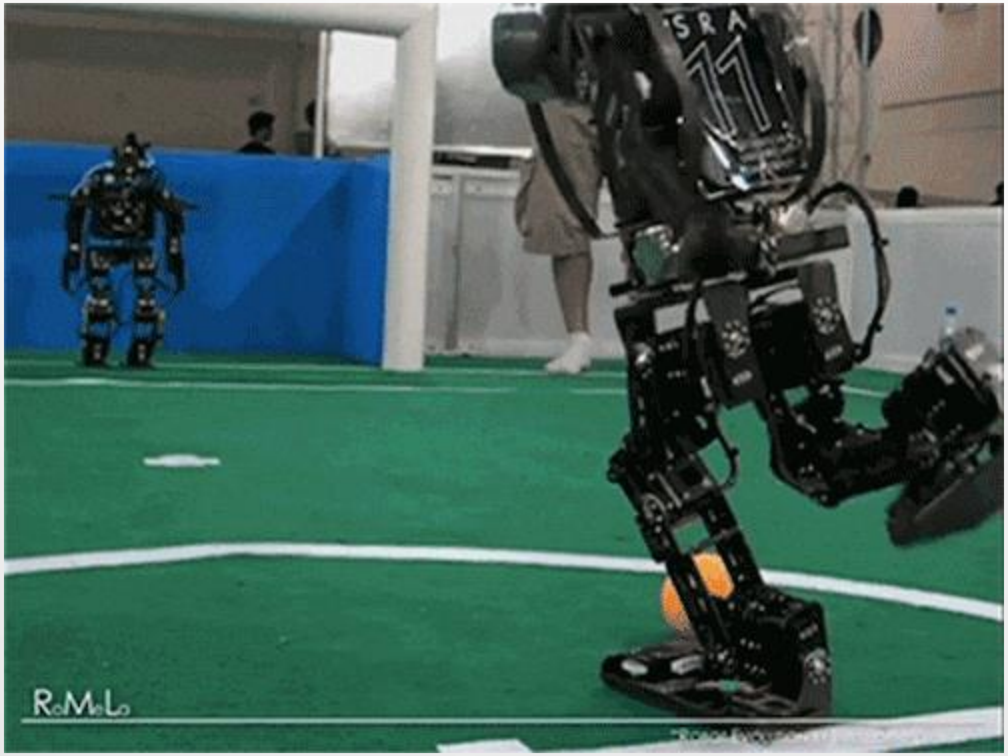
- **Soft Robotics**: Use of flexible materials for safe human-robot interaction.





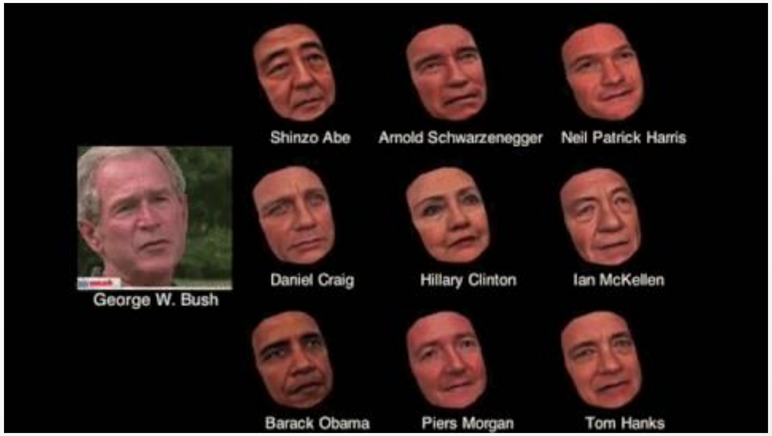
Current Trends in Robotics

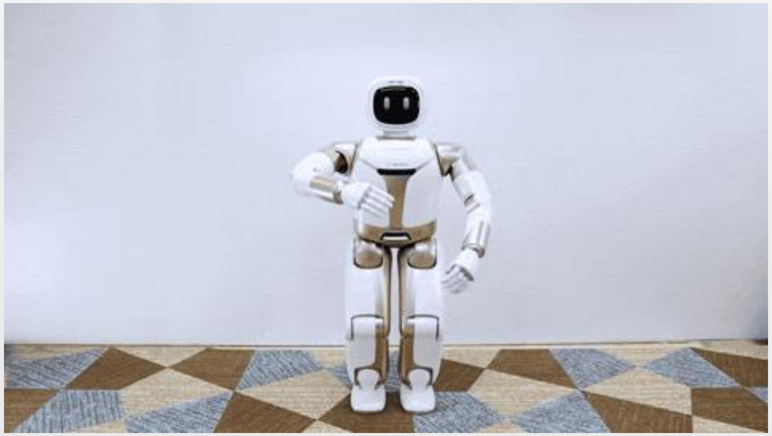
- **Swarm Robotics**: Multiple robots working in coordination, inspired by natural phenomena like ant colonies.



Current Trends in Robotics

- **AI Integration**: Improved machine learning algorithms that enable robots to adapt and optimize their performance.





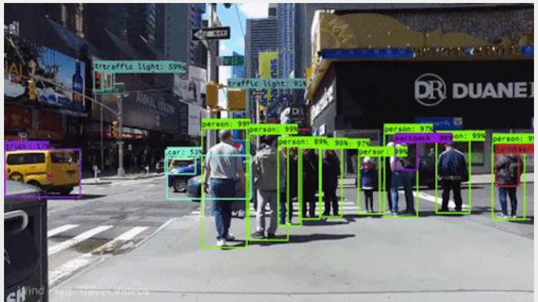
Intelligent Systems

Intelligent systems refer to computational systems that can perceive their environment, reason about it, and take actions based on that reasoning.

These systems utilize various technologies:

Key Components

- **Machine Learning**: Enables systems to learn from data and improve performance over time.
- **Natural Language Processing** (**NLP**): Allows machines to understand and respond to human language.
- **Computer Vision**: Enables interpretation of visual data from the environment.



Components of Robots

Robots are made up of several essential components that work together to achieve their functions:

1. Sensors

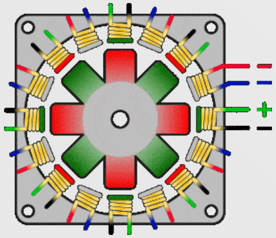
- Devices that collect data about the robot's environment.
- Types include:
  - **Cameras**: For visual input.
  - **LIDAR**: For distance measurement and mapping.
  - **Ultrasonic Sensors**: For proximity detection.

Components of Robots

2. Actuators

- Mechanisms that enable movement and manipulation.
- Types include:
  - **Electric Motors**: Commonly used for precise movements.
  - **Hydraulic Systems**: Used in heavy-duty applications.
  - **Pneumatic Systems**: Utilized for rapid movement.

Stepper motor



DC motor

Components of Robots

3. Controllers

- The **brain of the robot**, responsible for processing inputs from sensors and sending commands to actuators.
- Can range from simple **microcontrollers** to **complex embedded systems** running sophisticated algorithms.

Kinematics of Serial Robots:

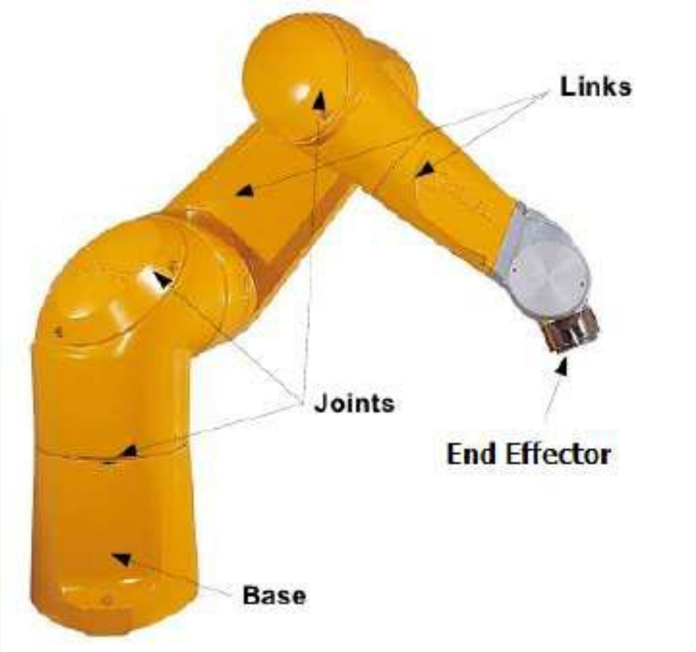
Position Analysis

- In this chapter, we will study **forward and inverse kinematics of serial robots**.
- With **forward kinematic** equations, we can determine where the robot's end (hand) will be if all joint variables are known.
- **Inverse kinematics** enables us to calculate what each joint variable must be to position the hand at a desired location and orientation.
- Using **matrices**, we first establish a method of **describing objects, locations, orientations, and movements**.
- Then we study the forward and inverse kinematics of different serial robot configurations such as Cartesian, cylindrical, and spherical coordinates.
- Finally, we use the **Denavit–Hartenberg (D-H)** representation to derive forward and inverse kinematic equations of all possible configurations of serial robots – regardless of number of joints, order of joints, and presence (or lack) of offsets and twists.

Structure of Robot Manipulators:

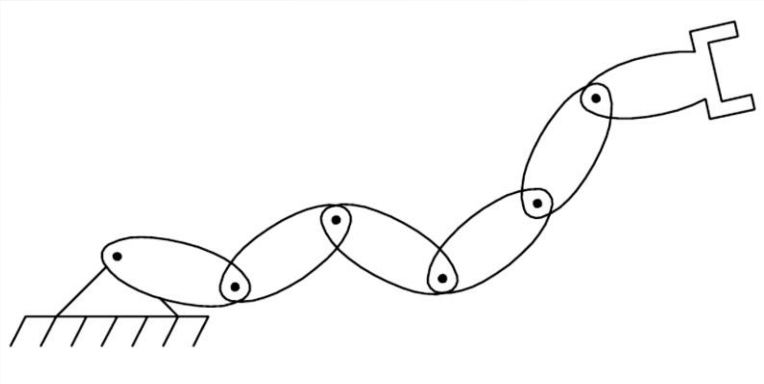
The robotic manipulators are composed of:

- **Kinematic open chain** composed of **Rigid Links** and **Joints**.
- **The BASE**: can be either **fixed** in the work environment or placed on a **mobile** platform.
- **End-Effector**: Tool is located at the end, used to execute the desired operations [gripper or specific tool].



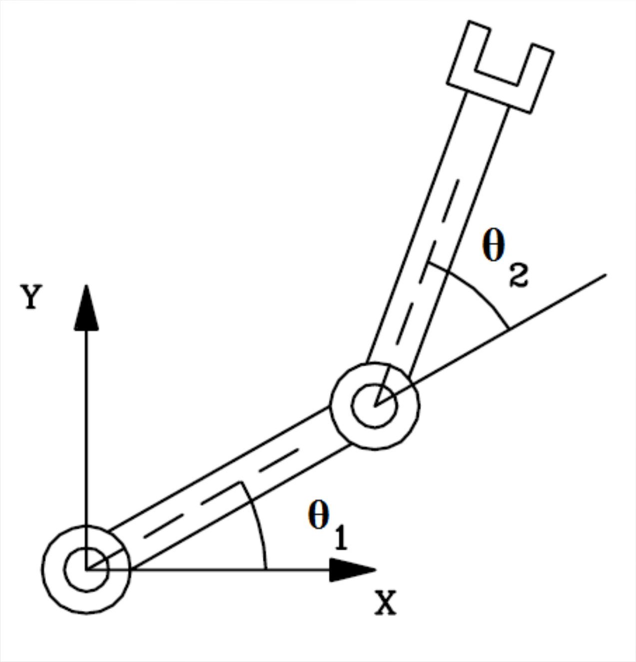
Each joint connects two links together

A **manipulator** is a kinematic chain composed by a **series** of rigid bodies, the links, connected by joints that allow a relative motion.

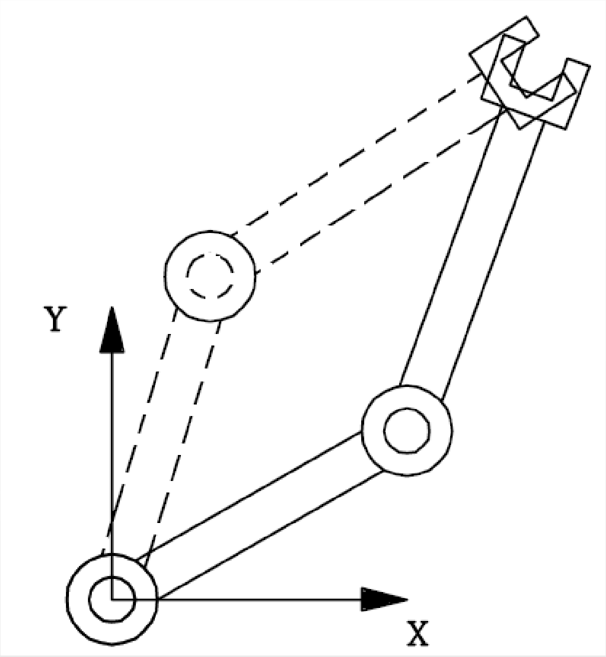


In robotic manipulation we are concerned with two common kinematic problems:

Forward Kinematics



Inverse Kinematics

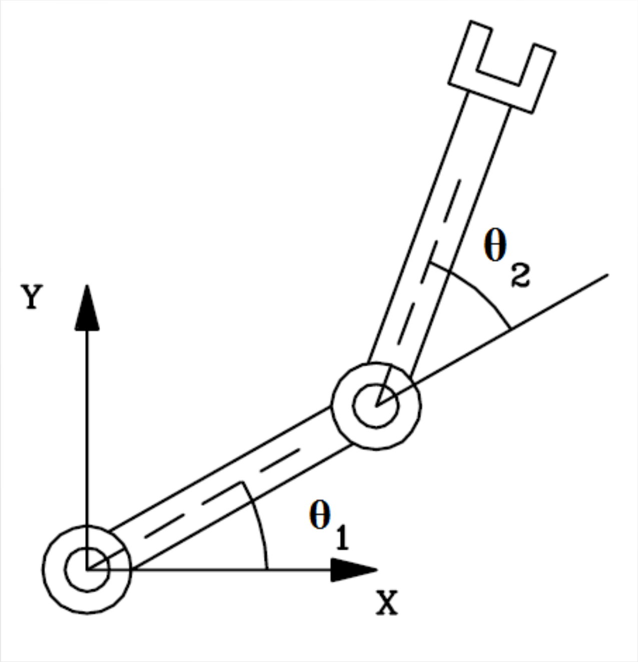


Forward Kinematics

Given: Joint Variables $\mathbf{q}$ (θ or d)
Required: Position and orientation of end-effector, $\mathbf{p}$.

$$\mathbf{p} = f(q_1, q_2, \ldots, q_n) = f(\mathbf{q})$$

EASY!

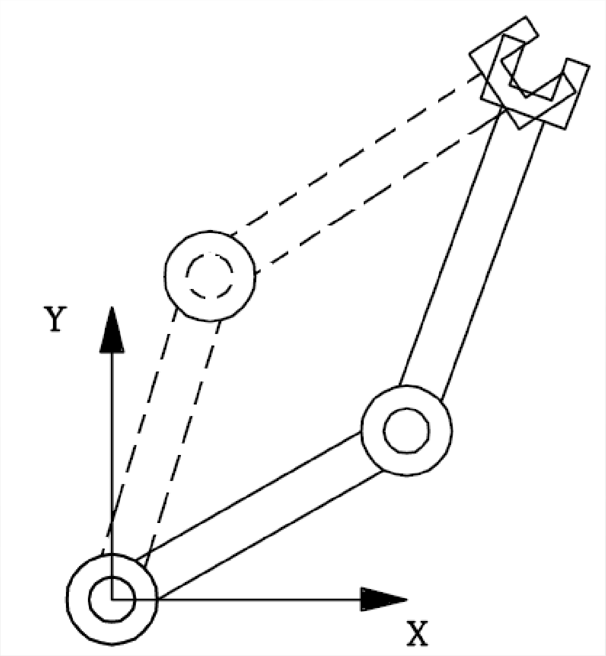


Inverse Kinematics

Given: Position and orientation of end-effector, $\mathbf{p}$.
Required: Joint Variables $\mathbf{q}$ (θ or d) to get $\mathbf{p}$

$$\mathbf{q} = f(\mathbf{p})$$

DIFFICULT (May be infinite solutions exist)!

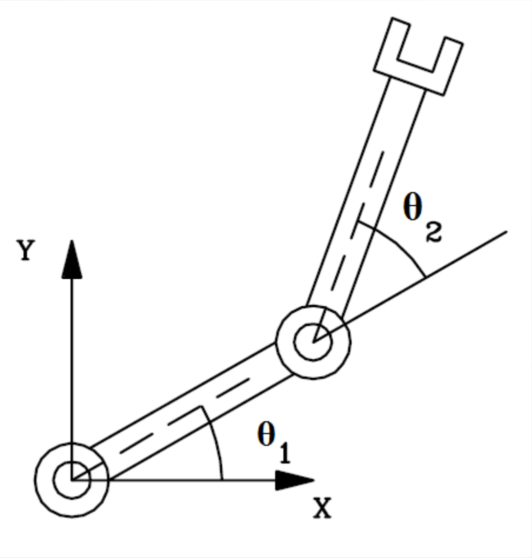


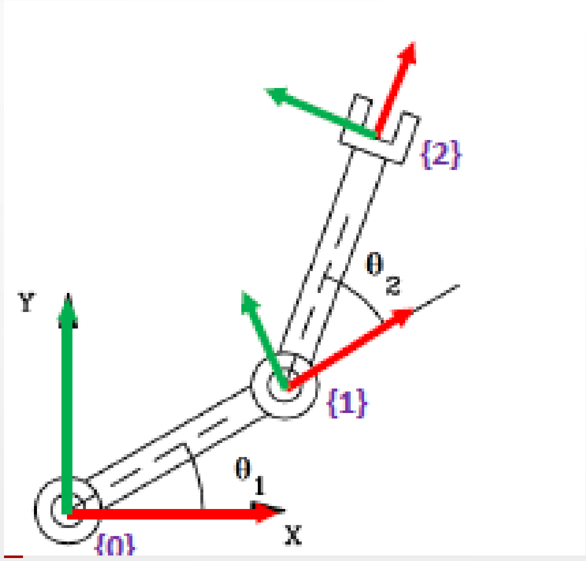
- Solving the manipulator kinematics requires the assignment of different coordinate frames on each joint and the end-effector.
- The goal is to find the **transformation** between the **end-effector** and the **base** frames.
- In robotic manipulators, two basic transformations are used:

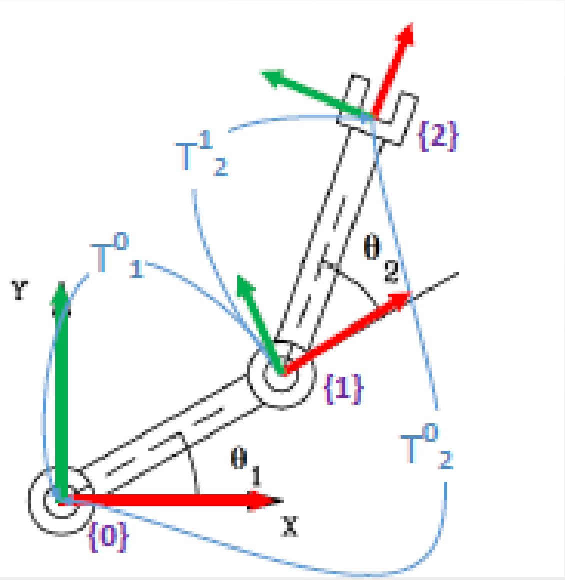
Translation and **Rotation.**

The **transformation** between the **end-effector** and the **base** frames

$$T_2^0 = T_1^0 * T_2^1$$





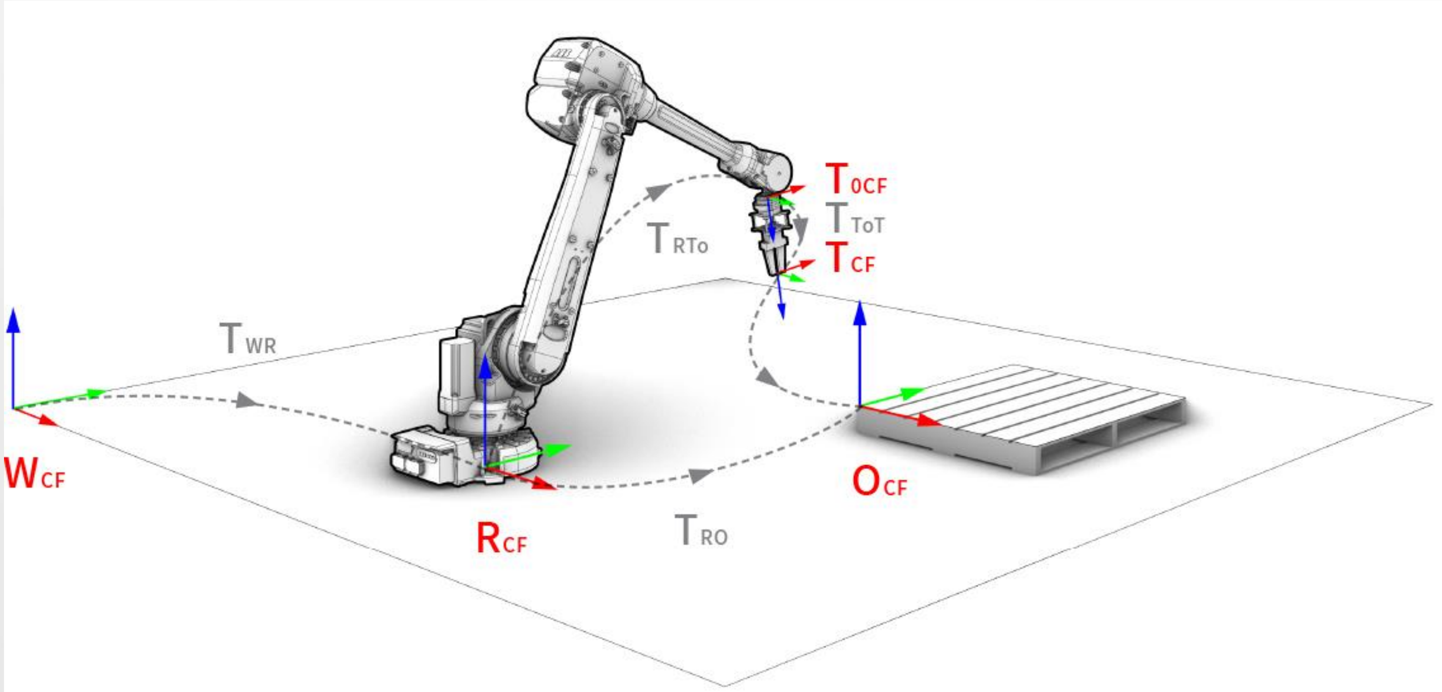


Representation of Translation:

Coordinate Frame:

The position and orientation of an object in space is referred to as its pose. Any description of an object's pose must always be made in relation to some coordinate frames.

In robotics, it is often convenient to keep track of multiple coordinate frames. (*Camera frame, robot frame, user frame, world frame, . . . etc*.)

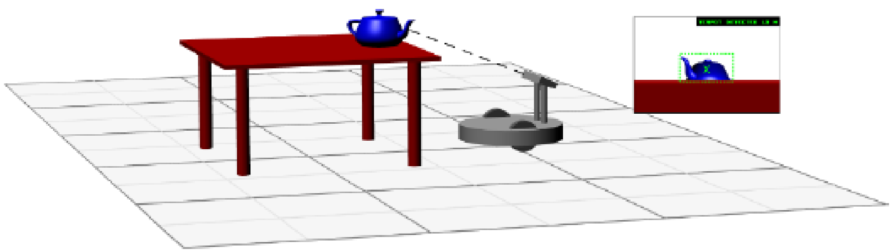


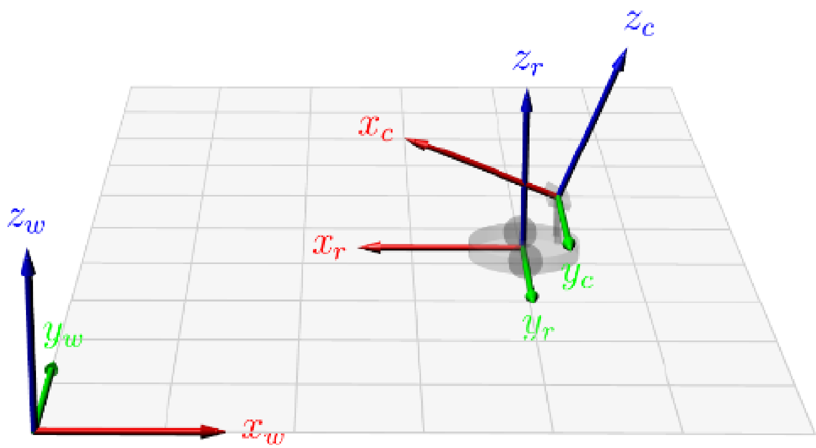
Coordinate Frame: **A set n of orthonormal basis vectors spanning R^n**

Coordinate Frames: [Example]

In this scenario, the user wants to know **where in the room the teapot is located**. Providing this information requires us to know each of the following:

- The position of the teapot relative to the camera.
- The position and orientation of the camera relative to the base of the robot.
- The position of the robot in the room.



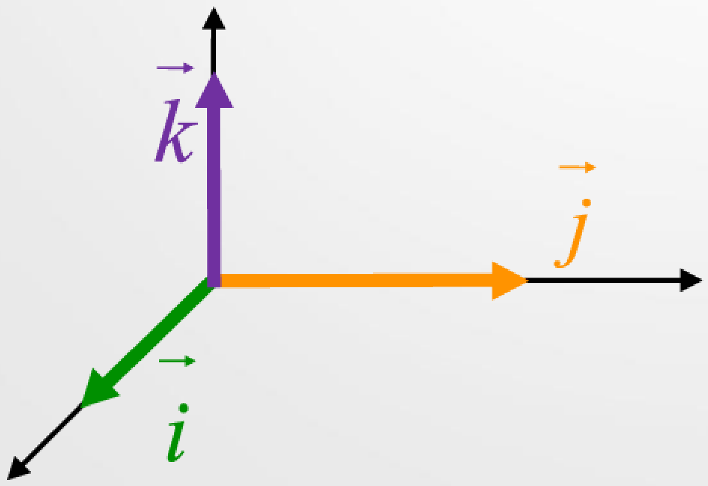


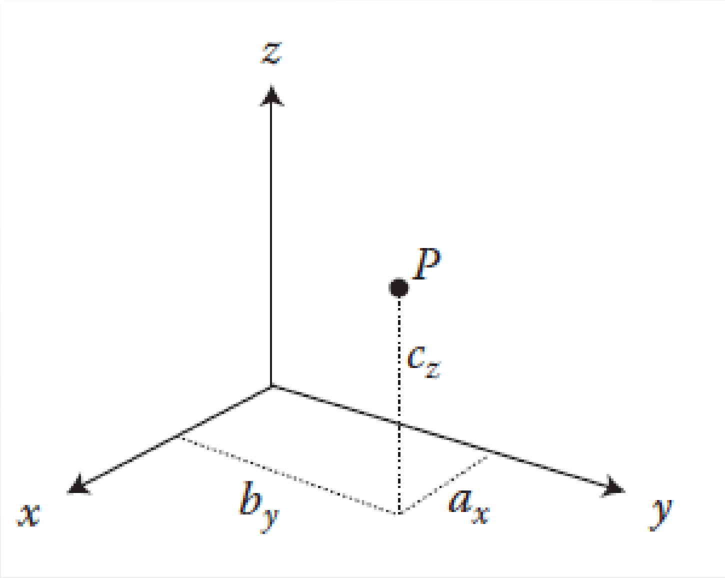
Representation of a Point in Space

A point P in space can be represented relative to a reference frame as:

$$P = a_x\mathbf{i} + b_y\mathbf{j} + c_z\mathbf{k}$$

3D Vectors





Finding Vectors

Given A(x_1, y_1, z_1) and B(x_2, y_2, z_2) then vector $\overrightarrow{AB} = \langle x_2 - x_1, y_2 - y_1, z_2 - z_1 \rangle$.

And to find the length (magnitude) of a 3D vector, we simply extend the distance formula and the Pythagorean Theorem.

Given $\vec{a} = \langle a_1, a_2, a_3 \rangle$, the length of vector $\vec{a}$, denoted $\|\vec{a}\|$ is $\|\vec{a}\| = \sqrt{a_1^2 + a_2^2 + a_3^2}$.

Example – How To Find Position Vectors

Suppose we wish to find the position vector corresponding to AB with A(2,-4,3) and B(4,7,-3) and determine its magnitude.

First, we find the position vector by subtracting components.

$$\overrightarrow{AB} = \langle 4 - 2, 7 - (-4), -3 - 3 \rangle = \langle 2, 11, -6 \rangle$$

Next, we use the formula above to find the length of our vector.

$$\text{If } \overrightarrow{AB} = \langle 2, 11, -6 \rangle, \text{ then } \|\overrightarrow{AB}\| = \sqrt{(2)^2 + (11)^2 + (-6)^2} = \sqrt{161}$$

Unit and Zero Vectors

The zero vector is the only vector with a length of 0 and has no specific direction. We denote the zero vector as follows:

$\vec{o} = \langle 0,0,0 \rangle$.

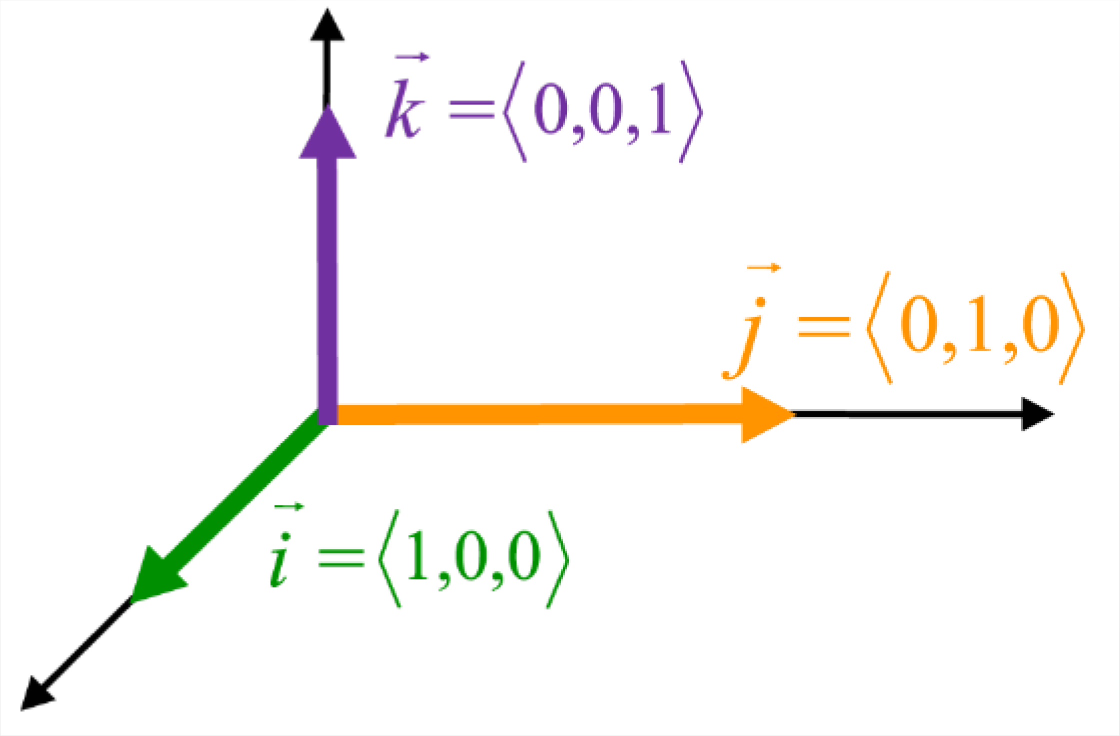
And the unit vector is a vector of length 1, and is denoted

$\vec{I} = (1,1,1)$

In general, **a unit vector** is found by dividing each component of a given vector by its magnitude, which will yield a magnitude of 1 but maintain its direction.

Standard Basis Vectors

And the most famous unit vectors are the standard basis vectors, $\vec{I} =\langle 1,0,0\rangle$, $\vec{J} =\langle 0,1,0\rangle$, $\vec{K} =\langle 0,0,1\rangle$ as they point in the directions of the positive x-,y-, and z-axes and intersect at a 90 degree angle.



Using matrix notation, we can represent the vector V in the following form:

$$V = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}$$

This representation can be modified to include a scale factor w, such that we can represent the vector V in the following form:

$$V = \begin{bmatrix} a_x \\ a_y \\ a_z \\ w \end{bmatrix}$$

Where:

$$v_x = \frac{a_x}{w} \qquad v_y = \frac{a_y}{w} \qquad v_z = \frac{a_z}{w}$$

If the value of the scale factor **w** changes, the magnitude of the vector changes accordingly.

- If w is bigger than 1, all vector components enlarge;
- if w is smaller than 1, all vector components become smaller.

If w = 0, the components will be infinity. So it represents a **direction vector** (**this means that a direction vector can be represented by a scale factor of w = 0, where the length is not important**)

- When w is 1, the size of these components remains unchanged; in this case, the actual vector is represented.

Example 2.1: A vector V is described as V= 3 i + 4 j + 12 k, represent it with a scale factor of 3, then represent a unit vector in its direction.

Solution

$$V = \begin{bmatrix} 3 \\ 4 \\ 12 \\ 1 \end{bmatrix} \quad \text{with } \underline{\text{a scale factor of 3 }} \text{then } V = \begin{bmatrix} 9 \\ 12 \\ 36 \\ 3 \end{bmatrix}$$

To have a unit vector in the direction of V, we should divide its components by its magnitude, ||V||

Where: $\|V\| = \sqrt{3^2 + 4^2 + 12^2} = 13$

So a unit vector in the direction of V is:

$$V_{unit} = \begin{bmatrix} 3/13 \\ 4/13 \\ 12/13 \\ 0 \end{bmatrix} \cong \begin{bmatrix} 0.23 \\ 03077 \\ 0.9203 \\ 0 \end{bmatrix}$$

Example 2.2 A vector **p** is 5 units long and is in the direction of a unit vector **q** described as follows. Express the vector in matrix form.

$$\mathbf{q}_{unit} = \begin{bmatrix} 0.371 \\ 0.557 \\ q_z \\ 0 \end{bmatrix}$$

Solution:

The unit vector's length must be 1. Therefore,

$$\lambda = \sqrt{q_x^2 + q_y^2 + q_z^2} = \sqrt{(0.371)^2 + (0.557)^2 + q_z^2} = 1 \quad \rightarrow \quad q_z = 0.743$$

$$\mathbf{q}_{unit} = \begin{bmatrix} 0.371 \\ 0.557 \\ 0.743 \\ 0 \end{bmatrix} \text{ and } \mathbf{p} = \mathbf{q}_{\text{unit}} \times 5 = \begin{bmatrix} 1.855 \\ 2.785 \\ 3.715 \\ 1 \end{bmatrix}$$

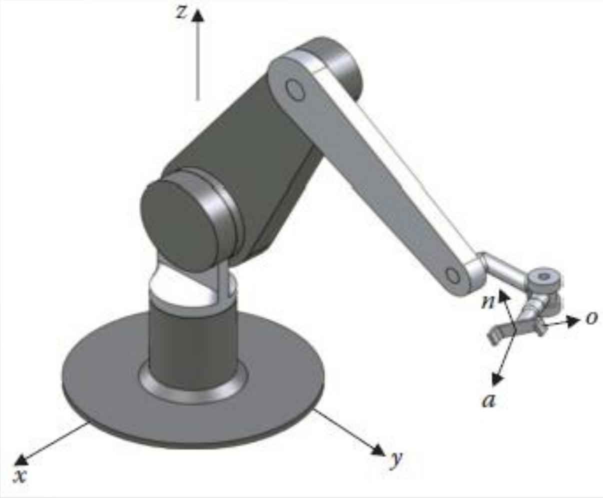
Representation of a Frame in Space

We use axes ***x, y and z*** to represent the fixed **Universe** frame (***Fx,y,z***), and use ***n, o and a*** axes to represent the moving (**current**) frame (***Fn,o,a***).

The letters ***n, o, and a*** are derived from the words ***normal***, ***orientation***, and ***approach*** the robot would have to approach it along the z-axis of the gripper. In robotic nomenclature, this axis is called approach-axis and is referred to as the ***a-axis***.

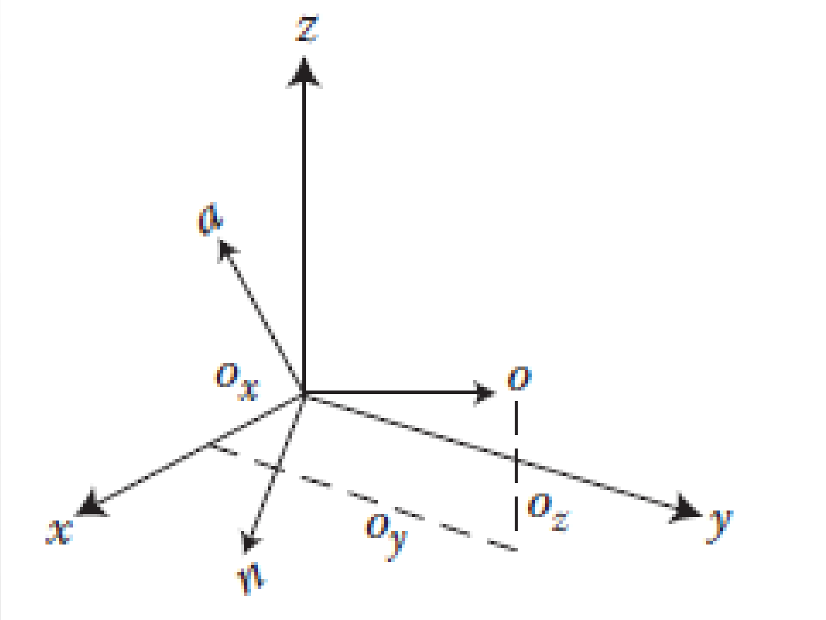
The ***orientation*** with which the gripper frame approaches the part is called orientation-axis, and is referred to as the ***o-axis***.

Since the ***x-axis*** is normal to both, it is referred to as the ***n-axis***.



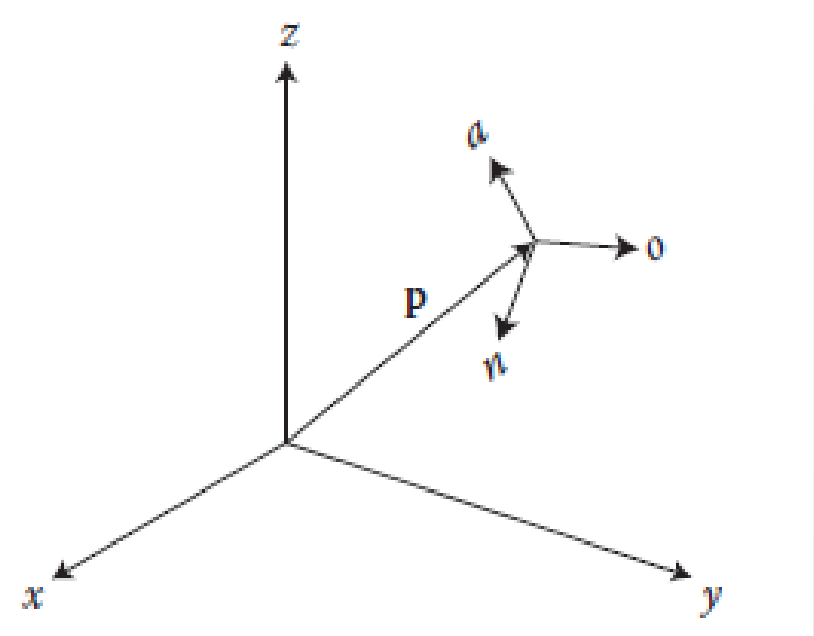
Assume a moving frame $F_{n,o,a}$ with its origin coincides with the origin of the reference frame $F_{x,y,z}$. As shown in figure, the vectors n, o and a are located in the fixed frame, we can represent that frame using a matrix contains these three vectors as follows

$$F = \begin{bmatrix} n_x & o_x & a_x \\ n_y & o_y & a_y \\ n_z & o_z & a_z \end{bmatrix}$$



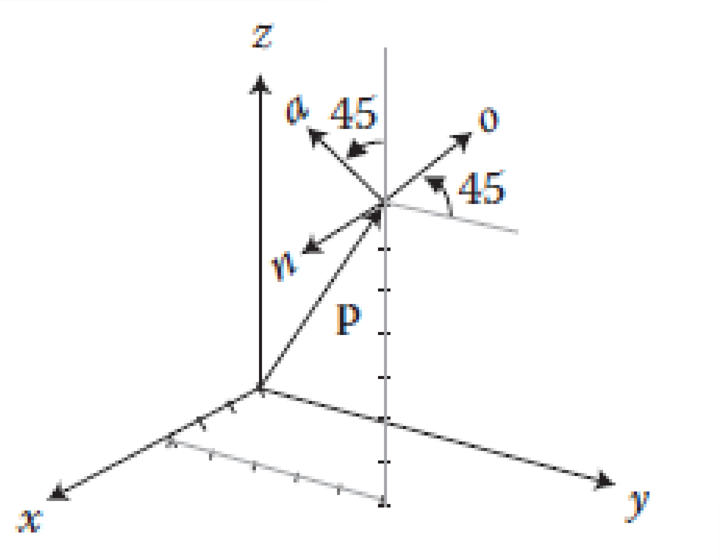
In fact the *moving frame is not attached to the origin* of the reference frame, So the moving frame shown in figure is represented by three vectors describing its directional unit vectors (n, o and a) and a fourth vector describing the **location of its origin (P)** relative to the fixed frame

$$F = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



As n, o and a are unit vectors, we use a scale w = 0 with them. But the vector P which represents the origin of the moving frame has a scale w = 1 as it is important to know its actual length (the matrix makes it 4×4 which is called **Homogenous** matrix)

Example 2.3 The frame F shown in Figure is located at 3,5,7 units, with its n-axis parallel to x, its o-axis at 45° relative to the y-axis, and its a-axis at 45° relative to the z-axis. The frame can be described by:



$$F = \begin{bmatrix} 1 & 0 & 0 & 3 \\ 0 & 0.707 & -0.707 & 5 \\ 0 & 0.707 & 0.707 & 7 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

End