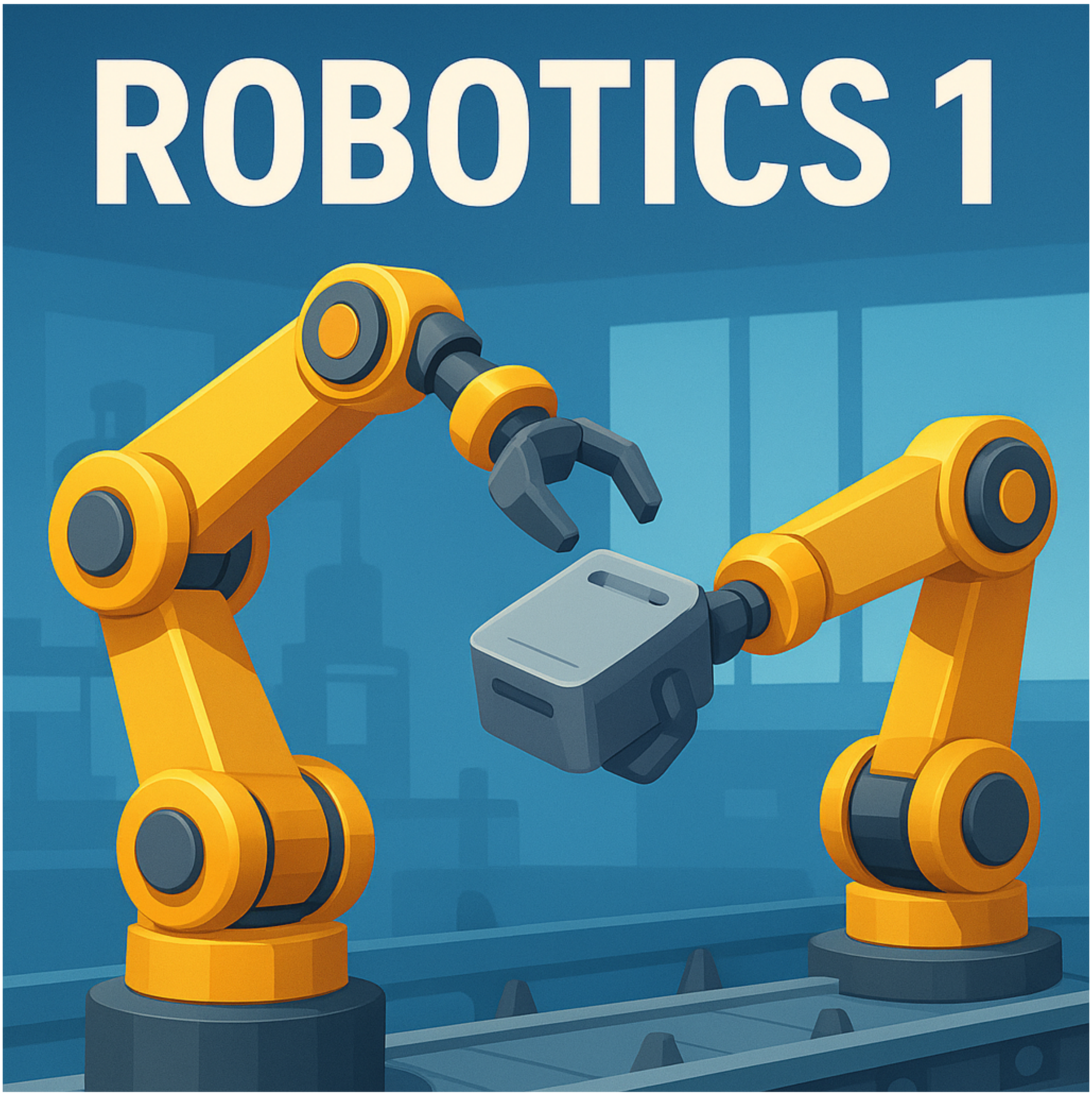
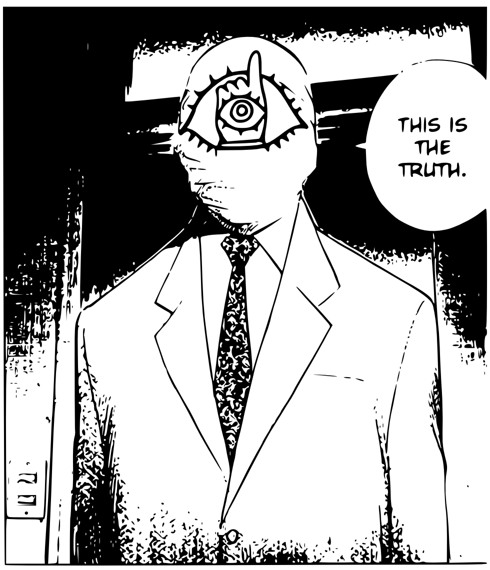
Marco Casu



SAPIENZA
UNIVERSITÀ DI ROMA

Faculty of Information Engineering, Computer Science and Statistics
Department of Computer, Control and Management Engineering
Master's degree in Artificial Intelligence and Robotics

This document summarizes and presents the topics for the Robotics 1 course for the Master's degree in Artificial Intelligence and Robotics at Sapienza University of Rome. The document is free for any use. If the reader notices any typos, they are kindly requested to report them to the author.



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CHAPTER

1

INTRODUCTION

In this chapter we will see a brief introduction to the mathematical tools used in the main topics of the course. The topics presented in this section may seem somewhat unclear, as many concepts and definitions are only briefly introduced and deliberately not elaborated upon. They will be discussed in detail in their respective chapters.

1.1 About the End Effector Pose

A robot is made up of a series of arms connected to one another by joints, these joints can be **revolut** or **prismatic** (as shown in figure 1.1), a revolut joint rotate the link connected along 1 axis, the prismatic joint can make the link extend or contract, making them translate along 1 axis.

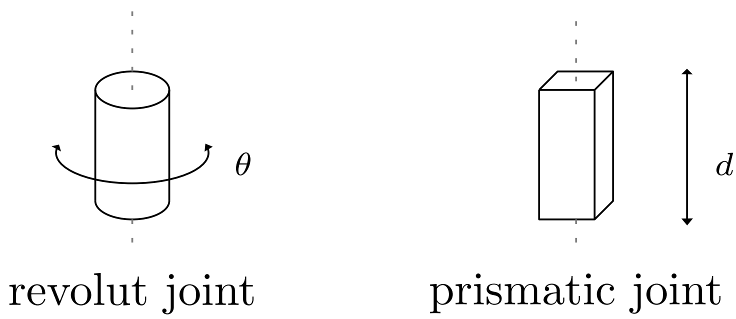


Figure 1.1: two types of joints (spatial representation)

It is important to know that that if the angle θ increase the joint is rotating counter clock wise. In a planar drawing, the joints are denoted as shown in image 1.2.

In the mathematical/geometrical model of a robotic arms, it is important the *kinematic skeleton*, the quantities involved are

- the current angle of the joints
- the length of the links

everything is defined respect to the base frame, usually denoted as Σ_0.

The robot shown in figure 1.3 is an *R4 robot* (4 revolut joints) with three links. With ${}^0\mathbf{p}_e$ and Σ_e we denote the position and the reference frame of the **end effector**, if there are a 0 supscript to a vector, we mean that is expressed in the base reference frame.

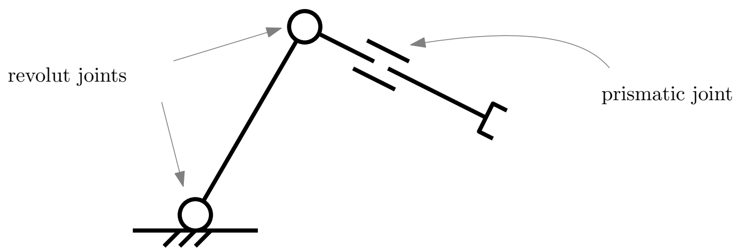


Figure 1.2: planar representation of the joints

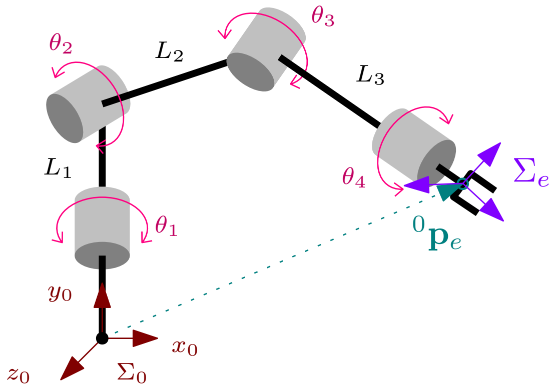


Figure 1.3: spatial R4 robot

With **Direct Kinematics**, we define the problem to find what are the **pose** (position and orientation) of the end effector, in function of the joint's angles.

$$Kin_p(\boldsymbol{\theta}) : \Sigma_0 \to \Sigma_e \tag{1.1}$$

$$\boldsymbol{\theta} = \begin{pmatrix}\theta_1 & \theta_2 & \theta_3 & \theta_4\end{pmatrix}^T \tag{1.2}$$

With Σ_e is denoted the reference frame of the end effector. How can we compute $Kin_p(\boldsymbol{\theta})$? This is given by an homogeneous 4×4 matrix defined as follows:

$${}^0T_e = \begin{pmatrix} & {}^0R_e & & {}^0\mathbf{p}_e \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1.3}$$

where

- ${}^0R_e \in SO(3)$ is the rotation matrix, and depends from $\boldsymbol{\theta}$
- ${}^0\mathbf{p}_e \in \mathbb{R}^3$ is the translation vector.

Recall: $SO(3)$ is the group of all the orthogonal 3×3 matrices with determinant equals to 1.

The matrix ${}^0T_e$ is obtained by multiplying n matrix (where n is the number of joints)

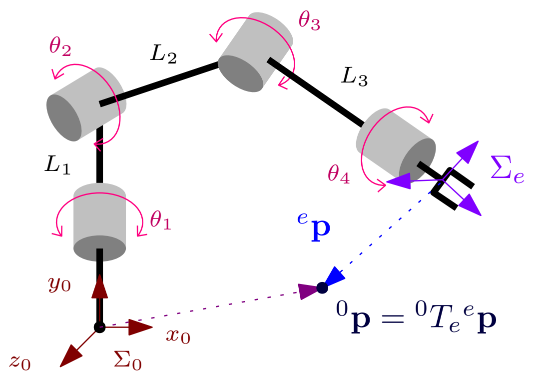
$${}^0T_e = {}^0A_1(\theta_1){}^1A_2(\theta_2)\dots{}^{n-1}A_n(\theta_n) = \tag{1.4}$$

$$\prod_{i=0}^{n-1} {}^iA_{i+1}(\theta_{i+1}). \tag{1.5}$$

Each *homogeneous matrix* ${}^{i-1}A_i$ describe the pose of the i-th joint's frame respect to the previous joint's frame, and depends from θ_i (the i-th joint's angle). A more detailed description of the matrix describing the direct kinematics will be given later.

If there are another frame Σ_w, the new matrix can be computed as follows

$${}^wT_e = {}^wT_0{}^0T_e. \tag{1.6}$$



the end effector position respect to the base frame is ${}^0T_e\mathbf{0}$

The **Inverse Kinematics** is the opposite problem, given a position ${}^0\mathbf{p}_e$ for the end effector, we want to find the values of $\boldsymbol{\theta}$ such that

$$ {}^0\mathbf{p}_e = Kin_p(\boldsymbol{\theta}) \tag{1.7} $$

to find $\boldsymbol{\theta}$, we have to solve a non-linear system of equations, this is generally an undecidable problem, but for some specific cases, there exists a closed form, that can be found analytically, there are also numerical methods. Clearly, for the positions out of the work space, the system does not admit solutions (also this can be checked analytically).

1.2 About the End Effector Velocity

Let's now consider **Differential Kinematics**, that is the problem to find the end effector velocity in the workspace given the velocity of the joint's angles. Since the superposition principle is valid, the components resulting from the movement of each individual joint, which constitute the final velocity of the end effector, can be considered separately. It is important to know that the velocity component of the end effector given by a joint, is always orthogonal to the rotation axis of that joint.

The end effector have

- a linear velocity, usually denoted $\mathbf{v}$
- an angular velocity, usually denoted $\boldsymbol{\omega}$.

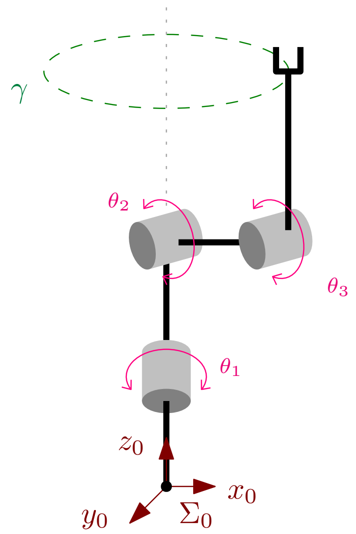


Figure 1.4: possible trajectory by moving θ_1

In the figure 1.4 the curve γ represent all possible positions where the end effector could lie if the angle θ_1 change, the linear velocity of the end effector is orthogonal to the z_0 axis. The velocity of the end effector doesn't depend only from the angular velocity, but also from the current configuration of the angles $\boldsymbol{\theta}$.

Even if the end effector is a rigid body, is sufficient to know the linear velocity of only one point and his angular velocity to compute the velocity of all the other points, since the following relation holds:

$$\mathbf{v}_2 = \mathbf{v}_1 + \boldsymbol{\omega} \times \mathbf{r}_{12} \tag{1.8}$$

where

- $\mathbf{v}_1$ is the velocity of the first point
- $\mathbf{v}_2$ is the velocity of the second point
- $\boldsymbol{\omega}$ is the angular velocity of the rigid body
- $\mathbf{r}_{12}$ is the difference between the positions of the two points.

Let's analyze the velocity components of the end effector. If the i-th joint is changing is angle, the linear velocity of the end effector will have one component that is

$$\mathbf{v}_i = \mathbf{j}_i(\boldsymbol{\theta})\dot{\theta}_i \tag{1.9}$$

where $\mathbf{j}_i$ is a 3 components vector describing the direction of the velocity. Since the direction depends from the configuration, the vector $\mathbf{j}_i$ is in function of $\boldsymbol{\theta}$. This holds for all the angles θ_i, the resultant linear velocity of the end effector will be

$$\mathbf{v} = \sum_{i=1}^{n} \mathbf{j}_i(\boldsymbol{\theta})\dot{\theta}_i \tag{1.10}$$

it can be written in matrix form

$$\mathbf{v} = J_L(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} = \begin{pmatrix} \mathbf{j}_1(\boldsymbol{\theta}) & \dots & \mathbf{j}_n(\boldsymbol{\theta}) \end{pmatrix} \begin{pmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{pmatrix} \tag{1.11}$$

where $J_L(\boldsymbol{\theta})$ is a $3 \times n$ matrix called the **Jacobian Matrix**, where n is the number of joints. This description were given in terms of the linear velocity, but it holds also for the angular velocity of the end effector, indeed we have two Jacobian Matrix:

- we denote $J_L(\boldsymbol{\theta})$ the Jacobian matrix for the linear velocity
- we denote $J_A(\boldsymbol{\theta})$ the Jacobian matrix for the angular velocity

$$\boldsymbol{\omega} = J_A(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} \tag{1.12}$$

the matrix

$$J(\boldsymbol{\theta}) = \begin{pmatrix} J_L(\boldsymbol{\theta}) \\ J_A(\boldsymbol{\theta}) \end{pmatrix} \in Mat(6 \times n) \tag{1.13}$$

it's called **basic Jacobian**.

The Jacobian matrix is a mapping from the joint velocity space to the end effector velocity space. Let's ignore the angular velocity for now, suppose that we want to impose to the end effector a desired linear velocity (in a specific time instant)

$$\mathbf{v} = \mathbf{v}_d \in \mathbb{R}^3 \tag{1.14}$$

we need to find the values for the vector $\dot{\boldsymbol{\theta}}$ such that

$$\mathbf{v}_d = J_L(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} \tag{1.15}$$

if we have 3 joints, the matrix J is squared and can be inverted

$$\dot{\boldsymbol{\theta}} = J_L^{-1}(\boldsymbol{\theta})\mathbf{v}_d \tag{1.16}$$

but this is not the general case, if $n > 3$, the system of equations given in (1.15) could

- have zero solutions

- have infinite solutions

if the determinant of J_L^{-1} is zero, the system admit infinite solutions if and only if the desired velocity vector $\mathbf{v}_d$ is in the range space of J_L^{-1}

$$\det J_L^{-1} = 0 \implies \exists \text{ inf. sol.} \iff \mathbf{v}_d \in \text{Range}(J_L^{-1}) \tag{1.17}$$

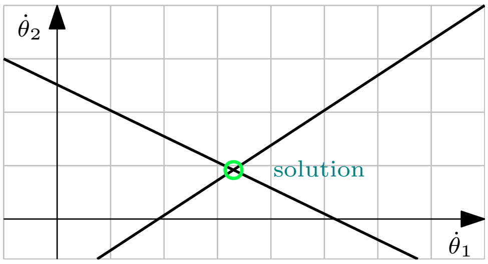
we remind that the range space of a matrix, is the set of all the linear combinations of the matrix's columns. If this isn't true, the system does not admit any solution, it means that no possible combination of velocity $\dot{\boldsymbol{\theta}}$ could realize the desired end effector velocity.

1.2.1 Singularity

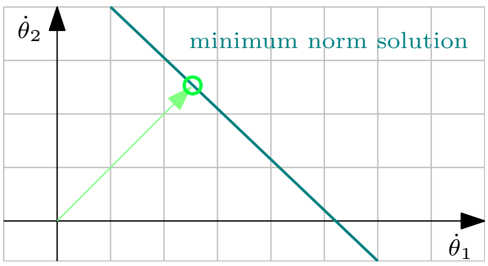
Let's talk about **singularities** in the joint velocity space, we will give a geometric example. Let's consider a 2R planar robot, with a fixed joints configuration $\boldsymbol{\theta}$, the Jacobian is a 2×2 matrix. Let $\mathbf{v}_d$ to be the desired velocity, the system is the following

$$\begin{pmatrix} v_d^x \\ v_d^y \end{pmatrix} = \begin{pmatrix} \mathbf{j}_1^T \\ \mathbf{j}_2^T \end{pmatrix} \begin{pmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{pmatrix} \tag{1.18}$$

the two linear equation of the system is represented on the plane as two lines. If $\det J_L \neq 0$, there are only one solution, and is the intersection between the two lines.



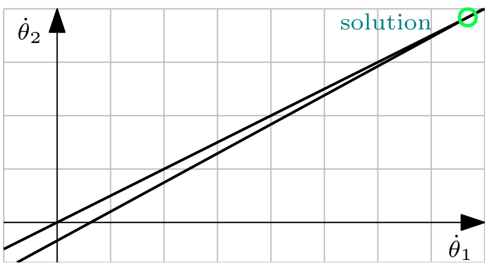
If $\det J_L = 0$, the two lines are parallel, so either they have no intersection, or they are the same line. If there are infinite solutions, we can choose the one with the smallest norm, since represents the "minimum energy" solution (the solution that requires the least joint rotation speed intensity).



We have a *singularity* when the determinant approaches zero

$$\det J_L \to 0 \tag{1.19}$$

The closer the determinant (in absolute value) gets to zero, the more "nearly" parallel the row vectors (and thus the lines they represent) become, which means the angle of intersection approaches zero. In this case the norm of the solution could be large.



This is true also because the following relations holds

$$J_L = \begin{pmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{pmatrix} \implies \tag{1.20}$$

$$J_L^{-1} = \frac{1}{\det J_L} \begin{pmatrix} j_{22} & -j_{12} \\ -j_{21} & j_{11} \end{pmatrix} \tag{1.21}$$

$$\mathbf{v}_d = J_L \dot{\boldsymbol{\theta}} \tag{1.22}$$

$$\dot{\boldsymbol{\theta}} = J_L^{-1} \mathbf{v}_d \tag{1.23}$$

$$\dot{\boldsymbol{\theta}} = \frac{1}{\det J_L} \begin{pmatrix} j_{22} & -j_{12} \\ -j_{21} & j_{11} \end{pmatrix} \mathbf{v}_d \tag{1.24}$$

with $\det J_L \to 0$ the term $\frac{1}{\det J_L}$ (and with it, also $\dot{\boldsymbol{\theta}}$) became bigger and bigger. In this case, the required joint rotation velocity might not be achievable by the robotic arm's motors.

The previous example showed how certain algebraic relationships are connected to physical problems in robot joint control. Another similar example is the following, consider the robotic arm shown in figure 1.5.

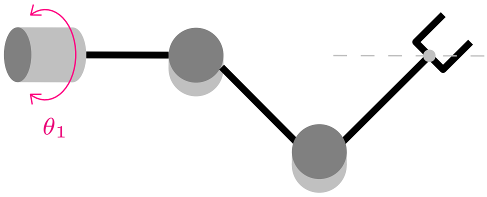


Figure 1.5: 3R spatial robot

Geometrically, it can be seen that by rotating only the first joint θ_1, the position of the end effector will not change, this condition holds when

$$J_L(\boldsymbol{\theta}) \begin{pmatrix} \dot{\theta}_1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \tag{1.25}$$

this is true if the vector $\begin{pmatrix} \dot{\theta}_1 & 0 & 0 \end{pmatrix}^T$ is in the kernel of the Jacobian matrix

$$\begin{pmatrix} \dot{\theta}_1 \\ 0 \\ 0 \end{pmatrix} \in \ker J_L(\boldsymbol{\theta}). \tag{1.26}$$

Therefore, the vectors contained in the kernel of the Jacobian matrix for the linear (or angular) velocity represent all possible combinations of individual joint velocities that would not change the position (or orientation) of the end effector.

1.3 Brief Overview of Planning and Control

When we want to control the end effector of a robotic arm, we want to know how to move the joints to get a specific position for the end effector, and also how to control the joints over the time to get a particular *trajectory* in the working space.

Consider a 2R planar robot, as shown in figure 1.6, where $\boldsymbol{\theta}$ is the angular position of the joints, and $\mathbf{p}_e = f(\boldsymbol{\theta})$ is the position of the end effector for some $f_{\mathbb{R}}^2 \to \mathbb{R}^2$.

We would like to move the end effector from a certain starting point $\mathbf{p}_a \in \mathbb{R}^2$ to an another point $\mathbf{p}_b \in \mathbb{R}^2$. We could consider the segment line from $\mathbf{p}_a$ to $\mathbf{p}_b$ defined as follows:

$$\mathbf{p}(s) = s\mathbf{p}_b + (1-s)\mathbf{p}_a \qquad s \in [0,1]. \tag{1.27}$$

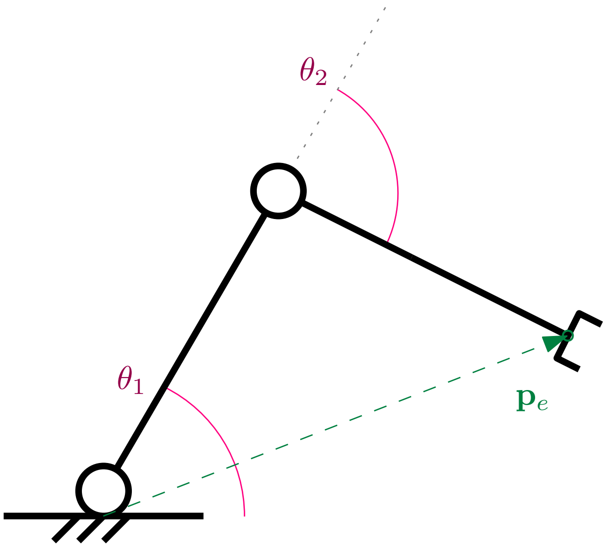


Figure 1.6: a 2R planar robot

Such a trajectory can be represented by a time-dependent function that starts from an initial time $t_0 = 0$ until a final time T, making s a monotonically increasing function of $t \in [0, T]$:

$$s : [0,1] \longmapsto [0,T] \tag{1.28}$$
$$s(0) = 0 \tag{1.29}$$
$$s(1) = T \tag{1.30}$$
$$\mathbf{p}(s) = \mathbf{p}(s(t)) \tag{1.31}$$

We say that a trajectory is rest-to-rest if the velocity of the end effector at the start and at the end of that trajectory is zero:

$$\dot{\mathbf{p}}(s(0)) = \dot{\mathbf{p}}(s(T)) = \mathbf{0} \tag{1.32}$$

we need to include boundary conditions. Considering the chain rule, the derivative of $\mathbf{p}$ respect to the time t is

$$\dot{\mathbf{p}} = \frac{d\mathbf{p}}{dt} = \frac{d\mathbf{p}}{ds}\frac{ds}{dt} = \frac{d\mathbf{p}}{ds}\dot{s} \tag{1.33}$$

since

$$\frac{d\mathbf{p}}{ds} = \frac{d}{ds}\left(s\mathbf{p}_b + (1-s)\mathbf{p}_a\right) = \mathbf{p}_b - \mathbf{p}_a \tag{1.34}$$

we have

$$\dot{\mathbf{p}} = \frac{d\mathbf{p}}{ds}\dot{s} = \dot{s}(\mathbf{p}_b - \mathbf{p}_a) \tag{1.35}$$

the acceleration is

$$\ddot{\mathbf{p}} = \ddot{s}(\mathbf{p}_b - \mathbf{p}_a) + \dot{s} \cdot \mathbf{0} = \ddot{s}(\mathbf{p}_b - \mathbf{p}_a) \tag{1.36}$$

we have that

$$\dot{\mathbf{p}}(s(0)) = 0 \iff \dot{s}(0)(\mathbf{p}_b - \mathbf{p}_a) \iff \dot{s}(0) = 0 \tag{1.37}$$
$$\dot{\mathbf{p}}(s(T)) = 0 \iff \dot{s}(T)(\mathbf{p}_b - \mathbf{p}_a) \iff \dot{s}(T) = 0 \tag{1.38}$$

The starting velocity and the final velocity is zero, so the variation of the velocity is zero, this can be seen by the integral of the acceleration

$$\int_0^T \ddot{\mathbf{p}}dt = \int_0^T \ddot{s}(\mathbf{p}_b - \mathbf{p}_a)dt = (\mathbf{p}_b - \mathbf{p}_a)\int_0^T \ddot{s}dt = (\mathbf{p}_b - \mathbf{p}_a)(\dot{s}(T) - \dot{s}(0)) = 0. \tag{1.39}$$

Now we consider the *control aspects* of the problem, we denote $\mathbf{p}_e(t)$ the position of the end effector at the time t, and $\mathbf{p}_d(t)$ the **desired position** at time t.

$$\mathbf{p}_d(0) = \mathbf{p}_a. \tag{1.40}$$

We define the **error** such as the difference between the current position and the desired position:

$$\mathbf{e}(t) = \mathbf{p}_d(t) - \mathbf{p}_e(t) \tag{1.41}$$

The aim of the *control system* of the robot is to maintain $\mathbf{e}$ as close to zero as possible. This can be done by computing the initial error, and by giving to the system a new command $\dot{\boldsymbol{\theta}}(t)$ to correct it such that $\mathbf{e}(t) \to \mathbf{0}$. Let's denotate the error as follows

$$\mathbf{e}(t) = \begin{pmatrix} e_x(t) \\ e_y(t) \end{pmatrix} \tag{1.42}$$

For now, we will not discuss in detail how to control the error through the control of joint velocities $\dot{\boldsymbol{\theta}}$; it is sufficient to know that the following condition is required:

$$\dot{\mathbf{e}}(t) = -K\mathbf{e}(t) = \begin{pmatrix} -k_x & 0 \\ 0 & -k_y \end{pmatrix} \begin{pmatrix} e_x(t) \\ e_y(t) \end{pmatrix} \tag{1.43}$$

with $k_x, k_y > 0$. Why this conditions is required?

- if $e_x(t)$ is greater than zero, the condition $\dot{e}_x(t) = -k_x e_x(t)$ describes a decrease in error, making it approach zero
- if $e_x(t)$ is smaller than zero, the condition $\dot{e}_x(t) = -k_x e_x(t)$ describes an increase in error, making it approach zero
- same for e_y.

The system of equations

$$\dot{\mathbf{e}}(t) = \begin{pmatrix} -k_x & 0 \\ 0 & -k_y \end{pmatrix} \begin{pmatrix} e_x(t) \\ e_y(t) \end{pmatrix} \implies \begin{cases} \dot{e}_x(t) = -k_x e_x(t) \\ \dot{e}_y(t) = -k_y e_y(t) \end{cases} \tag{1.44}$$

admits exponential functions as a solution

$$e_x(t) = e_x(0)e^{-k_x t} \tag{1.45}$$

$$e_y(t) = e_y(0)e^{-k_y t} \tag{1.46}$$

if the initial error $\mathbf{e}(0)$ is not zero, then the error will approaches zero, without never reaching it. For practical applications it goes sufficiently fast to values very close to zero.

We introduce now an important concept in linear differential equations systems.

Definition 1 *Let $A \in M_{n,n}(\mathbb{R})$ to be a squared real-valued matrix. The **matrix exponential**, denoted e^A, is the $n \times n$ matrix defined as follows:*

$$e^A = \sum_{k=0}^{\infty} \frac{A^k}{k!} \tag{1.47}$$

Given a linear system

$$\dot{\mathbf{x}} = A\mathbf{x} \tag{1.48}$$

the solution is

$$\mathbf{x}(t) = e^{At}\mathbf{x}(0) \tag{1.49}$$

In some cases the exponential matrix can be computed easily, let's assume that A is diagonal

$$A = \begin{pmatrix} a_1 & 0 & \cdots & 0 \\ 0 & a_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_n \end{pmatrix} \tag{1.50}$$

in this case we have that

$$A^k = \begin{pmatrix} a_1 & 0 & \cdots & 0 \\ 0 & a_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_n \end{pmatrix} \times \cdots \times \begin{pmatrix} a_1 & 0 & \cdots & 0 \\ 0 & a_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_n \end{pmatrix} = \begin{pmatrix} a_1^k & 0 & \cdots & 0 \\ 0 & a_2^k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_n^k \end{pmatrix} \tag{1.51}$$

so

$$e^A = \sum_{k=0}^{\infty} \frac{1}{k!} \begin{pmatrix} a_1^k & 0 & \cdots & 0 \\ 0 & a_2^k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_n^k \end{pmatrix} = \begin{pmatrix} \sum_{k=0}^{\infty} \frac{a_1^k}{k!} & 0 & \cdots & 0 \\ 0 & \sum_{k=0}^{\infty} \frac{a_2^k}{k!} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sum_{k=0}^{\infty} \frac{a_n^k}{k!} \end{pmatrix} \tag{1.52}$$

$$= \begin{pmatrix} e^{a_1} & 0 & \cdots & 0 \\ 0 & e^{a_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{a_n} \end{pmatrix}. \tag{1.53}$$

So, if a system is described by a diagonalizable matrix A there exists a diagonal matrix Λ and an invertible matrix T such that

$$A = T\Lambda T^{-1} \tag{1.54}$$

in this case we can easily calculate the exponential matrix

$$e^{At} = T^{-1}e^{\Lambda t}T. \tag{1.55}$$

Note: The Sections 1.4, 1.6, 1.7, 1.5, 1.8 are written with the aid of Gemini, by having the model process the information taken from the professor's slides and the lecture notes.

1.4 Defining Robots

The concept of a robot is formalized through several key definitions, spanning from strict industrial standards to more encompassing theoretical perspectives.

1.4.1 Standardized Definitions

1. Industrial Definition (Robotic Institute of America - RIA)

The RIA defines a robot as a **re-programmable, multi-functional manipulator** designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks. A crucial element of this definition is the requirement that the robot must **acquire information from the environment** and move intelligently in response, setting it apart from simpler automated machinery.

2. ISO 8373:2012 Definition

The International Organization for Standardization (ISO) provides a formal, international standard: an industrial robot is an **automatically controlled, re-programmable, multi-purpose manipulator** programmable in **three or more axes**. The manipulator may be either **fixed in place or mobile** and is intended for use in industrial automation applications. This specific definition helps to delineate complex, versatile machines from basic mechanical devices.

1.4.2 The Visionary Definition: Perception and Action

A broader, more "visionary" definition emphasizes the cognitive and functional aspects of robotic systems: the **intelligent connection between perception and action**.

- **Perception:** This is the process of acquiring and processing sensing information from the environment.

- **Action:** This involves not just controlling the robot's current state, but actively **making some changes in the physical world** to achieve a goal.

This relationship forms a continuous feedback loop that governs autonomous behavior:

$$\text{percept} \longrightarrow \text{action} \longrightarrow \text{percept}$$

The robot's understanding of its environment (*percept*) drives its movement or operation (*action*), which modifies the environment, leading to a new cycle of perception.

1.5 Notable Robot Examples

Throughout history, various robots have exemplified different facets of the definition of robotics, from pure industrial work to exploration and human interaction.

- **Comau H4 (1995):** Representing the industrial segment, these manipulators were widely used in **automotive industries** (e.g., owned by Fiat at the time). They are a classic example of fixed, multi-functional, re-programmable automation.
- **Waseda WAM-8 (1984):** This famous **humanoid robot** from a Japanese university demonstrated early cognitive abilities. It was capable of complex tasks such as playing an organ and reading music from a sheet, combining perception (reading) and fine manipulation.
- **Spirit Rover (2002):** An excellent example of **autonomous mobile robotics and exploration**.
  - It was landed on Mars, featuring articulated wheels and solar panels.
  - Its mission was to move, analyze material, and send gathered information back to Earth.
  - While the **global target** is **specified remotely**, the rover must operate with significant **local autonomy** because of the approximately 8-minute communication delay required to receive instructions from Earth. This necessity highlights the critical role of the onboard perception-action loop for mission success.

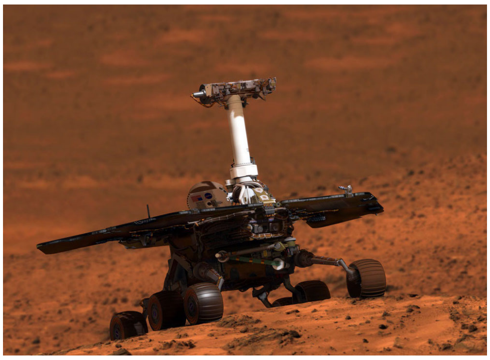


Figure 1.7: Spirit Rover (2002)

According to the rigorous **ISO 8373:2012** definition, certain devices and systems are **not considered robots**. These exclusions are typically applied to specific devices with only **one or two degrees of freedom (DOF)** and complex software systems lacking the physical manipulator required by the standard. Systems that are not classified as robots under the ISO 2012 standard include:

- Software "bots", Artificial Intelligence (AI), and Robotic Process Automation (RPA).
- Voice assistants.
- Automatic Teller Machines (ATMs).
- Cooking machines, smart washing machines, and similar appliances.

Furthermore, advanced mobile systems like drones and autonomous cars are generally not classified as robots under this definition. However, in a **2021 revision**, the term **robotic device** was introduced to encompass these increasingly sophisticated, automated machines that fall outside the strict definition of an industrial robot.

The word ”robot” has an historical and literary origin that is foundational to the field:

- The term derives from the Slavic word **Robota**, meaning ”work” or ”forced labor.”
- The first recorded use of the word ”Robot” in a theatrical context was in **1920** by Czech writer **Karel Čapek** in his science-fiction play, *Rossum's Universal Robots (R.U.R.)*. In the play, ”robots” are artificial, human-like creatures created to be inexpensive workers.

1.6 The Ethical Framework: Asimov's Three Laws of Robotics

The science fiction author Isaac Asimov defined a set of foundational ethical rules for robotics in his short stories.

1. **First Law:** A robot may not injure a human being or, through inaction, allow a human being to come to harm.
   - This law is fundamental to modern **collaborative robotics** (cobots), ensuring human safety is prioritized as robots and humans work in close proximity.
2. **Second Law:** A robot must obey orders given to it by human beings, except where such orders would conflict with the First Law.
   - This establishes the robot's subordination to human command. Situations like robots used in war or faulty programming clearly violate this rule.
3. **Third Law:** A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.
   - The robot's self-preservation is conditional, being secondary to human safety and commands.

1.7 Evolution and Characteristics of Robot Manipulators

The journey toward the industrial robot began around the 1950s with the convergence of **Computerized Numerically Controlled (CNC) machines** and **mechanical telemanipulators**. This synthesis led to the development of the first **robot manipulators**, with the **Unimation PUMA (1970)** being a key early example.

Unlike the early mechanical telemanipulators, which often required continuous human control, true robot manipulators offered several distinct advantages:

- **Absence of Position Memory:** The robot operates based on its programmed coordinates, not needing to remember past states.
- **Adaptivity** to conditions previously unknown.
- High **Accuracy** in positioning.
- Superior **Repeatability** of operation (the ability to return consistently to a programmed point).

For an industrial manipulator, it is often noted that **repeatability** and **compliance** (adaptivity to variations) are more fundamental for task success than absolute accuracy.

The history of industrial robotics is marked by key patented designs and technological firsts: **The First Industrial Robot** The very first industrial robot was installed at a General Motors plant in **1961**. It was developed by **George Devol and Joseph Engelberger** of Unimation.

- **Kinematics:** This design featured a total of **6 Degrees of Freedom (DOF)**, comprising five revolute (rotational) joints and one prismatic (linear) joint. This combination was considered the optimal solution at the time to achieve **full control over the end effector's pose** (position and orientation).

Key Successor Robot Manipulators Following the first installation, several robots introduced foundational innovations:

- **ASEA IRB-6 (1973):** The first robot where all axes were driven by **electric motors** (all-electric drives), featuring 5 DOF.
- **Cincinnati Milacron T3 (1974):** Recognized as the first industrial robot to be controlled by a **micro-computer**.
- **Hirata AR-300 (1978):** Introduced the first **SCARA (Selective Compliance Assembly Robot Arm)** robot, which has a distinct cylindrical workspace, prioritizing speed and rigidity in the vertical axis.
- **Unimation PUMA 560 (1979):** Characterized by its 6 revolute joints, this was the first truly **'anthropomorphic'** robot, offering human-like dexterity.

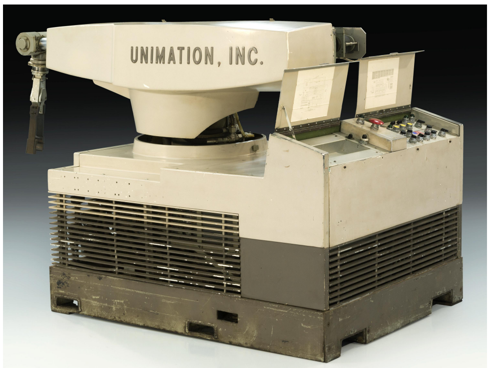


Figure 1.8: Unimation PUMA 560 (1979)

Actuators power the robot and sustain its payload. **Electric motors** are the most common choice, converting electrical energy to torque. However, when required to sustain a **heavy payload**, a **hydraulic actuator** generally works better due to its higher power-to-weight ratio.

1.8 Global Industrial Robotics Market Statistics

The following statistics are sourced from the **International Federation of Robotics (IFR)** World Robotics documents (Executive Summary for 2025 statistics). These figures illustrate the rapid global expansion of industrial automation.

1.8.1 Operational Stock and Growth Rates

The total worldwide operational stock of industrial robots reached **4.6 million units** at the end of 2024. This represents a substantial growth of **+9%** compared to 2023. Over the five-year period from 2019 to 2024, the market demonstrated a robust Compound Annual Growth Rate (**CAGR**) of **+11%**.

The Compound Annual Growth Rate is calculated as:

$$\text{CAGR} = \left(\frac{V_{\text{end}}}{V_{\text{begin}}}\right)^{1/\text{years}} - 1$$

New robot sales in 2024 reached **542,000 units**, maintaining stability ($\pm 0\%$) compared to 2023, and demonstrating a +7% CAGR from 2019–2024. This marks the **fourth consecutive year** that annual new installations have surpassed 500,000 units. The estimated average service life of an industrial robot is between **12 and 15 years**.

Regarding market size, the value of the robot market (excluding software and peripherals) was **$15.7 billion** in 2022. The value of the total robotic systems market, which includes surrounding equipment and services, is estimated to be approximately **four times** this core market value.

1.8.2 Sectoral and Geographic Distribution

The market growth is primarily driven by the **electronics** and **automotive** industries, with collaborative robots (cobots) also contributing significantly to market expansion.

The global distribution of installations is highly concentrated:

- **China** is the world's largest market for new installations, a position it has held since 2013. China installs **every other robot** globally, accounting for **54%** of all new annual installations.
- A vast majority—**80%** of all new robot installations—occur in just five countries: **China, Japan, USA, Korea, and Germany**.
- Within Europe, **Italy** stands out as the second-largest European country for new installations.

The scale of growth is highlighted by the historical operational stock data: starting from a modest 3,000 units in 1973, stock grew to 66K in 1983, 575K in 1993, and 800K in 2003, culminating in the 4.6 million units recorded in 2024.